DEMAND MODEL FOR CRUDE OIL RAIL AND PIPELINE SHIPMENTS IN CANADA

by

Adam Peter Lloyd Morrison

A thesis
presented to the University Of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Applied Science
in
Civil Engineering

Waterloo, Ontario, Canada 2018

AUTHORS DECLATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

This thesis contains sections that have been previously incorporated in journal articles, a report and conference proceedings, noted below:

"Modelling Crude Oil Rail and Pipeline Shipments in Canada for Quantitative Risk Assessment"

A report that was prepared for Transport Canada co-authored by Dr. Bachmann and Dr. Saccomanno, with myself contributing research to the development of the paper.

- **Chapter 1: Introduction:** Use of similar introductory content, with revision of information ordering as to fit thesis formatting.
- **Chapter 2: Literature Review:** Inclusion of the background and modal split literature from this report.
- **Chapter 3: Canadian Zonal Crude Oil Production and Destination Zones:** The original section from this report has been used.
- **Chapter 8: Conclusions and Direction of Future Work:** Original conclusions and direction of work from the report.

"Developing an Empirical Pipeline and Rail Crude Oil Mode Split and Route Assignment Model"

A conference paper, scheduled for publication by the Transportation Research Record in 2018, co-authored by Dr. Bachmann and Dr. Saccomanno, with myself as the primary author.

- **Chapter 5: Mode Split and Route Assignment Example:** The methods section from the paper were used to complete this section of the paper.
- **Chapter 6: Demand Model Trip Assignment:** The same case study was used in this paper, drawing the same conclusions between these two papers.

"Generalized Pipeline Cost Function"

Published in the Canadian Transportation Research Forum (CTRF) 52nd Annual Conference proceedings, taking place in May 2017. This paper was co-authored by Dr. Bachmann and Dr. Saccomanno and myself as the primary author.

- **Chapter 4: Generalized Cost Functions for Shipping Crude:** Section 4.1 of this chapter discusses the same results as we described in the paper.

ABSTRACT

Global energy demand is expected to increase significantly over the next 10-20 years, and in the absence of an increase in pipeline capacity, Canadian crude oil shipments are likely to be diverted to rail. The current rail loading capacity originating in western Canada is 754,000 barrels/day. This rail capacity is expected to meet the 1 million b/d deficit between western Canadian production forecasted for 2025 (5 million b/d) and existing pipeline capacity (4 million b/d). Western Canadian production is further forecast to reach 5.4 million b/d by 2030, representing a 39% increase from 2016.

The primary objective of this research is to obtain accurate current estimates of crude oil shipments by pipeline and rail in Canada (tonnages and volumes), and to use these data to calibrate and evaluate an empirical model of crude oil shipments by shippers' mode choice (pipeline and rail) and route selection. Modelling crude oil shipments allows for an assessment of the impacts of future changes in pipeline/rail network connectivity, modal attributes, and shipment protocols, on the expected pattern of crude oil shipments.

Origin Destination (OD) demands were based on empirical trade data. In particular, crude oil shipments beginning and ending in Canada are available from CANSIM, Statistics Canada's key socioeconomic database. These data were supplemented with other data from the National Energy Board (NEB) and the U.S. Energy Information Administration. Due to data limitations and the need for more disaggregated zones to characterize crude oil shipment patterns more precisely, shipments originating from (destined for) British Columbia or Alberta were split based on total production (attraction) data from the Canadian Association of Petroleum Producers, Alberta Energy, and the Canadian Fuels Association.

Numerous data sources were compiled to estimate cost functions for shipping crude by pipeline and rail in Canada. For pipelines, cost performance functions (shipper tolls) were found to depend significantly on shipping distance, route pipe diameters and shipment destination (domestic vs international). Moreover, medium and heavy crude were found to be more expensive to ship compared to condensate and light crude due to their lower viscosities. For rail, the distance shipped, a terminal fee and an international tariff surcharge were found to be statistically significant in explaining shipper costs along a route. These pipeline and rail cost models yielded R^2 values of 0.85 and 0.83, respectively.

Conventional Random Utility Models (RUM) fail to capture the complex interactions of pipeline shipments to determine mode and route choice shipper decisions, resulting in the development of a rule-based approach for mode choice and route assignment. This research found that the mode split, and route assignment of crude oil shipments are jointly determined by shipper types, destination types, prioritization rules, and allocation rules. This approach was validated by comparing predicted throughputs with those reported for Canada's Group 1 and Group 2 export pipelines, and applied to determine the impact of a 39% increase in western Canadian crude oil production, as forecasted by CAPP for 2030. Assuming no new pipeline infrastructure is constructed before 2030, several rail lines would carry increased amounts of crude oil.

ACKNOWLEDGEMENTS

I would first like to thank my two supervising professors, Chris Bachmann and Frank Saccomanno, both of which were incredibly patient and kind to me. During my two years there were many times that I had difficulty completing work for either personal or professional reasons, but the stuck through it with me. Giving me guidance and understanding time and again, pushing me to be able to complete this thesis. As well, a bright student, Daniel Chisholm, greatly aided in the research, helping to complete the Origin Destination data. Also researching the regulatory practices around crude oil productions and shipments.

I would like to thank my family and friends for being there during this time, providing me with constant encouragement and love. This thesis would not have been possible without them.

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1 INTRODUCTION

1.1 Background

Over 80% of bulk crude oil is shipped in Canada by pipeline, with most of the remaining quantity being shipped by rail tanker. Rail tanker shipments become feasible where pipeline capacity is limited, or where access to pipelines is unavailable due to poor connectivity at the origin and/or destination points. In recent years, improvements in pipeline capacities and connectivity have been inhibited in a large part by serious environmental and political concerns, namely unintended releases where detection and containment is difficult for pipelines buried several meters below ground. Recent moratoria on the Dakota and Keystone pipeline expansion projects are two examples of the uphill battle faced by industry proponents to get government approval for new pipeline construction. This has resulted in a greater dependency on rail tanker transport. Green and Jackson (2015) suggest that without expansion of the pipeline network, every new barrel of oil will need to be transported by rail. In 2015, about 140,000 barrels per day of crude oil - or about 4% of total Western Canada production were shipped by rail (Canadian Association of Petroleum Producers, 2016).

This transfer of crude oil shipment from pipelines to rail is likely to become more pronounced in the future, as the demand for crude increases subject to expanding global markets (especially in Asia). According to CAPP (2017), almost 100,000 barrels per day (b/d) of western Canadian crude oil were transported to market by rail in 2016, and almost 140,000 b/d were transported by rail in the first quarter of 2017. Moreover, the current rail loading capacity originating in western Canada is 754,000 b/d. This rail capacity is expected to meet the 1 million b/d deficit between western Canadian production forecasted for 2025 (5 million b/d) and existing pipeline capacity (4 million b/d). Western Canadian production is further forecast to reach 5.4 million b/d by 2030, representing a 39% increase from 2016.

1.2 Problem Statement

The risk implications of these pipeline to rail modal shifts is not well understood, and need further scientific study. A review of US crude oil incidents from 2005 to 2009 indicates that rates for pipelines per ton-miles are overwhelmingly lower than rail. This review suggested only 0.58 pipeline incidents would occur as compared to 2.08 rail incidents on a per billion ton-miles basis (Furchtgott-Roth & Green, 2013). The Fraser Institute presented similar conclusions for Canada, finding that between 2003 and 2013, there were 0.049 pipeline incidents compared to 0.226 rail incidents, per million barrels of oil. (Green and Jackson, 2015).

These studies only focused on rates of incidents and not their consequences. Failure in pipelines can occur in a number of ways, such as, corrosion of welds and tank walls, crush loads from overburden, impact puncture loads experienced during excavation, damage to valves (normally at the terminus or trans-shipment points), etc. Any of these releases can involve fire, which has its own release hazard mechanism. While the risk of accidental releases from pipelines is lower than for rail, if a spill or leak were to occur and remain undetected for a period of time, the long-term impact on the environment could be extensive. Streams, lakes, rivers and groundwater would be contaminated for many years into the future.

To analyze the risks associated with the transportation of crude oil, a freight model is required for predicting shipment volumes, modes, and routes for different shipment scenarios.

1.3 Research Objectives

Notwithstanding the importance of quantitative risk assessment (QRA), the research discussed in this thesis only covers a small but important step in the process - that of estimating crude oil flows by mode, and route for input into a future crude oil QRA model. The primary objective of this research is to obtain estimates of crude oil shipments by pipeline and rail from existing Canadian data sources, and to use these data to calibrate and evaluate Canada-wide empirical models of crude oil mode split and route assignment. These models permit an objective assessment of how expected crude oil volumes and tonnages are affected by changes in transport conditions and protocols. For example, policy makers could use a crude oil freight demand model to estimate the impact of implementing the Keystone XL pipeline expansion project on the distribution and costs of shipments by mode in the US and Canada. Alternatively, historic or forecasted growth rates could be applied to existing demands to estimate crude oil shipments on a mode and route specific basis in future years.

This research comprises four major tasks:

1. Obtain current estimates of crude oil production and consumption totals by shipper and in total by origin/destination zonal pairs for Canada and border gates.
2. Configure the current Canada-wide rail and pipeline freight networks and obtain corresponding empirical link/route generalized cost functions for the transport of bulk crude oil.
3. Develop and validate a rule-based mode choice-route assignment algorithm for shipping crude oil by pipeline and rail. The rule-based algorithm should reflect current National Energy Board (NEB), Transport Canada (TC), and assumed carrier shipper prioritization in allocating limited pipeline capacity.
4. Apply the model to the existing pipeline/rail crude oil distribution network (the base case), and demonstrate how it can be used to predict changes in crude oil flow patterns and mode share subject to changes in specific transportation protocols using two case studies.

1.4 Research Scope

This thesis is constrained to the North American crude oil distribution network. Shipping patterns within Canada and internationally to the United States are the primary focus with; intra-US shipments being excluded from the analysis. Shipments to the US are only modelled on physical pipeline and rail infrastructure in Canada, as US destinations are represented by external zones with centroid connectors to a Canadian gateway. Finally, even though there are other modes of transport, such as highway and marine, these modes are not taken into consideration as the pipeline and rail modes account for almost all shipments of crude oil in Canada.

1.5 Thesis Organization

The remainder of this thesis is organized into six major sections. Section 2 introduces typical concepts in freight demand modelling, including an in-depth literature review of the regulatory practices around crude oil companies, pipeline regulation, generalized cost functions and freight mode choice models. Due to the lack of prior research in modelling crude oil shipments, a number of gaps are identified, which are tackled in subsequent sections. Section 3 presents the results of a data collection effort from various sources to establish origin-destination (OD) matrices of crude oil shipments for Canada. OD matrices represent the "demand" side of a freight demand model. Section 4 estimates generalized cost functions for shipping crude by pipeline and rail. Generalized cost functions are used to represent the costs of using the transportation network and represent the "supply side" of a freight demand model. Section 5 presents a joint mode split and route assignment model that combines OD demands with generalized cost functions to determine the tonnage of crude oil shipped by rail and pipeline. A hypothetical example demonstrates how this model may be applied to a full-scale Canadian application. Section 6 presents a full-scale Canadian crude oil freight demand model, which is applied to changing pipeline capacities and crude oil demands Section 7 provides a summary of key findings, limitations, and a discussion of future research directions.

2 LITERATURE REVIEW

2.1 Background

Many concepts in freight demand modelling have been borrowed largely from travel demand modelling. As noted by de Jong, Gunn, & Walker (2004), important differences between modelling freight and personal travel demand include: the diversity of decision-makers (shippers, carriers, intermediaries, drivers, operators), and items being transported (such as, parcel deliveries with many stops to single bulk shipments comprising hundreds of tonnes). Despite the differences between freight and personal travel, researchers have successfully applied the four-stage model paradigm to predict and describe shipper decision-making patterns.

The four-stage model of shipper decisions involving crude oil transport (tonnes or m^3 per month or year) is illustrated schematically in Figure 2.1, as aggregated at the zonal level (sources of production and attraction). The model describes and predicts changes in crude oil shipment patterns (OD, mode choice, route selection) subject to changes in modal characteristics and shipment protocols. For example, how does the addition of a pipeline link to the network affect current rail movements between a given production and destination point? What are the expected changes in risk? What are the cost implications? Etc. The key aspects of this four-stage model application to crude oil shipments is illustrated in Figure 2.2.

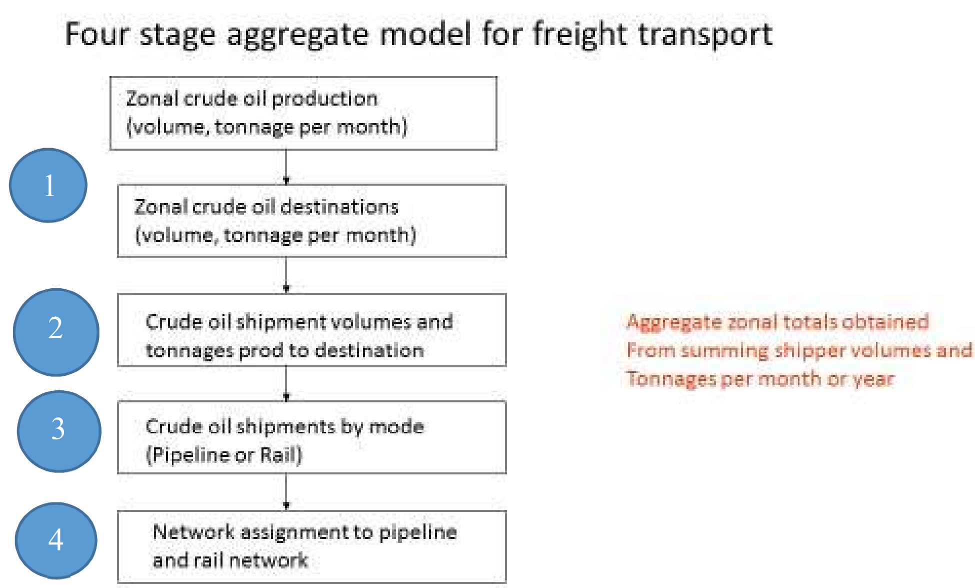

Figure 2.1: Four stage model framework for crude oil shipment analysis

The specification of these models at various stages requires accurate crude oil shipment data at both the shipper and aggregate zonal levels. These data would apply to current or base year observed shipping scenarios. In this thesis, the primary focus of the discussion is pipeline/rail mode split and route assignment (Stages 3 and 4 in the process). Total crude oil tonnages produced in each origin zone and processed at a given destination (port or refinery) have been extracted from the crude oil data obtained from Statistics Canada, the NEB, and the Energy Information Administration (EIA) for the years 2010-2015. These estimates serve as basic inputs into Stages 1 and 2 of the sequential four stage process. These data are also used to validate and calibrate the models developed as part of Stages 3 and 4.

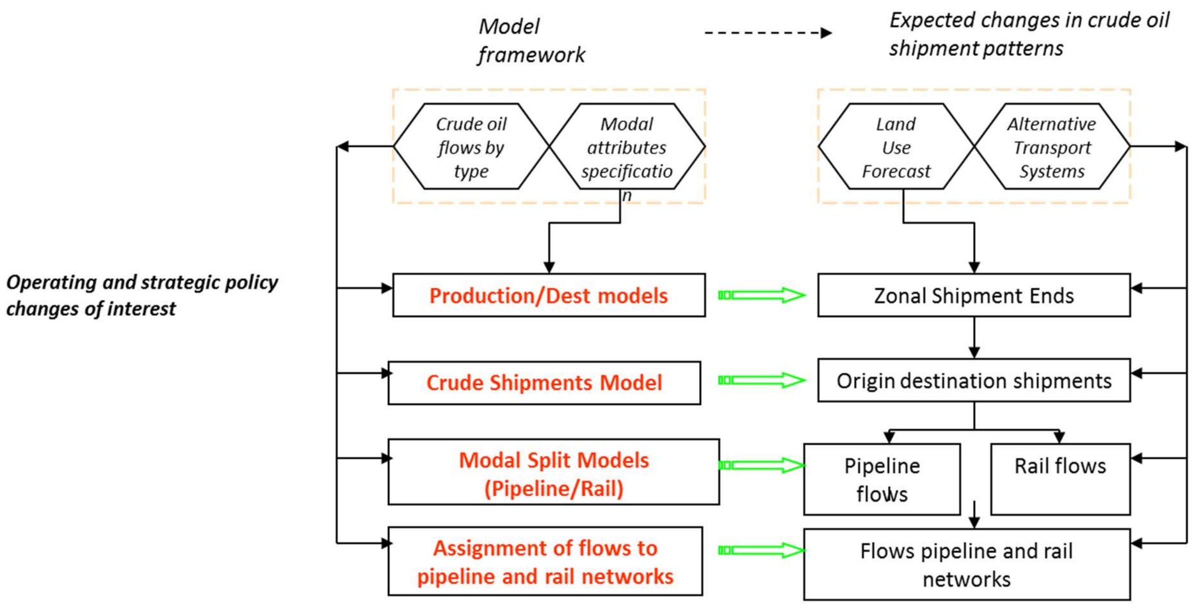

Figure 2.2: Schematic framework for analysis of selected changes in crude oil operating and strategic policies.

2.2 Crude Oil Regulations

An understanding of key stakeholders and regulations is necessary to determine stages 3 and 4 of a freight demand model and apply the decision-making framework to crude oil producers in Canada. Figure 2.3 outlines the interactions of governing bodies in their regulatory roles, as well as their connections to decision making by crude oil producers and pipeline owners. This discussion centers on pipelines, since they are initially the preferred mode for shippers of crude oil.

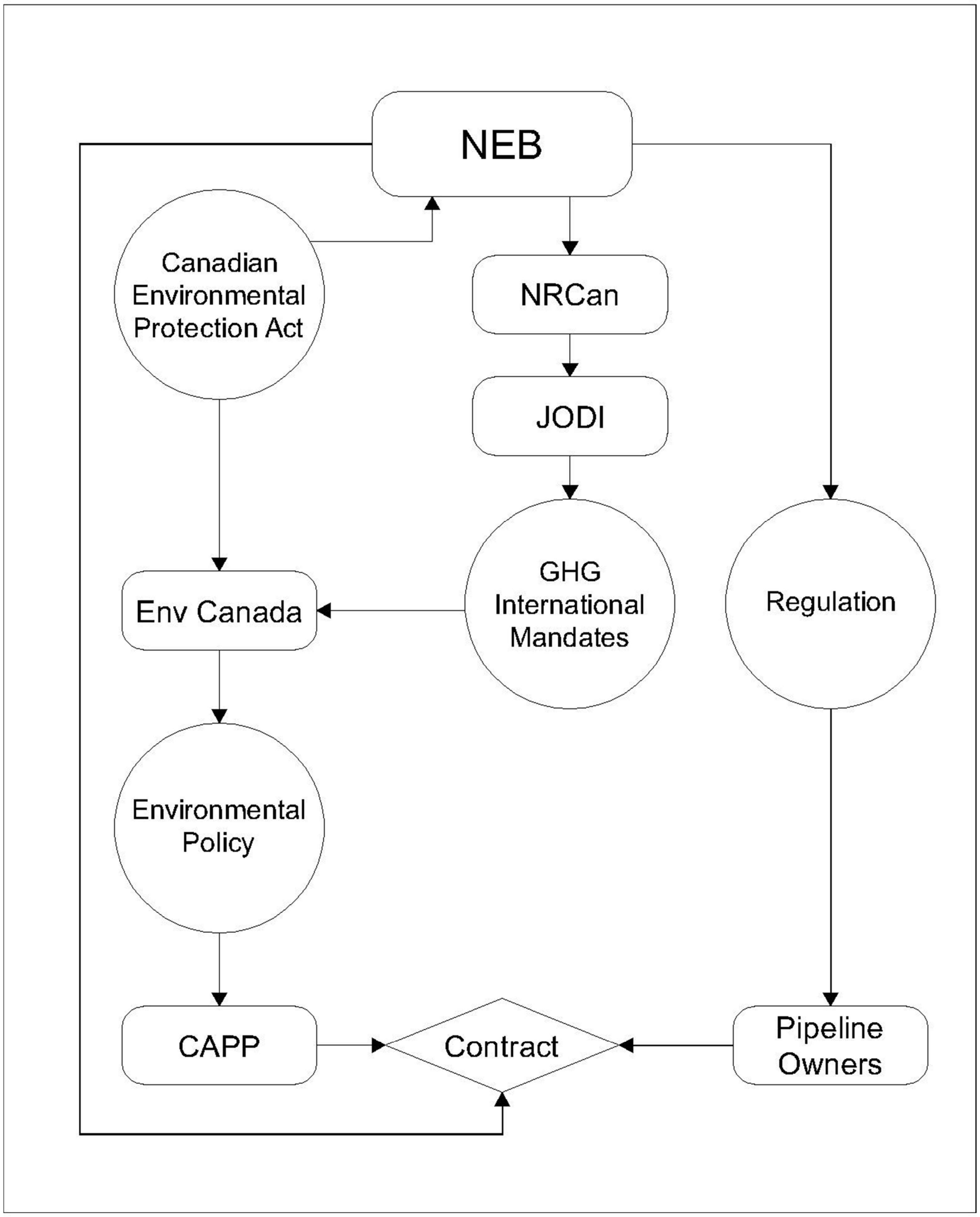

Figure 2.3: Canadian Crude Oil and Gas Contract Flow Chart

The National Energy Board (NEB) creates regulations for pipeline owners and approves contracts between petroleum producers and pipeline owners (NEB, 2016). The NEB regulates the interprovincial and international pipelines, while the intra-provincial pipelines are regulated by the provincial energy regulator (NEB, 2016). The Canadian Association of Petroleum Producers (CAPP) represents 90% of petroleum producers in Canada and is therefore used to represent all crude oil producers (CAPP, 2014). The NEB also supplies shipment data, including imports and exports, to Natural Resources Canada's (NRCan) energy division for use in statistical data which is compiled and used internationally in the Joint Organisations Data Initiative (JODI) database (Wright, 2012). The JODI hosts statistical data on 90 countries regarding import, export, and production of oil and gas (Wright, 2012). JODI provides information to world leaders which may in part help determine GHG international mandates. These mandates along with the Canadian Environmental Protection Act are presumed to influence Environment Canada's determination of environmental policy. Environmental policies apply to all industries including both petroleum producers and pipeline owners.

The NEB's 2016 Canadian Pipeline Transportation System Energy Market Assessment (NEB, 2016) outlines how pipeline owners determine usage and the NEB's role in taking in complaints filed by producers against a pipeline company in regard to tolls, tariffs or access. This document also discusses the idea of netback price which is the world oil price of a comparable type of oil minus the cost of moving the product to the market. Since the netback price on pipelines compared to rail lines is considerably lower, a much greater proportion of crude oil is shipped on pipelines. The North American comparable reference type is West Texas Intermediate, WTI, while the offshore crude oil reference type is North Sea Brent or Brent.

The following excerpt from the NEB webpage (2016) outlines NEB regulation regarding tolls, tariffs, and access:

"A pipeline company cannot charge a toll unless it is included in a tariff filed with the NEB or approved by a Board order."

"A pipeline company's tariff contains the conditions under which transportation service is provided. The tariff includes conditions related to accepting new shippers, allocating capacity to shippers, and describing the type of service offered and associated terms as the quality of hydrocarbons and financial assurances requirements for shippers."

"Pipeline companies must operate according to the principle of open access. This means that all parties must have access to transportation without discrimination, as long as they meet the requirements of the tariff."

Pipeline capacity use is further determined by pipeline type. There are two types of pipeline carriers: common and contract. A common carrier has producers nominate volumes for delivery into the pipeline and if the total volume between all shippers reaches or exceeds the capacity of the line, each shipper's nominated volume is apportioned not to exceed total pipeline. Contract carriers require a take or pay contract that specifies that the shipper must pay for the contracted volume whether they use it or not. Most contracted carriers maintain volume for common carriage as well (NEB, 2016).

If pipelines are at capacity, producers may lose money as they may not be able to sell as much of their product. This in turn can justify the switch to an alternative mode. Pipeline is the predominate mode of transport due to cost of rail being far more expensive, but as the netback available to sellers increases, this mode may become a viable option.

An additional piece of information that is key to understanding where and by what mode a producer will use is to consider any outstanding take or pay contracts they may have. With these contracts, a consumer has negotiated a fixed price, usually lower than the current market price as of signing, for the product with the understanding that whether the consumer takes the product they must pay this price (Rogers & White, 2014). This form of contract is used to protect the producer against market fluctuations.

2.3 Freight Mode Split Modelling

Two types of approaches have been adopted in freight demand modelling: aggregate and disaggregate. The aggregate approach describes the volume of freight being moved from a given production or origin zone to a given destination or zone of disposition (e.g. crude oil refinery, trans-shipment or storage complex or port). The model serves to predict flows from origin to destination, predicts the mode used by the shipper, and identifies the desired routes for each selected mode. Disaggregate freight models consider the individual shipper and their shipping "behavior" and costs. Zonal trips in the aggregate models are simply totals of individual shippers located in each zone. Since destination points in crude oil models tend to be larger entities, a good way to carry out a disaggregate analysis is to focus on the production end (individual shipper) and ship to common point of disposition at the destination end.

The conventional approach to modelling mode choice at the aggregate and disaggregate levels is based on Random Utility Maximization (RUM) theory. In RUM mode split models, a decision maker (or shipper, s) faces a choice among P modes (e.g., pipeline and rail). The decision maker chooses the mode that provides the greatest utility (U_{sp}). Some attributes of the utility function are from a shipper perspective and some are from a modal point of view. We begin by specifying a function (linear) that relates mitigating factor inputs to an "observed" V_{ss}. Utility is expressed into that which can be measured and that which is unknown and not included, such that utility is expressed as $U_{sp} = V_{sp} + \varepsilon_{sp}$, where ε_{sp} captures the factors that affect utility but are not included in V_{sp}. Since the researcher does not know $\varepsilon_{sp}\ \forall\ p$, these terms are treated as random.

If it is assumed that ε_{sp} is independently and identically distributed (iid) (Gumbel) for all p, the Multinomial Logit (MNL) model can be derived (Train, 2009), which has a closed-form probabilistic expression of the form:

$$P_{sr} = \frac{e^{V_{sr}}}{\sum_{p=1}^{P} e^{V_{sp}}} \quad \textbf{(2.1)}$$

where P_{sr} is the probability that decision maker s chooses alternative r. Representative or systematic utility is commonly specified to be linear in parameters, $V_{sp} = \boldsymbol{\beta}'\mathbf{x}_{sp}$, where $\mathbf{x}_{sp}$ is a vector of observed variables relating to alternative p. With this specification, the MNL choice probabilities become:

$$P_{sr} = \frac{e^{\beta'_{sr}}}{\sum_{p=1}^{P} e^{\beta'_{sr}}} \quad \textbf{(2.2)}$$

In typical MNL model applications for travel demand models, model parameters ($\boldsymbol{\beta}'$) are estimated using maximum likelihood methods on disaggregate data (i.e., choice data). In freight demand modelling, where there are limited data (especially disaggregate data, partly due to confidentiality reasons), the model parameters are sometimes estimated using a regression of log market shares on aggregate data (i.e., market shares):

$$\ln\left(\frac{S_r}{S_p}\right) = \beta'(x_r - x_p) \qquad \textbf{(2.3)}$$

where S_r and S_p are the aggregate market shares (from all decision makers) for alternatives r and p respectively, representing estimates of the overall choice probabilities (P_r, P_p). Equation 2.3 is referred to as an "aggregate logit model" and is derived by dividing two logit probabilities (Equation 2.2) by each other, and taking the natural logarithm of both sides of the resulting expression.

Although the aggregate logit model is based on utility maximizing behavior, it assumes all variation in characteristics of individual decision makers belongs to the error component of the utility function (ε). This assumption is somewhat far-reaching, and hence aggregate logit models are often viewed simply as pragmatic models that yield plausible results (Tavasszy & de Jong, 2014). Several RUM models that have been applied to freight mode choice are summarized in Table 2.1.

Table 2.1: RUM Mode Choice Freight Models

Reference	Model (Data)	Modes	Variables
Arencibia, Feo-Valero, García-Menéndez, & Román (2015)	Multinomial Logit, Mixed Logit (Disaggregate – SP)	Road Road - Rail Road - Marine	Cost Time Delay Frequency
Kawamura, Mohammadian, Pourabdollahi, & Samimi, (2014)	Binary Probit (Disaggregate – RP)	Road Road – Rail	Distance Weight Impedance (distance, travel time, and cost) Containerized* Commodity*
Pourabdollahi, Karimi, & Mohammadian (2014)	Multinomial Logit (Disaggregate – RP)	Road Rail Air Courier	Commodity* Containerized* Fragile* Perishable* Value International* Cost Distance
Lloret-Batlle & Combes (2013)	Multinomial Logit (Disaggregate - RP)	Private Carrier Common Carrier Rail Combined Transport Inland Waterway Sea Air	Size Value Density Distance Refrigerated* Hazardous* Fragile* Rail Access* Waterway Access*

Table 2.1 - Continued

Ding, Liu, Xie, & Wang (2013)	Binary Probit Binary Logit (Aggregate – Freight Analysis Framework (FAF))	Road Rail	Commodity* Value of Time* Trade Type* Origin* Highway Mileage/Railway Mileage Ratio in Origin Zone Highway Mileage/Railway Mileage Ratio in Destination Zone Weight Value Distance Fuel Cost
Mitra (2013)	Multinomial Logit HEV Probit Model Mixed-Logit Model (Disaggregate – RP)	Rail Road	Cost Time Capacity Quantity Commodity*
Shen & Wang (2012)	Binary Logit Regression (Aggregate – Freight Analysis Framework (FAF))	Rail Road	Weight Value Distance Time Fuel Cost
Rich, Holmblad, & Hansen (2009)	Weighted Multinomial Logit (Aggregate and Disaggregate)	Road Road - Rail Road – Marine Rail Marine	Time Cost
de Jong & Ben-Akiva (2007)	Multinomial Logit (Disaggregate)	Road Rail Marine Air	Marine Access* Rail Access* Company Size* Value Density Cost Time
Norojono & Young (2003)	Heteroscedastic Extreme Value (HEV) (Disaggregate - SP)	Rail Road	Cost Time Reliability Flexibility Containerized* Value* Size*

** indicates an interval or "dummy" variable that takes a value of either 1 or 0.*

In recent years, a number of activity-based models have been adopted for mode choice/route assignment applications. Several of these models use decision trees to explain mode choice and routing decisions, replacing conventional RUM models. However, it is believed that the structure of decision trees may be highly correlated to predictors that aspire to capture the shipper behavior mechanism, i.e., how shippers decide between pipelines and rail in their crude oil transport decision, and how they seek to reduce their shipping costs through cost-effective mode and routing choices. This makes the process difficult to model using simple decision tree structures.

A rule-based approach was suggested by Arentze & Timmermans (2004) to address some of the mechanistic limitations of decision trees. This model is referred to as ALBATROSS for A Learning-Based, Transportation-Oriented Simulation System. ALBATROSS adopts an activity based logic to underscore decisions of mode and route choice by shippers. Travel (shipping) behavior is derived from theories of choice heuristics that consumers apply when making decisions in complex environments. The approach is most comprehensive in predicting which activities are conducted (prioritization of activities), when, where, for how long, and with whom, and the transport mode involved. In addition, various temporal, spatial, spatial-temporal, and institutional constraints have been incorporated in the ALBATROSS logic.

Along similar lines to ALBATROSS, a rule-based intelligent network simulation model expert system known as the INSIM was developed to simulate time-dependent mode choice decision-making for movements in the presence of multimodal information (Memon, Meng, Wong, Lam, 2015). The Intelligent Expert System (IES) model was initially developed for person trips, but in this discussion our focus is on its applicability to the movement of freight. In this context, IES can be used to capture interactions among available modes and decides on the desired shipper mode, based on shipper attributes, commodity type and prevailing shipping conditions. The shipper mode choice behavior can be represented by cognitive rules in the rule-base of the IES. Three different models were considered by Memon et al. (2015): (1) pure rule-based models (PRB), (2) discrete choice models (DCM), and (3) probabilistic models (COM), which were applied to investigate trip-making patterns and formulate mode choice decisions.

2.4 Factors Affecting Shipper Mode Choice and Routing Selection

As illustrated in Figure 2.4, the two most important factors affecting freight mode choice in a sample of freight shipping studies are time and cost. Characteristics of the shipment, such as value/density and weight/size/quantity were also found to influence mode choice in half of the studies. It is not that shippers do not consider characteristics of the shipment, but rather that they may have used different related variables including interval variables such as commodity type, containerized, refrigerated, hazardous, etc. (not shown in Figure 2.4). Delay/reliability, frequency and flexibility were used less often in these studies, as it was likely hard to obtain detailed information on these characteristics for choice modelling.

Overall, even from a relatively small sample of recent studies, it is clear that the characteristics of the mode, especially time and cost, and the characteristics of the shipment, particularly the value and size, are important determinants of a shipper's mode choice.

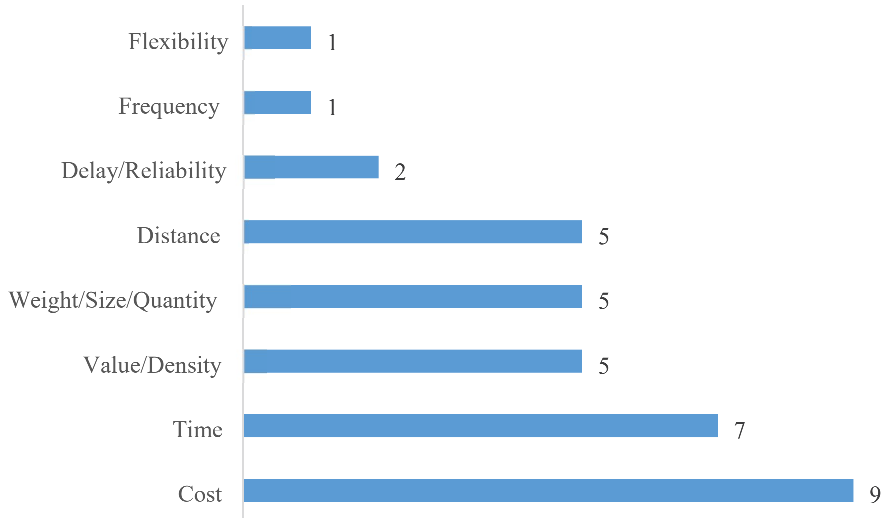

Figure 2.4: Attribute Occurrences in Previous Mode Choice Models (Table 2.1)

It can be noted that there does not appear to have been any specific study dealing with specific components of a freight demand model applied to crude oil shipment. Hence, the remainder of this thesis builds upon the four-step model paradigm (Figure 2.1) to develop a Canadian crude oil freight demand model.

2.5 Freight Network Models

A generalized cost function defines the cost of using a link or route in a network model. While there is currently no research describing the generalized cost functions of pipelines, there are numerous studies focusing on the shipment of freight by rail. These approaches can be applied to pipelines using similar theories and regulatory rules between these two modes. Cost functions can be found in an array of different model types, including demand models, scheduling optimization models, and literature related to the observation of how policy has affected freight networks.

As this thesis focuses on developing a freight demand model, previous freight demand models were the most heavily studied articles for developing generalized cost functions. Research in this field dates back several decades, the first paper reviewed is from 1980 (Friedlaender & Spady, 1980). Models improved over time with multiple additions to the preceding models and cost functions. One advancement occurred with the introduction of geospatial networks, using the geographic information system (GIS), creating freight shipment modelling programs such as NODUS (Jourquin & Beuthe, 1996). GIS allowed for extremely complex and accurate network models to be developed, along with a visual interpretation of the data, giving researchers greater ability to implement demand models. An example of one of the first models of this type was the US network based on the 1997 Commodity Flow Survey (Southworth & Peterson, 2000).

A primary consideration of cost functions is congestion: the increase in the cost of using a link with increases of its usage. Considering congestion is important as many networks will suffer from bottle necking and high levels of congestion, altering the initial shortest path routing patterns to compensate for these cost increases. The evidence of increasing congestion has been used to provide reasoning for the investment in new rail infrastructure in numerous countries to either counter bottle necks or reduce network costs, as seen in the Philippines (Yamada, Russ, Castro, & Taniguchi, 2009) and the US (Pazour, Meller, & Pohl, 2010). These models consider how post haulage of freight could cause additional costs and congestive effects due to the increased load on the road network from trucks taking the rail freight from the rail yards to their final destination. Thus, increasing the complexity in models by considering the destination point congestion that generates bottle neck effects, in which the processing times for the freight transfers begins to limit the shipping capacity, increases the overall shipment times and costs at specified terminals.

There has also been research into the elasticity and sensitivity of the network link performance with respect to both monetary costs and shipping time. Studies observe aspects of the cost functions that could be impacted by alterations of network demands or infrastructure availability. An example of this was the observation of adding unannounced shocks on the Australian network (Wijeweera, To, & Charles, 2014), with Jourquin, Tavasszy, & Duan (2014) observing similar effects on the European network.

The most recent work has been moving towards increasing the complexity of models, solving them using discrete choice models on a multimodal network. An example of this was completed by Feo-Valero, García-Menéndez, & Saz-Salazar (2016), observing the Spanish network, using this higher degree of complexity to understand why there is lack of rail freight shipments. Multiple demand models that were researched have been summarized below in Table 2.2.

