A Techno-Economic Assessment of Bitumen and Synthetic Crude Oil Transport (SCO) in the Canadian Oil Sands Industry: Oil via Rail or Pipeline?

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Abstract.

The growth in bitumen and synthetic crude oil (SCO) production in the Canadian oil sands industry has superseded pipeline capacity growth in recent years, leading to the increased interest in the transport of crude oil by rail to desired markets. However, the specific techno-economic parameters that facilitate increased competitiveness of either transportation mode against the other is seldom addressed in the existing literature. This paper involves the development of a rail and pipeline techno-economic transport model, which is used to ascertain the transportation cost of both options for a market distance range of 1-3000 km and a production scale of 100,000-750,000 barrels per day (bpd). The transportation cost for either option is highly sensitive to the market distance, transportation scale and crude grade being transported; however, pipelines are generally more competitive for large transportation scales, while the cost-effectiveness of rail

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transport is realized particularly at smaller transportation scales. In general, pipelines are cost efficient for the transportation of crude oil in the majority of scenarios investigated. Rail can be more economical than pipeline under certain conditions. The use of insulated rail cars for the transport of raw bitumen is the area with greatest potential for cost competitiveness against pipelines.

Keywords: Pipeline transport; rail transport; cost; bitumen; synthetic crude oil; oil sands

1 Introduction

As of 2012, Canada harbored the third largest proven oil reserves in the world, with the oil sands of Alberta constituting the overwhelming majority of the country's total reserves [1-3]. The resource wealth of the oil sands in Alberta amounts to approximately 176.8 billion barrels of crude bitumen (initial established reserves) [2, 4]. In 2012, production levels reached 1.8 -1.9 million bpd [1, 4]. Of this production volume, 52 -58% was converted into synthetic crude oil[2] (SCO) and the rest remained as non-upgraded bitumen [1, 4]. Furthermore, in the long term, production of the resource is expected to increase to 3.2 million bpd in 2020 (assuming a competitive oil price), with bitumen accounting for approximately 60% of total production [1, 4].

Even though production is expected to increase, the abundance of oil sands can only translate into sustained economic growth and development if the industry is granted the security and accessibility to prime markets, characterized by reliable long term demand and prices that do not undermine the resource's value. In this light, the predominant mode of transportation for the oil industry has been by pipeline. For this transportation method, the increasingly greenhouse gas (GHG) constrained North American energy market and the heightened environmental consciousness of the populace, have made the environmental and social license of pipeline projects increasingly difficult to obtain. This is reflected by the elevated levels of stringency and due process incorporated into permitting regimes by regulatory bodies over time. Consequently, pipeline permitting processes, especially for new pipeline construction, have gradually become a difficult, time consuming and expensive task for the oil industry [6-8].

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[2]Bitumen is upgraded to SCO (via hydrogen addition or carbon rejection) to reduce its viscosity and increase its hydrogen (H_2) to carbon (C) ratio. The reduced viscosity and increased H_2 to C ratio facilitate pipeline transportation and increased market value respectively [5]. In the case of non-upgraded bitumen (raw bitumen), pipeline transportation is facilitated by the addition of diluents which decreases the viscosity of bitumen to acceptable levels. The industry term for the transport of bitumen with diluent is dilbit.

Driven by the uncertainty and the potential economic ramifications of a supply constraint in the oil industry, stakeholders have begun assessing the efficacy and techno-economic viability of alternative transportation modes, most notably, rail. In this regard, it is worth mentioning that the existing North American rail network is more extensive and far reaching compared to its pipeline counterpart [9-13] (see Figures 1 and 2). In addition, the construction of new rail lines is unlikely to experience the same level of stringency and permitting resistance faced by pipeline projects [6-7, 10, 13-14]. Furthermore, compared to pipelines, the scalability, reduced time to market, flexibility and the degree of responsiveness of rail transport to ever changing market dynamics, is particularly attractive [6, 9-11, 15]. Aside from this, the investment cost and contractual agreement time frame of rail transport is reduced relative to pipeline [6, 13, 16].