Table 2.2: Summary of Demand Models

Number	Article Name	Author	Date	Model Summary	Unit Cost
(1)	A Derived Demand Function for Freight Transportation	Ann F. Friedlaender and Richard H. Spady	Aug-80	Demand model that observes the network in short term equilibrium. Reviewing labour, capital, and materials as the variables for costs, with the distance as a modifier. Also using dummy variables for product types, and regions.	Monetary
(4)	Predicative intercity freight network models	Terry L. Friesz, Roger L. Tobin, and Patrick T. Harker	Nov-83	Models for predicting intercity freight, with discussion on combined shipper-carrier models, spatial process equilibrium and their uses to increase the accuracy of models.	N/A
(6)	Transportation Policy Analysis with a Geographic Information System the Virtual Network of Freight Transportation in Europe	Bart Jourquin and Michel Beuthe	Dec-96	Presents a multi-modal freight based on digitized geospatial network. Performing an analysis on all aspects of modal transport using software called NODUS. Specified around wood transportation.	Monetary
(7)	Intermodal and international freight network modeling	Frank Southworth and Bruce E Peterson	Feb-00	Large US network simulation, based on a multimodal and intercontinental freight system with shortest path solution. Utilizing approximately 5 million OD's	Distance

Table 2.2 – Continued

(8)	Comparison of external costs of rail and truck freight transportation	David J. Forleenbrock	May-01	The estimation of external costs for four different types of freight trains, for each type three general cost and a comparison to private costs. The general costs include accidents, emissions and noise. Observing the modal split when user incurs full costs of transportation.	Monetary
(9)	Designing Multimodal Freight Transport Networks - A Heuristic Approach and Applications	Tadashi Yamada, Bona Frazila Russ, Jun Castro and Eiichi Taniguchi	May-09	This model was used for evidence in the investment of rail freight infrastructure in the Philippines. Based on a multilevel, multimodal assignment method, the upper-level using combinatorial optimization and heuristic approach.	Monetary
(10)	A model to design a national high speed rail network for freight	Jennifer A. Pazour, Russell D. Meller and Letitia M. Pohl	Mar-10	A model to incorporate a high-speed rail freight network into the existing US network, using it to reduce the congestion on the highway freight network. Using the parameters of distance, flow, average velocity and budget.	Time
(12)	Market area of intermodal rail-road container terminals embedded in a hub-and-spoke network	Sabine Limbourg, and Bart Jourquin	Mar-10	This is a comparison of the road and road-rail networks, taking the network structure, operational costs and location of the road-rail terminals into consideration, with an attempt to reduce costs. Based on a Hub-and-Spoke modelling method for Europe.	Monetary
(15)	On the generalized cost - demand elasticity of intermodal container transport	Bart Jourquin, Lóránt Tavasszy and Liwei Duan	Jan-14	Developing the elasticities that are typically unavailable for freight transportation, and looking at how the modes that compliment each other are different to what is discussed. This is based off a cross continental European model using a sensitivity analysis.	Monetary
(16)	An empirical analysis of Australian freight rail demand	Albert Wijeweera, Hong To and Michael Charles	Mar-14	Modeling the impact of an unannounced shock in freight on the Australian network using vector regressive (VAR) model and annual data set over 40 years. Model having been based on aggregate data, ignoring sectoral impacts, effects being related to the commodity type.	Monetary

Table 2.2 – Continued

(18)	Estimating Freight Transport Price Elasticity in Multi mode Studies: A Review and Additional Results from a Multimodal Network Model	Michel Beuthe, Bart Jourquin and Natalie Urbain	Sep-14	This is a detailed comparative review of the price elasticities between multiple papers. Determining factors to explain the diversity of estimates such as data aggregation, different markets and methodology. Developing elasticity estimates for Rhine area market.	Monetary
(19)	Assignment of Freight Shipment Demand in Congested Rail Networks	Taesung Hwang and Yanfeng Ouyang	Dec-14	In the foreseeable future US rail freight is expected to increase dramatically, approximately 88% by 2035, causing congestion and inefficiency on the existing network. The base model is a multimodal disaggregate model.	Time
(20)	Cost Functions in Freight Transport Models	Katrin Brumerstedt, Verena Flitsch and Carlos John	Aug-15	Using models to estimate the expected impact of policy and to justify investment in infrastructure for Port Hamburg. With the impact assessment, typically generalized cost for purchase costs which amount operator's costs passed onto the shippers.	Monetary
(22)	Rail freight transport and demand requirements: An analysis of attribute cut-offs through a stated preference experiment	Maria Feo-Valero, Leandro Garcia-Menendez, and Salvador del Saz-Salazar	Jan-16	What the road and rail freight split in Spain is, and discussing how the rail is lacking. It is a discrete choice model, established through a 2-phase fieldwork.	Monetary

Aside from these typical demand models there are also models specifically designed for the optimization of scheduling. The earliest of the reviewed papers observed the additions to the Brazilian freight network in (CRAINIC et al., 1990), in which there was an introduction to the strategic analysis and planning of national freight network model (STAN). Since there was increasing rail freight shipments in the 90's there was an increased interest in scheduling, due to associated times at rail terminals resulting in additional congestion. Kwon, Martland, & Sussman (1998) observed the US network with statistics from the 1997 US Survey, researching how congestion could be minimalized through optimized scheduling.

Another aspect of scheduling and planning for the network model is optimizing fleet sizing as demonstrated by (Bojović, 2002). Based on the existing European rail freight system, using a 3-step hierarchy for decision making; optimization; adaptation; self organizing, to determine the fleet sizes to be applied on the network. More recently, a similar model has been developed considering of elasticities (Kuo, Miller-Hooks, & Mahmassani, 2010). These models have been shown to train slot selections in a multi-commodity networks, while minimizing the costs. The most recent model is still observing the fleet optimization, however, increasing the complexity of prior models by using stochastic modelling, specifically the rolling horizon approach (Milenković, Bojović, Švadlenka, & Melichar, 2015). Below, examples of the scheduling models have been summarized in Table 2.3.

Table 2.3: Summary of Scheduling Models

Number	Article Name	Author	Date	Model Summary	Unit Cost
(2)	A Model for the Strategic Planning of National Freight Transportation by Rail	Teodor Gabriel Crainie, Micheal Florian and Jose Eugenio Leal	Feb-90	A multimodal, multiproduct network optimization with an iterative strategic analysis and planning of national freight (STAN). Developing a network to incorporate the rail freight network into the existing Brazilian model.	Time
(3)	Routing and scheduling temporal and heterogeneous freight car traffic on rail network	Oh Kyoung Kwon, Carl D. Martland and Joseph M. Sussman	Jun-98	Review of several ways to improve scheduling practice and describe dynamic freight routing and scheduling model that can produce more achievable and market sensitive analysis. Using a linear multi-commodity flow problem on a time-space network.	Time
(5)	A general system theory approach to rail freight car fleet sizing	Nebojsa J. Bojovie	Jan-02	Based on the existing European freight rail system, modeling fleet sizes to reduce costs of and optimize shipments. Based on a 3-step hierarchy for decision making; Optimization (lowest current costs); Adaptation (future costs); Self organization (required freight).	Time
(14)	Freight train scheduling with elastic demand	April Juo, Elise Miller-Hooks and Hani S. Mahmassani	Nov-10	Improvement of train slot selection in a multicommodity network, minimizing costs and delays. It is a simulation-based iterative framework with the rail service recomputed based on a developed algorithm.	Monetary and time
(21)	A stochastic model predictive control to heterogeneous rail freight car fleet sizing problem	Milos S. Milenkovic, Nebojša J. Bojović and Libor Švadlenka	Oct-15	Using stochastic modelling, specifically using the rolling horizon approach, an optimization of rail fleet and its allocation is observed. This is a dynamic model with loaded and empty car flows to explicitly treat state, control and station capacity constraints.	Time

The final set of literature reviewed focuses on the importance of how regulations and policies effect the pricing of freight shipments, first reviewing the effects on shipment regulation when the same authority controls and plans both the supply and transportation of freight (Crainic & Rousseau, 1986). Their paper observes the delays caused by the policies effecting the terminalling of freight as opposed to the physical limits, giving congestive effects that are not based on typical capacities. Spychalski & Swan (2004) considered the effects of major deregulation on shipping requirements from the US government, starting in 1975 and observed till 2004.

Reports commissioned by the Government of Canada, led by Transport Canada, observe the total cost of rail shipments. By understanding the total usage costs for the ownership of a rail line, Transport Canada sought to provide insight into whether or not the charges applied by rail companies are acceptable, or if these carrier companies need to change their fee schedules. In the (Group, 2008) and (Government of Canada, 2007) reports, it is investigated whether these carriers would be able to pay social costs with their existing shipment fees. However, the Government of Canada (2007) report was later criticized by the CN rail company for improperly representing their costs (as provided in the appendix).

A review of the common fee structures and additional fees of the rail companies were observed. While these are not applicable to the pipeline companies, they are still beneficial for the rail specific cost functions. Also, as previously discussed in Section 2.2, there has already been a review of typical pipeline shipping practices. The first major rail company discussed is CN, which owns a substantial portion of the Canadian Class 1 freight shipping lines. There are many rules applicable to the shipment rates that CN will apply based on different aspects of the shipment itself, as well as the route that shipment will take. The first of these are the acceptance of intermodal traffic, detailing the acceptable containers for movement on the CN network with penalty for the infringement of these restrictions. Continuing to the mileage equalization, in which if cars owned by CN, are shipped on the network without any loading, to make up for the used space there is an additional fee of $1/empty mile, enacted if the distance travelled while empty exceeds the loaded miles by 6% (i.e. for a trip of 100 miles with loading, the distance traveled while unloaded may not exceed 106 miles, if it does an additional fee 1$/mile will be added). For privately owned cars these fees will only apply to shipments that have occurred entirely within Canada, to the portion of an international movement that is within Canada, or Canadian domestic movements where a portion of the movement occurs within the US, excluding the traveled distance within the US.

For this thesis, especially as the focus is on a dangerous good, the regulations are paramount to the understanding of rail freight shipping. Tariffs are scheduled by both CN and CP, however only the CP tolling rates were publicly available. From the set of tariffs available from CP, four are applicable to the rail network, as listed below:

Tariff #1 – Products and services guide

This tariff is the outline to all available services provided by CP, describing that "CP" shall mean, each and together, Canadian Pacific Railway Company, Dakota, Minnesota & Eastern Railroad Corporation, Delaware and Hudson Railway Company, Inc., and SOO Line Railroad Company. That all subsequent tariffs shall be applicable to the listed rails.

Tariff #2 – Railcar supplemental services

This tariff outlines all additional fees incurred when paper work is incorrectly reported or that there is infringement upon the agreed shipping terms. Also, outlines the surcharges typical to shipments such as the use of shipment containers and the rental fees (outlined in Tariff #8) and a customs user fee of $9.75 per car when shipping into the US on CP.

Tariff #3 – Intermodal supplemental

This tariff outlines the post delivery charges and to facility fees primarily detailing additional fees for CP to assist in the post processing of all deliveries, also the penalties incurred for improper shipment. The most applicable surcharge being the Customs user fee at $2.36 (USD) per container, applicable to all shipments into the US. All other fees are not reasonably applicable for the scope of this project.

Tariff #8 – Hazardous commodities

This document outlines the surcharges and penalties around the shipment of dangerous goods, the most prevalent and applicable being the charges is Asset Use. A fee of $160 per day for the shipment of dangerous goods on a CP rail car, and Hazardous commodity surcharge intermodal at $80 per container, applied to US domestic, cross border, and international import/exports of dangerous goods.

These policy and regulatory papers have been summarized in Table 2.4 shown below.

Table 2.4: Summary of Policy Papers

Number	Article Name	Author	Date	Model Summary	Unit Cost
(11)	Multicommodity, multimode freight transportation a general modeling algorithmic framework for the service network problem	Teodor Gabriel Crainie and Jean-Marc Rousseau	Jun-86	Observation of the problems with of freight transportation when the same authority controls and plans both supply of transport and routing of transport. Network was solved using an optimization algorithm.	Monetary
(13)	US rail freight performance under downsized regulation	John C. Spychalski and Peter F. Swan	Sep-04	US rail freight has drastically changed since economic regulation downsizing in 1975. The Class I sector becoming highly concentrated causing the transportation rates to have dropped, which could be possibly damaging for the recapitalization of the infrastructure.	Monetary
(17)	Estimation of Unit Costs of Rail Transportation in Canada*	DAMF Consulting Inc., Joseph Schulman Consulting and CANRAIL Consultants Inc.	Mar-07	A review of current Canadian rail freight shipments observing the operational fees. Determining an average toll for deliveries using the product density, volume and distance.	Monetary
(23)	Estimates of the Full Cost of Transportation in Canada	Transport Canada	Nov-08	A review of current Canadian rail freight shipments and comparing the operational costs with the social costs. Determining an average toll for deliveries using the product density, volume and distance.	Monetary

* This article was disputed by the CN Rail company in an attached appendix, arguing costs were not represented accurately

2.6 Generalized Cost Functions of Rail Freight

A number of explicit cost functions have been developed as summarized in Table 2.6 below, and these are used to derive the cost function that form the base case for both the rail and pipeline in this research.

Table 2.5: Cost Function Summary Table

Paper Number	Function	Variable Values
(2)	$C_t = \frac{1}{2}\pi_t^s\gamma^2 + \pi_t^h\gamma\eta + \frac{1}{2}\pi_t^u\eta^2$	π_t^s, π_t^h, π_t^u are the coefficients for all car types (Refer to pg. 16/17 of document) η is average number of loaded cars γ is average freight car type inventory and storage status

Table 2.5 – Continued

(4)	$c_a(x_a^i, y_a) = \rho_a^i + \alpha^i d_a^i(x_a^i, y_a)$ $d_a^i(x_a^i, y_a) = t_a\left[1 + \phi_1 x_a^i + \phi_2\left(\frac{x_a^i}{r_{0a} + y_a r_a}\right)^{\gamma}\right]$	x_a^i is the flow on link a ρ_a^i fare on link a α^i time value d_a^i time spent on link a t_a free travel time on link a r_{0a} exisiting link capacity r_a capacity to be added ϕ_1,ϕ_2,γ are coefficients to be calibrated
(6)	$c = V\rho d\alpha$	V is the flow on link a ρ density of product being shipped α cost of freight per tonne-km (€0.042/T-km) d distance
(8)	$C = Td(C_p + C_e)$	C_p is the private costs (Table 1) C_e is the external costs (Table 9) d is the distance of the trip T is the tonnage of the shipment
(10)	$C_g^{rail} = a_{rail}\left(\frac{h_{rail}}{f_{rail}} + e_{rail}\right)$	a_{rail} is the distance (748km) e_{rail} is the transportation costs (0.53€/cont.km) f_{rail} is the speed (40 km/hr) h_{rail} is the value of time (€/cont.hr) **Based on a 40ft trailer**
(12)	$C_g^m = a_m\left(\frac{h_m}{f_m} + e_m\right)$	a_m distance h_m Value of time f_m speed of the model e_m transportation cost
(15)	$t = m_e + \frac{\alpha_e d_e}{100} e^{w_e \beta_e}$	d_e is the distance m_e is the free flow time w_e is the number of trains/day α_e, β_e are specific rail properties based on side spacing, headway, mile % double tracks, speed difference, track outages and temporary slow order
(17)	$c = V\rho d\alpha$	V is the flow on link a ρ density of product being shipped α cost of freight per tonne-km ($0.024/T-km) d distance

Table 2.5 – Continued

(20)	$$A = \frac{FH_i}{u_i T}$$ $$B = \frac{F + bu}{uvT} s_j$$	$\boldsymbol{A}$ is the loading and unloading costs (Table A.2) $\boldsymbol{B}$ is the operational costs (Table A.2) $\boldsymbol{b}$ is the cost of energy consumption $\boldsymbol{F}$ is the annual fixed cost of mode (capital annuity, insurance, maintenance and wages) $\boldsymbol{H_i}$ is the time taken for a particular handling operation at terminal i $\boldsymbol{s_j}$ is the distance of link j $\boldsymbol{T}$ is average load of vehicles in tonnes $\boldsymbol{u}$ is the number of working hours per year $\boldsymbol{v}$ is the vehicle speed
(23)	$$c = V\rho d\alpha$$	$\boldsymbol{V}$ is the flow on link a $\boldsymbol{\rho}$ density of product being shipped $\boldsymbol{\alpha}$ cost of freight per tonne-km (\$0.0218 - 0.0231/T-km) $\boldsymbol{d}$ distance

These functions are structurally complex or simple. This depends on the availability of freight data availability and the scope of the study being undertaken.

3 CANADIAN ZONAL CRUDE OIL PRODUCTION AND DESTINATION ZONES

This section presents origin-destination (OD) demand estimates for crude oil as obtained from Canadian databases. These demands include external zones, such the Petroleum Administration for Defense Districts (PADDs) in the United States, since Canadian imports and exports of crude oil use the domestic transportation (pipeline and rail) networks. Developing OD demands are the first two steps of a four-step freight demand model (generation and distribution) and are performed simultaneously from trade data in this chapter. In other words, trade statistics supply both the production/attraction and distribution of crude oil shipments (Stages 1 and 2 of the Four Stage paradigm).

3.1 Data Collection

Table 3.1 shows the structure of the zonal OD matrix required for a Canadian crude oil freight demand model. The complete matrix has essentially three quadrants: Canada to Canada (upper-left square); Canadian exports (upper-right rectangle); and Canadian imports (bottom-left rectangle). Commo mathematical nomenclature is used to classify partitions: matrices are indicated by upper-case bold letters, vectors by lower-case bold letters, and scalars by italicized lower-case letters. Row vectors are also distinguished from column vectors by an apostrophe. Partitions are color-coded according to data availability: red indicates data is not publicly available; green indicates data is publicly available by crude type; and yellow indicates data is only available for total crude (i.e., not by type).

Table 3.1: Structure of Canadian Crude Oil OD Matrix

Origin \Destination	Canada by Region	Canada (Total)	US by PADD	US (Total)	Other (Total)	Total Production
Canadaby Region	**A**	**b**	**C**	**d**	**e**	**f**
Canada (Total)	**g'**	*h*	**i'**	*j*	*k*	*l*
US by PADD	**M**	**n**				
US (Total)	**o'**	*p*				
Other (Total)	**q'**	*r*				
Total Attraction	**s'**	*t*				

3.2 Total OD Crude Oil Shipment Data (not mode specific)

Crude oil shipments beginning and ending in Canada are available from Statistics Canada's key socioeconomic database, CANSIM. In particular, CANSIM Table 126-0001 describes the historical supply and disposition of crude oil and equivalent in Canada (cubic meters) (Statistics Canada, 2017a). Canada is disaggregated into provinces, providing interprovincial trade flows of total crude oil for the **A** matrix in Table 3.1. Hence, **b**, **g'**, and *h* can also be determined from column, row, and matrix summations of **A**, respectively. The data are available monthly, from January 1985 to February 2016. Crude oil is not separated by type.

It is important to recognize that Statistics Canada uses supply and disposition tables, which present data differently than OD matrices (Table 3.2). For each province, supply is the sum of the crude produced by the province and imports, while disposition is the sum of the province's total crude consumption and exports. Hence, production and disposition should balance for each province. On the other hand, the total number of shipments originating from a province is the sum of the crude produced in the province, and total crude destined for the province is the sum of crude consumed or disposed in the province. Hence, shipment production and attraction totals may not balance for each province. Table 3.2 illustrates these differences with hypothetical values.

Table 3.2: Hypothetical Example to Illustrate the Difference between a Supply and Disposition Table and an Origin and Destination Matrix

Supply and Disposition Table

Total Supply	**9**
Produced	6
Imports	3
Total Disposition	**9**
Consumed	7
Exports	2

Supply (9) = Disposition (9)

Origin and Destination Matrix

Origin \ Destination	Domestic	Export	**Total Production**
Domestic	4	2	**6**
Import	3		
Total Attraction	**7**		

Productions (6) ≠ Attractions (7)

Canadian exports are also included in CANSIM Table 126-0001 (Statistics Canada, 2017a). In particular, exports from Canadian provinces to US PADDs (matrix **C**) are available, as well as total exports from each province to all countries other than the US (vector **e**). Total production by province is available (vector **f**) by six crude and equivalent types: 1) Heavy crude oil; 2) Light and medium crude oil; 3) Synthetic crude oil; 4) Crude bitumen; 5) Condensate; and 6) Pentane Plus. Naturally, the remaining elements of the Canadian exports partition (**d**, **i'**, *j*, *k*, *l*) can be determined from appropriate summations of the other elements in this partition (or be taken directly from Table 126-0001).

Canada's total shipment of crude to individual PADDs (vector **i'**) is also available quarterly from the NEB, broken down by type (Conventional Light; Conventional Medium; Conventional Heavy; Synthetic; and Bitumen & Blended Bitumen) (NEB, 2017). Canada's total shipments of crude to the US (j) and to all other countries combined (k) is also available quarterly by these same types. This dataset spans 1985 to 2016.

In terms of Canadian imports, CANSIM Table 126-0001 (Statistics Canada, 2017a) only provides total imports from all sources to Canada ($p + r$). However, Canada's total import of crude from the US (p) is available monthly from 1993 to 2016 from the EIA (EIA, 2017a), and hence total imports from other countries (r) can be deduced. Total attraction by province and for Canada as a whole (s, r) is also available from CANSIM Table 126-0001 (Statistics Canada, 2017a), by summing Canadian and foreign sources. Total foreign sources were then split into the US and other countries by subtracting the US from total foreign sources.

CANSIM Table 126-0001 (Statistics Canada, 2017a) was discontinued in February 2016, and replaced with CANSIM Table 126-0003 (Statistics Canada, 2017b). Unfortunately, changes were made to the content and methodology, and interprovincial crude oil flows are no longer disseminated. Moreover, exports are still divided between the US and all other countries, but the US is no longer divided into US PADDs. For each province, Table 126-0003 (Statistics Canada, 2017b) is useful for providing: provincial production totals by type (vector **f**), exports from Canadian provinces to US total (vector **d**), and total exports from each province to all countries other than the US (vector **e**). There are two new types of data provided by this table (compared to Table 126-0001 (Statistics Canada, 2017a)):

1) total shipments to all Canadian refineries from each province (vector **b**) by crude type (light and medium crude oil; heavy crude oil; crude bitumen; condensate and pentanes plus; and synthetic crude oil); and
2) exports from Canadian provinces to US total (vector **d**) specifically by pipeline. Overall, the new table provides various production and attraction totals, but no origin-destination flows (i.e., between provinces, or between provinces and PADDs), making it less useful for freight demand modelling than its predecessor.

CANSIM Table 134-0001, "Refinery supply of crude oil and equivalent", describes Canadian provincial imports of crude oil by country (Statistics Canada, 2017c). Values are presented monthly from January 1956 to November 2016. Prior to January 1973, only a grand total of receipts is available, and only after January 1979 does supply data from the US become available. These data can be used to determine Canadian provincial imports of crude oil from the US (**o'**), and all other countries (**q'**).

3.3 Mode Specific OD Data

The EIA disseminates data on "Movements of Crude Oil and Selected Products by Rail" (EIA, 2017b), which includes data on *rail* movements between Canada and individual US PADDs (vectors **i’** and **n**). This dataset starts in 2010 for some data, and more recently 2012 or 2014 for other data, and is updated monthly. The table suggests rail imports to Canada are non-existent or small (i.e., below the threshold for recordkeeping - volume of less than 0.5 thousand barrels per day), while some export rail shipments from Canada to US PADDs do take place.

Recently, CANSIM began disseminating Table 133-0006, which describes “Canadian monthly pipeline transport of oil and other liquid petroleum products” (Statistics Canada, 2017d). Of relevance to this project, is that *pipeline* imports and exports by province are available. If pipeline imports are generally assumed to contain crude from the US, this table provides crude imports by province from the US (vector **o’**), given that none is arriving by rail (as per above). Unfortunately, data for this table is only available from March 2016 to December 2016, but will be updated in the future. However, Table 133-0003 (Statistics Canada, 2017e) precedes Table 133-0006 (Statistics Canada, 2017d) for imports and exports for the period of Jan 1997 to Feb 2016.

3.4 Developing Canada-Wide Crude Oil OD Matrices

Tables 3.3-3.5 indicate the Canadian crude oil OD matrix (Table 3.1) for 2015. Table 3.3 shows Canada to Canada flows; Table 3.4 applies to Canadian exports to US PADDs; and Table 3.5 reflects imports from US to Canada. As shown in Table 3.3, Canada attracted a total of 124 million cubic meters of crude oil in 2015. Newfoundland and Labrador and Nova Scotia attracted the most crude oil in Canada in 2015 (30%), followed by Quebec (26%), Alberta (20%), and Ontario (16%). 73% of this crude was sourced domestically, 11% from was sourced from the US, and the remainder (16%) originated at foreign sources. As shown in Table 3.4, Canada produced a total of 267 million cubic meters of crude oil 2015. Alberta produced the most (71%), followed by Newfoundland and Labrador (4%). Where the remaining proportions were produced is unknown due to missing and suppressed data. 34% of Canada’s production was used domestically, 65% was exported to the United States, and the remainder (1%) was exported to other trade partners. As for Table 3.5, no OD data is available from PADDS to provinces, and even the US to provincial flow estimates are based on suppressed data.

Despite the multiple data sources describing crude oil flows in Canada (discussed previously), many values shown in the OD matrices are subject to some caveats. First, Statistics Canada often suppresses monthly data to maintain confidentiality. Second, monthly data is not always available. Third, data for Canadian imports from US PADDs are not available. Hence, the collected OD data only serve as a starting point for developing an OD matrix for Canadian crude oil shipments. Aside from collecting more data, bi-proportional updating (also known as Iterative Proportional Fitting (IPF) or the RAS algorithm) or a gravity model would be required to update individual values such that they equal production and attraction totals. In this analysis we have assumed that shipment estimates in Tables 3.3-3.5 are representative of the relative distribution of crude oil shipments. Similar Canadian crude oil OD Matrices are provided in Appendix A.

Table 3.3: Canadian Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canada to Canada

O\D	Atlantic Provinces	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Canada
Atlantic Provinces	0.0*	0.0*	0.0*	0	0	0	0	x
Newfoundland and Labrador	2094.3**	774.2**	0.0**	0	0	0	0	x
Nova Scotia	0.0*	0	0.0*	0	0	0	0	x
Ontario	0	0	57.2	0	0	0	0	x
Manitoba	0	0	0.0*	0	0	0	0	x
Saskatchewan	0	0	0.0*	0.0*	0.0*	0	0	x
Alberta	0	0	11791.9	4931.2	22800.6	2813.9	0	x
British Columbia	0	0	0	0	0.0*	0.0*	0	x
Northwest Territories	0	0	0.0*	0	0	0	0	x
Canada	19597.9	16618.9	19664.1	7632.2	24409.6	3441.4	0	91364.1 [c]
US	0.0*	793.63*	0	0	0	0	0	13501.564* [c]
Other Foreign	17503.6*	14778.77*	0.0**	0.0**	0	0	0	19574.436*** [c]
Total Attraction	37101.5* [r]	32191.3* [r]	19664.1** [r]	7632.2** [r]	24409.6 [r]	3441.4 [r]	0	124440.1*** [r]

* *indicates a value that includes suppressed monthly data*
** *indicates a value that includes unavailable monthly data*
*** *indicates a value that includes suppressed and unavailable monthly data*
x *indicates a value unavailable from public sources*
c *indicates a value from a column sum*
r *indicates a value from a row sum*

Table 3.4: Canadian Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canadian Exports

O\D	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	US	Other Countries	Total Production
Atlantic Provinces	0.0*	0	0.0*	0	0	0.0*	0.0*	0.0* c
Newfoundland and Labrador	5658.8	0	214.1**	0	0	5872.9	1123.3**	9864.7** c
Nova Scotia	0.0*	0	0.0*	0	0	0.0*	0	0.0* c
Ontario	0	0	0	0	0	0	0	57.2 c
Manitoba	0.0*	0.0*	0.0*	0.0*	0	0.0*	0	0.0* c
Saskatchewan	0.0*	0.0*	0.0*	0.0*	0.0*	0.0*	0	0.0* c
Alberta	3034	109633.9	2978.1	18644.6	11851.5	146142.2	140.8**	188620.6** c
British Columbia	0	0	0.0***	0	0.0*	0.0*	0.0*	0.0*** c
Northwest Territories	0	0	0	0	0	0	0	0.0* c
Canada	11869.4	128103.4	3831.9	18644.6	12036.6	174485.3	1272.2**	267121.6** c

* *indicates a value that includes suppressed monthly data*
** *indicates a value that includes unavailable monthly data*
*** *indicates a value that includes suppressed and unavailable monthly data*
x indicates a value unavailable from public sources
c indicates a value from a column sum
r indicates a value from a row sum

Table 3.5: Canadian Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canadian Imports

O\D	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Newfoundland and Labrador	Nova Scotia	Manitoba	Prince Edward Island	New Brunswick	Yukon	Nunavut	Canada
PADD 1	x	x	x	x	x	x	x	x	x	x	x	x	X	x
PADD 2	x	x	x	x	x	x	x	x	x	x	x	x	X	x
PADD 3	x	x	x	x	x	x	x	x	x	x	x	x	X	x
PADD 4	x	x	x	x	x	x	x	x	x	x	x	x	X	x
PADD 5	x	x	x	x	x	x	x	x	x	x	x	x	X	x
US	793.63*	0	0	0	0	0	3940.004*	0	0	0	0.0*	0	0	13501.564* [c]

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

3.5 Zone System for Crude Oil Production and Attraction

A more spatially detailed zone system is required in this study to characterize crude oil shipment patterns from source to disposition for the Canadian pipeline and rail networks. If properly specified, these zones can account for homogenous group (aggregate) decisions concerning which mode to ship, which route is selected and at what cost?

As illustrated in Figure 3.1, our study area has been structured spatially into 17 production/disposition zones: 12 for Canada, and 5 (PADDs) for the continental US. Alberta was expressed by four zones, British Columbia by two zones (one in the north and one in the south). In addition, we have one zone for each province, Saskatchewan, Manitoba, Ontario and Quebec. The Northwest Territories are given a separate zone. Finally, all four Atlantic Provinces are represented by one zone.

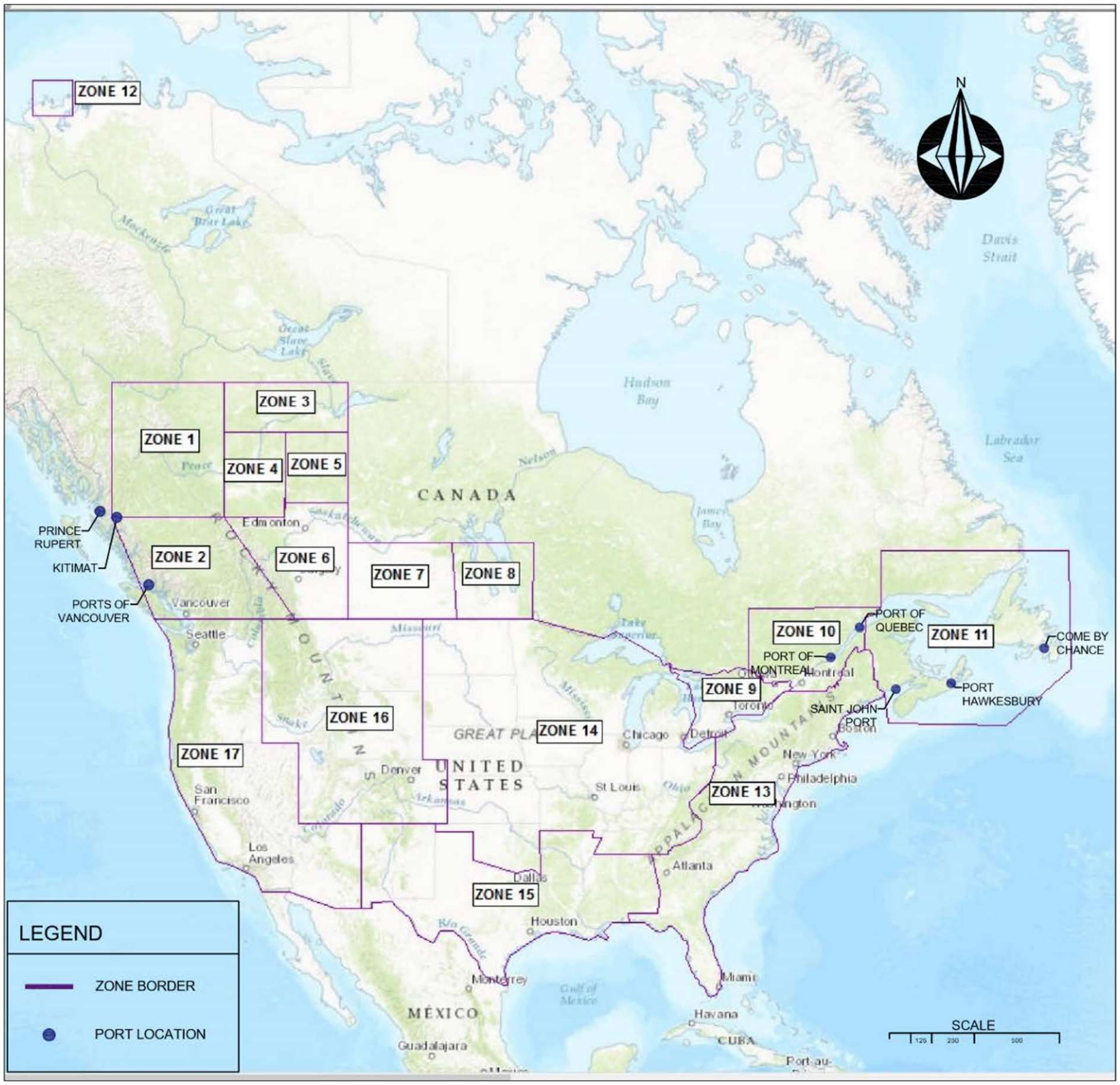

Figure 3.1: Zone system for modelling Canadian crude oil shipments

Since more disaggregate OD data is not publicly available, shipments originating from British Columbia or Alberta can be split based on total production data. Shipments destined for British Columbia or Alberta can be split based on total attraction data. Table 3.6 shows the total production and attraction percentages for British Columbia and Alberta. These estimates are based on apportioning values provided by the Canadian Association of Petroleum Producers (2017), Alberta Energy (2016), and the Canadian Fuels Association (2017).

The underlying data and sample calculations used to develop Table 3.6 are provided in Appendix A. Production percentages can then be applied to Tables 3.3 and 3.4 to disaggregate provincial OD flows to zonal OD flows. For example, 100% of shipments originating from British Columbia come from Zone 1 (Figure 3.1), whereas 100% of shipments destined for British Columbia go to Zone 2 (Figure 3.1). In a similar manner, the majority of shipments originating from Alberta come from Zone 5 (89%), whereas 100% of shipments destined for Alberta go to Zone 6. In this way, Tables 3.3-3.5 can be disaggregated to provide OD flows for all zones shown on Figure 3.1 (Tables A.10-A.12 in Appendix A).

Table 3.6: Production and Attraction for British Columbia and Alberta

Province	Zones	Production (%)	Attraction (%)
British Columbia	1	100%	0%
	2	0%	100%
Alberta	3	0.3%	0%
	4	4.3%	0%
	5	89.2%	0%
	6	6.2%	100%

* Source: Canadian Association of Petroleum Producers, 2017; Alberta Energy, 2016; and Canadian Fuels Association, 2017.

Foreign sources require additional external zones (port locations shown on Figure 3.1) so as to accurately represent the usage of the Canadian pipeline and rail networks. On the West coast, crude is shipped through the Ports of Vancouver, Prince Rupert and Kitimat. On the East coast, crude is predominantly shipped to the ports of: Come by Chance, Port Hawkesbury, Saint John, Port of Quebec, and Port of Montreal (Transport Canada, 2016). Data describing inbound and outbound crude oil shipments at the Port of Vancouver and the Port of Montreal are readily available (e.g., Port Metro Vancouver, 2015; Port of Montreal, 2016), but other ports do not publish similar statistics. Also note that data on inbound and outbound crude shipments may include transshipments (involving the US). Nonetheless, if data for all ports were collected, foreign sources in the crude oil matrix could be disaggregated into individual zones (ports), based on inbound and outbound crude oil shipments.

3.6 Limitations of Existing Crude Oil Databases

Freight or trade values from input-output (IO) tables or other statistics are often used for the first and second steps of a typical freight demand model: freight generation and distribution. Unfortunately, a comprehensive set of statistics describing crude oil shipments in Canada is not publicly available. Hence, several separate data sets were stitched together in this section in order to estimate a Canadian crude oil OD matrix.

Despite the relatively high coverage of these datasets when combined (revisit Figure 3.1), several limitations were identified when the data were investigated thoroughly. First, little data is available describing crude oil shipments by type. However, crude oil types have unique shipping characteristics and costs (see next sections), necessitating a determination of shipments by crude oil type. Second, even when aggregate crude oil shipments were included as an attribute of a dataset, the numerical value was often suppressed (due to confidentiality reasons) or unavailable (due to a lack of records), leading to substantial discrepancies between OD shipments and the total shipments produced or attracted at an origin or destination, respectively. In this light, the data cannot be implemented "as-is", without further pre-processing to ensure accounting identities are respected. Third, there is no data set publicly available (to the best of the authors' knowledge) which provides Canadian imports separated by US PADDs. Knowledge of the originating PADD for imports of US crude oil is needed to identify the relevant Canadian gateway. Fourth, the origin/destinations of foreign sources (other than the US) are not specified in the obtained data sets. Again, knowledge of the originating country for crude oil imports is needed to identify the port of entry. Fifth, notwithstanding the above limitations, provincial flows in Alberta and British Columbia need to be disaggregated to smaller zones to accurately model the usage of the Canadian pipeline and rail networks. Given the lack of more aggregate data, zonal flows were estimated based on zonal production and attraction totals. In summary, issues surrounding data availability and suppression precluded a complete determination of a Canadian crude oil OD matrix.

There are two avenues for further work on crude oil demands. First, data sets not publicly available can be pursued. For example, it is likely the NEB has a considerable amount of pipeline data that could greatly inform the estimation of the Canadian crude oil OD matrix. Whether or not these data can be easily shared is unknown at this time. Second, modelling techniques such as biproportional updating and gravity models can be used to balance and estimate incomplete or missing data. For example, the inter-provincial OD matrix, which includes unavailable and missing data, can be balanced to match the known production and attraction totals using bi-proportional updating. The US PADDs to provinces partition of the OD matrix can be estimated with a gravity model, which assumes a distance decay effect in the spatial interaction of productions and attractions. Using these modelling techniques and/or through further data collection, the estimated crude oil OD matrix presented in this thesis can be enhanced for use in a complete Canadian crude oil freight demand model.

4 GENERALIZED COST FUNCTIONS FOR SHIPPING CRUDE

4.1 Crude by Pipeline

4.1.1 Background

In Section 4.1, cost functions for shipping crude oil by pipeline in Canada are developed. These cost functions are a form of "link-performance functions" applied to pipeline route segments for a given mix of shipping conditions. Developing these cost functions involves several important steps: 1) Researching the relevant explanatory variables that impact the cost of shipping crude oil by pipeline; 2) Collecting data on the relevant explanatory variables (identified in 1.); and 3) Obtaining empirical cost functions based on the Canadian data (collected in 2.).

4.1.2 Data Collection

Three sources of data are used to obtain OD crude oil pipeline distributions and tolls in Canada: The National Energy Board (NEB), Natural Resources Canada (NRCan), and individual producer reports. The National Energy Board (NEB) regulates pipelines, energy development and trade in the Canadian public interest. The NEB has publicly available data on the tariffs/tolls charged by Canadian pipeline companies, including the fees charged to crude shippers, which consist of usage fees as well as surcharges (National Energy Board, 2017). In addition to these quantitative data, the NEB also provides information about the corresponding rules and regulations (e.g., what is an acceptable shipment and what capacity limitations may be in place aside from the physical system constraints). Other NEB reports describe the current state of the pipeline transportation system, upcoming projects for all major pipeline companies, and trends in tolls over time (National Energy Board, 2016; and National Energy Board, 2014). The trends in tolls compared to the pipeline utilization over multiple years gives insight into how utilization along with recent construction can affect the costs of shipments. For example, the steady increase in tolls since 2010 on the Enbridge mainline system directly correlates with the increase in capacity of the system. These coupled price and capacity increases are due to the construction costs associated with network expansion increasing the capital costs of the pipeline, and subsequently the tolls required for capital cost recovery.

Natural Resource Canada (NRCan) is charged with developing policies and programs related to enhancing the natural resources sector of the Canadian economy. NRCan has Geographic Information System (GIS) data for both the Canadian rail and pipeline transportation networks. These data were used for determining distances between the Origin-Destination (OD) pairs given by the NEB toll and tariff documents. For some pipelines not covered in the NRCan GIS data, the Canadian Energy Pipeline Association (CEPA) liquids pipeline maps were used (CEPA, 2014; and CEPA, 2017).

Remaining data were gathered from pipeline company websites. These companies consisted of Enbridge Inc. (Enbridge Inc., 2017), Kinder Morgan (Kinder Morgan, 2015a), Plains Midstream Canada (Plains Midstream Canada, 2017), Spectra Energy Corp. (Spectra Energy Corp., 2017), and TransCanada Corp. (TransCanada Corp., 2017). These data include pipeline specifications, such as age and diameter.

Data from all sources were collected manually, through the reading of the reports and documents, and have been summarized into Excel templates. Note that OD path distances were first estimated by the sum of all used pipeline links in ArcMap (ArcGIS, 2017) , where the NRCan GIS data were imported and refined along with the CEPA maps.

In summary, nine documents related to the producer tolling were used (Enbridge Pipelines Inc., 2011; Kinder Morgan Cochin LLC & Kinder Morgan Cochin ULC, 2015; Kinder Morgan Cochin ULC, 2015; Trans Mountain Pipeline ULC, 2013b; TransCanada Keystone Pipeline Limited, 2015b ; Express Pipeline Ltd., Express Pipeline LLC, & Platte Pipe Line Company, LLC, 2015; Plains Midstream Canada ULC, 2013c; Plains Midstream Canada ULC, 2013d; and Plains Midstream Canada ULC, 2013b), and another six for the rules and regulations (Enbridge Pipelines Inc., 2011; Kinder Morgan Cochin LLC & Kinder Morgan Cochin ULC, 2015; TransCanada Keystone Pipeline Limited, 2015a; Express Pipeline Ltd., 2014; Plains Midstream Canada ULC, 2013a; and Trans Mountain Pipeline ULC, 2013a). Distances required two maps and the GIS data set of approximately 900 segments. As several production companies own multiple pipelines, only 6 companies were uniquely identified for data collection. In total, the resulting database includes 323 observations of pipeline shipping costs and corresponding explanatory variables to complete the regression models were estimated in the next section.

4.1.3 Regression Analysis for Pipeline Cost Performance Functions

Several linear and non-linear regression models were established to provide empirical estimates of transport costs for crude oil shipments in Canada. Regression models are most often evaluated in terms of their ability to replicate observed outcomes. In particular, R^2 values indicate the proportion of variance in the dependent variable that is explained by the independent variables (i.e., the ratio of explained variance to total variance). The statistical significance of individual parameters is assessed using a *t*-statistic (or *p*-values less than 0.05 or 5% level of significance). The two-tailed *t*-statistics suggests that only parameters that are significant are used in the resultant performance function, such that other factors would have negligible effects on pipeline costs. The parameters also should reflect expected positive or negative relationships based on intuitive logic (makes sense test).

Before hypothesizing explanatory variables, it is necessary to develop an understanding of how costs are actually determined in the real-world. A general equation takes the form:

$$Toll = Base\ Rate + (\beta x Distance) + Surcharges \quad \textbf{(4.1)}$$

Where,

$$Base\ Rate = \frac{Capital\ Cost + Operat \quad and\ Maintenance}{Throughput} \quad \textbf{(4.2)}$$

and β is a parameter applied to the distance. For a given shipper and route segment, cost is expressed in terms of $/m^3. All companies will determine the costs associated with the ownership and usage of the pipeline, referred to as the "Capital Costs" (CC) and "Operation and Maintenance" (OM), respectively. The CC is associated with the depreciation, interest expense, return on equity and forecasted tax allowance. The OM is associated with wages, construction and property taxes.

To create a market in which all shippers are fairly charged, the total shipment amount, “Throughput”, then divides the total cost to create the “Base rate”.

Since pipelines are owned by different companies, there is a large variability of other costs that they may include in their tolls, referred to as surcharges. The most prevalent charge attributed to the tolls is the abandonment surcharge: to account for the possibility of a pipeline being shut down, and the numerous costs associated with its decommissioning, all shippers are required to pay a small additional fee. Companies are expected to determine a fair abandonment surcharge, to be approved by the NEB, and added to all shipments (on a per cubic meter basis).

For companies that ship internationally (predominantly to the US) there is an additional payment captured by International Joint Tolls (IJT). Canadian Local Tariffs (CLT) are the tolling rates applied only to Canadian receipt and terminal locations, while IJTs are the tolls applied to crude shipments from Canada to the US.

Additionally, some companies may have special cost structures, such as the Enbridge tankage fees and Kinder Morgan Firm Service Fee (FSF). Enbridge is unique in that they own their own tanks for oil storage, allowing them to charge additional fees for storing crude oil. These fees are applied separately from the shipment tolls and are only applicable in the case that the shipper is using the tank farms associated with Enbridge. The Kinder Morgan FSF stems from the Westridge Docks that are connected to this pipeline. Kinder Morgan decided that due to the large amount of shipments that are being sent to this dock, a specific amount of capacity would be allocated to these shipments. If a shipper was to occupy some of this capacity, then an additional fee, dependent on the percentage of the separate capacity, is set on top of the existing net toll. Due to this allocated capacity, an additional complication was added to the tolling process, known as toll bidding. The companies who are to acquire a portion of this capacity must bid on the volume and toll rate they are to pay. However, the final decision on the allocation comes down to the ranking of the companies, based on the bid premium (i.e., *bid toll x bid volume*), with the highest bidding companies receiving the capacity.

Finally, not all crude shippers have contracts for their shipments, which differentiates the tolls into committed and uncommitted rates. Committed toll rates refer to the rates applied to contracted shippers, which are typically determined through negotiated toll settlements. Committed toll rates are the primary focus of this study, as there is a large variance in how uncommitted shipment tolls are determined (due to the pipeline owners giving varying incentives to contracted shippers).

With the above understanding developed from the toll applications and regulatory documents described previously, a set of explanatory variables was hypothesized. First, and perhaps most important, is distance. When comparing distance to tolls by crude oil type (condensate, light, medium, heavy) and destination (CLT, IJT), distance explains a high proportion of the variance in tolls. If companies are examined individually, distance (along with a base rate) accounts for over 90% of the variance in tolls. These early analyses suggested that notwithstanding differences between crude types, destinations, and companies, distance is a key factor in determining the cost of crude oil shipments (with a positive parameter value).

Since data on individual pipeline throughputs was not available, pipe diameter was used as a surrogate. The underlying assumption is that larger pipelines have larger capacities and therefore larger throughputs. Based on the general equation presented previously (4.1), it is hypothesized that larger diameter pipelines would decrease the toll cost, all else being equal (since the larger throughput splits the total cost among more shippers). In the future, inclusion of throughputs would be preferred, since the toll could then vary as function of usage in the associated transport network model.

Initially, it was thought that the age of a pipeline might be correlated to the capital costs, reflecting the significance of capital recovery costs for carriers in setting their tolls on individual lines. Since capital costs are based on depreciation, and depreciation occurs over time, the age of the pipeline was hypothesized to impact the associated tolls. However, it was found that the age of the pipeline was not meaningful to the capital costs, since there are constant expansions and additional costs to the pipeline which are not reflected in its age. For example, the likelihood of an expansion to a pipeline may increase with age. For this reason, although the ages of pipelines were collected, they are not used as explanatory variables in this study.

4.1.4 Cost Functions

4.1.4.1 Disaggregate Cost Functions

The initial cost functions are expressed in disaggregate form per shipper, resulting in eight separate functions. These functions represent different crude oil types (Condensate, Light, Medium, Heavy), and destination-based tolling agreements (CLT, IJT). The estimated functions are linear in form, such that:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi \qquad \textbf{(4.3)}$$

where,

y is the toll value for a specific OD pair ($/m^3)

d is the OD distance (km)

ϕ is the maximum pipeline diameter per segment (inches)

The results of the estimated cost functions described by (4.3) are summarized in Table 4.1:

Table 4.1: Summary of Coefficients for Equation (4.3)

Crude Oil Type	Toll Type	t_0	β_0	t_1	β_1	t_2	β_2	$t_{2.5\%}$	R^2	Data Quantity
Condensate	CLT	1.12*	0.51	41.51	0.008	1.71	0.03	2.12	0.99	20
	IJT	5.02	29.52	1.64*	0.003	-3.52	-0.54	2.23	0.58	13
Light	CLT	2.83	4.28	9.97	0.005	-0.34*	-0.02	2.01	0.66	56
	IJT	4.69	11.28	9.63	0.005	-2.36	-0.15	2.00	0.66	61

Medium	CLT	-1.38*	-1.14	24.89	0.010	3.05	0.07	2.05	0.96	31
	IJT	4.46	13.58	6.74	0.005	-2.21	-0.15	2.03	0.63	39
Heavy	CLT	5.23	10.19	7.56	0.005	-2.55	-0.14	2.02	0.64	42
	IJT	5.90	15.67	8.52	0.005	-3.62	-0.19	2.00	0.72	61

* indicates parameter estimate is not significant

The intercept coefficient, β_0, should take positive values as the intercept should be representative of the average base rate plus the average of all surcharges applicable to crude oil shipments via pipeline for the given crude and toll type. However, the value should remain relatively small as the observed data set has small base rates for distances that are close to zero.

The regression results indicate that there is high variation in coefficients among crude types. The tolling type coefficients were found to be consistently lower for the CLT in comparison to the IJT. From the above analysis, there are two discrepancies in the expected value from the Medium CLT and Condensate IJT, in which the first is a negative value and the second is quite large. Also, the Condensate CLT intercept is not significant (*t*-statistic).

The distance coefficients were found to be as expected (i.e. positive) and significant, but for Condensate IJT the coefficient was found to be not statistically significant. The coefficients for this variable are very consistent throughout the eight models, demonstrating very little sensitivity to both crude and toll type.

The diameter coefficients usually have their expected sign (negative), except for the Medium and Condensate CLT values (positive). Also, note the Light CLT coefficient is not statistically significant. The diameter coefficients have some similar values, but are mostly inconsistent. The R^2 values averaged about 73%, indicating that these functions explain just over 70% of the variance in observed toll values. The Condensate IJT model has the lowest goodness-of-fit, however, primarily due to a lack of observations in the observed database.

Since there are some not statistically significant and unexpected parameter estimates within this set of models, additional forms are considered, which combine the models through interval (or "dummy") variables, thereby increasing the number of observations used for each regression analysis.

4.1.4.2 Toll Type Combined Cost Functions

In this model, a dummy variable is introduced to combine the two tolling types, as shown below:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi + \beta_3 D_T \qquad \textbf{(4.4)}$$

where,

D_T = Binary value for the toll type ($D_T = 0$ for a CLT and $D_T = 1$ for an IJT)

The results of the estimated cost functions described by (4.4) are summarized in Table 4.2:

Table 4.2:Summary of Coefficients for Equation (4.4)

Crude Oil Type	t_0	β_0	t_1	β_1	t_2	β_2	t_3	β_3	$t_{2.5\%}$	R^2	Data Quantity
Condensate	4.23	11.56	4.15	0.005	-3.35	-0.31	2.84	7.53	2.045	0.864	34
Light	4.76	6.02	14.26	0.005	-2.14	-0.09	4.82	3.58	1.986	0.848	117
Medium	3.54	5.78	10.68	0.006	-1.46*	-0.07	2.08	2.55	2.014	0.848	70
Heavy	7.42	10.83	11.62	0.005	-4.79	-0.18	6.21	5.37	1.991	0.851	103

* indicates parameter estimate is not significant

In these models, it is seen that these equations all have adequate and statistically significant coefficients and intercepts. There is an apparent improvement of the values of the intercepts. There appears to be some effect on cost for crude oil type. This is reasonable since typically the highest shipping products are medium and light crude, resulting in lower intercepts, than heavy crude with the highest associated costs and coefficient values.

The distance coefficients are adequate and significant. There, again, is no significant sensitivity across the crude oil types as there is alteration to the cost of shipment per distance based on a crude oil type. Most values are consistent with the previous regression models, with improvement in the uniformity of the coefficient values.

The diameter coefficients are all adequate, with only the Medium coefficient being not significant. This now presents a significant sensitivity to the crude oil type, as the medium and light values are quite low in magnitude compared to the other values. However, this makes sense given that the two largest throughputs are typically light and medium crude oil (i.e., with there being an expected higher utilization of the light and medium pipelines, the intercept will require a lower reduction in magnitude to accurately depict the base rate of the considered pipeline). This is a large improvement from the previous function as the coefficient values are now what was anticipated for this variable in terms of sign and magnitude.

The coefficient for the toll type dummy variable, β_3, should be positive and moderately small. This is because there is a small additional charge applied to the tolls as an international shipping tariff. From the above summary table, combining the previous models was appropriate since the coefficients for this dummy variable are all significant and are compatible with the assumption made. Across the crude oil types there is no discernible pattern or sensitivity to type, just a slight variance in the magnitudes.

The R^2 values have improved substantially from the previous results (above) yielding a value of 85.2%. The more aggregate crude oil classification in Table 4.2 reduced the number of equations by half, while increasing the accuracy of the model results.

4.1.4.3 Fully Combined Cost Function

An additional regression was performed with a combination of the entire data set, using a linear function of the form:

$$y = \beta_0 + \beta_1 d + \beta_2 \phi + \beta_3 D_T + \beta_4 D_L + \beta_5 D_M + \beta_6 D_H \quad \textbf{(4.5)}$$

where,

D_L = Binary value for light crude, where $D_L = 1$ if the type is light crude, $D_L = 0$ for all others

D_M = Binary value for medium crude, where $D_M = 1$ if the type is medium crude, $D_M = 0$ for all others

D_H = Binary value for heavy crude, where $D_H = 1$ if the type is heavy crude, $D_H = 0$ for all others

The results of the estimated cost functions described by (4.5) are summarized in Table 4.3:

Table 4.3: Summary of Coefficients for Equation (4.5)

t_0	β_0	t_1	β_1	t_2	β_2	t_3	β_3	t_4	β_4	t_5	β_5	t_6	β_6	$t_{2.5\%}$	R^2	Data Quantity
7.93	7.19	21.35	0.005	-6.12	-0.14	8.19	4.27	-0.59*	-0.38	2.01	1.40	4.05	2.69	1.967	0.85	323

* indicates parameter estimate is not significant

Table 4.3 indicates that this model has an intuitively reasonable and statistically significant intercept, β_0, which is relatively high in comparison to the previous values obtained. However, it is still small with regard to the tolls.

The distance coefficient is also reasonable and significant, maintaining the same value as obtained in previous general cost function regressions. The diameter coefficient is statistically significant, with approximately an average of the previous coefficients, imparting a respectable influence to the effects of pipe diameter on tolls charges.

The toll type coefficient has remained an adequate value, taking an expected average across all types for the increase of international shipping. The coefficient for the crude type dummy variables, β_4 to β_6, should be positive and moderately small. This dummy variable was based on the changing viscosity of crude oil types, using condensate as the base value since it is the least viscous crude oil. These values should then be small and positive, increasing as you go from light to heavy, to compensate for the equivalent volume based on the compared viscosity. From the summary table, it is seen that the medium and heavy crude types have proper coefficients while the light crude type has an unintuitive coefficient. This is not an issue as the light crude coefficient is also not statistically significant in the model, and can therefore be removed. The R^2 value has remained the same as the previous results, indicating that this function is equivalent to the previous set of functions. While there were numerous equations developed, many of which yield high R^2 values.

The final cost function suggested in this study is a slight variation on the Fully Combined Cost Function (4.5). The modifications introduced in this function is the removal of the light crude dummy variable, since it was found to lack statistical significant (t-stat is less than the $t_{\alpha/2}$ for 95% significance). The final equation is of the form:

$$y = 6.92 + 0.005d - 0.142\phi + 4.26D_T + 1.70D_M + 3.00D_H \tag{4.6}$$

Equation 4.6 was selected because it yielded an equivalent goodness-of-fit to the Toll Combined functions, while also reducing the number of equations by four. Although the Disaggregated Cost functions yielded a higher R^2, they goodness-of-fit was not consistently high across all models.

4.1.5 Summary Findings for Cost Performance Functions

Overall, results indicate that the distance shipped along each pipeline segment is statistically significant in establishing the shipper toll, as is the pipeline's diameter. Separate models estimated by toll type revealed that the effect of distance and diameter are relatively constant across toll types (i.e., same distance and diameter parameter signs across toll types), allowing for the effect of toll type to be captured by a statistically significant interval ("dummy") variable. Similarly, the effect of crude type was captured by interval variables in a combined cost function. The combined cost function has an R^2 value of 0.852, indicating good model fit as 0.5 indicates correlation and a 0.8 indicates good correlation (Montgomery, D. C., 2012). The resulting cost function can be used to model the cost of shipping crude oil of a certain type (condensate, light, medium, heavy) in a given diameter pipeline for a distance to a Canadian (CLT) or US (IJT) location.

4.2 Crude by Rail

4.2.1 Background

Rail is becoming an alternative mode to pipelines for shipping crude oil in Canada. This is due in large part to a lack of pipeline capacity, to a reluctance by governments to undertake pipeline expansion projects in environmentally sensitive areas, and to limited integration and connectivity in the existing pipeline network with respect to sources of production and destination disposition points. To develop sound and reliable models of mode choice and route assignment from a shipper perspective, we need accurate estimates of the shipper costs by mode on a route specific basis. As previously discussed for pipelines, in this section we present the results of an empirical regression analysis of cost performance for crude oil shipments by rail in Canada.

4.2.2 Data Collection

Rail shipment costs will depend on a number of mitigating factors, such as, whether these shipments are under contract to the Canadian National (CN) or Canadian Pacific (CP) railway, on whether they take place using dedicated unit or conventional mixed trains, on the type of crude oil being shipped, on capital costs recovered on specific routes, etc. CP publicly disseminates a full tariff schedule for origin destination pairs of crude oil shipments (Canadian Pacific Railway, 2016). This tariff schedule includes all products that fall under the Standard Transportation Commodity Code (STCC) codes: 1311110 (Petroleum oil or shale oil, crude), 4910165 (Crude oil), and 2911716 (Diluted Bitumen). Published tariffs are based on uncommon shippers, representing those that do not have a contract with CP. The data provided by CP in cost per bulk tanker has been converted in this thesis to cost ($) per cubic meter, using a typical crude oil tanker capacity of 130 m^3 (CTC-111A). The complete OD rail cost table is provided in Appendix C. Similar data were not available from CN during the preparation of this thesis.

Rail distances between origins and destinations were determined from the NRCan Geographic Information System (GIS) data, which includes both the Canadian rail and pipeline transportation networks. These GIS data were again processed using the ArcMap program to determine rail distances. A CP rail map (Hatra, 2016) was used to determine the precise location of origins and destinations (zonal centroids), and to identify US locations for trans-border shipments by rail.

4.2.3 Base Regression Analysis

A regression model was established to express rail shipper costs as a function of selected mitigating factors. The best fit function was found to be linear in form with two input terms: shipping distance and a dummy variable to denote whether a shipment is domestic or trans-border (US), such that:

$$z = \beta_0 + \beta_1 d + \beta_2 D_t \tag{4.7}$$

where,

z is the toll value for a specific OD pair ($CND/$m^3$);

d is the OD distance (km); and

D_T is a binary value for the toll type ($D_T = 0$ for a Canadian destination and $D_T = 1$ for a US destination)

The resultant coefficients for equation (5.1) are given in Table 5.1, together with their corresponding t-static for significance (5% level). These regressions are based on a sample size of n= 917 OD pairs, for a critical t = 1.96 for this expression.

Table 4.4: Summary of Coefficients for Equation (4.7)

β_0	t_0	β_1	t_1	β_2	t_2	$t_{2.5\%}$	R^2	Observations
30.35	45.66	0.0123	45.94	13.29	20.53	1.96	0.744	917

Distance as expected has the highest correlation with shipper costs. The longer the distance shipped the higher the cost charged by the rail carrier for a given shipment of crude. International shipments, as expected, would incur a higher cost since they would be subject to an additional tariff to/for US destination. Given these relationships, parameter estimates are expected to be positive in both cases.

As given in Table 4.4, the R^2 value yielded an overall model goodness of fit of 74.4% (ratio of explained variance to total variance), which was considered to be good given the internal variance in the observed cost values. All coefficients yielded statistically significant results at the 5% level of significance. The positive nature of the coefficients is considered to be intuitively reasonable given expected relationship to shipper cost.

The intercept value = $30.35 reflects the fixed crude oil fee charged at zero distance. This base fee per m^3 corresponds to about $25 for Canadian destinations, and $32 dollars for US destinations (Diagonal of Appendix Table C.1). The distance parameter was found to be statistically significant, and positive as expected. Since distance is measured in kilometers, a coefficient of \$0.01234/km is reasonable. The coefficient for US destinations was also found to be statistically significant and positive reflecting the additional tariffs charged on US shipments (\$13.29/m^3) for crude oil.

Unexplained variance (approximately 26%) in the regression results could be due to congestion and handling fees occurring at terminal locations, which have not been considered in the model specification. For example, shipping from the Vancouver Area to stations between Calgary and Edmonton costs about \$42/m^3, but shipping to Calgary and Edmonton costs about \$44 and \$45/m^3, respectively (Table C.1). Note that Calgary is closer (in rail distance) to the Vancouver Area than the stations between Calgary and Edmonton but has a higher shipping cost. Hence, it may be possible to improve the rail cost function if terminal fees are expressed in terms of volume, capacity, congestion, etc., by incorporating corresponding dummy variables (e.g., high (1) or low (0) volume terminals).

4.2.4 Terminal Usage Regression Analysis

Through the use of data supplied by Transport Canada (unable to be disclosed here due to an NDA) there was a regression done interpreting the tonnage dispositioned as a congestive cost factor. This specification uses a dummy variable to convey a high or low usage terminal to create the final function of:

$$z = \beta_0 + \beta_1 d + \beta_2 D_T + \beta_3 D_U \qquad \textbf{(4.8)}$$

Where,

D_U is a binary value for the toll type ($D_U = 0$ for a low usage destination and $D_U = 1$ for a high usage destination).

The resultant coefficients for equation (4.5) are given in Table 4.5, together with their corresponding t-static for significance (5% level). These regressions are based on a sample size of n= 408 terminal tonnages, for a critical t = 1.97 for this expression.

Table 4.5:Summary of Coefficients for Equation (4.8)

β_0	t_0	β_1	t_1	β_2	t_2	β_3	t_3	$t_{2.5\%}$	R^2	Observations
29.25	31.46	.0134	33.22	12.92	12.71	9.81	6.39	1.966	0.807	408

Again, the distance coefficient proved to be the most valuable, having only altered a slight amount from the previous estimate. The international shipping tariff estimate remaining approximately the same value, providing expected results as this should not be affected by the terminalling fees. The usage variable now provides increased accuracy with an expected positive value, increasing the shipment values when there is a high terminal usage.

As given in Table 4.5, the R^2 value yielded an overall model goodness of fit of 80.7% (ratio of explained variance to total variance), which was considered to be good given the internal variance in the observed cost values. All coefficients yielded statistically significant results at the 5% level of significance. The positive nature of the coefficients is considered to be intuitively reasonable given expected relationship to shipper cost.

The usage coefficient of $9.81/m^3 is a reasonable value as a terminal with high usage will incur numerous cost increases due to costlier infrastructure, delay fees and higher storage fees. However, there is still unexplained variance (approximately 19%) due to unobserved costs during the shipping process, as well as the aggregate nature of the shipping location data. For example, there are shipping locations such as Calgary to Edmonton, in which there are multiple terminals, all sharing the same OD cost, but having varying distances as well as usages. With an improved tolling OD matrix as well as unseen shipping costs, such as specific terminal handling fees and post haulage fees.

4.2.5 Summary Findings for Rail Cost Performance Functions

Overall, results indicate that the distance shipped is statistically significant in explaining differences in shipper rail costs along a given route. Also, a significant contribution was provided by shipment destination (domestic vs international), where international destinations have an added tariff surcharge. The rail cost function developed in this thesis has an R^2 value of 0.81, indicating good model fit. It is hypothesized that the model fit could be improved by considering additional terminal fees, related to post haulages and handling, etc. These factors were not available for this thesis. Nonetheless, the resulting cost function can be used to model the cost of shipping crude oil by rail for a given distance to a Canadian or US location.

5 MODE SPLIT AND ROUTE ASSIGNMENT MODEL AND ALGORITM

This section presents a mode split and route assignment model that reflects real-world Canadian allocation, assignment and apportionment rules for crude oil pipeline and rail shipments (Kinder Morgan, 2015b). The decision-making process underlying this model is the shipper, who is prioritized by the carrier when there is limited pipeline capacity available. Priority is established on the basis of contractual arrangements between shippers and carriers (e.g., such as whether the producer is a term shipper or uncommitted), other attributes of the destination points (e.g., such as whether the destination is accessible by other modes), and sometimes by the shipper's willingness to pay. In Canada, the term "carriers" refers to common transportation companies (e.g., for pipelines: Enbridge, or Trans-Canada Pipelines; and for rail: Canadian National (CN) or Pacific (CP) railways). Shippers refers to the oil production companies, who are normally members of the Canadian Association of Petroleum Producers (CAPP) in Canada.

From the perspective of mode choice and routing decisions, shippers are assumed to bear the full brunt of transportation costs and tolls, and hence they are assumed to adjust their decisions in order to minimize shipment costs on a given route and mode. Shipper costs for crude oil transport are obtained for each mode by empirically based cost functions:

$$c_i = f(\mathbf{X}_\mathrm{i}) \tag{5.1}$$

where c_i is the cost of route i, and $\mathbf{X}_\mathrm{i}$ is a vector of variables that affect the costs along route segment i (such as distance, capacity, throughput, etc.). We assume that shippers will always first select pipelines (given their lower costs) and then, when pipeline capacity is reached, the remaining crude oil demand is diverted to rail at a higher cost to the shipper. The capacity of pipeline segments are determined based on their diameters. In this paper, we have assumed rail capacity to be unrestricted (or un-capacitated). No transfers are permitted between modes en-route.

For real-world applications, shippers can be aggregated into representative zones. Zonal production totals are the sum of individual shipper production levels in the zone. Similarly, all shipments to a destination zone are assumed to concentrate on a common attraction centroid within the zone.

5.1 Shipper Types

Two types of shippers are considered: term shippers and uncommitted shippers.

- *Term Shippers* are defined as shippers who are subject to legal contracts with the carriers (pipeline operators or railways), and hence are prioritized in the order of allocated modal capacities over uncommitted shippers who don't have any binding agreement with the carriers.
- *Uncommitted Shippers* are either not subject to contract with the carriers, or they are designated as term shippers, but have desired shipment volumes exceeding the amounts specified in their monthly maximum contracted volumes.

The contract refers to the "Term Service Transportation Service Agreement" entered into between the carrier and the term shipper. It also refers to any other agreement for service between the carrier and a term Shipper (e.g., as per Kinder Morgan introduction of a service fee to Westridge Marine Terminal shipments in Canada).

5.2 Destination Types

Different delivery points have different shipment priorities, as established by the regulatory agencies. In Canada, these agencies are the National Energy Board (NEB) for pipelines and Transport Canada for rail). Three types of destination points are considered:

- *Designated Delivery Points* are designated by the shippers. These destinations can be either crude oil refineries (e.g., Edmonton), industrial user (e.g., petroleum user), or a port terminal/transshipment point (e.g., Westridge Marine Terminal in Vancouver).
- *Priority Destinations* refers to refineries, marketing terminals or other facilities connected to and capable of receiving petroleum from facilities of a given carrier (e.g., Trans Mountain Pipeline to Puget Sound) and not capable of being supplied economically from alternative sources (e.g., no rail connection).
- *Alternate Delivery Point* refers to a demand by a shipper to a destination other than the Designated Delivery Points.

5.3 Prioritization Rules

Priority rules are commonly adopted by the pipeline industry to allocate limited capacity on specific routes (or route segments) and to specific points of disposition. In the model, it is assumed that all shipments are assigned to the minimum (i.e., shortest) paths for pipeline and rail.

The default priority ranking used in this model is:

1. Term shipper to priority destinations
2. Uncommitted shipper to priority destinations
3. Term shipper to designated destinations
4. Uncommitted shipper to designated destinations (based on bid premiums)
5. Term shipper to alternative delivery points (based on proportionate allocation)
6. Uncommitted shipper to alternative delivery points

As noted previously, shipments begin with assignment to pipelines, since pipelines have lower transport costs than rail. Once a pipeline segment has reached capacity, any remaining shipments seek an alternative pipeline route. If there is no available pipeline route, the shipment is diverted to the rail network.

5.4 Allocation Rules

When multiple shippers of the same type compete for limited pipeline capacity to the same destination point (i.e., the shippers have the same priority in the above ranking), the carrier allocates capacity either proportionally or according to bid premiums:

- *Proportional Allocation*: all shippers demands $(d_1, d_2, \ldots, d_n)$ are reduced proportionally (i.e., divided by $d_{total} = \sum_i^n d_i$).

- *Bid Premium Allocation*: all shippers bid on the capacity by submitting a bid premium, where the bid premium is the multiplication of their bid price ($\$/m^3$) and volume ($m^3$). For the purpose of this model, we have assumed that the bid price is the difference in cost between shipping by pipeline and rail, since any higher value for the bid premium would make rail cheaper than pipeline, and any lower value would result in a potential transfer to rail at a higher cost. The bid price (difference in cost) between origin r and destination s is denoted as Δp_{rs}.

The following hypothetical example illustrates how mode split and route assignment are jointly determined by shipper types, destination types, prioritization rules, and allocation rules.

5.5 Numerical Example

Consider a hypothetical region consisting of two crude oil production sources (zones O_1 and O_2) to three destinations (zones D_3, D_4 and D_5). Origin zone O_1 comprises 3 individual shippers (1 term (T) and 2 uncommitted (U)) and zone O_2 has 2 shippers (1T and 1U). The pipeline and railway networks connecting these zones is illustrated in Figure 5.1a, with a few key link/node attributes summarized in Table 5.1. The costs given in Table 5.1 include tolls and other fees charged by the pipeline and rail carriers, which are assumed to be some function of link distance, congestion, and other financing and contractual arrangements established between the carrier, shipper, and regulatory agencies (e.g., toll charges and service fees).

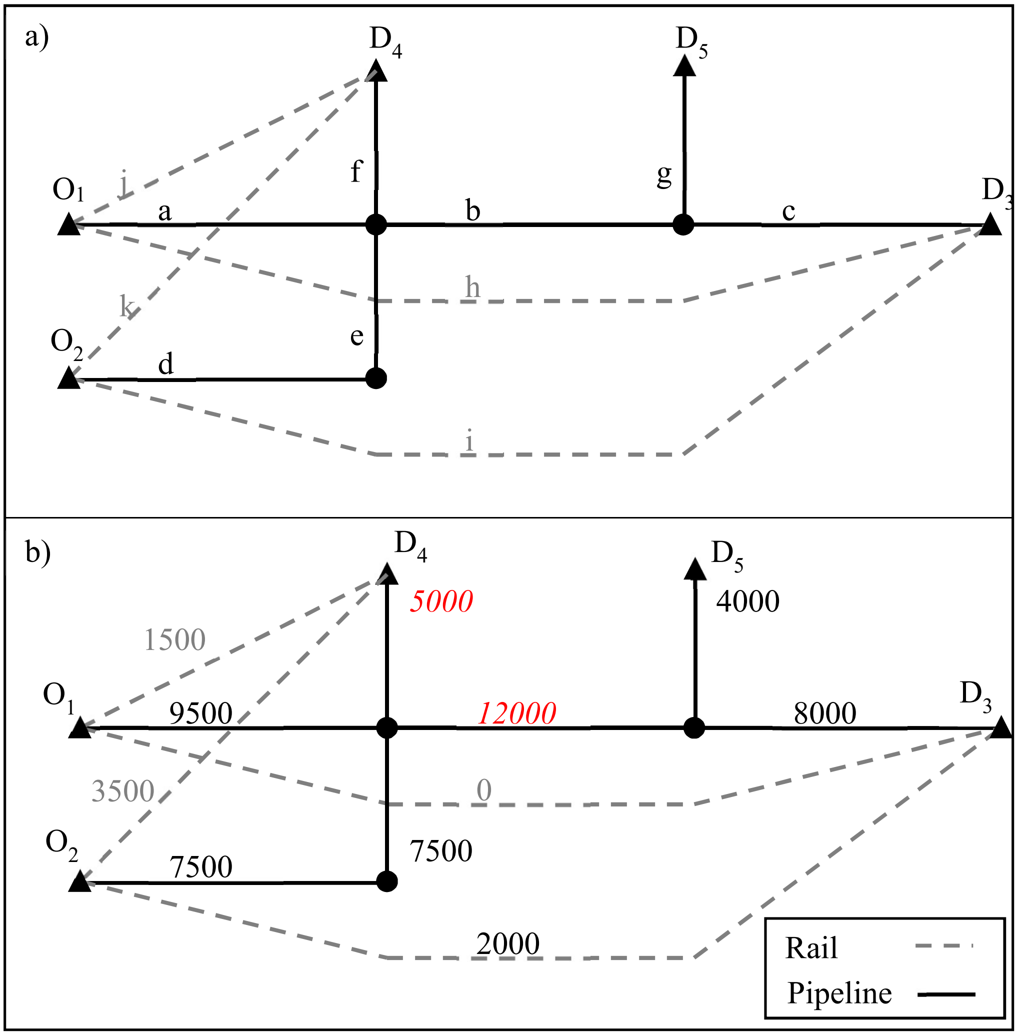

Figure 5.1: a) Hypothetical pipeline and rail network; b) Hypothetical pipeline and rail network flows (after mode split and route assignment).

Table 5.1: Hypothetical Pipeline Link and Rail Path Attributes

Pipeline			Rail		
Link	Cost ($/unit)	Capacity	Path	Cost ($/unit)	Capacity
a.	10	12000	h.	200	Unlimited
b.	20	12000	i.	150	Unlimited
c.	12	12000	j.	100	Unlimited
d.	16	12000	k.	250	Unlimited
e.	18	12000			
f.	14	5000			
g.	8	5000			

Table 2 provides a summary of the assumed total crude oil volumes or tonnages which are desired to be shipped from a given origin to a given destination zone, by individual shippers and in total for each zonal pair. Each volume can be represented by V_{rs}^{mn}, where *r* is the origin zone, *s* is the destination zone, *m* is the shipper type (T or U), and *n* is the shipment number.

Table 5.2: Hypothetical Origin-Destination Matrix of Shipment Tonnages

Origin \ Destination	D3 (Designated)	D4 (Alternate)	D5 (Priority)	Total
O1	1000 (T) 2000 (U) <u>3000 (U)</u> 6000	1000 (U) 1000 (U) <u>1000 (U)</u> 3000	1000 (T) <u>1000 (U)</u> 2000	11, 000
O2	2000 (T) <u>2000 (U)</u> 4000	3000 (U) <u>4000 (U)</u> 7000	1000 (T) <u>1000 (U)</u> 2000	13,000
Total	10,000	10,000	4000	24 ,000

5.5.1 Mode Split and Route Assignment

The mode split and route assignment algorithm proceeds by assigning shipments in order of their priority.

Step 1: Assign Term Shipper Flows to Priority Destination

$V_{15}^{T1} = 1000$; $V_{25}^{T1} = 1000$.

Step 2: Assign Uncommitted Shipper Flows to Priority Destination

$V_{15}^{U1} = 1000$; $V_{25}^{U1} = 1000$.

Step 3: Assign Term Shippers to Designated Delivery Point

$V_{13}^{T1} = 1000$; $V_{23}^{T1} = 2000$.