In previous studies, the estimation of the unit cost (i.e. $/bbl) of either transportation mode is predominantly over-simplified, without explicit consideration of the sensitivity of cost estimates to production scale or transportation distance [1, 6, 9, 16-19]. Production scale and transportation distance are key determining factors for the costs associated with rail and pipeline transport. Therefore, the understanding and characterization of their impact on cost estimates is duly warranted. Moreover, as highlighted by some authors [9], the cost estimates in existing studies are often based on pipeline tolls and rail car leases of different contractual timeframes - which are not necessarily indicative of the 'real' costs. In addition, the differing contractual timeframes make it difficult to compare either transportation mode fairly and transparently. Furthermore, cost estimates are often generic as to the commodity type and transportation regime they correspond to [16-19]. For a holistic examination of both transportation modes, a multitude of scenarios will need to be considered – e.g. pipeline transportation of dilbit with or without diluent return, pipeline transportation of SCO, rail transportation in non-insulated/ insulated rail cars with or without the use of diluent etc. These different transportation regimes have a telling effect on cost estimates, but studies that account for these transportation scenarios are quite limited. There is also a scarcity of cost estimates based on transparent verifiable models that stem from scientific and engineering principles. Moreover, a scarcity of independent unbiased comparative analysis of rail and pipeline transport exists in the available literature. Politicization and conflicts of interest in the existing research often hinder thorough objective analysis of the issue at hand.

The focus of this study is not on socio-economic issues in rail and pipeline transportation of bitumen and synthetic crude oil. Such issues are project-specific and relevant to the routes where pipelines/rail infrastructure are developed. The focus here is to present results independent of location and prepare a generic case using fundamental engineering models to develop the costs of transportation. There is no detailed study in the public domain with this aim. This study is an effort to address gaps in this research area.

As a result, the objective of this paper is the development of data-intensive techno-economic models for rail and pipeline transport of bitumen and SCO, built from engineering and scientific governing principles. The models will facilitate an independent, specific, and quantitative portrayal of the cost competitiveness of rail and pipeline transportation, for different crude grades, production scales and market distances. Furthermore, the models developed account for the impact of market distance and production volume explicitly; considering crude grades that are specific to the Canadian oil sands industry, but retain far-reaching relevance in the global oil industry. In addition, the utility of the models is enhanced by the fact they provide an estimate of the transportation cost via rail and pipeline for a number of different scenarios likely to be considered by oil industry operators. Seven scenarios were considered in this study. Specific details of each scenario are provided in section 2. It is worth mentioning that the analysis presented in subsequent sections of this paper is germane to the state of the North American oil industry as of 2013 to early 2014, prior to the significant depression in oil prices, which occurred in the last quarter of 2014. Notwithstanding, crude oil transportation cost is the primary focus of this paper, and as such is relatively unaltered by the effects of a low oil price environment. All costs specified in this paper are reported in 2013 Canadian dollars[3].

1.1 North American Oil Market

1.1.1 Crude oil via pipeline – Challenges, trends and market dynamics

The existing and proposed trans-border pipeline network between Canada and the United States is illustrated in Figure 1. From a Canadian standpoint, the existing pipeline capacity compared to the anticipated production increase in the oil sands industry creates a significant degree of uncertainty about the industry's long-term prospects [17, 20-21]. In the case where no new pipeline projects are commissioned, the industry runs the risk of a pipeline capacity deficit, which is expected to occur on or before 2016 – 2020 [6, 9, 20]. The economic ramifications of a pipeline capacity deficit are prohibitive for the oil sands industry as it can result in an increase in pipeline tolls due to the heightened sense of urgency of producers to avoid production shut-ins, and get their products to market [6]. More importantly, a capacity deficit will often lead to the discounting of oil prices [6, 9, 10, 12, 15, 17-18, 21-22]. Discounted prices of oil sands products against other crude benchmarks (e.g. Western Canadian Select (WCS) relative to West Texas Intermediate (WTI)) have been attributed to the attenuating pipeline capacity at supply hubs

[3] An inflation rate of 6% has been assumed in this paper (see the rationale behind this relatively high inflation rate in Table 2), along with an exchange rate of $1US = $1CAN.

(most notably, Cushing, Oklahoma) in moving oil sands volumes to market [6, 9, 12, 15, 17, 21-22]. Contrastingly, some authors suggest that the much-cited WCS-WTI negative price differential is independent of pipeline capacity, and is simply a function of the difference in crude quality[4] [23]. However, discounting of comparable or higher quality light crudes, relative to comparable or lower quality crudes, has occurred in other sectors of the oil market where pipeline capacity has been deficient [9-10, 12, 18]. A prime example of this is illustrated in the case of U.S. inland and U.S. coastal crude oil production, where discounting[5] of WTI relative to Louisiana Light Sweet (LLS) and international grades such as Brent has occurred, irrespective of their similar quality grade[6] [9-10, 18, 24-25].

Having appreciated the pipeline supply constraints and their implications above, it becomes apparent that arbitrage opportunities exist within the oil market due to heterogeneous prices for practically the same commodity [10, 14, 18, 26]. The primary beneficiaries of this market trend have been the refineries in the downstream portion of the oil industry value chain [10, 12, 21]. The heterogeneous prices have provided an added incentive, and prompted upstream stakeholders in the oil industry to get their products to market in a manner which is responsive to the evolving market trends. In essence, they pursue markets where their commodity has the highest value. This has led to the increased adoption of rail for oil transportation.

1.1.2 Crude oil via rail – Challenges, trends and market dynamics

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[4] The premise of this notion is based on the fact that, due to its lower quality, the processing of WCS incurs added costs for oil refineries relative to WTI. Thus, the price differential is a reflection of the quality margin between both crudes [23].

[5] The discounting of WTI relative to LLS extends significantly beyond any differences in transportation costs to market [12].

[6] Historically WTI has traded at a premium to Brent mainly due to its superior quality [10, 12].

North America has an extensive widespread rail network that serves different regions of the continent (see Figure 2). In terms of the freight traffic, petroleum products as a whole account for about 2% and 1.5% of the commodity flux in the United States and Canada respectively, which highlights the limited market penetration of crude oil volumes across rail networks in North America [6, 27]. The current capacity of the entire North American rail network to accommodate crude volumes is difficult to determine with a reasonable degree of certainty. This is because the capacity will be dependent upon the supply and demand forces of competing commodities that use rail, infrastructure constraints and the availability of technology, etc. In terms of competing commodities, coal has the single highest traffic accounting for 43-45% of freight movements in the U.S. [6, 27]. Chemicals and agricultural products also account for significant freight movements [27].

Despite the apparent uncertainty for the increased penetration of crude volumes on rail networks, the oil industry has experienced a considerable rise in crude shipments via rail [6, 9-12, 26]. Some authors characterize the increased use of rail as an alternative to pipelines as a short-term market transient that exists because of extended delays to pipeline projects [16, 18]. Furthermore, as mentioned earlier, delays to pipeline projects have created a market environment with arbitrage opportunities. However, some authors make the assertion that these opportunities will dissipate once a number of ongoing pipeline projects are approved [18]. This will in turn negate the current economic justification for oil by rail, and the industry will then revert to its business as usual paradigm of pipelines. Moreover, the confinement of rail as a short-term market trend is also due to its perceived inability to accommodate sharp increases in crude volumes for sustained periods. However, certain market trends and developments have made this short-term characterization of rail questionable. In fact, there is an increased certainty and growing confidence about the long-term viability of oil by rail, especially as a compliment to pipelines [9-10, 12-14, 26].

Oil via rail has demonstrated its ability to achieve rapid capacity increases while remaining in harmony with production surges in the oil industry. This is especially evident in the case of the Bakken formation[7] [6, 9-10, 12, 15]. From 2009 to 2012, production volumes in this formation rose from 150,000 bpd to 617,000 - 800,000 bpd [10, 15]. In this light, the rail take away capacity in the Bakken region experienced a marked increase from 275,000 bpd in 2011 to over 700,000 bpd in 2012 [10, 15]. A similar trend of oil via rail adoption is occurring in relatively new surging (shale) oil production regions like the Permian Basin and Eagle Ford, where investment in rail loading infrastructure and take away capacity is occurring [9, 15]. What these market trends suggest is that, as opposed to pipelines, rail is the transportation mode of choice in circumstances where market accessibility and rapid capacity additions are needed in a relatively short period. There are two primary reasons for this preference. Firstly, the rail network is more widespread compared to pipeline, with existing connections (right of way) to these new production regions where pipeline capacity is limited or non-existent. This negates the need for industry operators to embark on rigorous permitting applications, thereby saving time and financial resources. Secondly, the absolute construction lead time for rail is relatively shorter when compared to pipeline [10, 13]. In this regard, it is worth mentioning that construction lead times for new loading and off-loading terminals for rail is 12-18 months [6, 9]. On the other hand, for expansion of existing facilities, this lead time is reduced to 6-12 months [9]. Furthermore, the manufacturing lead time for rail cars is 15-18 months [10]. This is in sharp contrast to pipeline projects, which can take a number of years to complete.