Step 4: Assign Uncommitted Shippers to Designated Delivery Point (based on bid premiums)

For V_{13}^{U1}: Δp_{13} x V_{13}^{U1} = [200 – (10 + 20 + 12)] x 2000 = 158 x 2000 = \$316,000

For V_{13}^{U2}: Δp_{13} x V_{13}^{U2} = [200 – (10 + 20 + 12)] x 3000 = 158 x 3000 = \$474,000

For V_{23}^{U1}: Δp_{23} x V_{23}^{U1} = [150 – (16 + 18 + 20 + 12] x 2000 = 84 x 2000 = \$168,000

Therefore, priorities are: 1) V_{13}^{U2}; 2) V_{13}^{U1}; and 3) V_{23}^{U1}.

Assigning all uncommitted shipments from highest to lowest priority, one shipper at a time:

V_{13}^{U2} = 3000 (1st rank); V_{13}^{U1} = 2000 (2nd rank);

Pipeline segment (b.) is now at capacity. Note assigning V_{23}^{U1} to pipeline, will exceed the pipeline capacity of 12,000 tonnes for route segment (b.). Hence, the decision is made to divert this shipment (V_{23}^{U1}) to rail.

Step 5: Assign Uncommitted Shippers to Alternative Land Destinations (based on proportionate allocation)

We need to assign the following uncommitted volumes to D_4 from O_1: V_{14}^{U1} = 1000; V_{14}^{U2} = 1000; V_{14}^{U3} = 1000. We need to assign following uncommitted volumes to D_4 from O_2: V_{24}^{U1} = 3000; V_{24}^{U2} = 4000. If all shipments were assigned to pipeline, cumulative flow on links (a.), (d.), and (e.) would be below capacity (no apportioning required). However, cumulative flow on link (f.) would be 10000, which is double the 5000 capacity for this segment (requiring apportioning). Therefore, capacity of pipeline segment (f.) is allocated proportionately to shippers at origins *1* and *2*, and the remaining flows are assigned to rail: V_{14}^{U1}: 1000 x 5/10 = 500; V_{14}^{U2}: 1000 x 5/10 = 500; V_{14}^{U3}: 1000 x 5/10 = 500; V_{24}^{U1}: 3000 x 5/10 = 1500; V_{24}^{U2}: 4000 x 5/10 = 2000.

The final assignment of crude oil flow to the hypothetical network is given in Figure 1b, with pipeline bottlenecks shown in *red*. This assignment approach is similar to a traditional incremental assignment, where each increment has been prioritized by shipper type, destination type, prioritization rules, and allocation rules.

In this example we have assumed that rail capacity is unrestricted (to reduce complexity). In reality, the above results represent the *demand* for crude oil rail transport, but these demands may not materialize due to rail capacity restrictions. For example, the Fair Rail for Grain Farmers Act of 2014 (Bill C-30) was passed in Canada to mandate grain shipment levels due to competition for rail transport. Hence, the crude oil rail flows that ultimately materialize in real-world networks may be the result of complex market interactions. To properly address these issues is considered to be outside the scope of this thesis.

6 CANADIAN CRUDE OIL FRIEGHT DEMAND MODEL

6.1 Network Model

The crude oil mode split model introduced in Chapter 5 prescribes an incremental allocation of crude oil volume to the pipeline until its capacity is reached, and then the residual demand is allocated to rail on an all-or-nothing shortest path basis. However, simplifications were made to this assignment procedure due to data limitations. Since the available shipping data does not distinguish between designated and alternative delivery locations, the pipeline assignment rules were combine for these shipments. The pipeline bidding process was however maintained in the logic of the trip assignment, discussed furthered in section 6.2, since the priority destinations, referred to as special case shipments, could be disaggregated from the collected shipping data.

The simplified priority ranking system used in the Canadian nation-wide assignment model is:

1. Term shipper to special destination
2. Uncommitted shipper to special destination
3. Term shipper to typical destination
4. Uncommitted shipper to typical destination

The OD matrix data, as previously stated, gave insight into the shipping details for the Canadian network, treating the US and foreign destinations as external zones. This matrix was then disaggregated into the cases of special and typical shipments based on the total shipping volumes. These two cases were based on the modal split logic categories of priority, designated and alternative destinations. As mentioned previously, priority shipments could be disaggregated from the shipping totals, but the designated and alternative could not be distinguished, resulting in their combination, and the creation of two cases. In this case, the special and typical represent the volumes from the priority and combined destinations, respectively.

The special case shipments account for approximately 26% of the west coast shipments to Southern British Columbia and Western International shipments by water (the international port on the west coast). This is due to the share of the Kinder Morgan pipeline making special case shipments to these areas, according to the report by NEB (2016), and assuming this would dominate the shipping volumes and therefore dictate the percentage made to this area. These new special case shipping volumes were modified from their original origin point. This is because the special case shipping always originated in Edmonton. To accommodate this aspect of the shipment assignment, the special case volumes that were to be shipped to Westridge Dock from Western Canada were summed and then added to the Zone 6 value. However, to compensate for this additional shipment, volumes were added to the appropriate origins to be shipped to Zone 6 under the typical volumes. This was to simulate the volumes as a storage shipment to the zone, to be sent subsequently to the Westridge dock. The remaining 74% of the shipments that were to be sent to Zone 2 were then treated as a typical shipment, with no alteration to their shipment origin.

The other alteration to the shipping structure was that for certain zones, the centroid connectors were limited, as the stop locations along the pipeline could not be capped or monitored as to the specific shipment volume to cities along their path. That is, in the case of the Enbridge Mainline there are multiple stops within the each of the zones, but to maintain an observable usage of this assignment, the centroid connecters were limited to major cities. This is demonstrated in Figure 6.1, showing the Enbridge Mainline locations that were used (Edmonton, Hardisty, Kerrobert, Regina and Cromer, from left to right) along with the smaller city locations that were unused (Milden, Stony Beach and Gretna, from left to right).

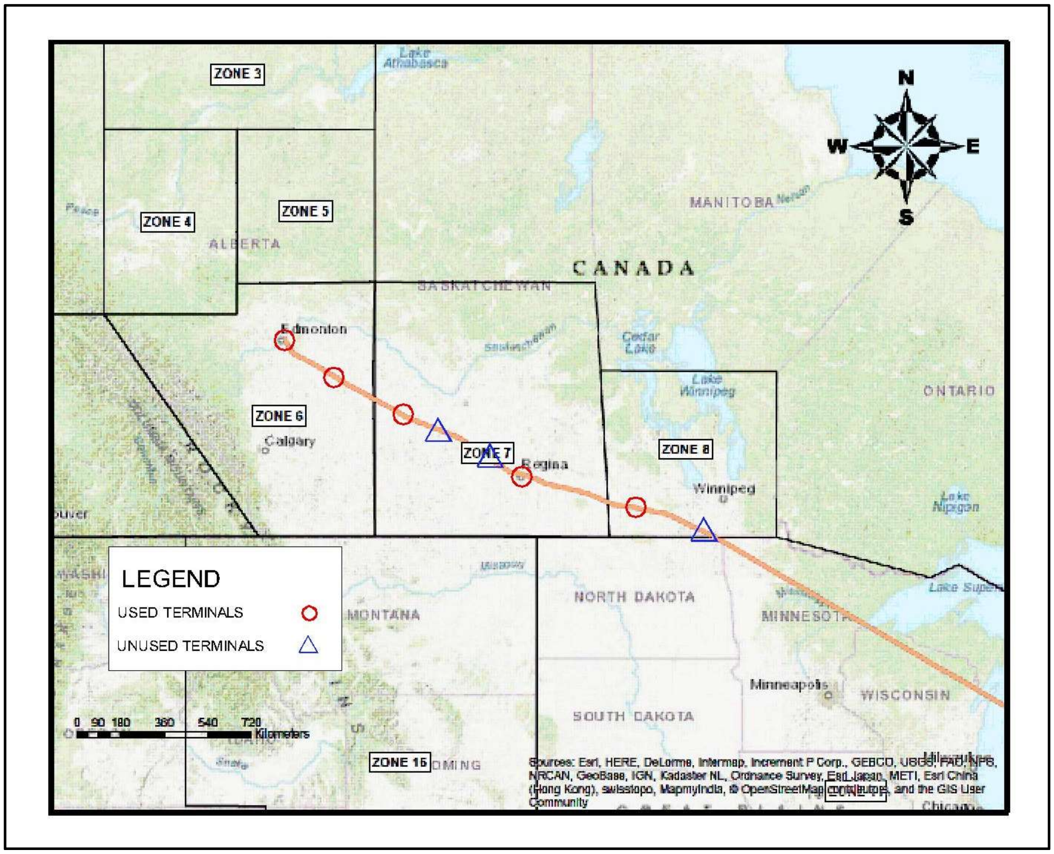

Figure 6.1: Enbridge Mainline Primary Production and Demand Locations

6.2 Pseudo Code

Two programs were used to implement the logic of the mode split and route assignment algorithm and to represent the physical attributes of the network. ArcMap was used because of its GIS mapping abilities as well as the shortest path function. The trip assignment itself, including the mode split, was performed using a Python (Python, 2016) script, connecting to Arcpy (ArcGIS, 2017), and using other Python libraries such as Pandas and Numpy.

The logic and progression of steps in the shipment allocation process is described below in pseudo code. Indented steps signify a portion of the code occurring inside of a loop or statement. This pseudo code is also illustrated as flow charts in Figure F.1 – 3, Appendix F.

The code reflects the following procedural logic:

- Import the system modules for python to utilize in the code.
- The default settings and property values for the trip assignment are applied by editing the current network analysis file to match the shipment and network values.

- **While Loop**: This is the main analysis of the program, running until the sum of the volumes in both the special case and typical case shipments have been completely allocated to the network.
    - To start the analysis there must be a check of the volume type that is to be added to the network, using an **If Statement.**
    - If the Special Case OD Volume matrix has a sum greater than zero:
        - Then the volume type will be set to “S”, and an array of OD pairs and their associated volumes will be created from the special case shipments.
    - Else if the Typical Case OD Volume matrix has a sum greater than zero:
        - Then the volume type will be set to “T”, and an array of OD pairs and their associated volumes will be created from the typical case shipments.
    - Then, the OD pairs will start a **For Loop** over the length of the array. A **Try Statement** will be the primary function inside the loop, with the ArcMap python plugin, known as Arcpy, as the subject of the statement.
        - This will start by trying to solve for a route using available pipelines between the Origin and Destination variables from the loop statement. If the pair can be solved using the pipelines then the statement will end, a file for the directions is exported and the mode will be recorded. This repeats until all OD pairs have been solved.
        - If the pipelines will not suffice for the shipment due to lack of connectivity or due to lack of capacity, then the rail network will be utilized after to complete the shipment.
            - If the rail lines also fail, then there will be a break in the code as to analyze whether there is no connectivity to this spot with either mode.
            - If the pair can be solved using the rails then the statement will end, a file for the directions is exported and the mode will be recorded. This will then repeat until all OD pairs have been solved.
    - After all the routes have been solved next is to analyze the direction files to see what links were utilized in each pair. To make the links unique as well as the centroid connectors a special character was placed to signify the start of these attributes, a “!” for centroid connectors and a “~” for links.
    - These link files are then compared against each other, observing which OD pairs utilize the same links and storing them in a multiuse array. At the same time each of the individual links are stored in a separate array, as to be able to account for every single link used in the analysis. These files are then merged with the properties of all the rail and pipelines that are associated to the ArcMap IDs.
    - Next, a **For Loop** will run through the OD pairs to determine the limiting link in each shipping case to determine the minimum capacity. As well, another **For Loop** will be nested inside this to run over the links in the multi and singular use arrays, with an **If Statement** to check whether a link has been used in a route.
        - Then there will be multiple **If Statements** to determine the shipment case as well as the capacity type. From there, additional shipping properties will be determined, such as whether the shipment will be split or not, and the other properties will also be recorded in an array.

- A part of the mode split logic is for special case shipments, when the uncommitted capacity has been exceeded by multiple shippers then a bid premium method of split is to be conducted.
    - This process is done in multiple stages, the first of which is calculating the cost of using pipelines for the trip based on the determined cost functions. Then using the previous **Try Statement** to determine the shortest path, it shall be used again for the rail lines. There will be another break in the code if there is no path on the rail available, to allow for an analysis of the network as to why there is a lack of connectivity. Using the direction file that has been exported from the previous shortest path, the cost of the rail shipment is then calculated. The two costs for the OD pair will be subtracted to find the difference in price and then multiply it by the volume of the shipment. The values will then be sorted in a descending order, with the highest value as the first rank.
- The final phase of this code is the actual trip assignment, with a **For Loop** running over the OD pairs, starting with an **If Statement** to determine if it is either a pipeline or a rail line route. If it is a rail route, then the entire volume for the OD pair is assigned to the route on an all-or-nothing basis. If it is a pipeline segment, then there are additional if statements to determine how the volume should be altered on a priority rule basis.
    - The pipeline checks are performed using the properties array that was built during the minimum capacity segment, first check is whether the capacity is committed or uncommitted. The next check is to see if it is a special or typical shipment and finally whether the volume needs to be split.
    - If the volume does not need to be split, the volume in the OD matrix will be added as is to the links in the route. As well, if the volume does need to be split then the volume will be added proportionally, asides from the special case uncommitted capacity. With the special case uncommitted capacity, the volume is allocated based on the rank of the OD pair.
- After all OD pairs have been analyzed the volumes on all the links are compared to the total capacity of the pipeline. If the volume matches the capacity of the pipeline, the one-way property is then altered to "n" to make the link restricted. Once all the edits have been made then the network analysis layer is edited and rebuilt using the Arcpy module.

- The final process is to sum the total OD matrix, both the special and typical cases, after the volumes have been altered above, to determine if the sum is greater than zero. If the sum is greater than zero, then the while loop will continue, and if it is equal to zero then the trip assignment has been completed, and the code will end with a statement of completion.

6.3 Base Case

The network for the base case utilizes the data as previously discussed for shipments, as well as the current existing physical pipeline and rail line network with no alteration to their availability or connectivity. The physical network is determined using GIS data provided by Natural Resource Canada and mapping provide by CEPA. The figures below describe the current state of the pipeline network, and the estimated volumes on the pipelines and rail lines using the trip assignment procedure in the model. Figure 6.2 summarizes pipeline ownership for the national network, while Figure 6.3 summarizes pipeline predicted throughputs in m^3/day for 2015.

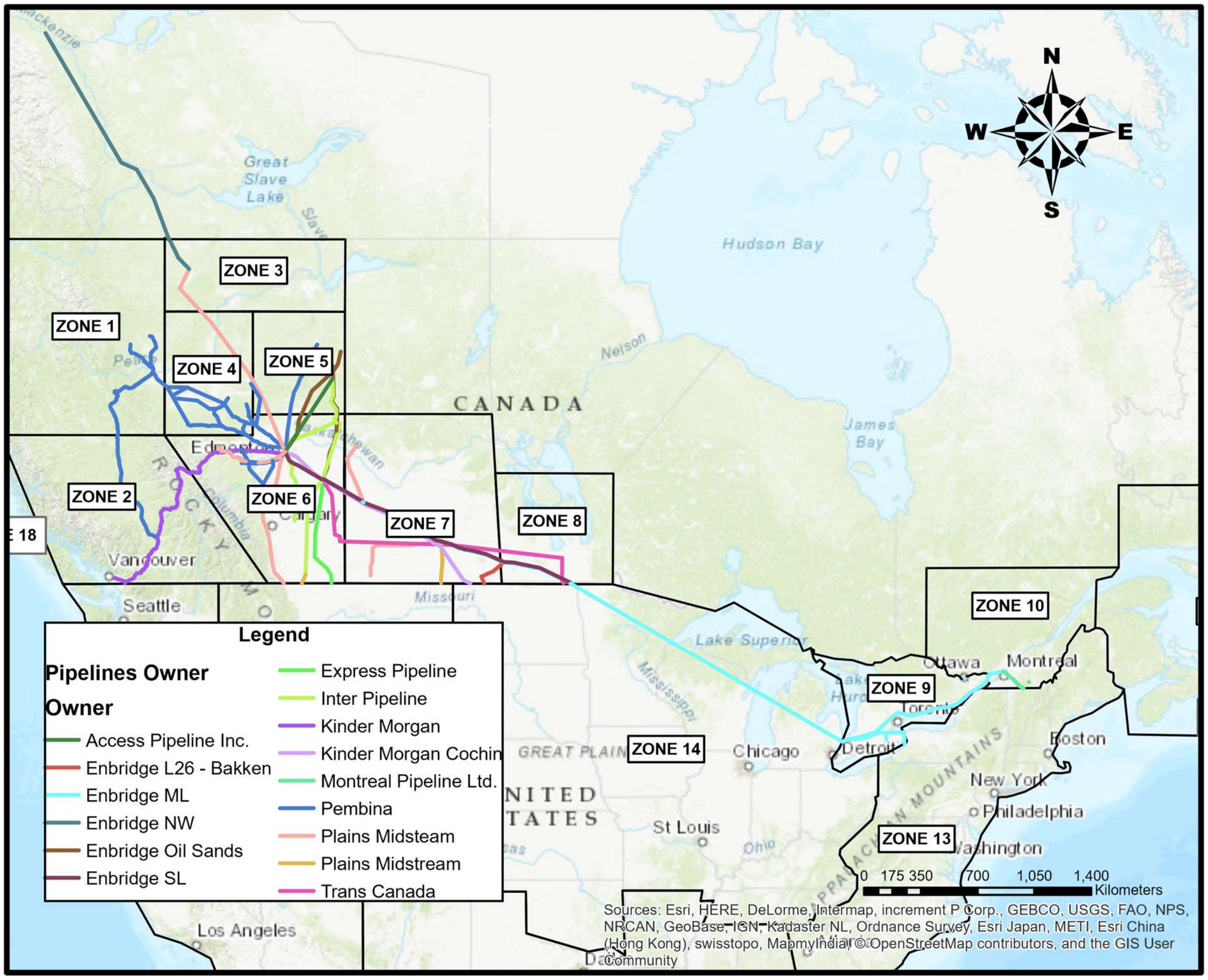

Figure 6.2: Pipeline Owners

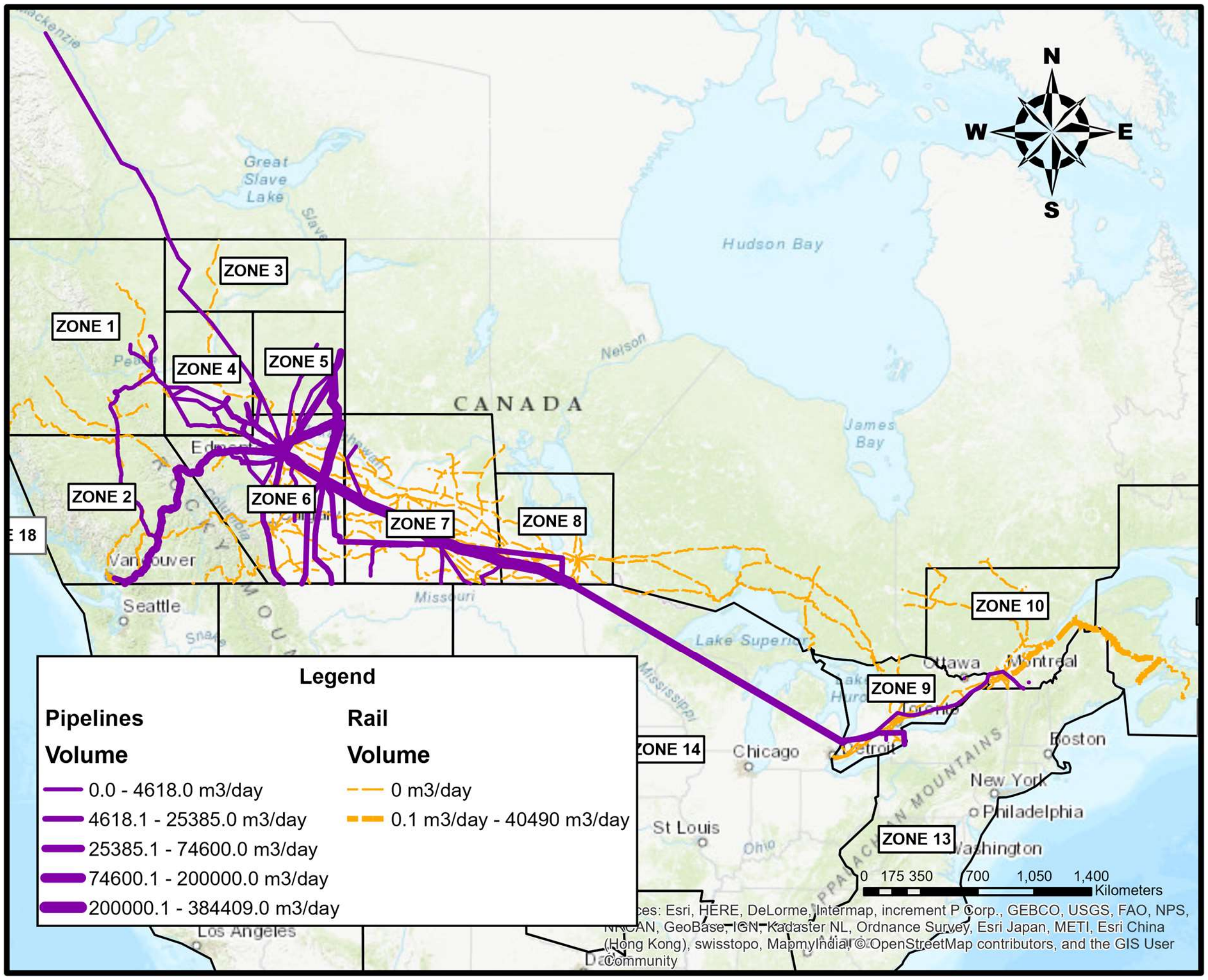

Figure 6.3: Base Case Volume Distribution (m^3/day)

As can be seen from Figure 6.3 there are many values not accounted for by the pipelines in terms of their estimated vs real world utilization. This is primarily due to the under prediction of origin-destination shipping values as well as missing pairs in the underlying StatsCan data. The values from Saskatchewan, Manitoba, British Columbia and the Northwest Territories have all been supressed by StatsCan, dramatically lowering the values from Western Canada, effecting major pipelines like the Trans Canada, since there are major production locations in Saskatchewan and Manitoba for this line. Additionally, the US import values are unavailable asides from the US to Quebec shipments. Although the value available does not specify that the shipment is from PADD I, it is assumed that the shipment would be from this PADD as there is the Montreal Pipeline specifically used for the shipment of US crude shipments to Quebec. The remaining US PADD to Canadian Zonal crude oil shipments are unavailable as they were suppressed by both the US Energy Information Administration (EIA) and StatsCan. This effects pipelines that only service the US to Canada shipments, that in the real-world they have moderate utilization, such as the Kinder Morgan Cochin line (at 84% utilization) will then be unused in the model due to the lacking import volumes. As described in Section 3, the shipping values from the US to Canada are aggregated, so there are no values that specify province or PADD.

Another problem typically encountered with demand models stems from the level of aggregation of the zones. In most cases, the zones reflect an extensive disposition area with many producers and points of disposition. This can result in significant flow assignment errors since many different links may connect the producer to the pipeline network. This also causes an issue when the production and distribution locations coincide within the same zone (i.e., an intrazonal assignment). This then forces this OD value to be treated as 0 within the model since the shortest path it will find will be between the two centroid connectors, since they have 0 cost each. An example of this is Zone 6, in which Edmonton is a major disposition and production location, causing there to be both a production and demand centroid to be connected to this location. In the OD matric the Zone 6 to Zone 6 location is then set to 0 as to avoid error in the model.

There are missing interprovincial data since StatsCan only specifies shipments provincially if they are being sent to the refineries within those provinces. While there are volumes for terminals and inventory changes for each province, there is no specification on where in the province or out of province this is occurring. This is another reason leading to certain lines either being underutilized or completely empty, such as Pembina in northern BC.

6.3.1 Base Case Validation

To provide some model validation the average utilization values from the NEB 2016 Pipeline report (National Energy Board, 2016) were adopted as the observed real-world throughputs. The maximum utilizations on these observed lines, were then taken from the predicted model pipeline throughputs and compared, as shown in Table 6.1.

Table 6.1: Validation Data

	Observed				Predicted		
	Pipeline	**Utilization**	**Capacity (m^3/d)**	**Throughput (m^3/d)**	**Utilization**	**Throughput (m^3/d)**	**Model Comment**
Group 1	Enbridge Mainline	85%	453300	385305	90.75%	411369.75	OK
	Keystone Pipeline	94%	94000	88360	9.41%	8845.4	Supressed production data from Manitboa and Saskatchewan
	Trans Mountain Pipeline	105%	47700	50085	92.21%	43984.17	OK
	ULC's Cochin Pipeline	84%	15100	12684	0.00%	0	Missing US Imports
	Enbridge Norman Wells Pipeline	24%	5087	1220.88	0.00%	0	Supressed production data from Northwest Territories
Group 2	Express Pipeline	78%	44500	34710	57.04%	25382.8	OK
	Enbridge Westspur Pipline	69%	40500	27945	0.00%	0	Supressed production data from Saskatchewan
	Southern Lights Pipeline	59%	28600	16874	0.00%	0	Missing US Imports
	Enbridge Bakken Pipeline	61%	23100	14091	0.00%	0	Missing US Imports
	Montreal Pipe Line	22%	44500	9790	4.89%	2176.05	Missing US imports
	Milk River Pipeline		18800	15087	100.00%	18800	OK

While the results suggest significant differences between observed and estimated throughputs on the existing network, the model still presents accurate results when considering the available data. Of the Enbridge pipelines, the Mainline has values that are not suppressed or effecting the shipment patterns, giving this line a high accuracy. However, when it comes to many of the other lines there is far less accuracy due either to missing data or data suppression, for example:

- The Enbridge Norman Wells pipelines has a zero value on this line since the Northwest Territories have a supressed crude oil production value and this pipeline only services this zone.
- Westspur is also zero as the Saskatchewan production values are supressed as well.
- The Southern Lights line has zero usage as the US exports to Canada values are too aggregate for there to be a proper zonal breakdown of the values, leaving them to be left out of the modeling process.
- Bakken, this is a US to Canada shipping line like the Southern Lights line, therefore the import values have been supressed.
- The TransCanada Keystone should have a large throughput; however, this line has such a low observed value in comparison to the real-world data due to the large aggregation of the US zones. For Zone 14, PADD II, in the US, as can be seen in the zonal figure, it is quite large and contains numerous major disposition locations. The Enbridge Mainline is then able to service the entire volume that is required by this zone, giving only the shipping volumes to Zone 15 to be serviced by this pipeline. Also, due to the suppression of shipping volumes from the Saskatchewan and Manitoba zones, there is a decrease in the overall shipments causing an under prediction.
- The Kinder Morgan Trans Mountain pipeline has a relatively close value, but there is still a variance due to the suppression of the BC production values.
- The Cochin ULC pipeline on the other hand has a zero value for the same reason as the Southern Lights line: there are no shipping values from the US into Western Canada.
- Spectra Express, now owned by Enbridge, has a 30% deficit on this pipeline for similar reasons to the Keystone pipeline, that while this is one of the few major pipelines to service Zone 16, PADD IV, it also services Zone 14, PADD II, of which all demand is serviced by the Enbridge Mainline taking away from the specific disposition locations only serviced by Spectra.
- The Montreal Pipeline Ltd. pipeline is under predicted since the US shipping values are under predicted for Canada, as this pipeline only services Zone 13, PADD I, to Montreal.
- Plains Midstream Canada ULC is over used as this is one of two other pipeline that services the US PADD IV, Zone 16, and it is the least costly to use this line in comparison to Spectra Express or the Inter Pipeline, the model uses its full capacity before switching to the Inter Pipeline and then Spectra Express pipeline subsequently.

When using the available and suppressed data that effects the pipelines described in Table 6.1, while excluding the unavailable data, the regression suggests the model is quite accurate. The regression, using throughputs, provided an R^2 of 0.96, shown in Figure 6.4. However, it should be noted that this value is slightly misleading. This value has become so large since the Enbridge Mainline has such a high shipment value, causing the error from the other pipelines, with far lower observed shipping values, to not impact the variance as much. For example, consider the predicted throughputs compared with those reported for Canada’s Group 1 and Group 2 export pipelines:

Enbridge Mainline, Keystone, Trans Mountain, Normal Wells, Express, Westspur, and Milk River. Their average throughputs in 2015 were 385305 m^3/day, 88360m3/day, 50085 m^3/day, 1221 m^3/day, 34710 m^3/day, 27945 m^3/day, and 15087 m^3/day, respectively. Their predicted throughputs were 411370 m^3/day, 8845 m^3/day, 43984 m^3/day, 0 m^3/day, 25383 m^3/day, 0 m^3/day, and 18800 m^3/day, respectively. These values have mean absolute percentage errors (MAPEs) of: 7%, 90%, 12%, 100%, 27%, 100%, and 25%. So, while there is a large error with the other pipelines, the impact they have on the overall error is reduced greatly as the Enbridge Mainline throughput value is greater than the sum of the remaining pipelines, giving it such a high importance in the validation.

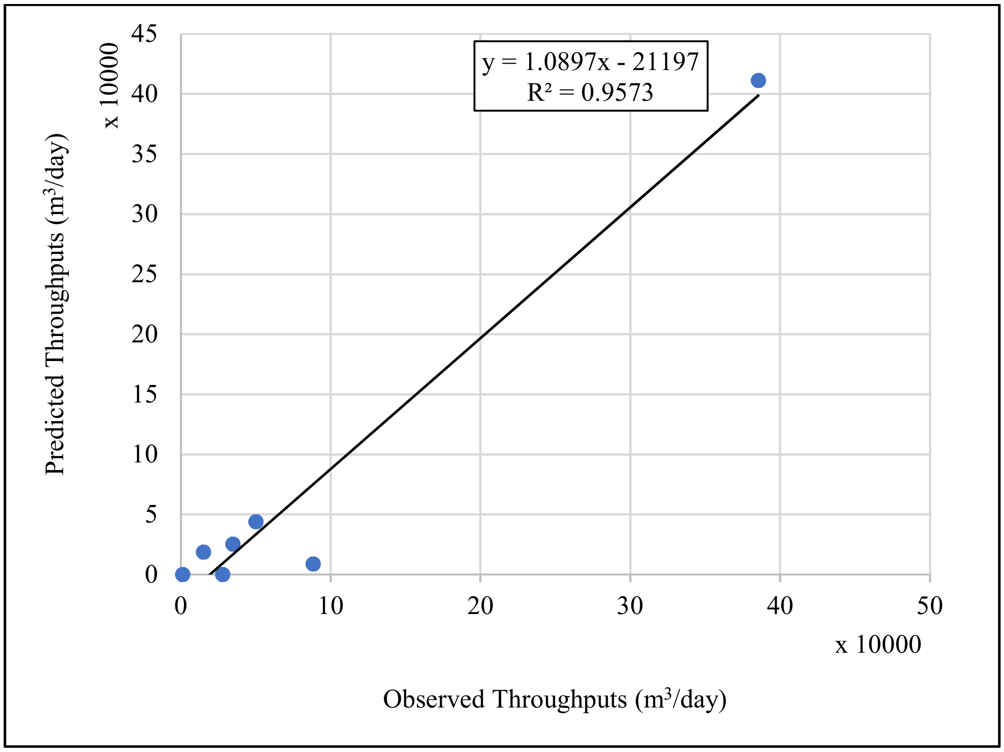

Figure 6.4: Predicted vs Observed Pipeline Throughputs

A validation of the rail volumes was not conducted, but the predicted rail shipments differ from general observations. Predicted volumes on the rail network only occur between Zone 11 and 10, since it is the only available mode between these two zones. The lack of rail shipments in the base case scenario is caused by the available capacity of the pipelines to handle all of the current network flows, as well as the aggregation of the zones. As can be seen in Western Canada, there are multiple points in which it is possible that rail may service specific locations inside these zones. While in the real-world network, specific shipments would be handled by rail due to existing contractual obligations or connectivity to certain locations, this information is currently unavailable. This first implementation of the crude oil model, while imperfect, still provides consistent results with the existing major pipelines. With additional information on the suppressed production values, this model could be drastically improved.

6.4 Case Study applications

Two case studies are presented along with the base case, both utilizing the existing network with anticipated future alterations. The first of these will observe the expected increase in Oil Sands production by the year 2030, increasing the shipment values by 39% from the current volumes. This forecast was taken from the Alberta Energy Regulator Oil Sands Production Profile report (Alberta Energy, 2016). The second case study will observe the impact on the network after the addition of the proposed Trans Canada Energy East pipeline (TransCanada Corp., 2017).

These two case studies will illustrate the importance and usefulness of the model, as well as its potential to be used for its future purpose of a quantitative risk assessment. The first case study will observe the adequacy of the existing network to handle the expected production increase from the Oil Sands. The second case study will develop an understanding of how the increase in capacity to a high congestion area will offset the volume distribution from the initial case study.

6.4.1 Case Study 1: 2030 Production Forecast with no new pipelines

The first case study seeks to show the effects on network volumes due to increased production brought about by the Alberta Oil sands, as predicted by the Alberta Energy Regulator (AER). In this case study, we expect an increase in production of 39% by 2030 on all productions in the Oil Sands zones, and this increase is to be distributed evenly over all shipments originating in the effected zones, Zone 4 and 5, increasing all values by 39%, as to assume that shipping patterns would not be affected, only their quantities. The figures below demonstrate the effects of this potential increase to the existing network. The figures below, Figure 6.5 and Figure 6.6, display the absolute volume increase in m^3/day and the percent increase from the base case, respectively.

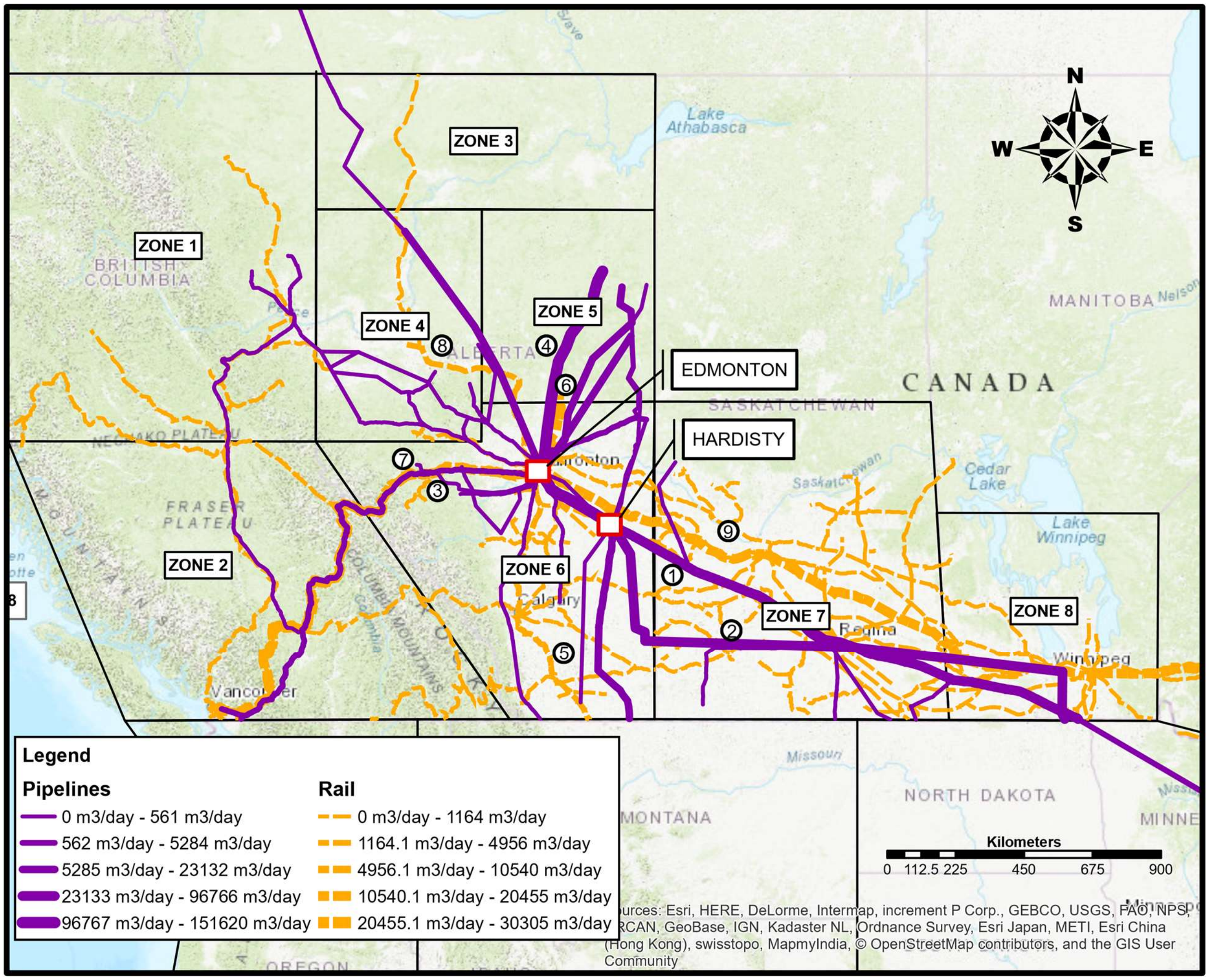

Figure 6.5: Case Study 1: Volume Difference (m^3/day)

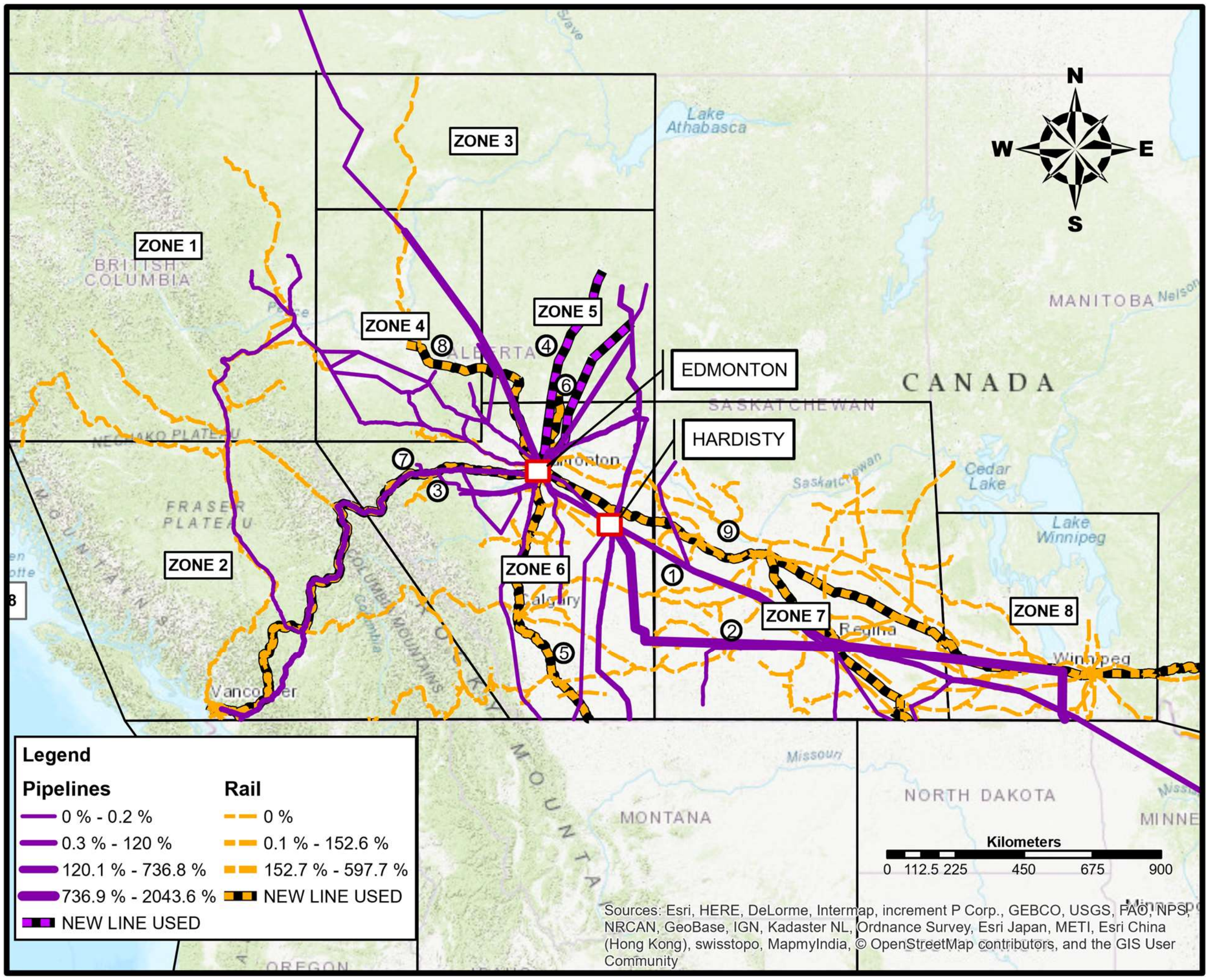

Figure 6.6: Case Study 1: Volume Difference (%)

As can be seen from the figures above, there have been numerous changes on the network with increases on numerous pipelines as well as new rails being utilized due to the pipeline capacities being reached.