[7] The use of rail in the Bakken play stemmed from the inability of pipeline capacity to keep pace with growing production capacity [9, 11].

2 Oil sands via rail or pipeline – Transportation Scenarios

As mentioned, a number of transportation scenarios likely to be considered by oil sands industry operators are addressed in this study. These scenarios are indicative of the relevant transportation regimes that can be configured to transport bitumen and SCO via rail or pipeline. All scenarios have a base case production scale of 750,000 bpd to transport to market. The large production scale incorporated into the scenarios is reflective of the anticipated surge in production capacity of the oil sands industry, which stresses the need to transport oil sand volumes in large quantities. Secondly, it is worth mentioning that this study assumes all scenarios use feeder pipeline networks to transport SCO or bitumen from the actual point of production to the main pipeline or rail terminals. However, the cost of the feeder pipelines in comparison to the main pipeline or rail infrastructure is likely to be negligible, and thus not considered.

Considering all railroad scenarios, it is important to highlight the fact that the use of a single track has been assumed, which has an effect on the level of congestion, number of railway sidings, process lead times, and inevitably, costs associated with oil by rail transport. However, the effect of having an additional track is examined in later sections (see section 4.3.3). For all scenarios involving the transportation of dilbit via rail or pipeline, the cost of diluent is not considered explicitly. Rather, the diluent cost is assumed to have an equivalent effect on all dilbit scenarios, as they use a similar amount of diluent per barrel (see Table 1). The premise of this base case assumption is to mitigate the uncertainty surrounding the 'real' diluent cost incurred by a given operator. This is because some operators are integrated/non-integrated with/without downstream refinery assets. The integrated/non-integrated nature of a given operator is important because diluents are often purchased from refineries - hence, depending on the degree of strategic investment and advantage a given operator has in the oil sands value chain, diluent costs are likely to vary significantly from operator to operator. That said, the explicit consideration of the diluent cost is addressed as a sensitivity analysis in section 4.3.4. Details of each scenario developed are provided in Table 1.

3 Techno-economic model development

3.1 Modelling methodology – Overview

Data intensive techno-economic models for the transport of SCO and bitumen via rail and pipeline were developed in this study. These models stem from the governing engineering and scientific principles that are relevant to both transportation modes. The techno-economic modeling was carried out in a thorough holistic fashion; accounting for all the unit operations involved for both rail and pipeline transport of SCO and bitumen. Upon the identification of each unit operation, the required process equipment (e.g. the size and quantity of pumps, booster stations, locomotive engines etc.) were characterized using the governing equations of fluid flow and turbo machinery, along with data from industrial operators. Having characterized the required equipment, the quantification of the resource inputs (e.g. diesel, electricity, steam consumption etc.) into these unit operations was then carried out. Once the technological aspects of the model had been fully established, this was then coupled to the economic model - which consisted of mainly of cost metrics for each unit operation including: capital, operating and maintenance, labour and variable costs. The techno-economic model developed allows transportation cost metrics and cost sensitivities to be ascertained. Figure 3 illustrates the generalized modeling methodology adopted in this study.

3.1.1 Techno-economic model - Transportation of SCO and bitumen via pipeline

A conceptual illustration of some of the key components of this techno-economic model is provided in Figure 4. As seen in Figure 4, the operating parameters of the pipeline are specified based on calculations, data from literature, as well as consultation with experts. For reduced complexity, no sectional or elevation losses are included in the model, as the number of bends and elevation changes along a given pipeline route are highly localized and specific to a given pipeline project; hence, it is difficult to generalize.

A vast number of technical variables were characterized during the course of the model development, but two variables in particular are of central importance. These parameters are the pipeline diameter and the pipeline pressure gradient, which, in this model, is determined by the head loss due to friction. The diameter of the pipeline was calculated by specifying the velocity in the pipeline (2.5 m/s in this study), within the acceptable range used in industry (1.4 - 3 m/s), and then determined using the governing fluid flow equation pertaining to the conservation of mass (see Appendix A[8], Eq. 1).

[8] All equations pertaining to pipelines and rail are included in appendix A and B, respectively.

The head loss due to friction is a function of a multitude of flow variables (e.g. fluid viscosity, Reynolds number, pipe roughness, friction factor etc.), all of which were determined for the different crude grades, capacities and transportation distances considered in this study. It is important to note that the head loss is a key determining factor for the size (power rating) and number of pumps and booster stations required for a given pipeline. The head loss is calculated from the Darcy-Weisbach equation (see Appendix A, Eq. 2)

Once the technical model of the pipeline had been developed, the consideration of capital costs, operating and maintenance costs, along with variable costs were then coupled to it. Some of the principal cost data and flow parameters that were used in the model are also provided in Table 2.

3.1.2 Techno-economic model - Transportation of SCO and bitumen via rail

A key feature of the oil by rail techno-economic model developed in this study is the use of unit[9] train technology as opposed to manifest trains. This is mainly due to the superior economics, time and process efficiency unit trains have over their manifest counterparts [6, 10]. In comparison to pipelines, rail has an elevated degree of process complexity for the transportation of crude oil (see Figure 5). As a result, the characterization of the required infrastructure is not achieved as readily as pipelines. In the model developed, the determination of the total number of trains[10] required for a given production capacity and market distance, is a key deliverable. The total number of trains is a function of the number of trains per day, which in turn, is a function of

[9] A unit train is one that is dedicated to a single commodity and, hence, a particular type of rail car. Unit trains travel from a single loading point to a single destination using loading and discharge terminals that are purpose-designed for the commodity [8]. This is in sharp contrast to the traditional manifest trains that carry a multitude of commodities and hence use different types of rail cars. Furthermore, manifest trains usually have pickups and drop-offs in multiple locations [8].

[10] In this study, each unit train consists of 100 cars.

the number of rail cars required per day (see Appendix B, Eq. 1). However, before addressing the calculation of the total number of trains, it is important to stress the distinction between the total number of trains required and the number of trains required per day. The number of trains required per day is the number of trains that need to depart from the terminal per day, while the entire rail fleet needed to ensure the continuous delivery of a given capacity of crude is defined as the total number of trains. The difference between both parameters has to do with the total time taken to get from the point of supply to the demand destination, defined here as the total transit time.

The impact of the total transit time on the total number of trains is due to the time lag between the departure of a train from and its return to the terminal. Thus, before a given train completes the cycle of departure and return, a number of trains per day will have been dispatched from the terminal to ensure consistent delivery of crude volumes. As a result, the total number of trains required is a function of both the number of trains required per day and the total transit time. However, the transit time defined in this study is not simply the two-way journey time. It also includes the time taken for loading and unloading at the terminals, and more importantly, the time taken for sidings[11] (shunting time); see Appendix B, Eq. 2.

Upon the determination of the total number of trains and transit time involved, the core of the technical model is complete. After the calculation of other secondary technical variables, this model is coupled to the cost model, which involves capital, operating, variable and maintenance costs, in similar fashion to the pipeline model. A number of key process variables and techno-economic parameters that were used are provided in Table 3.

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[11] Sidings are smaller lengths of rail tracks connected to the main track, which allows one train to cross another at significantly reduced speeds of about 2km/hr.

4 Results and discussion

4.1 Capital cost of oil via rail and pipeline

The aggregate capital cost for pipelines, with the exception of SCO transport, is higher than its railroad counterpart for a long distance to market of 3000km, and for a base case production capacity of 750,000 bpd (see Figures 6 and 7). However, at smaller production capacities and shorter distances to market, the capital cost for rail becomes significantly lower than pipelines for all the crude grades considered (see Figure 8). Thus, it becomes apparent that the capital cost associated with both modes is highly dependent upon the market distance and production scale; the implications of these trends are given greater scrutiny in section 4.2.