The primary increases on the network can be seen around the pipelines going directly from the Oil Sands, understandably as this case study observes the impacts of the predicted production increases on the Oil Sands. ID 1 denotes the Enbridge Main line, in which there was an increase of 97.2% or 143,152 m^3/day to 10.2% or 39,192 m^3/day, however this large increase was associated with the lower usage areas from the base case. As seen in the above figures as well as Figure 6.2, there are no east traveling pipelines out of Edmonton asides from Enbridge ML, causing it to be the primary used pipeline for Oil Sands transport out of Edmonton. In the base case though, the volume to be shipped out of Zone 5 is mostly handled by the Inter Pipeline and Enbridge Line that connect to Hardisty, causing the Enbridge ML connection pipeline between Edmonton and Hardisty to be underutilised. This is also evident in the new lines that are being used, seen in Figure 6.6 the lines from Zone 5 which terminate in Edmonton, that prior to the volume increase of this case study the demands could be met by the capacity of the pipelines in the shorter path routes. For these reasons there was a large increase on the Edmonton to Hardisty portion of the Enbridge line, while the Hardisty to the east segment only incurred a small increase in volume prior to hitting its capacity. ID 2 denotes the Trans Canada pipeline with an increase of 962.6% or 85,154 m^3/day. This large increase is mostly due to the Enbridge Main line reaching its capacity. Since the US zones are so large, it begins to cause issues with the split between the pipelines as PADD 2 is the largest delivery point for both Enbridge and Trans Canada. Enbridge tends to dominate however due to its cheaper path and much larger capacity in comparison to Trans Canada. ID 3 is for the Kinder Morgan Trans Mountain pipeline, with a minor increase of 8.5% or 3718 m^3/day, reaching its capacity. This is important as this pipeline is a major shipper for the West Coast of Canada and the US, especially since in recent news there has been a halt to the expansion of this line. With the capacity having been reached so quickly, it seems imperative that this line is expanded to deal with the increasing productions and possible trading.

The only new lines that have been required by the pipeline network were the Pembina Horizon/Syncrude line and Enbridge Line 70/18, shown by ID 4. Until this point all the crude oil demand could be handled by Inter Pipelines, Enbridge and Access, however with such a large increase in demand all pipelines were needed until their capacities to handle this additional volume. However, due to the other pipelines reaching their capacities before this line, capacity was still not reached on the Enbridge pipelines, the Pembina however did with a volume of 101,500 m^3/day.

As previously stated, the major pipelines in the network have all reached their capacities with the Oil Sands production increase. This has resulted in a large switch to the use of rail lines, with IDs 5, 6, 7, 8 and 9 denoting the new major routes on rail. ID 5 is CP, shipping 4,956 m^3/day to cover the remaining demand from Edmonton to Zone 16 (PADD 4) as the Inter Pipeline, Spectra Express and Plains Midstream have both reached their capacity, and these two pipelines are the only connection to this zone. ID 6 is Canadian National Railway, shipping 30,305 m^3/day. This rail is now being used since the Oil Sands pipelines are all either at capacity or the lines connected to them for the shipment to the zones are at capacity as well. For example, the major pipelines from Hardisty, Enbridge and Inter Pipeline, are at capacity leaving the rail to compensate for the shipments to Saskatchewan, Manitoba and Ontario. ID 7 is also Canadian National Railway, with a volume of 12,382 m^3/day. This is now required to ship the remaining volume from Alberta primarily to Zone 17, PADD 5, as well as to Zone 2 and 18. ID 8 shows the shift to the Canadian National Railway from Zone 4, now shipping 1,992 m^3/day. Due to the capacity constraint at Edmonton, in which the major lines have all reached their capacities, the volume is then initially placed on a rail. This is due to the inability to perform an intermodal split on the network, as all pipeline to rail transition points are unavailable. So, while the Plains Midstream line into Edmonton still has available capacity, the shipments from Zone 4 will have to be put on rail initially. The last example, ID 9, is placed on Canadian National Railway as well, shipping 15,499 m^3/day. This will provide the remaining shipments to the east of Alberta, including Saskatchewan, Manitoba, Ontario, and Zone 13.

As can be seen from the pattern of new rail lines and the utilization of the pipeline network, there are two major issues to be addressed with the increasing oil production rates. First, the major issue is the bottlenecking effect occurring at Hardisty. This is concerning since this is a major hub for shipments to originate from, including the Enbridge Mainline which alone has a capacity of

423,600 m^3/day, making it the largest Canadian shipper of crude oil by a large margin, supplying numerous locations. If this pipeline is hitting capacity as well as the other major shippers out of this location, that means that a large portion of Eastern Canada and US will be unable to effectively acquire crude oil. This also effects the Oil Sands pipelines as the Enbridge 70/18 lines are highly underused since the Enbridge Mainline reaches its capacity at Hardisty. So, while there is available capacity from the Oil Sands to Edmonton and Edmonton to Hardisty, there are no available pipelines out of the Hardisty location due to all pipelines having reached capacity, unnecessarily allocating shipments onto the rail network, as seen from ID 6 in Figure 6.5 and 6.6. The next issue is that the Kinder Morgan Trans Mountain line has reached capacity, that if trade is to increase, especially with such a large increase in the production of crude oil, then an increase in this capacity is substantial. Due to the large difference in price and shipping efficiency, an increased pipeline capacity could cause a shift in the OD pair volumes within Canada, causing a greater portion of shipments to be sent to the Westridge docks and the west coast of the US in PADD 5.

6.4.2 Case Study 2: 2030 Forecast with New Energy East Pipeline

The second case study models the effects of increased production of the Alberta Oil sands in combination with the introduction of the proposed Trans Canada Energy East pipeline. The properties of this new pipeline were taken from the Trans Canada – Energy East website, where the capacity and locations of the pipeline were shown (TransCanada Corp., 2017). For this case study, the base case for comparison of volume changes is the first case study (i.e., 2030 forecast). Hence, this case study examines the impacts of introducing a new pipeline to the already congested 2030 network. Figure 6.7 and Figure 6.8, display the absolute volume increase in m^3/day and the percent increase from Case Study 1, respectively, summarized by Table 6.2.

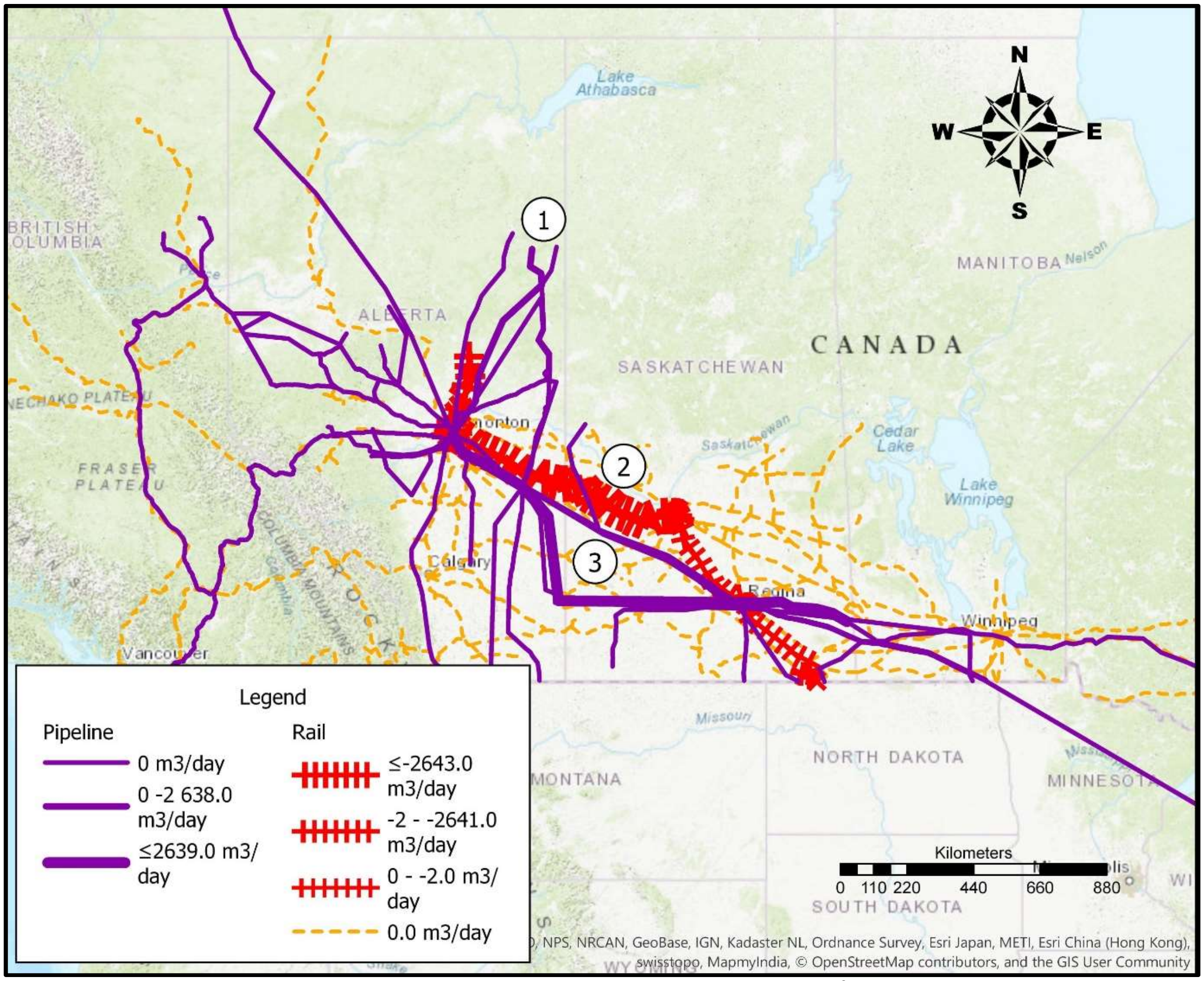

Figure 6.7: Case Study 2: Volume Difference (m³/day)

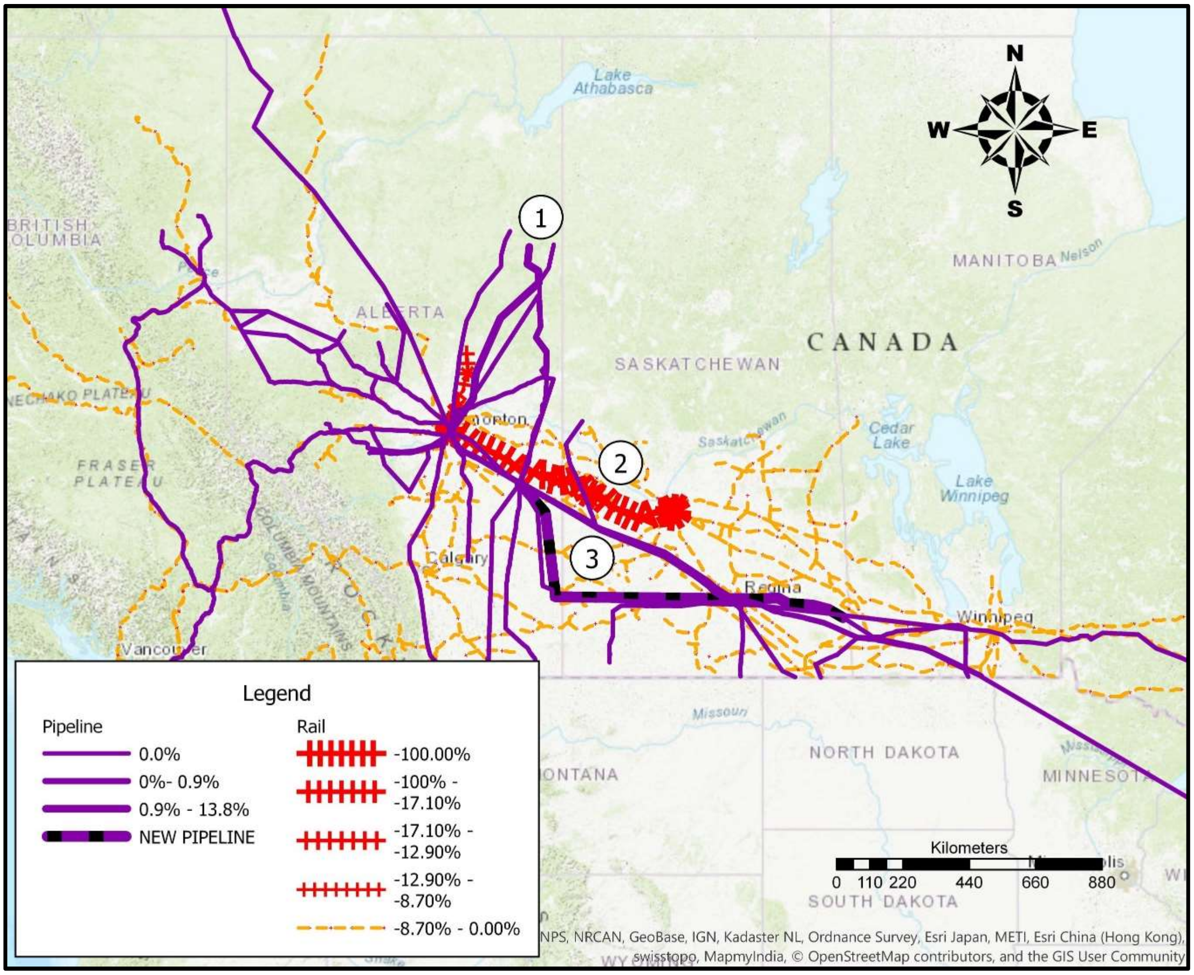

Figure 6.8: Case Study 2: Volume Difference (%)

Table 6.2: Case Study 2: Volume Difference Summary

ID Number	Mode	Company	Volume Change	
			m^3/day	%
1	Pipeline	Enbridge Oil Sands	2,638	13.8
2	Rail Line	Canadian National (CN)	-2,643	-17.1
3	Pipeline	Trans Canada Energy East	2,638	New Line

There is very little increase to the pipeline network as many of the lines were already at capacity and the use of the new line that has been implemented is quite low. The change onto the pipeline network is noticed at ID 1 in Figure 6.7/8 in which an additional 13.8% and 2,638 m^3/day has been allocated to the Enbridge Oil Sands Line.

The only new pipeline in use with this case is the new pipeline added, the Energy East line, as denoted by ID 3 in the above figures. Due to the lack of shipments from Alberta to the east coast, as per the existing OD pairs, this new pipeline remains highly unused. Especially since the new pipeline only has disposition points in Saskatchewan, Montreal and Saint John, and the largest area in need of additional capacity is in Ontario, since the largest volume from Alberta is deposited in southern Ontario or travels through it.

Directly linked to the increase in pipeline usage, discussed above, the rail network has now had a decrease in the same area, denoted by ID 2.

While this new line provides a low effectiveness to alleviate the requirement for using rail, it is associated with the limitations of the model. This is in part due to the fact that while this model is comprehensive in the physical attributes of the network, the shipping data remains lacking in comparison. As well, the model does not consider that with an additional capacity or cost reduction to allow for the shift of shipping volumes. In other words, OD demands are not a function of shipping costs. For example, if this new pipeline were to be implemented, much like the discussion on the Kinder Morgan expansion, there is a high chance that other shipments would be reduced while the shipment from Alberta to Eastern Canada would then be increased. This is especially true since there are multiple major ports on the east coast of Canada, with this line directly linking to the Saint John port.

6.5 LIMITATIONS

As this is only the first iteration of a crude oil freight demand model, several limitations of the current model remain. The first set of limitations come from the scope of this model. To reduce complexity, there was no consideration of truck or marine oil transfers. While there was the inclusion of the foreign shipments at the west and east coast ports, the marine vessels themselves were excluded. Moreover, due to a lack of data, the terminals at which crude oil was deposited or transferred were also not included. Future models could consider the capacity of each of the storage facilities or the capacity of different refineries and factories that utilize crude oil. This could give a better split of the crude oil on the pipelines and rails, especially in situations where there are single lines to multiple facilities. While this was a multimodal system, it was assumed during trip assignment that there were no intermodal transfers in the network. Additional limitations lie within the scope of the area observed in this research, primarily that while North America and foreign shipments are considered, the physical network is only modelled for Canada. Although there is still Canadian owned rail lines and pipelines within the US, these are not part of the current model. Due to limitations with the data, the method in which the crude oil types (i.e., condensate, light, medium and heavy crude) are applied to the network are limited. Due to an incomplete disaggregation of the crude oil types for all shipments, the capacity and ability of pipelines to ship certain product types is also limited. This has also limited the cost functions allowable in this model since the original function relies on a specification of the crude oil type. Instead a slightly less accurate function using the average crude oil costs is currently used.

Along with the scope of this project, there are also transportation theories that could not be applied, primarily effecting the accuracy of the shipping patterns. The idea that the OD pair shipping volumes can be altered based on cost of shipment, quantity of shipment and capacity available to ship, is known as a feedback. This effect on the current network has not been included in the current model as this is the very first iteration and including these behavioural dynamics requires a large validation effort. Moreover, the OD volumes in the 2030 forecast are only increased based on an assumed increase in production in selected zones, whereas the alteration to the physical network has no effect on these values.

The final limitation that effected this study, and most significantly, was the lack of disaggregate data available on crude oil and pipelines. Due to a lack of data, the terminals at which the crude oil was deposited or transferred was also not included. This would include the capacity of each of the storage facilities or the capacity of different refineries and factories that utilize these products. This could give a better split of the crude oil on the pipelines and rails, especially in situations where there are single lines to multiple facilities. As previously mentioned, the modal split was reduced in complexity due to a lack of shipper specific data. Unless the pipeline companies themselves or the shipping companies were to provide this data, it would be impossible to conduct this modal split. For the shortest path assignment, there was an inability to utilize the developed cost function as well since the program ArcMap is only able to work on a link basis as opposed to the how these cost functions work on a route specific basis. While basing the trip assignment on only the length of each of the trips is less accurate, the distance variable in the function accounts for a very large percentage of the cost of the trip, allowing this method of shortest path to remain adequate.

In conclusion, while this model has many limitations, primarily due to the lacking data, it is the first step toward modelling the existing pipeline network. With solutions to these current limitations, the model could be greatly improved upon.

7 CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

This section outlines some key findings from this initial research and provides some direction for future work.

7.1 Key Findings

Establishing a Canadian crude oil OD demand matrix (refer to Section 3) led to the following key findings:

- A comprehensive set of statistics describing crude oil shipments in Canada is not publicly available. Hence, several separate data sets were combined to yield the base Canadian crude oil OD table or matrix.
- Several limitations were identified with the data currently available, including: a lack of available data by crude type; suppression (due to confidentiality reasons) or unavailability of specific values; no indication of the origin or destination of foreign sources (other than the US) for imports and exports, respectively; and origin and destination zones too spatially aggregated for accurately determining usage of the Canadian pipeline and rail networks (e.g., Alberta and British Columbia).
- Data on sub-provincial areas or individual pipeline owner's shipments are not available. Hence, zonal OD flows were estimated by proportioning aggregate OD flows based on zonal production and attraction totals.

Estimating cost functions for shipping crude oil by pipeline (refer to section 4.1) led to the following key findings:

- The distance shipped along each pipeline segment and the pipeline's diameter are statistically significant in establishing the shipper toll.
- Separate models estimated by toll type revealed that the effect of distance and diameter are relatively constant across toll types (i.e., same distance and diameter parameter positive or negative signs across toll types). Toll type is captured by a statistically significant interval ("dummy") variable. Similarly, the effect of crude oil type was captured by interval variables in a combined cost function.
- The combined cost function has an R^2 value of 0.85, indicating good model fit. The resulting cost function can be used to model the cost of shipping crude oil of a certain type (condensate, light, medium, heavy) in a given diameter pipeline for a distance to a Canadian (CLT) or US (IJT) location.

Estimating cost functions for shipping crude oil by rail (refer to section 4.2) led to the following key findings:

- For rail, the distance shipped was found to be statistically significant in explaining shipper costs ($\$/m^3$) along a given route.

- Also, a significant contribution was provided by shipment destination (domestic vs international), where international destinations have an added tariff surcharge.
- The rail cost function developed in this thesis has an R2 value of 0.81, indicating good model fit.
- The rail cost functions developed in this thesis can be used to model the cost of shipping crude oil by rail for Canadian or US locations.

Developing a crude oil pipeline-rail mode split and route assignment model (refer to section 5) led to the following key findings:

- Conventional Random Utility Models (RUM) fail to capture the complex interactions of crude shippers, pipeline carriers, and regulatory bodies, who interact through contracts and regulations to determine mode and route choice shipper decisions concerning crude oil transport.
- A rule-based approach was developed for mode choice/route assignment applications for pipelines and rail, replacing the conventional RUM approach. The logic of the rule based model reflects shipper behavior, derived from theories of choice heuristics that consumers apply when making decisions in complex environments.
- As demonstrated by the hypothetical example, the model can be used to assess likely cost and risk implications of alternative crude oil shipping protocols, applied to pipeline and rail transport.

Implementing a crude oil trip assignment (refer to section 6) led to the following key findings:

- The allocation of shipments on the network using the shortest path trip assignment provided accurate results in comparison to the existing network, with issues arising from supressed data sets primarily, especially in the consideration of pipelines that only transport US imports.
- When considering the oil forecasting of an increase of 39% by 2030 on the Oil Sands productions, the existing pipeline network no longer remains able to provide service for all shipments, and there is a large shift to the rail line network. There is an apparent bottle neck that occurs at Hardisty due to the capacity of all pipelines being reached, causing Eastern Canadian and US shipments to be shifted to rail.
- In the second case study, while there is a shift from rail to pipeline when implementing the Trans Canada Energy East pipeline, the pipeline disposition locations are very important in ensuring it is utilized effectively. While this pipeline has a large capacity it highly underutilized as the modelled Eastern Canadian Shipments are currently not large enough to justify the implementation of a new pipeline.

7.2 Directions for Future Research

While the current model reflects a set of Canadian rules, it can be extended to other geographic areas or contexts by modifying the shipper types, destination types, prioritization rules, and allocation rules. For example, it is possible that shipper allocations might increasingly be based on bid premiums (as opposed to proportional allocations) as a greater proportion of the network reaches capacity. The model may also require modifications depending on the scope of the application and data availability. In this light, it is suggested that future researchers carefully review the rules and regulations applicable to their study area, available data sources, and their study purpose and scope, to make modifications as necessary. Once developed, the model can be used to predict changes in crude oil flow patterns and mode shares subject to changes in specific pipeline or rail network attributes or crude oil demands.

For a complete crude oil freight quantitative risk assessment, the following steps will need to be taken:

- Further data sources on crude oil OD flows need to be explored (e.g., NEB). If no further data can be made available, modelling techniques such as bi-proportional updating and gravity models can be used to balance and estimate any incomplete and missing OD data.

- Disaggregation of the current zonal network to allow for more appropriate disposition and production areas for the pipelines and rail lines to allow for a more accurate representation of the OD flows, especially for the rail specific disposition and production zones, since specific areas are rail specific.

- Improved travel demand modeling software, such as TransCAD, to allow for the proper inclusion of cost functions on the pipeline and rail line links. ArcMap does allow for a very basic modeling of freight transportation, however for the complexity of this model, a more comprehensive modeling software would greatly improve upon the accuracy of the results.

- The implementation of additional infrastructure within the modal to allow for the use of intermodal transfers as well as the post haulages from certain pipeline locations on rail.

After a crude oil freight demand model is developed, a comprehensive quantitative risk assessment (QRA) can be applied to a wide spectrum of shipment scenarios, shipping regulations and guidelines, as well as future changes in crude oil throughputs (origin-destination). Such a model permits a complete objective assessment of the risk implication of transporting crude oil by pipeline as compared to rail. This assessment will assist in developing informed, safe, and cost-effective decisions on how best to transport crude oil.

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Appendices

Appendix A – OD Matrices and Supporting Calculations

A.1 OD Matrix for 2014

Table A.1: Canadian Crude Oil Demand Matrix for 2014 (cubic meters x 1,000) – Canada to Canada

O\D	Atlantic Provinces	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Canada
Atlantic Provinces	0.0*	0.0*	0.0*	0	0	0	0	x
Newfoundland and Labrador	579.8**	1351.7	1.2**	0	0	0	0	x
Nova Scotia	0.0*	0	0.0*	0	0	0	0	x
Ontario	0	0	69.3	0	0	0	0	x
Manitoba	0	0	0.0*	0	0	0	0	x
Saskatchewan	0	0	0.0*	0.0*	0.0*	0	0	x
Alberta	0	0	12027.5	4846.9	25895.8	2579.6	0	x
British Columbia	0	0	0	0	0.0*	0.0*	0	x
Northwest Territories	0	0	0.0*	0	0	0	0	x
Canada	16779.1	17236.9	20561.5	6628.3	27095.2	3203.3	0	91504.3 [c]
US	0.0*	0.0*	0	0	0	0	0	11346.629* [c]
Other	16199.3*	15885.2*	0.0**	0	0	0	0	20737.871*** [c]
Total Attraction	32978.4* [r]	33122.1* [r]	20561.5** [r]	6628.3 [r]	27095.2 [r]	3203.3 [r]	0	123588.8*** [r]

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

Table A.2: Canadian Crude Oil Demand Matrix for 2014 (cubic meters x 1,000) – Canadian Exports

O\D	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	US	Other Countries	Total Production
Atlantic Provinces	0.0*	0	0.0*	0	0	0.0*	0.0*	0.0* c
Newfoundland and Labrador	6195.4	0	0.0**	0	0	6195.4	4442.3**	12570.4** c
Nova Scotia	0.0*	0	0.0*	0	0	0.0*	0	0* c
Ontario	0	0	0	0	0	0	0	69.3 c
Manitoba	0.0*	0.0*	0.0*	0.0*	0	0.0*	0	0.0* c
Saskatchewan	0.0*	0.0*	0.0*	0.0*	0.0*	0.0*	0	0.0* c
Alberta	4008.9	95235.3	2163.2	17077.1	10569.6	129053.9	165.0**	174568.7** c
British Columbia	0	0	0.0**	0	0.0*	0.0*	0.0*	0.0*** c
Northwest Territories	0	0	0	0	0	0	0	0.0* c
Canada	14618.9	114180.7	3464.3	17077.1	11276.8	160616.8	4713.3**	256834.4** c

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

Table A.3: Canadian Crude Oil Demand Matrix for 2014 (cubic meters x 1,000) – Canadian Imports

O\D	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Newfoundland and Labrador	Nova Scotia	Manitoba	Prince Edward Island	New Brunswick	Yukon	Nunavut	Canada
PADD 1	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 2	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 3	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 4	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 5	x	x	x	x	x	x	x	x	x	x	x	x	x	x
US	0.0*	0	0	0	0	0	272.051*	0	0	0	0.0*	0	0	11346.629* c

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

A.2 OD Matrix for 2013

Table A.4: Canadian Crude Oil Demand Matrix for 2013 (cubic meters x 1,000) – Canada to Canada

O\D	Atlantic Provinces	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Canada
Atlantic Provinces	308.5*	194.1***	130.1***	0	0	0	0	x
Newfoundland and Labrador	920.0**	1153.2**	344.4**	0	0	0	0	x
Nova Scotia	0.0***	0	26.2***	0	0	0	0	x
Ontario	0	0	77.4	0	0	0	0	x
Manitoba	0	0	283.2*	0	0	0	0	x
Saskatchewan	0	0	611.6*	302.0*	68.2*	0	0	x
Alberta	0	0	11289.7	5121.2	24473.8	2303.5	0	x
British Columbia	0	0	0	0	128.1*	214.5*	0	x
Northwest Territories	0	0	123.4*	0	0	0	0	x
Canada	20884.2	17504.6	20953.9	6721.8	25650.8	3522.1	0	95237.4 c
US	1106.92*	334.248*	0	0.0*	0	0.0*	0	5264.875* c
Other	18857.28*	16000.952*	1372.5	0	0	0	0	32407.025* c
Total Attraction	40848.4* r	33839.8* r	22326.4 r	6721.8* r	25650.8 r	3522.1* r	0	132909.3* r

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

Table A.5: Canadian Crude Oil Demand Matrix for 2013 (cubic meters x 1,000) – Canadian Exports

O\D	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	US	Other Countries	Total Production
Atlantic Provinces	1007.7*	0	0.0***	0	0	1007.7*	586.7*	2227.1*** c
Newfoundland and Labrador	6550.3	0	166.5**	0	0	6716.8	4210.9	13345.3** c
Nova Scotia	0.0***	0	0.0***	0	0	0.0***	0	26.2*** c
Ontario	0	0	0	0	0	0	0	77.4 c
Manitoba	63.0*	237.5*	2.0***	0.0***	0	302.6*	0	585.8*** c
Saskatchewan	508.8*	3102.0*	238.5*	0.0***	0.0***	3849.3*	0	4831.1*** c
Alberta	2888	84395.7	1208.4	17321.5	10275.8	116089	351.9**	159629.1** c
British Columbia	0	0	0	0	49.6*	49.6*	56.5***	448.7*** c
Northwest Territories	0	0	0	0	0	0	0	123.4* c
Canada	13396.4	102604.1	3078.9	17331.3	10968.3	147378.2	4649.7	247265.3 c

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

Table A.6: Canadian Crude Oil Demand Matrix for 2013 (cubic meters x 1,000) – Canadian Imports

O\D	Quebec	Ontario	Saskatchewan	Alberta	British Columbia	Northwest Territories	Newfoundland and Labrador	Nova Scotia	Manitoba	Prince Edward Island	New Brunswick	Yukon	Nunavut	Canada
PADD 1	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 2	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 3	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 4	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 5	x	x	x	x	x	x	x	x	x	x	x	x	x	x
US	334.248*	0	0.0*	0	0.0*	0	929.7*	0	0	0	0.0*	0	0	5264.875* c

* *indicates a value that includes suppressed monthly data*

** *indicates a value that includes unavailable monthly data*

*** *indicates a value that includes suppressed and unavailable monthly data*

x *indicates a value unavailable from public sources*

c *indicates a value from a column sum*

r *indicates a value from a row sum*

A.3 Zonal OD Matrices

As shown in Figure A.1, British Columbia is divided into northern and southern regions to uniquely identify the multiple oil fields in the north (production) and the multiple refineries in the south (consumption).

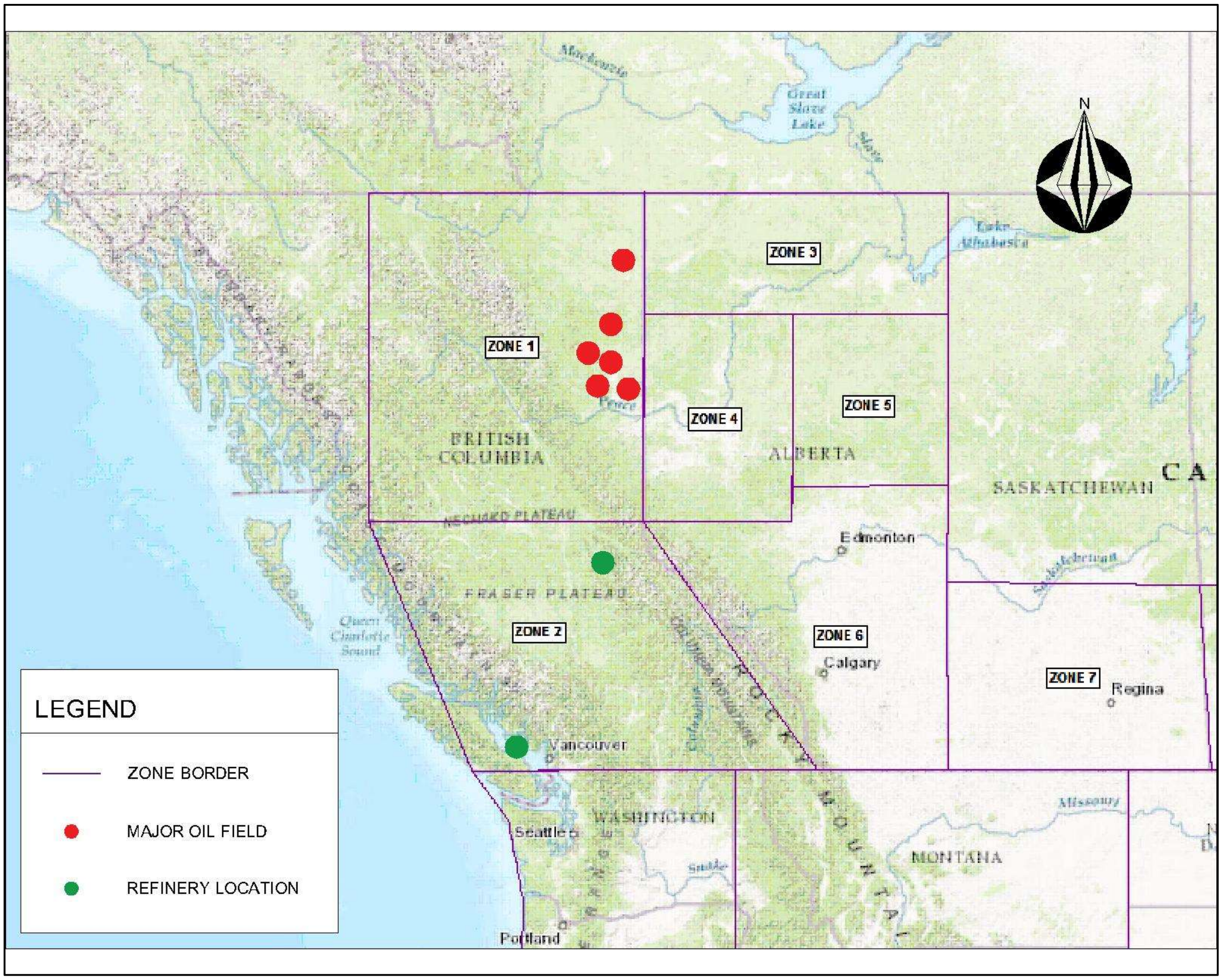


Figure A.1: Oil field and refinery locations in BC

As shown in Figure A.2, Alberta is split into four zones, corresponding to different production and attraction locations: Zone 3 contains an oil field and also marks the end of the Norman Wells pipeline, the only access to the oil from the Mackenzie Delta (Zone 12). Zone 4 contains the Peace River Oil Sands and a large grouping of oil fields known as the Swan Hills oil fields. Zone 5 contains the Athabasca and Cold Lake oil sands. Zone 6 contains all of Alberta's refineries as well as a high concentration of oil fields surrounding Edmonton and Calgary.