The capital cost distribution for the transportation of dilbit and SCO by pipeline is intuitive; the pipeline cost (material, construction, and right-of-way cost) proves to be the principal capital expenditure (accounting for 70-80% in this study), and other capital cost components (e.g., boosters stations, pumps, storage cost, etc.) are less significant.

In the case of rail, the costs of rail cars along with the cost of locomotives carry the highest weightage in the capital cost distribution. Other infrastructure and facilities such as terminals, pumps, storage facilities and building costs have a reduced share of the capital cost.

4.2 Comparative cost of transportation scenarios

4.2.1 Impact of market distance on transportation cost

First, it is worth re-iterating that the cost curves shown in Figure 9 are for the base case production capacity of 750,000 bpd. Additionally, these costs ($/bbl) include the capital variable, operating and maintenance costs of rail and pipeline transport - see Equation 6 in Appendix A and Equation 8 in Appendix B . As seen in Figure 9, the unit cost of transportation for rail and pipeline has a linear relationship with transportation distance. Comparing both transportation modes, it becomes evident that oil via rail has a significantly increased cost for the transportation of SCO over the entire range of distances addressed in this study (see scenarios 1 and 4). This trend remains true for the transportation of dilbit with and without diluent return (compare scenarios 2 and 3 with 5 and 6, respectively). Scenarios 1 to 6 show that the superior cost competitiveness of pipeline against rail becomes more profound as distance is increased. The reason for this trend can be appreciated when we consider the impact of distance on both transportation modes. For rail, the most significant effect of increased distance is an increase in the total transit time. The transit time determines the number of sidings, total number of rail cars, and subsequently, the number of locomotives required. These parameters are key determining factors for the transportation cost via rail.

On the other hand, an increase in pipeline distance will lead to increased booster station costs, labor costs, etc. However, these have a relatively minor effect on the transportation cost. With this in mind, the cost incurred for pipeline transportation is less sensitive to transportation distance compared to rail. This is reflected by the predominantly higher gradients in the rail scenarios compared to pipeline scenarios (see Figure 9). Another point worth highlighting is the fact that fixed costs, which are independent of distance (shown by the intercept of the scenario curves), are higher for rail than in pipelines.

Still focusing on the cost competitiveness of both transportation options, comparing scenarios 2 and 7, the effect of mitigating the use of diluent in the transport of bitumen can be appreciated. As shown in Figure 9, even though the use of diluent is negated with insulated rail cars, it still lags behind the pipeline transport of dilbit in terms of cost competitiveness.

Concerning the crude grades being transported, the increased cost of dilbit relative to SCO for the pipeline scenarios is mainly due the requirement of an additional diluent pipeline. In addition, the higher fluid viscosity and density of dilbit, which translates into higher energy requirements for its transport, increases the cost differential between both commodities further. For the rail scenarios, the higher density of dilbit reduces the loading capacity of the rail cars by about 10%. Consequently, a higher number of rail cars are required for dilbit relative to SCO for the transportation of the same amount of SCO, and this incurs significant costs. To a lesser extent, the elevated cost of dilbit is also attributed to the fact that the fuel consumption of the trains is higher during the return journey for dilbit (with diluent return) relative to SCO. The trains return with empty cars in the case of SCO leading to a significant drop in fuel consumption and cost.

4.2.2 Impact of production scale on transportation cost

The effect of production scale on the transportation cost of both modes is illustrated in Figure 10. Again, all cost components for rail and pipeline are included in the cost curves shown, in similar fashion as Figure 9. In the case of rail, its sensitivity to changes in production capacity, over a wide range, is limited; a minute, linear increase in the transportation cost occurs as capacity is increased. It is important to point out that as capacity increases, the number of rail cars, locomotives, and other key cost components also increase significantly. However, despite this rise in the major cost components, the production scale has a relatively weak impact on the unit transportation cost ($/bbl). This is because the rail track cost, which is a significant capital cost component (see Figure 7), is fixed for all capacities. Consequently, the unit transportation cost decreases markedly with an increase in the number of barrels being transported - leading to the realization of economies of scale between 100,000-300,000 bpd, for all crude grades. That said, for capacities greater than 300,000 bpd, the economies of scale are counter-balanced by the cost of track congestion, which becomes more dominant as transportation scale is increased. The cost of congestion can be appreciated when taking into account the rise in the number of sidings, rail cars and locomotives required as capacity is increased (refer Eq. 5 in Appendix B).