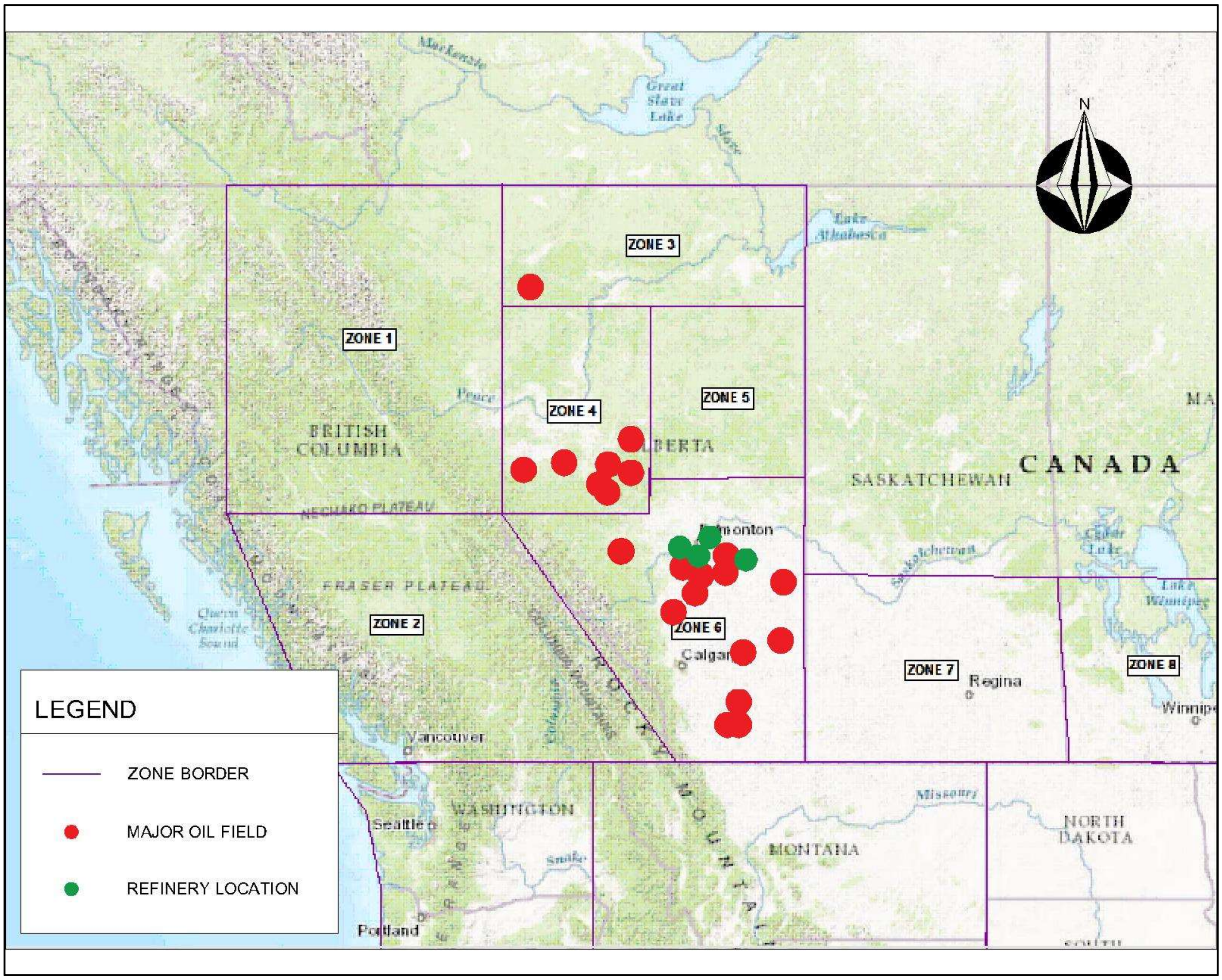


Figure A.2: Oil field and refinery locations in Alberta

Tables A.7-A.8 show refinery production and oil sands production for the zones in Alberta, respectively.

Table A.7: 2015 Refinery Production for Alberta

CANADIAN CRUDE OIL PRODUCTION BY MAJOR FIELDS

Oil Field Name and Location	Annual m³/year	Daily m³/day	Total Cubic Metres m³	Related Zone
ALBERTA				
Pembina	3 980 945.0	10 907.0	303 546 845.0	Z6
Swan Hills	868 698.0	2 380.0	146 281 098.0	Z4
Redwater	557 465.0	1 527.0	140 906 965.0	Z6
Rainbow	397 407.0	1 089.0	113 877 907.0	Z3
Provost	1 663 646.0	4 558.0	103 710 946.0	Z6
Bonnie Glen	4 301.0	12	82 966 101.0	Z6
Judy Creek	284 353.0	779	79 795 153.0	Z4
Swan Hills South	179 188.0	491	63 865 388.0	Z4
Mitsue	180 889.0	496	63 852 089.0	Z4
Leduc-Woodbend	190 680.0	522	63 314 580.0	Z6
Nipisi	275 538.0	755	61 643 338.0	Z4
Wizard Lake	3 392.0	9	54 351 292.0	Z6
Fenn Big Valley	47 633.0	131	53 789 733.0	Z6
Virginia Hills	167 959.0	460	36 404 859.0	Z4
Sturgeon Lake South	119 585.0	328	32 036 385.0	Z4
Golden Spike	5 925.0	16	30 974 525.0	Z6
Grand Forks	154 944.0	425	30 530 044.0	Z6
Willisden Green	583 583.0	1 599.0	29 777 383.0	Z6
Carson Creek North	89 355.0	245	28 549 255.0	Z4
Suffield	672 888.0	1 844.0	28 443 688.0	Z6
Turner Valley	176 562.0	484	26 075 362.0	Z6
Lloydminster	602 090.0	1 650.0	25 744 090.0	Z6
Valhalla	739 052.0	2 025.0	24 236 752.0	Z4
Westerose	5 681.0	16	23 671 381.0	Z6
Acheson	33 214.0	91	23 604 514.0	Z6

Source: Canadian Association of Petroleum Producers, 2017.

Table A.8: Oil Sands Production (bpd)

Area	2014	Zone
Athabasca North	1,240,106	Z5
Cold Lake	350,473	Z5
Conklin	459,162	Z5
Peace River	52,608	Z4
Wabiskaw	101,084	Z5
Total	2,203,433	

Source: Alberta Energy, 2016.

Hence, the total production for zone 4 can be determined by the sum of refinery production from Table A.7 (total of highlighted cells = 7959m^3/day) and oil sands production from Table A.8 (53,608 bpd = 8523m^3/day), resulting in a total production of 16,482m^3/day. Similarly, total production values can be calculated for all zones in British Columbia and Alberta, and the resulting proportions (Table 3.6) can be used to disaggregate the OD demands involving these provinces. Tables A.9-A.11 show the Canadian crude oil demand matrix disaggregated into zones.

Table A.9: Canadian Zonal Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canadian Zones

O\D	Province	British Columbia		Alberta				Saskatchewan	Ontario	Quebec	Atlantic Provinces	Newfoundland and Labrador	Nova Scotia	Northwest Territories	Canada
Province	Zone	1	2	3	4	5	6	7	9	10	11	11	11	12	n/a
British Columbia	1	0	0.0*	0	0	0	0.0*	0	0	0	0	n/a	n/a	0	x
	2	0	0	0	0	0	0	0	0	0	0	n/a	n/a	0	x
Alberta	3	0	7.9	0	0	0	63.8	13.8	33	0	0	n/a	n/a	0	x
	4	0	119.9	0	0	0	971.3	210.1	502.3	0	0	n/a	n/a	0	x
	5	0	2511.4	0	0	0	20349.5	4401.1	10524.3	0	0	n/a	n/a	0	x
	6	0	174.7	0	0	0	1415.9	306.2	732.3	0	0	n/a	n/a	0	x
Saskatchewan	7	0	0	0	0	0	0.0*	0.0*	0.0*	0	0	n/a	n/a	0	x
Manitoba	8	0	0	0	0	0	0	0	0.0*	0	0	n/a	n/a	0	x
Ontario	9	0	0	0	0	0	0	0	57.2	0	0	n/a	n/a	0	x
Atlantic Provinces	11	0	0	0	0	0	0	0	0.0*	0.0*	0.0*	n/a	n/a	0	x
Newfoundland and Labrador	11	0	0	0	0	0	0	0	0.0**	774.2**	2094.3**	n/a	n/a	0	x
Nova Scotia	11	0	0	0	0	0	0	0	0.0*	0	0.0*	n/a	n/a	0	x
Northwest Territories	12	0	0	0	0	0	0	0	0.0*	0	0	n/a	n/a	0	x
Canada	n/a	0	3441.4	0	0	0	24409.6	7632.2	19664.1	16618.9	19597.9	n/a	n/a	0	91364.1 [c]
US	n/a	0	0	0	0	0	0	0	0	793.63*	0.0*	3940.004	0	0	13501.564* [c]
Other	n/a	0	0	0	0	0	0	0.0**	0.0**	14778.77*	17503.6*	n/a	n/a	0	19574.436*** [c]
Total Attraction	n/a	0	3441.4 [r]	0	0	0	24409.6 [r]	7632.2** [r]	19664.1** [r]	32191.3* [r]	37101.5* [r]	n/a	n/a	0	124440.1*** [r]

Table A.10: Canadian Zonal Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canadian Exports

O\D	Province	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	US	Other Countries	Total Production
Province	Zone	13	14	15	16	17	n/a	n/a	n/a
British Columbia	1	0	0	0.0***	0	0.0*	0.0*	0.0*	0.0*** c
	2	0	0	0.0***	0	0.0*	0.0*	0.0*	0.0*** c
Alberta	3	8.5	307.0	8.3	52.2	33.2	409.2	0.39424**	528.13768** c
	4	129.2	4670.4	126.9	794.3	504.9	6225.7	5.99808**	8035.23756** c
	5	2707.8	97848.3	2658.0	16640.3	10577.5	130431.9	125.664**	168343.8855** c
	6	188.4	6808.3	184.9	1157.8	736.0	9075.4	8.74368**	11713.33926** c
Saskatchewan	7	0.0*	0.0*	0.0*	0.0*	0.0*	0.0*	0	0.0* c
Manitoba	8	0.0*	0.0*	0.0*	0.0*	0	0.0*	0	0.0* c
Ontario	9	0	0	0	0	0	0	0	57.2 c
Atlantic Provinces	11	0.0*	0	0.0*	0	0	0.0*	0.0*	0.0* c
Newfoundland and Labrador	11	5658.8	0	214.1**	0	0	5872.9	1123.3**	9864.7** c
Nova Scotia	11	0.0*	0	0.0*	0	0	0.0*	0	0.0* c
Northwest Territories	12	0	0	0	0	0	0	0	0.0* c
Canada	n/a	11869.4	128103.4	3831.9	18644.6	12036.6	174485.3	1272.2**	267121.6** c

Table A.11: Canadian Zonal Crude Oil Demand Matrix for 2015 (cubic meters x 1,000) – Canadian Imports

O\D	Province	British Columbia		Alberta				Saskatchewan	Manitoba	Ontario	Quebec	Newfoundland and Labrador	Nova Scotia	Northwest Territories	Prince Edward	New Brunswick	Yukon	Nunavut	Canada
Region	Zone	1	2	3	4	5	6	7	8	9	10	11	11	12	n/a	n/a	n/a	n/a	n/a
PADD 1	13	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 2	14	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 3	15	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 4	16	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
PADD 5	17	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
US	n/a	0	0	0	0	0	0	0	0	0	793.63*	3940.004*	0	0	0	0.0*	0	0	13501.564* [c]

Appendix B – Case Study Assignment Details

Figure B.1 and Tables B.1 and B.2 summarize the hypothetical case study example.

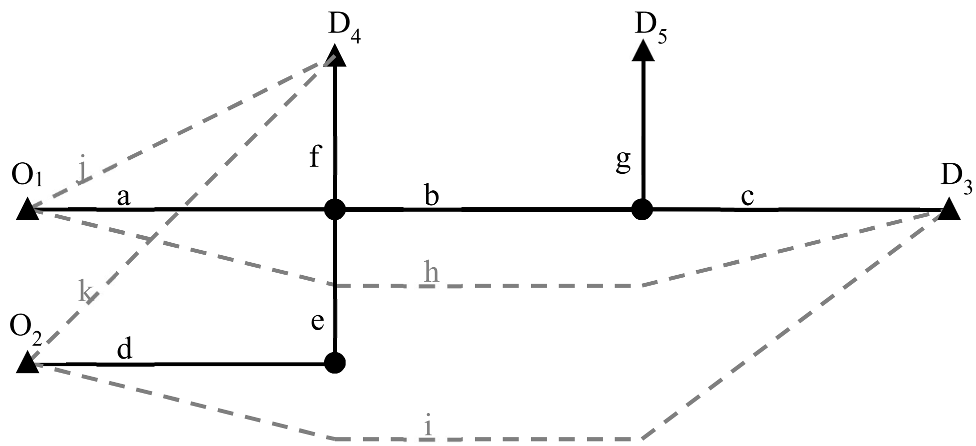


Figure B.1: Hypothetical pipeline and rail network

Table B.1: Pipeline Link and Rail Path Attributes

Pipeline			Rail		
Link	Cost ($/unit)	Capacity	Path	Cost ($/unit)	Capacity
a.	10	12,000	h.	200	Unlimited
b.	20	12,000	i.	150	Unlimited
c.	12	12,000	j.	100	Unlimited
d.	16	12,000	k.	250	Unlimited
e.	18	12,000			
f.	14	5,000			
g.	8	5,000			

Table B.2: Origin-Destination Matrix of Shipment Tonnages

Origin \ Destination	D3 (Designated)	D4 (Alternate)	D5 (Priority)	Total
O1	1000 (T) 2000 (U) 3000 (U) **6000**	1000 (U) 1000 (U) 1000 (U) **3000**	1000 (T) 1000 (U) **2000**	**11, 000**
O2	2000 (T) 2000 (U) **4000**	3000 (U) 4000 (U) **7000**	1000 (T) 1000(U) **2000**	**13,000**
Total	**10,000**	**10,000**	**4000**	**24 ,000**

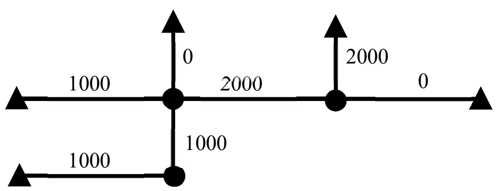
The detailed assignment steps are as follows:

Step 1: Assign Term Shippers to Priority Destinations (D5)

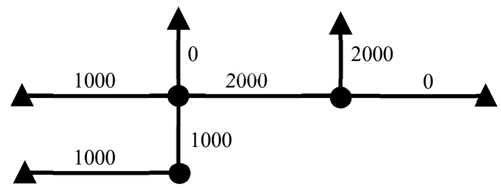
$V_{15}^{T1} = 1000$

$V_{25}^{T1} = 1000$

Incremental Assignment



Cumulative Assignment

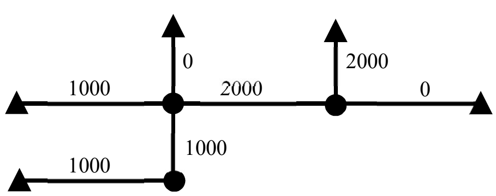


Step 2: Assign Uncommitted Shippers to Priority Destinations (D5)

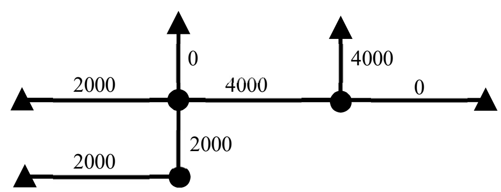
$V_{15}^{U1} = 1000$

$V_{25}^{U1} = 1000$

Incremental Assignment



Cumulative Assignment

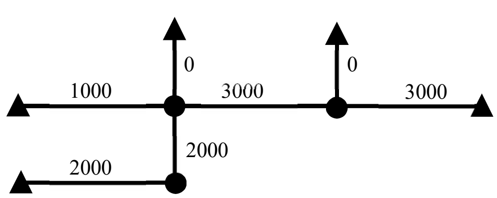


Step 3: Assign Term Shippers to Designated Delivery Points (D3)

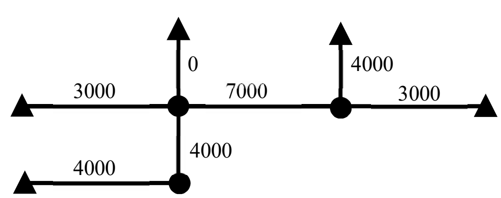
$V_{13}^{T1} = 1000$

$V_{23}^{T1} = 2000$

Incremental Assignment



Cumulative Assignment



Step 4: Assign Uncommitted Shippers to Designated Delivery Points (D3) (based on bid premiums)

Bid Premiums = Bid Price x Volume

For V_{13}^{U1}: Δp_{13} x V_{13}^{U1} = [200 – (10 + 20 + 12)] x 2000 = 158 x 2000 = \$316,000

For V_{13}^{U2}: Δp_{13} x V_{13}^{U2} = [200 – (10 + 20 + 12)] x 3000 = 158 x 3000 = \$474,000

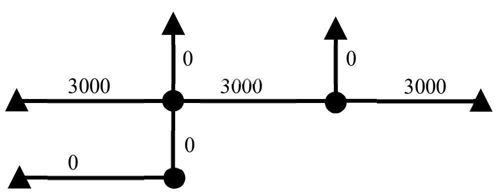
For V_{23}^{U1}: Δp_{23} x V_{23}^{U1} = [150 – (16 + 18 + 20 + 12] x 2000 = 84 x 2000 = \$168,000

Therefore, priorities are: 1) V_{13}^{U2}; 2) V_{13}^{U1}; and 3) V_{23}^{U1}.

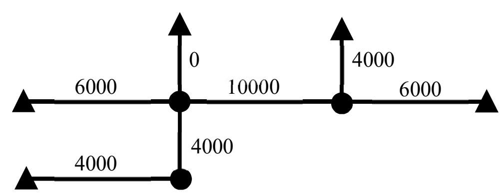
Assign from highest priority to lowest priority:

V_{13}^{U2} =3000

Incremental Assignment

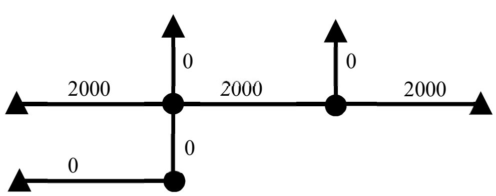


Cumulative Assignment

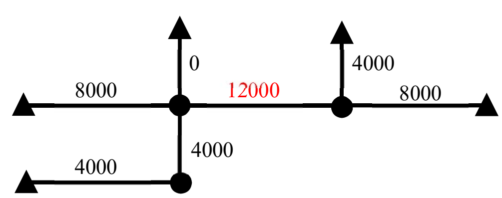


V_{13}^{U1} =2000

Incremental Assignment



Cumulative Assignment



V_{23}^{U1} cannot be assigned to pipeline since segment b. is at capacity (12000). Therefore, V_{23}^{U1} is assigned to rail.

Step 5: Assign Uncommitted Shippers to Alternative Land Destinations (based on proportionate allocation)

If *all shipments* are assigned:

V_{14}^{U1}: 1000

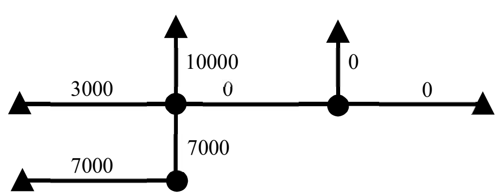
V_{14}^{U2}: 1000

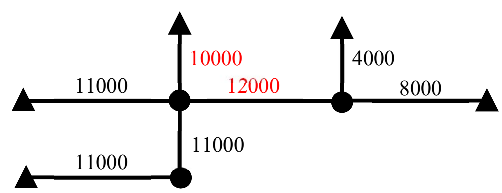
V_{14}^{U3}: 1000

V_{24}^{U1}: 3000

V_{24}^{U1}: 4000

Incremental Assignment **Cumulative Assignment**





Therefore, all shipments **cannot** be assigned to pipeline or segment f. will have a V/C ratio of 10000/5000. Therefore, capacity of pipeline segment f. is allocated proportionately to shippers at origins *1* and *2*, and reminders are assigned to rail:

V_{14}^{U1}: 1000 x 5/10 = 500

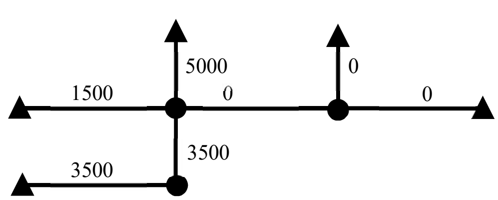
V_{14}^{U2}: 1000 x 5/10 = 500

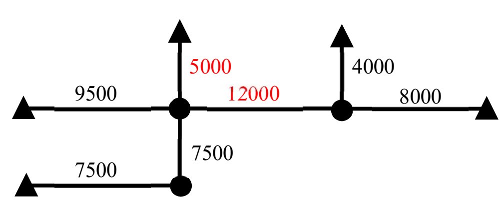
V_{14}^{U3}: 1000 x 5/10 = 500

V_{24}^{U1}: 3000 x 5/10 = 1500

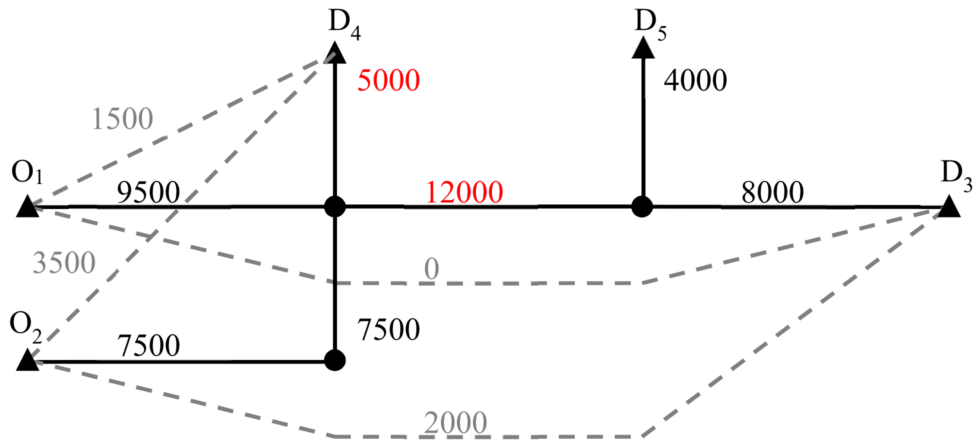
V_{24}^{U1}: 4000 x 5/10 = 2000

Incremental Assignment **Cumulative Assignment**





Final Cumulative Assignment (pipeline bottlenecks shown in red):



Appendix C – Rail Cost OD Data

Table C. 1: Rail Costs by OD Pair ($\$/m^3$)

O/D	Vancouver Area	BC North Line	BC South Line	BC North-South Line	Golden-Calgary	South of Calgary	Calgary-Edmonton	Edmonton	Calgary	Edmonton-Saskatoon	Calgary-Regina	Saskatoon	Regina	Regina-Portal	Saskatoon East	Regina-Winnipeg	Winnipeg	Winnipeg-Noyes	Winnipeg-Sudbury
Vancouver Area	25	32	46	42	39	45	42	45	44	47	46	49	45	52	51	47	50	49	59
BC North Line		25	40	38	33	38	33	37	36	39	39	40	39	42	43	41	46	44	57
BC South Line			25	33	35	34	37	38	35	40	36	41	41	45	43	43	47	45	57
BC North-South Line				25	34	34	39	41	38	42	40	43	42	46	44	44	48	48	58
Golden-Calgary					25	33	34	38	31	33	34	35	39	41	37	41	45	43	66
South of Calgary						25	31	34	31	47	34	48	36	47	49	44	50	49	60
Calgary-Edmonton							25	30	30	34	35	40	46	51	44	47	52	52	63
Edmonton								25	41	39	45	40	46	55	42	50	51	53	74
Calgary									25	40	31	34	32	39	36	37	42	41	51
Edmonton-Saskatoon										25	41	45	47	49	47	49	50	51	55
Calgary-Regina											25	46	39	45	47	40	37	43	62
Saskatoon												25	32	37	29	34	39	38	49
Regina													25	42	39	34	43	38	53
Regina-Portal														25	37	38	43	36	56
Saskatoon East															25	36	35	32	44
Regina-Winnipeg																25	38	32	42
Winnipeg																	25	31	43
Winnipeg-Noyes																		25	45
Winnipeg-Sudbury																			25

Table C.1: Rail Costs by OD Pair ($/m3) (continued)

O/D	Sudbury	HCRY	Sudbury-Toronto	Windsor-Toronto	Toronto	Toronto-Niagara Falls	Toronto-Montreal	Montreal	Montreal South	QGRY	Kingsgate	Coutts	Portal-St Paul	DMVW	Noyes-Glenwood	Corn Lines West	Twin Cities	Deluth/Superior	Corn Lines East	Kansas City	Chicago-Kansas City	Chicago-St Paul	Chicago	Chicago-Detroit	Buffalo-Albany	Albany North
Vancouver Area	64	69	67	75	70	82	75	76	92	77	55	60	68	74	65	74	71	74	74	93	86	75	85	81	109	121
BC North Line	60	64	63	62	66	74	69	72	88	73	51	53	55	67	58	62	59	61	60	75	68	61	68	67	105	116
BC South Line	63	66	66	62	69	76	71	73	90	75	42	43	59	69	59	67	63	65	65	79	70	63	70	68	107	118
BC North-South Line	64	69	67	65	69	78	71	75	90	76	46	48	61	72	62	66	63	65	64	80	71	64	71	70	107	118
Golden-Calgary	71	74	73	60	75	84	77	78	92	80	41	43	54	67	57	61	57	61	58	75	68	60	68	66	118	121
South of Calgary	65	68	68	64	70	78	73	75	90	77	43	38	61	74	65	67	63	65	64	79	71	64	70	70	107	118
Calgary-Edmonton	67	71	70	79	73	82	75	76	90	78	44	42	67	77	67	72	69	71	70	85	78	71	77	76	110	118
Edmonton	66	71	69	75	71	73	73	79	86	83	58	60	72	79	69	78	74	77	77	80	79	76	78	96	96	112
Calgary	56	60	58	72	61	79	70	67	84	69	44	39	51	63	54	56	51	53	52	79	69	56	68	62	98	110
Edmonton-Saskatoon	58	61	61	61	62	64	66	68	74	68	59	61	64	77	67	69	65	67	67	75	74	68	70	75	86	96
Calgary-Regina	65	68	68	57	70	71	73	76	82	78	57	54	59	67	57	64	60	63	62	71	69	63	68	69	97	107
Saskatoon	55	59	58	72	59	68	62	66	81	67	51	52	48	59	50	54	51	53	59	76	65	81	63	86	95	106
Regina	50	53	53	72	56	58	57	68	75	69	56	53	55	59	50	58	55	57	62	73	64	84	61	89	82	99
Regina-Portal	59	62	63	59	65	74	68	61	80	62	54	52	32	57	47	46	42	45	44	67	60	50	61	55	93	104
Saskatoon East	48	51	50	75	53	61	56	59	74	61	53	53	49	51	41	55	51	54	61	77	67	83	64	88	86	97
Regina-Winnipeg	53	54	54	75	56	65	58	61	80	62	51	49	50	51	42	53	51	53	56	73	63	78	61	84	93	104
Winnipeg	59	62	62	51	64	72	65	67	81	64	53	51	53	50	40	51	47	49	49	65	57	49	57	55	97	106
Winnipeg-Noyes	49	52	52	49	54	63	55	58	76	60	55	53	47	57	32	46	44	46	45	61	54	46	53	51	88	100
Winnipeg-Sudbury	37	42	37	63	62	43	37	42	57	42	72	74	73	69	59	72	75	69	70	85	77	68	78	69	64	75

Table C.1: Rail Costs by OD Pair ($/m3) (continued)

O/D	Sudbury	HCRY	Sudbury-Toronto	Windsor-Toronto	Toronto	Toronto-Niagara Falls	Toronto-Montreal	Montreal	Montreal South	QGRY	Kingsgate	Coutts	Portal-St Paul	DMVW	Noyes-Glenwood	Corn Lines West	Twin Cities	Deluth/Superior	Corn Lines East	Kansas City	Chicago-Kansas City	Chicago-St Paul	Chicago	Chicago-Detroit	Buffalo-Albany	Albany North
Sudbury	25	31	34	66	31	39	33	36	52	37	79	81	78	74	64	77	82	75	77	93	82	72	85	76	57	68
HCRY		25	37	70	38	46	40	44	59	45	83	87	82	78	69	83	87	79	80	97	88	78	89	81	67	77
Sudbury-Toronto			25	44	30	38	32	33	52	36	82	85	82	78	68	58	86	79	56	73	61	55	58	50	56	68
Windsor-Toronto				25	34	42	36	41	57	43	70	67	69	66	56	59	49	52	54	70	56	48	51	42	66	75
Toronto					25	36	30	34	41	45	85	86	85	81	71	55	50	55	52	68	56	52	55	46	48	54
Toronto-Niagara Falls						25	32	35	50	34	88	88	88	83	74	58	52	60	55	70	59	53	57	49	52	65
Toronto-Montreal							25	30	52	31	89	90	89	82	73	59	53	57	55	69	58	55	80	47	59	68
Montreal								25	44	30	93	95	80	86	76	64	58	62	60	75	66	60	63	53	62	58
Montreal South									25	32	97	98	87	92	83	68	61	68	64	79	69	62	67	50	46	32
QGRY										25	94	96	81	88	78	66	65	64	62	126	48	61	65	54	63	59
Kingsgate											32	47	54	65	55	61	58	60	59	75	66	59	65	65	102	114
Coutts												32	52	63	53	59	55	57	57	73	63	55	62	61	105	115
Portal-St Paul													32	57	47	46	42	45	44	67	60	50	61	55	93	104
DMVW														32	51	50	47	49	48	64	57	49	56	54	108	103
Noyes-Glenwood															32	46	44	46	45	61	54	46	53	51	88	100
Corn Lines West																32	43	45	40	56	51	48	56	54	74	85
Twin Cities																	32	38	37	54	47	39	47	44	71	78
Deluth/Superior																		32	40	57	49	41	49	47	77	85
Corn Lines East																			32	49	46	42	52	47	69	81
Kansas City																				32	57	49	51	54	73	85
Chicago-Kansas City																					32	41	44	46	70	82
Chicago-St Paul																						32	45	42	68	79
Chicago																							32	45	67	79
Chicago-Detroit																								32	64	67
Buffalo-Albany																									32	59
Albany North																										32

Source: CP, 2017

Appendix D – Pipeline OD Data

Table D.1: Group 1 Pipeline Data Set

Company	Origin	Destination	Condensate ($/m3)	Light ($/m3)	Medium ($/m3)	Heavy ($/m3)	Average Toll ($/m3)	Distance (m)	Diameter (in)				Age (years)	Througput (m3/day)	Capacity (m3/day)	Utilization (%)
									Condensate	Light	Medium	Heavy				
Trans Mountain Pipeline Inc.	Edmonton	Edmonton	-	-	-	-	$ 0.71	0	-	-	-	-	64.9	50085.00	47700.00	105.0%
		Kamloops	-	$ 10.47	-	-	$ 10.47	818	-	24.00	-	-	64.9	50085.00	47700.00	105.0%
		Sumas	-	$ 13.19	$ 13.78	$ 15.25	$ 14.07	1080	-	30.00	30.00	30.00	64.9	50085.00	47700.00	105.0%
		Burnaby	-	$ 14.17	$ 14.92	$ 16.46	$ 15.19	1125	-	36.00	36.00	36.00	64.9	50085.00	47700.00	105.0%
		Westridge	-	$ 14.55	$ 15.17	$ 16.71	$ 15.48	1125	-	36.00	36.00	36.00	64.9	50085.00	47700.00	105.0%
	Edson	Sumas	-	$ 10.78	$ 11.24	$ 12.18	$ 11.40	854	-	30.00	30.00	30.00	64.9	50085.00	47700.00	105.0%
		Burnaby	-	$ 11.89	$ 12.38	$ 13.37	$ 12.55	896	-	36.00	36.00	36.00	64.9	50085.00	47700.00	105.0%
		Westridge	-	$ 12.14	$ 12.64	$ 13.62	$ 12.80	896	-	36.00	36.00	36.00	64.9	50085.00	47700.00	105.0%
	Kamloops	Sumas	-	$ 4.26	-	-	$ 4.26	262	-	30.00	-	-	64.9	50085.00	47700.00	105.0%
		Burnaby	-	$ 5.37	-	-	$ 5.37	308	-	36.00	-	-	64.9	50085.00	47700.00	105.0%
Sunoco Pipeline L.P.	Toledo	International Boundary at the St. Clair River	-	-	-	-	$ 17.23	230	-	16.00	-	16.00	-	-	-	-
		Sarnia	-	-	-	-	$ 17.64	245	-	16.00	-	16.00	-	-	-	-
	International Boundary at the St. Clair River	Sarnia	-	-	-	-	$ 0.41	15	-	16.00	-	16.00	-	-	-	-
		Toledo	-	-	-	-	$ 17.23	230	-	16.00	-	16.00	-	-	-	-
	Sarnia	International Boundary at the St. Clair River	-	-	-	-	$ 0.41	15	-	16.00	-	16.00	-	-	-	-
		Toledo	-	-	-	-	$ 17.64	245	-	16.00	-	16.00	-	-	-	-
Enbridge	Edmonton Terminal, Alberta	Clearbrook, Minnesota	$ 12.57	$ 13.38	$ 14.32	$ 15.97	$ 14.06	1498	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Superior, Wisconsin	$ 15.07	$ 15.87	$ 17.01	$ 18.99	$ 16.73	1899	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Lockport, Illinois	$ 20.75	$ 21.55	$ 23.15	$ 25.95	$ 22.85	2626	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Mokena, Illinois	$ 20.75	$ 21.55	$ 23.15	$ 25.95	$ 22.85	2648	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Flanagan, Illinois	$ 20.75	$ 21.55	$ 23.15	$ 25.95	$ 22.85	2781	42.00	42.00	42.00	42.00	63.9	385305.00	453300.00	85.0%
		Griffith, Indiana	$ 20.75	$ 21.55	$ 23.15	$ 25.95	$ 22.85	2696	34.00	34.00	34.00	34.00	63.9	385305.00	453300.00	85.0%
		Stockbridge, Michigan	$ 22.88	$ 23.69	$ 25.46	$ 28.55	$ 25.15	3072	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Rapid River, Michigan	-	-	-	-	-	2709	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Marysville, Michigan	$ 22.88	$ 23.69	$ 25.46	$ 28.55	$ 25.15	3267	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, Ontario	$ 23.21	$ 24.03	$ 25.81	$ 28.91	$ 25.49	3259	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, Ontario	$ 25.22	$ 26.21	$ 28.16	$ 31.57	$ 27.79	3487	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		West Seneca, New York	$ 25.52	$ 26.53	$ 28.53	$ 32.02	$ 28.15	3589	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Hardisty Terminal, Alberta	Clearbrook, Minnesota	-	$ 11.96	$ 12.79	$ 14.24	$ 12.99	1320	34.00	34.00	48.00	36.00	67.2	385305.00	453300.00	85.0%
		Superior, Wisconsin	-	$ 14.45	$ 15.47	$ 17.25	$ 15.73	1721	34.00	34.00	48.00	36.00	67.2	385305.00	453300.00	85.0%
		Lockport, Illinois	-	$ 20.14	$ 21.62	$ 24.22	$ 21.99	2448	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Mokena, Illinois	-	$ 20.14	$ 21.62	$ 24.22	$ 21.99	2470	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Flanagan, Illinois	-	$ 20.14	$ 21.62	$ 24.22	$ 21.99	2603	42.00	42.00	42.00	42.00	63.9	385305.00	453300.00	85.0%
		Griffith, Indiana	-	$ 20.14	$ 21.62	$ 24.22	$ 21.99	2518	34.00	34.00	34.00	34.00	63.9	385305.00	453300.00	85.0%
		Stockbridge, Michigan	-	$ 22.27	$ 23.93	$ 26.82	$ 24.34	2894	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Rapid River, Michigan	-	-	-	-	-	2531	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Marysville, Michigan	-	$ 22.27	$ 23.93	$ 26.82	$ 24.34	3089	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, Ontario	-	$ 22.61	$ 24.27	$ 27.18	$ 24.69	3082	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, Ontario	-	$ 24.79	$ 26.63	$ 29.84	$ 27.09	3309	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		West Seneca, New York	-	$ 25.11	$ 26.99	$ 30.29	$ 27.46	3412	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Kerrobert Station, Saskatchewan	Clearbrook, Minnesota	-	$ 10.53	-	$ 12.50	$ 11.51	1147	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Superior, Wisconsin	-	$ 13.03	-	$ 15.51	$ 14.27	1548	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Lockport, Illinois	-	$ 18.71	-	$ 22.47	$ 20.59	2275	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Mokena, Illinois	-	$ 18.71	-	$ 22.47	$ 20.59	2297	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Flanagan, Illinois	-	$ 18.71	-	$ 22.47	$ 20.59	2430	42.00	42.00	42.00	42.00	63.9	385305.00	453300.00	85.0%
		Griffith, Indiana	-	$ 18.71	-	$ 22.47	$ 20.59	2345	34.00	34.00	34.00	34.00	63.9	385305.00	453300.00	85.0%
		Stockbridge, Michigan	-	$ 20.84	-	$ 25.08	$ 22.96	2721	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Rapid River, Michigan	-	-	-	-	-	2358	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Marysville, Michigan	-	$ 20.84	-	$ 25.08	$ 22.96	2916	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, Ontario	-	$ 21.18	-	$ 25.44	$ 23.31	2908	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, Ontario	-	$ 23.36	-	$ 28.10	$ 25.73	3136	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		West Seneca, New York	-	$ 23.69	-	$ 28.55	$ 26.12	3238	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Regina Terminal, Saskatchewan	Clearbrook, Minnesota	-	$ 7.67	-	$ 9.00	$ 8.34	804	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Superior, Wisconsin	-	$ 10.16	-	$ 12.02	$ 11.09	1204	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Lockport, Illinois	-	$ 15.85	-	$ 18.98	$ 17.41	1931	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Mokena, Illinois	-	$ 15.85	-	$ 18.98	$ 17.41	1953	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Flanagan, Illinois	-	$ 15.85	-	$ 18.98	$ 17.41	2087	42.00	42.00	42.00	42.00	63.9	385305.00	453300.00	85.0%
		Griffith, Indiana	-	$ 15.85	-	$ 18.98	$ 17.41	2001	34.00	34.00	34.00	34.00	63.9	385305.00	453300.00	85.0%
		Stockbridge, Michigan	-	$ 17.98	-	$ 21.59	$ 19.78	2377	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Rapid River, Michigan	-	-	-	-	-	2014	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Marysville, Michigan	-	$ 17.98	-	$ 21.59	$ 19.78	2572	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, Ontario	-	$ 18.32	-	$ 21.95	$ 20.13	2565	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, Ontario	-	$ 20.50	-	$ 24.61	$ 22.55	2793	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		West Seneca, New York	-	$ 20.82	-	$ 25.05	$ 22.94	2895	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Cromer Terminal, Manitoba	Clearbrook, Minnesota	-	$ 5.60	$ 5.92	$ 6.48	$ 6.00	540	20.00	20.00	20.00	48.00	67.2	385305.00	453300.00	85.0%
		Superior, Wisconsin	-	$ 8.10	$ 8.61	$ 9.50	$ 8.73	940	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Lockport, Illinois	-	$ 13.78	$ 14.75	$ 16.46	$ 15.00	1668	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Mokena, Illinois	-	$ 13.78	$ 14.75	$ 16.46	$ 15.00	1690	24.00	24.00	24.00	22.00	63.9	385305.00	453300.00	85.0%
		Flanagan, Illinois	-	$ 13.78	$ 14.75	$ 16.46	$ 15.00	1823	42.00	42.00	42.00	42.00	63.9	385305.00	453300.00	85.0%
		Griffith, Indiana	-	$ 13.78	$ 14.75	$ 16.46	$ 15.00	1737	34.00	34.00	34.00	34.00	63.9	385305.00	453300.00	85.0%
		Stockbridge, Michigan	-	$ 15.91	$ 17.06	$ 19.07	$ 17.35	2113	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Rapid River, Michigan	-	-	-	-	-	1751	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Marysville, Michigan	-	$ 15.91	$ 17.06	$ 19.07	$ 17.35	2309	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, Ontario	-	$ 16.25	$ 17.41	$ 19.42	$ 17.69	2301	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, Ontario	-	$ 18.43	$ 19.76	$ 22.09	$ 20.09	2529	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		West Seneca, New York	-	$ 18.75	$ 20.13	$ 22.53	$ 20.47	2631	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%

Table D.1: Group 1 Pipeline Data Set (Continued)

Company	Origin	Destination	Condensate ($/m3)	Light ($/m3)	Medium ($/m3)	Heavy ($/m3)	Average Toll ($/m3)	Distance (m)	Diameter (in)				Age (years)	Througput (m3/day)	Capacity (m3/day)	Utilization (%)
									Condensate	Light	Medium	Heavy				
Enbridge	Edmonton Terminal, Alberta	Edmonton Terminal, AB	$ 1.48	$ 1.48	$ 1.48	$ 1.48	$ **1.48**	0	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	$ 2.83	$ 2.95	$ 3.06	$ 3.27	$ **3.03**	178	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	$ 4.18	$ 4.42	-	$ 5.06	$ 4.55	351	24.00	24.00	24.00	22.00	67.2	385305.00	453300.00	85.0%
		Milden, SK	$ 5.06	$ 5.37	-	-	$ 5.22	459	24.00	24.00	24.00	22.00	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	$ 6.90	$ 7.37	$ 7.84	$ 8.66	$ **7.69**	632	42.00	42.00	42.00	42.00	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	$ 6.90	$ 7.37	$ 7.84	$ 8.66	$ **7.69**	695	34.00	34.00	34.00	34.00	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	$ 11.03	$ 11.87	-	-	$ **11.45**	1244	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	$ 10.57	$ 11.40	$ 12.24	$ 13.69	$ **11.98**	1244	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	$ 11.15	$ 11.99	$ 12.83	$ 14.30	$ 12.57	3259	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	$ 13.22	$ 14.24	$ 15.26	$ 17.05	$ **14.94**	3487	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	$ 12.97	$ 14.01	$ 15.05	$ 16.88	$ **14.73**	3537	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Hardisty Terminal, Alberta	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	$ 1.48	$ 1.48	$ **1.48**	0	34.00	34.00	48.00	48.00	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	$ 2.84	$ 2.96	$ 3.07	$ 3.28	$ **3.04**	173	24.00	24.00	24.00	22.00	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	$ 3.91	-	-	$ **3.91**	282	24.00	24.00	24.00	22.00	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	$ 5.91	$ 6.26	$ 6.88	$ **6.35**	454	42.00	42.00	42.00	42.00	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	$ 5.91	$ 6.26	$ 6.88	$ **6.35**	517	34.00	34.00	34.00	34.00	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	1066	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	$ 9.94	$ 10.66	$ 11.91	$ **10.84**	1066	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	-	$ 10.53	$ 11.25	$ 12.52	$ **11.43**	3082	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	-	$ 12.78	$ 13.68	$ 15.26	$ **13.91**	3309	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	-	$ 12.55	$ 13.47	$ 15.09	$ **13.70**	3359	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Karrobert Station, Saskatchewan	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	-	-	-	-	-	0	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	109	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	$ 4.43	-	$ 5.08	$ **4.76**	281	42.00	42.00	42.00	42.00	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	$ 4.43	-	$ 5.08	$ **4.76**	344	34.00	34.00	34.00	34.00	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	893	-	-	-	-	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	$ 8.47	-	$ 10.11	$ **9.29**	893	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	-	$ 9.06	-	$ 10.72	$ **9.89**	2908	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	-	$ 11.31	-	$ 13.47	$ **12.39**	3136	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	-	$ 11.08	-	$ 13.30	$ **12.19**	3186	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Regina Terminal, Saskatchewan	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	$ 1.48	$ 1.48	-	$ 1.48	$ **1.48**	0	34.00	34.00	34.00	34.00	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	$ 5.62	$ 5.98	-	-	$ **5.80**	549	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	$ 5.52	-	$ 6.51	$ **6.02**	549	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	-	$ 6.11	-	$ 7.12	$ **6.61**	2565	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	-	$ 8.35	-	$ 9.87	$ **9.11**	2793	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	-	$ 8.13	-	$ 9.70	$ **8.91**	2842	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Cromer Terminal, Manitoba	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	285	-	-	-	-	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	$ 3.39	$ 3.58	$ 3.91	$ **3.63**	285	30.00	30.00	30.00	30.00	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	-	$ 3.98	$ 4.17	$ 4.52	$ **4.22**	2301	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	-	$ 6.22	$ 6.60	$ 7.27	$ **6.70**	2529	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	-	$ 6.00	$ 6.40	$ 7.10	$ **6.50**	2579	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	International Boundary near Sarnia, ON	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Karrobert Station, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%

Table D.1: Group 1 Pipeline Data Set (Continued)

Company	Origin	Destination	Condensate ($/m3)	Light ($/m3)	Medium ($/m3)	Heavy ($/m3)	Average Toll ($/m3)	Distance (m)	Diameter (in) Condensate	Diameter (in) Light	Diameter (in) Medium	Diameter (in) Heavy	Age (years)	Througput (m3/day)	Capacity (m3/day)	Utilization (%)
Enbridge	International Boundary near Sarnia, ON	International Boundary near Gretna, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	$ 0.58	$ 0.59	$ 0.59	-	$ 0.59	14	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	$ 2.65	$ 2.84	$ 3.02	-	$ 2.84	242	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	$ 2.40	$ 2.61	$ 2.82	-	$ 2.61	291	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Sarnia Terminal, ON	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Kerrobert Station, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	$ 1.48	$ 1.48	-	-	$ 1.48	0	30.00	30.00	30.00	30.00	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	$ 3.55	$ 3.73	-	-	$ 3.64	228	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	$ 3.31	$ 3.51	-	-	$ 3.41	278	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
	Westover, ON	Edmonton Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Hardisty Terminal, AB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Kerrobert Station, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Milden, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Stony Beach Take-off, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Regina Terminal, SK	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Gretna Station, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		International Boundary near Gretna, MB	-	-	-	-	-	-	-	-	-	-	67.2	385305.00	453300.00	85.0%
		Corunna or Sarnia Terminal, ON	-	-	-	-	-	-	-	-	-	-	63.9	385305.00	453300.00	85.0%
		Nanticoke, ON	-	$ 1.12	$ 1.17	-	$ 1.15	32	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
		International Boundary near Chippawa, ON	-	$ 0.89	$ 0.96	-	$ 0.92	81	20.00	20.00	20.00	20.00	41.5	385305.00	453300.00	85.0%
Trans-Canada	Uncommitted - Hardisty, Alberta	Wood River or Patoka, Illinois	-	$ 14.51	-	$ 16.55	$ 15.53	3001	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 16.38	-	$ 18.43	$ 17.40	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Port Arthur, Texas	-	$ 16.38	-	$ 18.43	$ 17.40	3436	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
	Fixed Committed - Hardisty, Alberta	Wood River or Patoka, Illinois	-	$ 7.78	-	$ 7.78	$ 7.78	3001	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 9.68	-	$ 9.68	$ 9.68	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 9.34	-	$ 9.34	$ 9.34	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Port Arthur, Texas	-	$ 10.06	-	$ 10.06	$ 10.06	3436	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
	Variable Committed - Hardisty, Alberta	Wood River or Patoka, Illinois	-	$ 3.97	-	$ 5.67	$ 4.82	3001	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 3.97	-	$ 5.67	$ 4.82	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 3.97	-	$ 5.67	$ 4.82	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Port Arthur, Texas	-	$ 3.97	-	$ 5.67	$ 4.82	3436	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
	Total Committed - Hardisty, Alberta	Wood River or Patoka, Illinois	-	$ 11.75	-	$ 13.46	$ 12.60	3001	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 13.65	-	$ 15.35	$ 14.50	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Cushing, Oklahoma	-	$ 13.31	-	$ 15.02	$ 14.16	2691	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
		Port Arthur, Texas	-	$ 14.03	-	$ 15.74	$ 14.89	3436	-	36.00	-	36.00	7.5	88360.00	94000.00	94.0%
Kinder Morgan Cochin ULC	International Boundary near Alameda, Saskatchewan	Keyera Fort Saskatchewan Facility, Alberta	$ 24.21	-	-	-	$ 24.21	939	12.00	-	-	-	38.9	12684.00	15100.00	84.0%
	Cochin Terminal in Kankakee County, Illinois	Uncommitted - Keyera Fort Saskatchewan Facility, Alberta	$ 60.62	-	-	-	$ 60.62	2414	12.00	-	-	-	38.9	12684.00	15100.00	84.0%
		Committed - Keyera Fort Saskatchewan Facility, Alberta	$ 40.99	-	-	-	$ 40.99	2414	12.00	-	-	-	38.9	12684.00	15100.00	84.0%
		Volume Incentive - Keyera Fort Saskatchewan Facility, Alberta	$ 37.43	-	-	-	$ 37.43	2414	12.00	-	-	-	38.9	12684.00	15100.00	84.0%
Trans Northern	Montreal East	Montreal	-	-	-	-	$ 0.57	0	10.00	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	$ 1.70	37	10.00	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	$ 2.97	117	10.00	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	$ 4.82	204	12.00	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	$ 4.72	204	10.00	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	$ 6.45	289	10.00	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	$ 7.80	357	10.00	-	-	-	62.9	-	-	-
		North Toronto	-	-	-	-	$ 11.36	522	10.00	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 11.95	544	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	$ 12.14	556	10.00	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	$ 12.43	573	10.00	-	-	-	62.9	-	-	-
	Nanticoke	Montreal	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-

Table D.1: Group 1 Pipeline Data Set (Continued)

Company	Origin	Destination	Condensate ($/m3)	Light ($/m3)	Medium ($/m3)	Heavy ($/m3)	Average Toll ($/m3)	Distance (m)	Diameter (in)				Age (years)	Througput (m3/day)	Capacity (m3/day)	Utilization (%)
									Condensate	Light	Medium	Heavy				
Trans Northern	Nanticoke	North Toronto	-	-	-	-	$ 3.21	117	10.00	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 3.40	95	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	$ 2.43	83	16.00	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	$ 2.14	66	10.00	-	-	-	62.9	-	-	-
	Oakville	Montreal	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		North Toronto	-	-	-	-	$ 1.64	52	10.00	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 1.83	29	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	$ 0.90	18	10.00	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	-	0	-	-	-	-	62.9	-	-	-
	Clarkson	Montreal	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		North Toronto	-	-	-	-	$ 1.35	34	10.00	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 1.54	12	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	$ 0.90	18	10.00	-	-	-	62.9	-	-	-
	North Toronto	Montreal	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		North Toronto	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 1.16	22	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	$ 1.35	34	10.00	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	$ 1.64	52	10.00	-	-	-	62.9	-	-	-
	Toronto Airport Junction	Montreal	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Dorval (Jet)	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Cornwall	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Ottawa	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Maitland	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Kingston	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Belleville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		North Toronto	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Toronto Airport	-	-	-	-	$ 1.02	0	10.00	-	-	-	62.9	-	-	-
		Clarkson	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
		Oakville	-	-	-	-	-	-	-	-	-	-	62.9	-	-	-
Enbridge Pipelines (NW) Inc.	Norman Wells, NWT	Zama, Alberta	-	$ 100.97	-	-	$ 100.97	806.15	12.00	-	-	-	32.6	1220.88	5087.00	24.0%
	Kilometer Post 839.2, Ab		-	$ 3.37	-	-	$ 3.37	-	12.00	-	-	-	32.6	1220.88	5087.00	24.0%

Table D. 2: Group 2 Pipeline Data

Company	Origin	Destination	Condensate ($/m3)	Light ($/m3)	Medium ($/m3)	Heavy ($/m3)	Average Toll ($/m3)	Distance (m)	Diameter (in)				Age (years)	Througput (m3/day)	Capacity (m3/day)	Utilization (%)
									Condensate	Light	Medium	Heavy				
Express Pipeline Ltd.	Hardisty, Alberta - 3 to 4 year term	Edgar Station, Carbon County, Montana (Inlet to Silver Tip, ExxonMobil Pipe Line Company)	-	$ 17.90	$ 19.33	$ 22.29	$ 19.84	870	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Sinclair Pipeline, Casper, Natrona County, Wyoming	-	$ 18.87	$ 20.38	$ 23.49	$ 20.91	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Casper, Natrona County, Wyoming (inlet to Platte Pipe Line Company, LLC or CCR Pipeline, LLC)	-	$ 20.36	$ 21.99	$ 25.35	$ 22.57	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Guernsey, Platte County, Wyoming	-	$ 25.11	$ 26.74	$ 30.10	$ 27.32	1407	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
		Wood River, Madison County, Illinois	-	$ 38.49	$ 40.12	$ 43.48	$ 40.70	2771	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
	Hardisty, Alberta - 5 to 9 year term	Edgar Station, Carbon County, Montana (Inlet to Silver Tip, ExxonMobil Pipe Line Company)	-	$ 17.74	$ 19.16	$ 22.08	$ 19.66	870	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Sinclair Pipeline, Casper, Natrona County, Wyoming	-	$ 18.70	$ 20.19	$ 23.28	$ 20.72	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Casper, Natrona County, Wyoming (inlet to Platte Pipe Line Company, LLC or CCR Pipeline, LLC)	-	$ 20.17	$ 21.79	$ 25.12	$ 22.36	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Guernsey, Platte County, Wyoming	-	$ 24.88	$ 26.50	$ 29.82	$ 27.07	1407	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
		Wood River, Madison County, Illinois	-	$ 38.14	$ 39.76	$ 43.08	$ 40.33	2771	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
	Hardisty, Alberta - 10 to 14 year term	Buffalo Station, Fergus County, Montana (Inlet to Buffalo Station)	-	$ 14.47	$ 14.47	$ 14.47	$ 14.47	598	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Edgar Station, Carbon County, Montana (Inlet to Silver Tip, ExxonMobil Pipe Line Company)	-	$ 17.59	$ 19.00	$ 21.90	$ 19.50	870	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Sinclair Pipeline, Casper, Natrona County, Wyoming	-	$ 18.55	$ 20.03	$ 23.09	$ 20.55	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Casper, Natrona County, Wyoming (inlet to Platte Pipe Line Company, LLC or CCR Pipeline, LLC)	-	$ 20.01	$ 21.61	$ 24.91	$ 22.18	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Guernsey, Platte County, Wyoming7	-	$ 24.68	$ 26.28	$ 29.58	$ 26.85	1407	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
		Wood River, Madison County, Illinois	-	$ 37.83	$ 39.43	$ 42.73	$ 40.00	2771	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
	Hardisty, Alberta - 15 to 19 year term	Buffalo Station, Fergus County, Montana (Inlet to Buffalo Station)	-	$ 14.47	$ 14.47	$ 14.47	$ 14.47	598	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Edgar Station, Carbon County, Montana (Inlet to Silver Tip, ExxonMobil Pipe Line Company)	-	$ 17.23	$ 18.61	$ 21.45	$ 19.10	870	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Sinclair Pipeline, Casper, Natrona County, Wyoming	-	$ 18.30	$ 19.76	$ 22.78	$ 20.28	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Casper, Natrona County, Wyoming (inlet to Platte Pipe Line Company, LLC or CCR Pipeline, LLC)	-	$ 19.74	$ 21.32	$ 24.58	$ 21.88	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Guernsey, Platte County, Wyoming7	-	$ 24.35	$ 25.93	$ 29.18	$ 26.49	1407	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
		Wood River, Madison County, Illinois	-	$ 37.32	$ 38.90	$ 42.16	$ 39.46	2771	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
	Hardisty, Alberta - 20 or more year term	Buffalo Station, Fergus County, Montana (Inlet to Buffalo Station)**	-	$ 14.47	$ 14.47	$ 14.47	$ 14.47	598	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Edgar Station, Carbon County, Montana (Inlet to Silver Tip, ExxonMobil Pipe Line Company)	-	$ 17.10	$ 18.47	$ 21.29	$ 18.96	870	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Sinclair Pipeline, Casper, Natrona County, Wyoming	-	$ 18.03	$ 19.47	$ 22.45	$ 19.98	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Casper, Natrona County, Wyoming (inlet to Platte Pipe Line Company, LLC or CCR Pipeline, LLC)	-	$ 19.45	$ 21.01	$ 24.22	$ 21.56	1234	-	24.00	24.00	24.00	20.9	34710.00	44500.00	78.0%
		Guernsey, Platte County, Wyoming7	-	$ 23.99	$ 25.55	$ 28.76	$ 26.10	1407	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
		Wood River, Madison County, Illinois	-	$ 36.78	$ 38.33	$ 41.54	$ 38.88	2771	-	24.00	24.00	24.00	65.9	34710.00	44500.00	78.0%
Esso Imperial Oil	Wizard Lake Field	Edmonton, Alberta	-	-	-	-	$ 5.43	-	-	-	-	-	-	-	-	-
	Westerose Field		-	-	-	-	$ 6.31	-	-	-	-	-	-	-	-	-
	Rimbey Area		-	-	-	-	$ 7.78	-	-	-	-	-	-	-	-	-
Montreal Pipeline Ltd.	International Boundary (Highwater, Quebec)	Montreal East, Quebec -Tariff Rate	-	-	-	-	$ 0.45	151	-	-	-	24.00	76.3	9790.00	44500.00	22.0%
		Montreal East, Quebec -Tariff Rate - Abandonment	-	-	-	-	$ -	151	-	-	-	24.00	76.3	9790.00	44500.00	22.0%
		Montreal East, Quebec -Terminal Charge	-	-	-	-	$ 0.24	151	-	-	-	24.00	76.3	9790.00	44500.00	22.0%
		Montreal East, Quebec -Terminal Charge - Abandonment	-	-	-	-	$ 0.01	151	-	-	-	24.00	76.3	9790.00	44500.00	22.0%
		Montreal East, Quebec -Combined Rate	-	-	-	-	$ 0.70	151	-	-	-	24.00	76.3	9790.00	44500.00	22.0%
Plains Midstream Canada ULC	Points in Alberta	Milk River Pump Station	-	-	$ 2.25	$ 3.62	$ 2.94	17	-	-	10.00	10.00	16.9	15087.00	18800.00	80.3%
	The International Boundary Near Regway, Saskatchewan	Points in Saskatchewan	$ 5.77	-	-	-	$ 5.77	170	12.00	-	-	-	16.9	1540.00	-	-
	Points in Alberta	Pengrowth (North Cactus)	$ 1.73	-	-	$ 8.38	$ 5.06	-	12.00	-	-	12.00	16.9	-	-	-
		Pengrowth (South Bodo)	$ 4.21	-	-	$ 10.22	$ 7.22	-	12.00	-	-	12.00	16.9	-	-	-
	Points in Saskatchawan	Cromer-Connected Batteries	-	-	-	-	$ 11.40	214	-	-	-	-	16.9	-	-	-
		Cromer-Truck Unloading	$ 9.19	$ 7.57	$ 8.14	$ 9.27	$ 8.54	214	12.00	12.00	12.00	12.00	16.9	-	-	-

Appendix E – Python Script

```
# Import system modules
import arcpy
import traceback
import csv
from arcpy import env
import pandas as pd
import numpy as np
import os
import sys
import shutil
import re

# To reset the network there will need to be the addition of the original files to
overwrite the files that have been
# altered for the previous ananlysis
old_pipe = pd.read_csv('Pipelines_O.csv')
old_pipe.to_csv('Pipelines.csv',index=False)
old_rail = pd.read_csv('Rail_O.csv')
old_rail.to_csv('Rail.csv',index=False)
old_ODS = pd.read_csv('OD_S_O.csv',header=None)
old_ODS.to_csv('OD_S.csv',index=False,header=False)
old_ODT = pd.read_csv('OD_T_O.csv',header=None)
old_ODT.to_csv('OD_T.csv',index=False,header=False)

# This will pre set a file to save the OD volumes specific to the rails for a
validation
old_Rail_OD = pd.read_csv('Rail_OD_vols_O.csv',header=None)
old_Rail_OD.to_csv('Rail_OD_vols.csv',index=False,header=False)

# This will take the files that have overwritten the properties from a previous
analysis, and reset them to their
# original state for this analysis
props_ind=0
try:
    at_cap = pd.read_csv('Pipelines.csv', usecols=['Oneway'])
    fc = 'C:/arcgis/Network_2.gdb/Network_Analysis/Pipelines'
    workspace = 'C:/arcgis/Network_2.gdb'
    layer_name = ['Oneway']
    i = 0
    edt = arcpy.da.Editor(workspace)
    edt.startEditing()
    edt.startOperation()
    with arcpy.da.UpdateCursor(fc, layer_name) as cursor:
        for row in cursor:
            row[0] = at_cap['Oneway'][i]
            cursor.updateRow(row)
    edt.stopOperation()
    edt.stopEditing(True)
except arcpy.ExecuteError:
    print(arcpy.GetMessages(2))
print("Edited back to original successfully.")

# Check out the Network Analyst extension license
arcpy.CheckOutExtension("Network")

# Set environment settings
env.workspace = 'C:/arcgis/Network_2.gdb'

# Set local variables
network = "Network_Analysis/Pipeline_Analysis"

# Build the network dataset
```

```
arcpy.na.BuildNetwork(network)

# If there are any build errors, they are recorded in a BuildErrors.txt file
# present in the system temp directory, so copy this file to the directory
# containing this script.
temp_dir = os.environ.get("TEMP")
if temp_dir:
    shutil.copy2(os.path.join(temp_dir, "BuildErrors.txt"), sys.path[0])

print("Rebuilt back to original successfully.")



sum_while = 1
while sum_while >0:

    # Check which OD matrix has volume still
    # If there are any volumes remaining in the matrix that will then be the selected
set of values to be used in the
    # program. The if statement then preps the solve to be based on the matricies
retlated to the sum check
    # S represents the sepcial case volumes, T represents the typical volumes
    vol_type = []
    test_vols = []
    # First check step, seeing if there is some special OD volumes
    with open('OD_S.csv', 'r') as check:
        check_read = csv.reader(check)
        # Reset the sum to 0 for the if statement, that the case will be special if
the sum becomes greater than 0
        OD_count = 0
        sum = 0
        for row in check_read:
            w = len(row)
            for i in range(0,w):
                sum = sum + int(row[i])
                if int(row[i]) > 0:
                    OD_count += 1
        if sum > 0:
            vol_type = 'S'
            name_OD = 'OD_S.csv'
            test_vols = np.zeros((OD_count,3))
            check.seek(0)
            j = 0
            k = 0
            for row in check_read:
                w = len(row)
                l = 1
                for i in range(0,w):
                    if int(row[i]) > 0:
                        m = j +1
                        test_vols[k] = [m,l,int(row[i])]
                        k += 1
                    l += 1
                j += 1
            check.close()
        else:
            # This second check is to see if the sum of the typical volume OD matrix
is greater than
            # zero, meaning that it would then be a typical case
            check = open('OD_T.csv','r')
            check_read = csv.reader(check)
            for row in check_read:
                w = len(row)
```

```
                for i in range(0, w):
                    sum = sum + int(row[i])
                    if int(row[i]) > 0:
                        OD_count += 1
            if sum > 0:
                vol_type = 'T'
                name_OD = 'OD_T.csv'
                test_vols = np.zeros((OD_count, 3))
                check.seek(0)
                j = 0
                k = 0
                for row in check_read:
                    w = len(row)
                    l = 1
                    for i in range(0, w):
                        if int(row[i]) > 0:
                            m = j + 1
                            test_vols[k] = [m, l, int(row[i])]
                            k += 1
                        l += 1
                    j += 1
        check.close()
    # New file to save the remaining volume OD matrix paris
        np.savetxt('test_vols.csv',test_vols, delimiter=',', fmt ='%0.f')
    # Import in the pairs that were considered in the route analysis
    # bring in the zones required for the route analysis
    zone_pairs = pd.read_csv('test_vols.csv', header = None)
    # Preset variables for the properties of the shortest path analysis
    dir_names = []
    mode = []
    route_mode = []
    for ind, Or, De, vol in zone_pairs.itertuples():
        try:
            mode = 'Pipeline'
            # Check out Network Analyst license if available. Fail if the Network
Analyst license is not available.
            # Check out the Network Analyst extension license
            arcpy.CheckOutExtension("Network")

            # Set environment settings
            env.workspace = "C:/arcgis/Network_2.gdb"
            env.overwriteOutput = True

            # Set local variables
            inNetworkDataset = 'Network_Analysis/Pipeline_Analysis'
            outNALayerName = "Route" + str(Or)+'-'+str(De)
            impedanceAttribute = "length_geo"
            outLayerFile = 'C:/arcgis/Output'+'/'+outNALayerName+'.lyr'

            # Create a new Route layer. For this scenario, the default values for all
the
            # remaining parameters statisfy the analysis requirements
            outNALayer = arcpy.na.MakeRouteLayer(inNetworkDataset, outNALayerName,
                                                 impedanceAttribute)

            # Get the layer object from the result object. The route layer can now be
            # referenced using the layer object.
            outNALayer = outNALayer.getOutput(0)

            # Get the names of all the sublayers within the route layer.
            subLayerNames = arcpy.na.GetNAClassNames(outNALayer)
            # Stores the layer names that we will use later
            stopsLayerName = subLayerNames["Stops"]
```

```
            # In this origin destination subset the origin is determined through the 
use of the boolean of 1
            # for productions and 0 for demands
            arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Pipes','O_lyr')
            arcpy.SelectLayerByAttribute_management('O_lyr','NEW_SELECTION','Zone 
IN('+str(Or)+')')
            arcpy.SelectLayerByAttribute_management('O_lyr', 'SUBSET_SELECTION', 
'Node_Type IN(1)')

            arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Pipes','D_lyr')
            arcpy.SelectLayerByAttribute_management('D_lyr','NEW_SELECTION','Zone 
IN('+str(De)+')')
            arcpy.SelectLayerByAttribute_management('D_lyr', 'SUBSET_SELECTION', 
'Node_Type IN(0)')

            # Check that there is a value in the return on the Origin
            matchcount = int(arcpy.GetCount_management('O_lyr')[0])
            Current_O = []
            if matchcount == 0:
                print('no features matched spatial and attribute criteria')
            else:
                Current_O = arcpy.CopyFeatures_management('O_lyr','Current_O')

            # Check that there is a value in the return on the Dest
            matchcount = int(arcpy.GetCount_management('O_lyr')[0])
            Current_D = []
            if matchcount == 0:
                print('no features matched spatial and attribute criteria')
            else:
                Current_D = arcpy.CopyFeatures_management('D_lyr','Current_D')

            # This maps the O and D to the stops file
            fieldMappings = arcpy.na.NAClassFieldMappings(outNALayer, stopsLayerName)
            # Map the Origin first to input it as the first stop
            arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_O,fieldMappings, 
"")
            # Map the Destination next
            arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_D,fieldMappings, 
"")

            # Solve the route layer.
            arcpy.na.Solve(outNALayer)

            # Get the output Routes sublayer and save it to a feature class
            arcpy.SaveToLayerFile_management(outNALayer, outLayerFile,'RELATIVE')

            # Make a directions file as well
            outDirectionsFile = 'C:/arcgis/Output/'+outNALayerName+'Directions.TXT'
            arcpy.na.Directions(outNALayer, "TEXT", outDirectionsFile, 'Kilometers')
            arcpy.SaveToLayerFile_management(outNALayer, outLayerFile, 'RELATIVE')
            dir_names += [outDirectionsFile]
            print (outNALayerName + " completed successfully")
            route_mode += [mode]
        except Exception as e:
            # If an error occurred, print line number and error message
            tb = sys.exc_info()[2]
            print("An error occurred on line %i" % tb.tb_lineno)
            print(str(e))
            print (outNALayerName + " FAILED PIPE")
            # Since the pipeline route has failed due to lack of connectivity or 
availability, now there is a check of
            # the rail shortest route to be used
```

```
            try:
                mode = 'Rail'
                # Check out Network Analyst license if available. Fail if the Network
Analyst license is not available.
                # Check out the Network Analyst extension license
                arcpy.CheckOutExtension("Network")

                # Set environment settings
                env.workspace = "C:/arcgis/Network_2.gdb"
                env.overwriteOutput = True

                # Set local variables
                inNetworkDataset = 'Network_Analysis/Rail_Analysis'
                outNALayerName = "Route" + str(Or) + '-' + str(De)
                impedanceAttribute = "length_geo"
                outLayerFile = 'C:/arcgis/Output' + '/' + outNALayerName + '.lyr'

                # Create a new Route layer. For this scenario, the default values for
all the
                # remaining parameters statisfy the analysis requirements
                outNALayer = arcpy.na.MakeRouteLayer(inNetworkDataset, outNALayerName,
                                                     impedanceAttribute)

                # Get the layer object from the result object. The route layer can now
be
                # referenced using the layer object.
                outNALayer = outNALayer.getOutput(0)

                # Get the names of all the sublayers within the route layer.
                subLayerNames = arcpy.na.GetNAClassNames(outNALayer)
                # Stores the layer names that we will use later
                stopsLayerName = subLayerNames["Stops"]

                # In this origin destination subset the origin is determined through
the use of the boolean of 1
                # for productions and 0 for demands
                arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Rail',
'O_lyr')
                arcpy.SelectLayerByAttribute_management('O_lyr', 'NEW_SELECTION',
'Zone IN(' + str(Or) + ')')
                arcpy.SelectLayerByAttribute_management('O_lyr', 'SUBSET_SELECTION',
'Node_Type IN(1)')

                arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Rail',
'D_lyr')
                arcpy.SelectLayerByAttribute_management('D_lyr', 'NEW_SELECTION',
'Zone IN(' + str(De) + ')')
                arcpy.SelectLayerByAttribute_management('D_lyr', 'SUBSET_SELECTION',
'Node_Type IN(0)')

                # Check that there is a value in the return on the Origin
                matchcount = int(arcpy.GetCount_management('O_lyr')[0])
                Current_O = []
                if matchcount == 0:
                    print('no features matched spatial and attribute criteria')
                else:
                    Current_O = arcpy.CopyFeatures_management('O_lyr', 'Current_O')

                # Check that there is a value in the return on the Dest
                matchcount = int(arcpy.GetCount_management('O_lyr')[0])
                Current_D = []
                if matchcount == 0:
                    print('no features matched spatial and attribute criteria')
```

```
                else:
                    Current_D = arcpy.CopyFeatures_management('D_lyr', 'Current_D')

                # This maps the O and D to the stops file
                fieldMappings = arcpy.na.NAClassFieldMappings(outNALayer,
stopsLayerName)
                # Map the Origin first to input it as the first stop
                arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_O,
fieldMappings, "")
                # Map the Destination next
                arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_D,
fieldMappings, "")

                # Solve the route layer.
                arcpy.na.Solve(outNALayer)

                # Get the output Routes sublayer and save it to a feature class
                arcpy.SaveToLayerFile_management(outNALayer, outLayerFile, 'RELATIVE')

                # Make a directions file as well
                outDirectionsFile = 'C:/arcgis/Output/' + outNALayerName +
'Directions.TXT'
                arcpy.na.Directions(outNALayer, "TEXT", outDirectionsFile,
'Kilometers')
                arcpy.SaveToLayerFile_management(outNALayer, outLayerFile, 'RELATIVE')
                dir_names += [outDirectionsFile]
                print (outNALayerName + " completed successfully")
                route_mode += [mode]
                rail_vols = pd.read_csv('Rail_OD_vols.csv',header = None)
                index = (Or - 1)*19 + De - 1
                rail_vols[2][index] = vol
                rail_vols.to_csv('Rail_OD_vols.csv' ,index = False, header = False)
            except Exception as e:
                # If an error occurred, print line number and error message
                import traceback, sys

                tb = sys.exc_info()[2]
                print("An error occurred on line %i" % tb.tb_lineno)
                print(str(e))
                print (outNALayerName + " FAILED RAIL")
    # This is the directions reader, taking all values that could exist within the
direction file and adding them
    # to either the links aspect or the centroid
    i = 1
    list_name = []
    list_cent = []
    for file in dir_names:
        with open(file) as txt_file:
            name = 'route' + str(i) + '.csv'
            cent = 'centroid' + str(i) + '.csv'
            list_name += [name]
            list_cent += [cent]
            c = open(name, 'wb')
            d = open(cent, 'wb')
            cw = csv.writer(c)
            dw = csv.writer(d)
            b = []
            for line in txt_file:
                # Special characters have been used in the GIS data to seperate the
values of a link or a centroid
                # connector
                cnta = line.count('~')
                cntb = line.count('!')
```

```
                # If statement to control if there is more than one link or connector
in a direction list line
                # also, if the line is blank or not due to the export style of the
ArcMap program
                if cntb >= 1:
                    for m in re.finditer('!', line):
                        aa = [line[m.start():line.find(' ', m.end())]]
                        if aa != -1:
                            dw.writerow(aa)
                        if line.find('towards', m.end()) > 0:
                            break
                elif cnta >= 1:
                    for m in re.finditer('~', line):
                        aa = [line[m.start():line.find(' ', m.end())]]
                        if aa != -1:
                            cw.writerow(aa)
                        if line.find('towards', m.end()) > 0:
                            break
            c.close()
            d.close()
        i += 1

    # Generates the function to make it so the array can be indexed to build the
routes
    def numpy_fillna(data):
        # Get lengths of each row of data
        lens = np.array([len(i) for i in data])

        # Mask of valid places in each row
        mask = np.arange(lens.max()) < lens[:,None]

        # Setup output array and put elements from data into masked positions
        out = np.zeros(mask.shape, dtype=data.dtype)
        out.fill(99)
        out[mask] = np.concatenate(data)
        return out

    # Import all the OD pairs that have their associated volumes
    vols_route = pd.read_csv('test_vols.csv', header = None)
    # Now a for loop will be set up around the two mode types to determine the links
in rail network and pipe
    # network as well
    link_route_p = []
    link_route_r = []
    mode_types = ['Pipeline','Rail']
    for mode in mode_types:
        # Pre set the two arrays to hold the list of all the individual link names and
which route they first
        # occur in - links - and an array that will hold all the links that are
repeated with the associated
        # volumes of all the routes that the links are apart of
        links = [[0, 0]]
        link_same = [[0, 0]]
        link_route = []
        w = 0
        for route in route_mode:
            # This will start by running over each of the different files to be read
to combine the volumes
            # in the routes associated with a repeating link value
            # However, it will initially require an if statement to determine the mode
type
            if route == mode:
                check = pd.read_csv(list_name[w],header = None)
```

```
                check.sort_index()
                vol = vols_route[2][w]
                for ind,aid in check.itertuples():
                    m = 0
                    for L in links:
                        if L[0] == aid:
                            k = 0
                            m = 1
                            for j in link_same:
                                if aid == j[0]:
                                    k = 1
                            # If the link is not in the multiuse set yet then it will
be added along with the matching
                            # volume from its original
                            if k == 0:
                                vol_new = vol + L[1]
                                link_same += [[aid,vol_new]]
                                a = np.array(link_route,dtype=object)
                                a2 = numpy_fillna(a)
                                ls_ind = np.where(a2 == aid)[0][0]
                                link_route[ls_ind].append(w)
                            # If it is already a part of the set then the new volume
is added to the existing value
                            else:
                                a = np.array(link_same)
                                ls_ind = np.where(a == aid)[0]
                                link_same[ls_ind][1] += vol
                                a = np.array(link_route,dtype=object)
                                a2 = numpy_fillna(a)
                                ls_ind = np.where(a2 == aid)[0][0]
                                link_route[ls_ind].append(w)
                    # If the link has not been used before in the analysis, then it
will be placed into the file
                    # in which single use links exist, this is to allow for a
different allocation of the volumes
                    # to be easily assessed
                    if m == 0:
                        links += [[aid, vol]]
                        link_route += [[aid, w]]
            else:
                w += 1
                continue
            w += 1
        if mode == 'Pipeline':
            link_route_p = link_route
        else:
            link_route_r = link_route
        # Take out the first row of the link array to remove the zero array from the
presetting of the array
        if link_route == []:
            pass
        else:
            i = 0
            link_same_s = []
            for row in link_same:
                if i != 0:
                    link_same_s += [row]
                i += 1
            i = 0
            links_s = []
            for row in links:
                if i != 0:
                    links_s += [row]
```

```
                i += 1

            # Save it into a csv file to allow for the use of the pandas
            # Also premake the file name to coincide with the mode type
            m_name = 'Multiuse Links-'+mode+'.csv'
            l_name = 'Links-'+mode+'.csv'
            np.savetxt(m_name,link_same_s,delimiter=',', fmt = '%s', header =
'ArcmapID,Volume Applied',comments = '')
            np.savetxt(l_name,links_s,delimiter=',', fmt = '%s', header =
'ArcmapID,Volume Applied',comments = '')

    # Modify the mode matrix now based on if there are any routes involved with one
mode or the other or both
    if link_route_r == []:
        mode_types = ['Pipeline']
    elif link_route_p == []:
        mode_types = ['Rail']

    # Merge the file that has the multi-use links in it to add the properties of the
links in to find what the
    # minimum capacity of the links in the route would be to add the volume to.
    for mode in mode_types:
        if  mode == 'Pipeline':
            dfM = pd.read_csv('Multiuse Links-'+mode+'.csv')
            dfL = pd.read_csv('Links-'+mode+'.csv')
            com_caps = 'CAPACITY '+'S'+'-Committed'
            uncom_caps = 'CAPACITY '+'S'+'-Uncommitted'
            com_capt = 'CAPACITY '+'T'+'-Committed'
            uncom_capt = 'CAPACITY '+'T'+'-Uncommitted'
            df2 = pd.read_csv('Pipelines.csv', usecols =
['ArcmapID',com_caps,uncom_caps,com_capt,uncom_capt, 'VOLUME'])
            dfMp = dfM.merge(df2, on = 'ArcmapID', how = 'left')
            dfLp = dfL.merge(df2, on = 'ArcmapID', how = 'left')
        else:
            dfM = pd.read_csv('Multiuse Links-'+mode+'.csv')
            dfL = pd.read_csv('Links-'+mode+'.csv')
            df2 = pd.read_csv('Rail.csv', usecols = ['ArcmapID', 'Volume'])
            dfMr = dfM.merge(df2, on='ArcmapID', how='left')
            dfLr = dfL.merge(df2, on='ArcmapID', how='left')

    # The minimum capacity will then be based off of the capacity of the link being
considered
    # as well as the volume of all OD pairs being considered and the volume existing
on the link
    # currently.
    vol_prop_OD = []
    for ind, O, D, volo in zone_pairs.itertuples():
        if route_mode[ind] == 'Pipeline':
            min_cap = ['', -1]
            for inds, ID, req_vol, capcs, capus, capct, caput, vole in
dfMp.itertuples():
                contract_type = []
                volume_split = 'No'
                vol = 0
                # Check to see if a link is inside of a specific route to begin with
to ensure that the route has its
                # legitamate minimum or limitting factor determined
                # Default is false with an if statement running over that links OD
pair index to determine if the in_route
                # should be altered to True
                in_route = False
                a =numpy_fillna(np.array(link_route_p,dtype=object))
                ls_ind = np.where(a == ID)[0][0]
```

```
                for j in link_route_p[ls_ind]:
                    if j == ind:
                        in_route = True
                if in_route == False:
                    continue
                else:
                    if vol_type == 'S':
                        capc = capcs
                        capu = capus
                        captot = capc
                        if vole >= captot:
                            vol_un = 1
                        else:
                            vol_un = 0
                    else:
                        capc = capct
                        capu = caput
                        if vole >= capcs+capus+capc:
                            captot = capcs+capus+capc
                            vol_un = 1
                        else:
                            captot = vole
                            vol_un = 0
                    if vol_type == 'S':
                        vol = vole
                    else:
                        if vole >= capcs + capus:
                            vol = vole - capcs - capus
                        else:
                            vol = 0
                    # Initially determines if it is an uncommitted or committed
shipping type
                    if vol_un == 1:
                        cap = capu
                        contract_type = 'uncommitted'
                        vol = vol - capct
                        # Then if the total volume to be added exceeds the capacity
available of the shipment type
                        # then it will need to follow the shipper split rules
applicable to the shipment type
                        if (vol+req_vol) > cap:
                            min_temp = 0
                            volume_split = 'Yes'
                            # If the new volume value to be added is less than the
existing value then it will replace
                            # it. This ensures that the lowest available capacity is
utilized between the multiple
                            # OD pairs that may be using an individual link, reducing
the OD pair volume based on the
                            # volume increment
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<=min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                        # If there is available capacity then there is no split
```

```
required
                        else:
                            min_temp = cap - (vol+req_vol)
                            volume_split = 'No'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                    else:
                        cap = capc
                        contract_type = 'committed'
                        if vol_type == 'S':
                            vol = vole
                        else:
                            if vole >= capcs+capus:
                                vol = vole - capcs - capus
                            else:
                                vol = 0
                        if (vol+req_vol) > cap:
                            min_temp = 0
                            volume_split = 'Yes'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                        else:
                            min_temp = cap - (vol+req_vol)
                            if min_cap[1] == -1:
                                volume_split = 'No'
                                min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
            for inds, ID, req_vol, capcs, capus, capct, caput, vole in
dfLp.itertuples():
                in_route = False
                a =numpy_fillna(np.array(link_route_p,dtype=object))
                ls_ind = np.where(a == ID)[0][0]
                for j in link_route_p[ls_ind]:
                    if j == ind:
```

```
                        in_route = True
                if in_route == False:
                    continue
                else:
                    if vol_type == 'S':
                        capc = capcs
                        capu = capus
                        captot = capc
                        if vole >= captot:
                            vol_un = 1
                        else:
                            vol_un = 0
                    else:
                        capc = capct
                        capu = caput
                        if vole >= capcs+capus+capc:
                            captot = capcs+capus+capc
                            vol_un = 1
                        else:
                            captot = vole
                            vol_un = 0
                    if vol_type == 'S':
                        vol = vole
                    else:
                        if vole >= capcs + capus:
                            vol = vole - capcs - capus
                        else:
                            vol = 0
                    if vol_un == 1:
                        cap = capu
                        vol = vol - capct
                        contract_type = 'uncommitted'
                        if (vol+req_vol) > cap:
                            min_temp = 0
                            volume_split = 'Yes'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'L',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                        else:
                            min_temp = cap - (vol+req_vol)
                            volume_split = 'No'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'L',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                    else:
```

```
                        cap = capc
                        contract_type = 'committed'
                        if vol_type == 'S':
                            vol = vole
                        else:
                            if vole >= capcs+capus:
                                vol = vole - capcs - capus
                            else:
                                vol = 0
                        if (vol+req_vol) > cap:
                            min_temp = 0
                            volume_split = 'Yes'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'L',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                        else:
                            min_temp = cap - (vol+req_vol)
                            volume_split = 'No'
                            if min_cap[1] == -1:
                                min_cap = [ID,
min_temp,volume_split,contract_type,'L',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
                            elif min_temp <= min_cap[1] and (cap-vol)<= min_cap[5]:
                                vol_inc_pre = ((volo+0.0)/min_cap[6])*(min_cap[5]-
min_cap[12])
                                vol_inc_new = ((volo+0.0)/req_vol)*(cap-vol)
                                if vol_inc_new < vol_inc_pre:
                                    min_cap = [ID,
min_temp,volume_split,contract_type,'M',cap,req_vol,
                                           capcs,capus,capct,caput,vole,vol]
            vol_prop_OD.append(min_cap)
        else:
            vol_prop_OD.append(['','','','','',''])
    # This is the logic for the volume split on the Uncommitted Special Case
shipments, this is only run through
    # if there is a split value like this in the vol_prop_OD array.
    np.savetxt('PROPS'+str(props_ind)+'.csv', vol_prop_OD, delimiter=',', fmt='%s',
comments='')
    props_ind +=1
    use_route = 1
    rail_OD_ind = 0
    ranked = []
    dir_names = []
    for row in vol_prop_OD:
        if row[3] == 'uncommitted' and row[2] == 'Yes' and row[4]=='M' and vol_type ==
'S':
            print 'Special Case Split Check'
            # Take the cost of the trip if it were to be done over the existing
pipeline route using the
            # developed cost functions, and the required variables from the route
properties
            route = 'route'+str(use_route)+'.csv'
            cent = 'centroid'+str(use_route)+'.csv'
            pipe_all = pd.read_csv('Pipelines.csv')
```

```
            cent_all = pd.read_csv('Centroid Pipes.csv')
            pipe_route = pd.read_csv(route, header=None)
            cent_route = pd.read_csv(cent, header=None)
            pipe_prop = pipe_route.merge(pipe_all, left_on=0, right_on='ArcmapID',
how='left')
            cent_prop = cent_route.merge(cent_all,
left_on=0,right_on='ArcmapID',how='left')
            dist = 0
            for d in pipe_prop['LENGTH_GEO']:
                dist += d
            diam = max(pipe_prop['DIAMETER'])
            US_toll = 0
            for roww in cent_prop['US']:
                if roww == 1:
                    US_toll = 1
            cost_pipe =6.25+0.00345*dist-0.104*diam+9.56*US_toll
            a = numpy_fillna(np.array(link_route_p, dtype=object))
            ls_ind = np.where(a == row[0])[0][0]
            mode = []
            zone_pairs = pd.read_csv('test_vols.csv', header=None)
            Or = zone_pairs[0][rail_OD_ind]
            De = zone_pairs[1][rail_OD_ind]
            vol = zone_pairs[2][rail_OD_ind]
            try:
                mode = 'Rail'
                # Check out Network Analyst license if available. Fail if the Network
Analyst license is not available.
                # Check out the Network Analyst extension license
                arcpy.CheckOutExtension("Network")

                # Set environment settings
                env.workspace = "C:/arcgis/Network_2.gdb"
                env.overwriteOutput = True

                # Set local variables
                inNetworkDataset = 'Network_Analysis/Rail_Analysis'
                outNALayerName = "Route_Rank" + str(Or) + '-' + str(De)
                impedanceAttribute = "length_geo"
                outLayerFile = 'C:/arcgis/Output' + '/' + outNALayerName + '.lyr'

                # Create a new Route layer. For this scenario, the default values for
all the
                # remaining parameters statisfy the analysis requirements
                outNALayer = arcpy.na.MakeRouteLayer(inNetworkDataset, outNALayerName,
                                                     impedanceAttribute)

                # Get the layer object from the result object. The route layer can now
be
                # referenced using the layer object.
                outNALayer = outNALayer.getOutput(0)

                # Get the names of all the sublayers within the route layer.
                subLayerNames = arcpy.na.GetNAClassNames(outNALayer)
                # Stores the layer names that we will use later
                stopsLayerName = subLayerNames["Stops"]

                # In this origin destination subset the origin is determined through
the use of the boolean of 1
                # for productions and 0 for demands
                arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Rail',
'O_lyr')
                arcpy.SelectLayerByAttribute_management('O_lyr', 'NEW_SELECTION',
'Zone IN(' + str(Or) + ')')
```

```
                arcpy.SelectLayerByAttribute_management('O_lyr', 'SUBSET_SELECTION',
'Node_Type IN(1)')

                arcpy.MakeFeatureLayer_management('Network_Analysis/Zone_Rail',
'D_lyr')
                arcpy.SelectLayerByAttribute_management('D_lyr', 'NEW_SELECTION',
'Zone IN(' + str(De) + ')')
                arcpy.SelectLayerByAttribute_management('D_lyr', 'SUBSET_SELECTION',
'Node_Type IN(0)')

                # Check that there is a value in the return on the Origin
                matchcount = int(arcpy.GetCount_management('O_lyr')[0])
                Current_O = []
                if matchcount == 0:
                    print('no features matched spatial and attribute criteria')
                else:
                    Current_O = arcpy.CopyFeatures_management('O_lyr', 'Current_O')

                # Check that there is a value in the return on the Dest
                matchcount = int(arcpy.GetCount_management('O_lyr')[0])
                Current_D = []
                if matchcount == 0:
                    print('no features matched spatial and attribute criteria')
                else:
                    Current_D = arcpy.CopyFeatures_management('D_lyr', 'Current_D')

                # This maps the O and D to the stops file
                fieldMappings = arcpy.na.NAClassFieldMappings(outNALayer,
stopsLayerName)
                # Map the Origin first to input it as the first stop
                arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_O,
fieldMappings, "", )
                # Map the Destination next
                arcpy.na.AddLocations(outNALayer, stopsLayerName, Current_D,
fieldMappings, "", )

                # Solve the route layer.
                arcpy.na.Solve(outNALayer)

                # Get the output Routes sublayer and save it to a feature class
                arcpy.SaveToLayerFile_management(outNALayer, outLayerFile, 'RELATIVE')

                # Make a directions file as well
                outDirectionsFile = 'C:/arcgis/Output/' + outNALayerName +
'Directions-Rank.TXT'
                arcpy.na.Directions(outNALayer, "TEXT", outDirectionsFile,
'Kilometers')
                arcpy.SaveToLayerFile_management(outNALayer, outLayerFile, 'RELATIVE')
                dir_names += [outDirectionsFile]
                print (outNALayerName + " completed successfully")
            except Exception as e:
                # If an error occurred, print line number and error message
                import traceback, sys
                tb = sys.exc_info()[2]
                print("An error occurred on line %i" % tb.tb_lineno)
                print(str(e))
        # This is a copy of the text parse and write code from before
            i = 1
            list_name = []
            list_cent = []
            for file in dir_names:
                with open(file) as txt_file:
                    name = 'route_rank'+str(rail_OD_ind)+'.csv'
```

```
                    cent = 'centroid_rank'+str(rail_OD_ind)+'.csv'
                    list_name += [name]
                    list_cent += [cent]
                    c = open(name, 'wb')
                    d = open(cent, 'wb')
                    cw = csv.writer(c)
                    dw = csv.writer(d)
                    b = []
                    for line in txt_file:
                        cnta = line.count('~')
                        cntb = line.count('!')
                        if cntb >= 1:
                            for m in re.finditer('!', line):
                                aa = [line[m.start():line.find(' ', m.end())]]
                                if aa != -1:
                                    dw.writerow(aa)
                                if line.find('towards', m.end()) > 0:
                                    break
                        elif cnta >= 1:
                            for m in re.finditer('~', line):
                                aa = [line[m.start():line.find(' ', m.end())]]
                                if aa != -1:
                                    cw.writerow(aa)
                                if line.find('towards', m.end()) > 0:
                                    break
                    c.close()
                    d.close()
                i += 1

            # Now that the rank files with the Arcmap ID attribute have been generated
we need to do the same thing
            # as was completed with the pipeline and create the route cost
            route = 'route_rank'+str(rail_OD_ind)+'.csv'
            cent = 'centroid_rank'+str(rail_OD_ind)+'.csv'
            rail_all = pd.read_csv('Rail.csv')
            cent_all = pd.read_csv('Centroid Rails.csv')
            rail_route = pd.read_csv(route, header=None)
            cent_route = pd.read_csv(cent, header = None)
            rail_prop = rail_route.merge(rail_all, left_on=0, right_on='ArcmapID',
how='left')
            cent_prop = cent_route.merge(cent_all, left_on=0, right_on='ArcmapID',
how='left')
            dist = 0
            for d in rail_prop['LENGTH_GEO']:
                dist += d
            US_toll = 0
            H_U = 0
            for roww in cent_prop['US']:
                if roww == 1:
                    US_toll = 1
            for rows in cent_prop['Useage']:
                if rows == 1:
                    H_U = 1
            cost_rail =28.72+0.0139*dist+US_toll*12.55+H_U*9.53
            cost_diff = cost_rail-cost_pipe
            bid_premium = cost_diff*vol
            ranked.append([rail_OD_ind,bid_premium])
            ranked = sorted(ranked, key=lambda bid_premium: bid_premium[1],
reverse=True)
        rail_OD_ind += 1
    d = []
    OD_change = []
    cap = 0
```

```
    for ind, O, D, volo in zone_pairs.itertuples():
        if route_mode[ind] == 'Pipeline':
            # The appropriation of the volumes is now conducted in this step, looking
at the shipment type and the
            # capacity type as well, these rules can later be altered if there is an
alteration to the logic of the
            # program
            special_full = 0
            vol_exist_alt = 0
            file = 'Pipelines.csv'
            prop = vol_prop_OD[ind]
            req_vol = prop[6]
            vol_exist = prop[11]
            if vol_exist >= prop[7]+prop[8]:
                special_full = 1
            cap_avail = prop[7]+prop[8]-vol_exist
            capc = prop[7]+prop[8]
            capu = prop[7]+prop[8]+prop[9]
            # For the committed and uncommitted capacities the logic remains the same
for typical case shipments with an
            # even distribution of volumes. Where the added volume is based on the OD
pair volume (in the for loop)
            # divided by the total added volume. If there is a preexisting volume on
the link then it is taken away
            # from the total capacity to make it into the available capacity.
            if prop[3] == 'committed':
                if vol_type == 'T':
                    if special_full==1:
                        vol_exist_alt = vol_exist - capc
                    else:
                        vol_exist_alt= 0
                    if prop[2] == 'No':
                        vol_inc = volo
                    else:
                        cap = prop[9]-vol_exist_alt
                        vol_inc = ((volo+0.0) / req_vol)*cap
                else:
                    if prop[2] == 'No':
                        vol_inc = volo
                    else:
                        cap = prop[7] - vol_exist
                        vol_inc = ((volo + 0.0) / req_vol) * cap
            else:
                if vol_type == 'T':
                    if special_full == 1:
                        vol_exist_alt = vol_exist - capu
                    else:
                        vol_exist_alt = 0
                    if prop[2] == 'No':
                        vol_inc = volo
                    else:
                        cap = prop[10] - vol_exist_alt
                        vol_inc = ((volo + 0.0) / req_vol) * cap
                # If the case is such that the shipment type is Special and the
capacity is Uncommitted then the
                # case must be analyzed to see if the volumes need to be split or not.
                # If the volumes are in exceedance of the capacity, they need to be
split based on the highest bid
                # premium logic. These have already been sorted through the previous
for loop statement, so they will
                # be referrenced out of the array
                elif vol_type == 'S' and prop[2] == 'Yes':
                    sum = 0
```

```
                    r = np.array(ranked)
                    f = np.where(r == ind)[0][0]
                    if f == 0:
                        if cap_avail < volo:
                            vol_inc = cap_avail
                            # Place the remaining volume from the top ranked shipment
onto the rail line
                            file_r = 'Rail.csv'
                            vol_inc_r = volo - cap_avail
                            usecols = range(0, 8)
                            links = pd.read_csv(file_r, usecols=usecols)
                            route = pd.read_csv('route' + str(ind + 1) + '.csv',
header=None)
                            vol_ex = pd.read_csv(file_r, usecols=['ArcmapID',
'Volume'])
                            j = 0
                            for val in route[0]:
                                i = 0
                                for row in vol_ex['ArcmapID']:
                                    if val == row:
                                        vol_ex['Volume'][i] += vol_inc_r
                                    i += 1
                                j += 1
                            d = links.merge(vol_ex, right_on='ArcmapID',
left_on='ArcmapID', how='outer')
                            d['Volume'].fillna(value=0, inplace=True)
                            d.to_csv(file_r, index=False)
                            OD_name = 'OD_' + vol_type + '.csv'
                            OD_change = pd.read_csv(OD_name, header=None)
                            OD_change[D - 1][O - 1] = OD_change[D - 1][O - 1] -
vol_inc_r
                            OD_change.to_csv(OD_name, index=False, header=False)
                        else:
                            vol_inc = volo
                    else:
                        for sum_ind in range(0,f):
                            sum += zone_pairs[2][ranked[0][sum_ind]]
                        if sum >= cap_avail:
                            vol_inc = 0
                            # Place the remaining volume from the top ranked shipment
                            file_r = 'Rail.csv'
                            vol_inc_r = volo
                            usecols = range(0, 8)
                            links = pd.read_csv(file_r, usecols=usecols)
                            route = pd.read_csv('route' + str(ind + 1) + '.csv',
header=None)
                            vol_ex = pd.read_csv(file_r, usecols=['ArcmapID',
'Volume'])
                            j = 0
                            for val in route[0]:
                                i = 0
                                for row in vol_ex['ArcmapID']:
                                    if val == row:
                                        vol_ex['Volume'][i] += vol_inc_r
                                    i += 1
                                j += 1
                            d = links.merge(vol_ex, right_on='ArcmapID',
left_on='ArcmapID', how='outer')
                            d['Volume'].fillna(value=0, inplace=True)
                            d.to_csv(file_r, index=False)
                            OD_name = 'OD_' + vol_type + '.csv'
                            OD_change = pd.read_csv(OD_name, header=None)
                            OD_change[D - 1][O - 1] = OD_change[D - 1][O - 1] -
```

```
vol_inc_r
                            OD_change.to_csv(OD_name, index=False, header=False)
                        else:
                            if (cap_avail - sum) < volo:
                                vol_inc = cap_avail
                                # Place the remaining volume from the top ranked
shipment
                                file_r = 'Rail.csv'
                                vol_inc_r = volo - cap_avail
                                usecols = range(0, 8)
                                links = pd.read_csv(file_r, usecols=usecols)
                                route = pd.read_csv('route' + str(ind + 1) + '.csv',
header=None)
                                vol_ex = pd.read_csv(file_r, usecols=['ArcmapID',
'Volume'])
                                j = 0
                                for val in route[0]:
                                    i = 0
                                    for row in vol_ex['ArcmapID']:
                                        if val == row:
                                            vol_ex['Volume'][i] += vol_inc_r
                                        i += 1
                                    j += 1
                                d = links.merge(vol_ex, right_on='ArcmapID',
left_on='ArcmapID', how='outer')
                                d['Volume'].fillna(value=0, inplace=True)
                                d.to_csv(file_r, index=False)
                                OD_name = 'OD_' + vol_type + '.csv'
                                OD_change = pd.read_csv(OD_name, header=None)
                                OD_change[D - 1][O - 1] = OD_change[D - 1][O - 1] -
vol_inc_r
                                OD_change.to_csv(OD_name, index=False, header=False)
                            else:
                                vol_inc = volo
                else:
                    vol_inc = volo
            usecols = range(0, 13)
            links = pd.read_csv(file, usecols=usecols)
            route = pd.read_csv('route' + str(ind+1) + '.csv', header=None)
            vol_ex = pd.read_csv(file, usecols=['ArcmapID', 'VOLUME'])
            j = 0
            for val in route[0]:
                i = 0
                for row in vol_ex['ArcmapID']:
                    if val == row:
                        vol_ex['VOLUME'][i] += round(vol_inc,0)
                    i += 1
                j += 1
            d = links.merge(vol_ex, right_on='ArcmapID', left_on='ArcmapID',
how='outer')
            d['VOLUME'].fillna(value=0, inplace=True)
            d.to_csv(file, index=False)
            OD_name = 'OD_'+vol_type+'.csv'
            OD_change = pd.read_csv(OD_name, header = None)
            OD_change[D-1][O-1] = OD_change[D-1][O-1] - vol_inc
            OD_change.to_csv(OD_name,index=False,header=False)
        else:
            # There is no need to split in the case of rail allocation as there is no
capacity
            file = 'Rail.csv'
            vol_inc = volo
            usecols = range(0, 8)
            links = pd.read_csv(file, usecols=usecols)
```

```
            route = pd.read_csv('route' + str(ind+1) + '.csv', header=None)
            vol_ex = pd.read_csv(file, usecols=['ArcmapID', 'Volume'])
            j = 0
            for val in route[0]:
                i = 0
                for row in vol_ex['ArcmapID']:
                    if val == row:
                        vol_ex['Volume'][i] += vol_inc
                    i += 1
                j += 1
            d = links.merge(vol_ex, right_on='ArcmapID', left_on='ArcmapID',
how='outer')
            d['Volume'].fillna(value=0, inplace=True)
            d.to_csv(file, index=False)
            OD_name = 'OD_' + vol_type + '.csv'
            OD_change = pd.read_csv(OD_name, header=None)
            OD_change[D - 1][O - 1] = OD_change[D - 1][O - 1] - vol_inc
            OD_change.to_csv(OD_name, index=False, header=False)
    # Final check to see if any of the links have hit their total capacity
    # Setting the new Oneway attribute to 'n' to make it so the link has become
restricted

    check_cap = pd.read_csv('Pipelines.csv')
    for ind,OB,ID,AID,SL,LG,Oneway,CSC,CSU,CTC,CTU,CAP,D,ON,VOL in
check_cap.itertuples():
        if VOL >= CAP:
            check_cap['Oneway'][ind] = 'n'

    check_cap.to_csv('Pipelines.csv', index=False)

    fc = 'C:/arcgis/Network_2.gdb/Network_Analysis/Pipelines'
    workspace = 'C:/arcgis/Network_2.gdb'
    layer_name = ['Oneway']

    at_cap = pd.read_csv('Pipelines.csv', usecols=['Oneway'])
    i = 0
    edt = arcpy.da.Editor(workspace)
    edt.startEditing(False,True)
    edt.startOperation()
    with arcpy.da.UpdateCursor(fc,layer_name) as cursor:
        for row in cursor:
            row[0] = at_cap['Oneway'][i]
            cursor.updateRow(row)
            i += 1
    edt.stopOperation()
    edt.stopEditing(True)

    print("Edited successfully.")

    # Check out the Network Analyst extension license
    arcpy.CheckOutExtension("Network")

    # Set environment settings
    env.workspace = 'C:/arcgis/Network_2.gdb'

    # Set local variables
    network = "Network_Analysis/Pipeline_Analysis"

    # Build the network dataset
    arcpy.na.BuildNetwork(network)

    # If there are any build errors, they are recorded in a BuildErrors.txt file
    # present in the system temp directory, so copy this file to the directory
```

```
    # containing this script.
    temp_dir = os.environ.get("TEMP")
    if temp_dir:
        shutil.copy2(os.path.join(temp_dir, "BuildErrors.txt"), sys.path[0])

    print("Rebuilt successfully.")

    # Recheck the sum of the two matricies to ensure that there is still volume to be
added to the network

    with open('OD_S.csv', 'r') as check:
        check_read = csv.reader(check)
        checkt = open('OD_T.csv', 'r')
        check_readt = csv.reader(checkt)
        sum_while = 0
        for row in check_read:
            w = len(row)
            for i in range(0,w):
                sum_while = sum_while + int(row[i])
        for row in check_readt:
            w = len(row)
            for i in range(0, w):
                sum_while = sum_while + int(row[i])


print 'Trip Assignment Complete'
```

Appendix F – Python Script Flow Chart

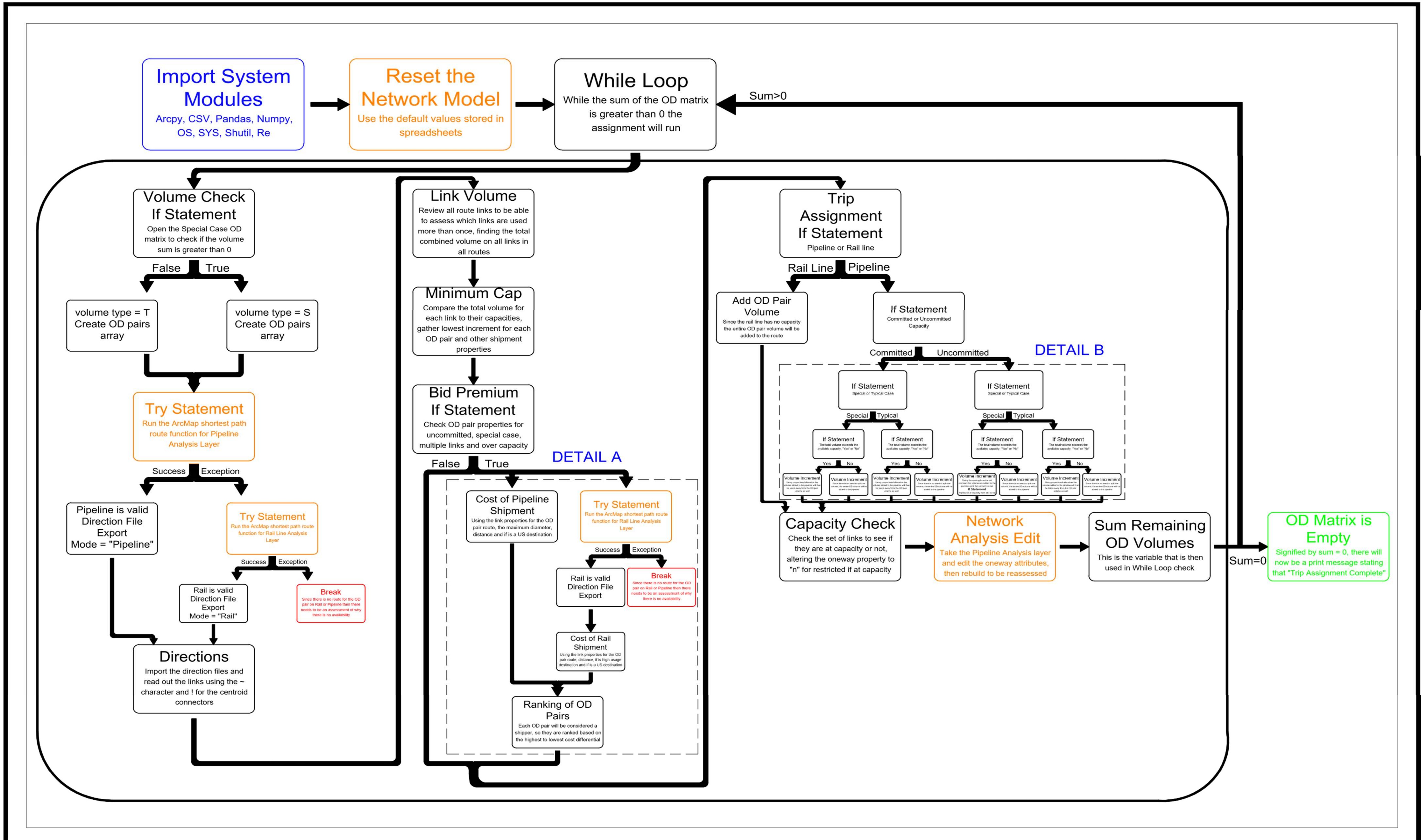


Figure F.1: Trip Assignment Python Code Flow Chart

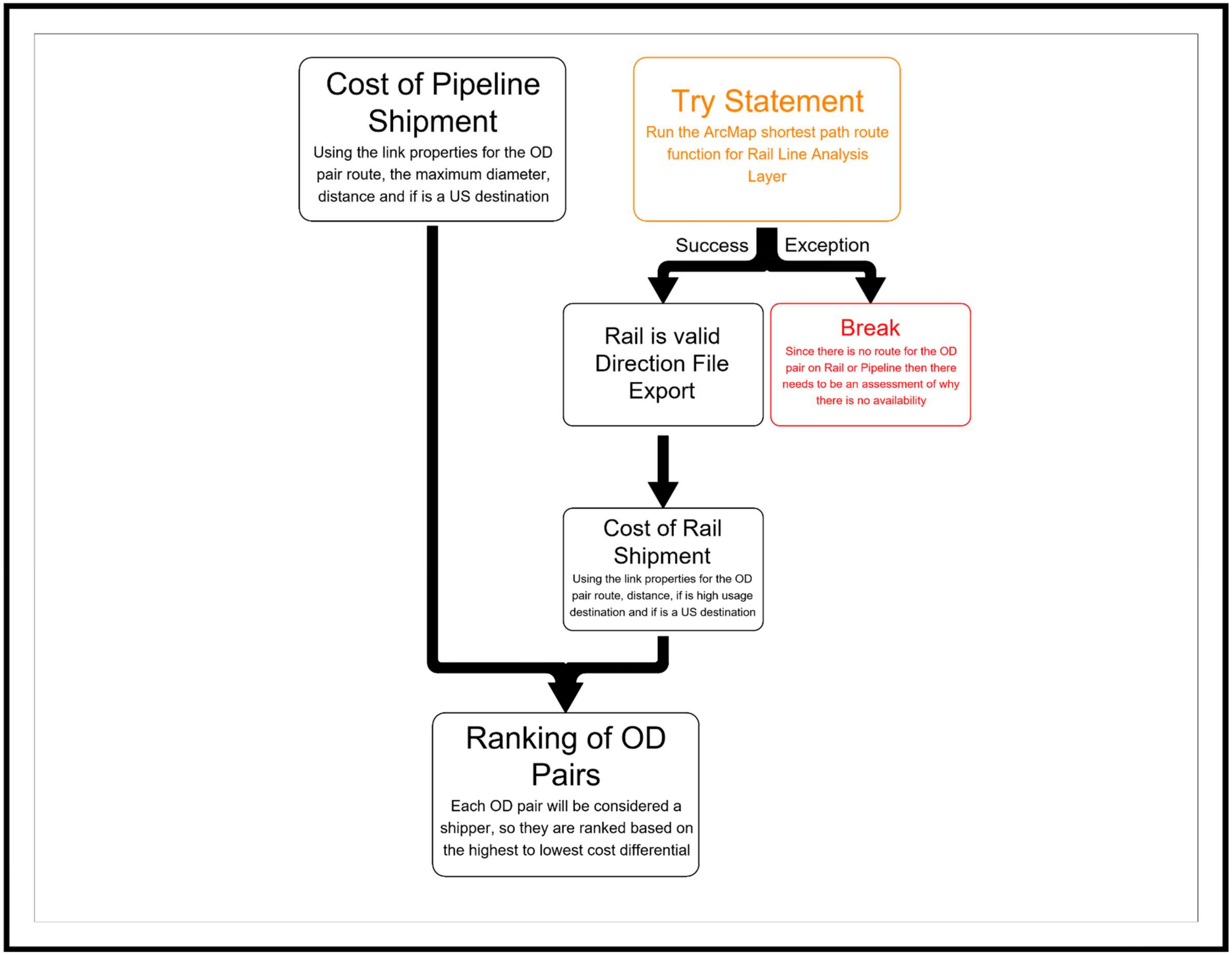


Figure F.2: Flow Chart Detail A

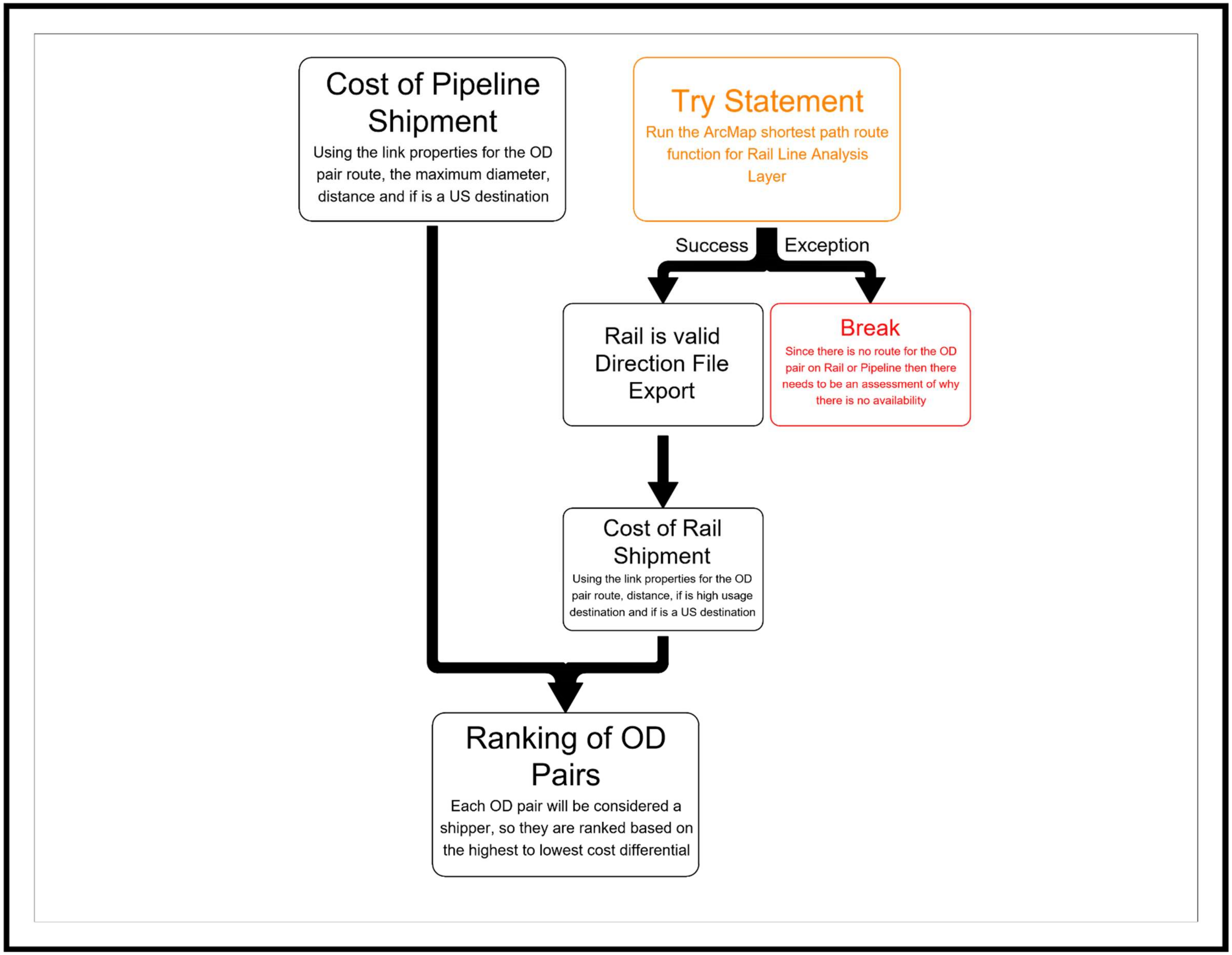


Figure F.3: Flow Chart Detail B