Apart from the competing factors of congestion costs and rail track economies of scale, another reason behind the reduced sensitivity of the rail costs to scale, is due to the limited effect of transit time. This is because the loading/unloading time[12] and the two-way journey time remain constant with changes in capacity. Only the siding time, which is a function of the number of trains required per day, changes; thus, limiting the degree to which transportation costs are altered by changes in capacity.

In the case of pipelines, in sharp contrast to rail, a non-linear decrease in the transportation cost occurs as production scale is increased. This is indicative of the strong economies of scale that exist with the use of pipelines. The reason for this is the rate of change of the incremental cost of transportation with capacity, which is relatively low for pipelines compared to rail. As capacity increases (for a fixed distance), the diameter of the pipeline increases to a lesser degree than the

[12]The loading and unloading time remain constant, even though the number of trains, and, therefore, the number of rail cars to be loaded/unloaded, increases. This is because the number of terminals required also increases to accommodate the elevated amount of trains that need to be loaded/unloaded.

volumes transported. As a result, the increase in cost is superseded by the increase in transportation volumes – leading to an overall decrease in the unit transportation cost.

As seen in Figure 10, considering the cost competitiveness of both transportation modes for a distance of 3000 km, in general, rail is the more cost efficient option for lower production scales, while pipelines are more cost effective for higher production volumes. Again, this is because the capital costs of pipelines are more inelastic to increases in production capacity compared to rail. Hence, at small scales, the capital costs incurred with pipeline are disproportionate compared to rail, and translate into high unit costs of transportation.

Considering the crude grades being transported, for the transportation of SCO, rail is the more economical option for production volumes below 100,000 bpd, with pipeline being the mode of choice for volumes exceeding 100,000 bpd. In addition, for the transportation of dilbit without diluent return, rail is more competitive than pipeline for ranges of 100,000-200,000 bpd; transportation capacities over 200,000 bpd will shift cost competitiveness to pipelines. Furthermore, for the transportation of dilbit with diluent return, the competitiveness of rail expands to a range of 100,000-400,000 bpd, with pipeline being the mode of choice for capacities greater than 400,000 bpd. Lastly, the cost efficiency of insulated rail cars against pipelines for the transport of bitumen (compare scenarios 2 and 7) holds true for the widest capacity range of 100,000 -520,000 bpd.

4.3 Sensitivity Analysis

4.3.1 Oil by Rail – Generalized Sensitivities

The sensitivity of the transportation cost of rail to key techno-economic parameters is demonstrated in Figure 11. As it is the scenario with the highest potential for cost competitiveness against pipelines, scenario 7 serves as the basis for the sensitivity analysis carried out. The sensitivity analysis results correspond to the base case capacity of 750,000 bpd and a market distance of 3000km. As seen in Figure 11, the parameter with the greatest degree of influence on the estimated costs is the crude density. This stems from its impact on the loading capacity of the train, which affects the number of rail cars, locomotives, sidings, as well as fuel consumption. Other variables that have a significant influence on costs include the speed of the train and the fuel efficiency of the locomotive. The high degree of sensitivity to the speed of the train stems from the highly dependent nature of rail transportation costs on the transit time. The sensitivity of the fuel efficiency is indicative of the energy-intensive nature of rail transport and the impact that future advances in locomotive technology can have on costs, e.g. the use of more efficient electric power trains. Some parameters, namely diesel (fuel), rail car, and locomotive costs, have a moderate effect on cost estimates. Lastly, the cost of rail track construction, number of rail cars per train, loading/unloading time, and the life-times of the rail car, the locomotive and the track have a minimal effect in terms of their impact on cost estimates, as shown by their overlapping curves in Figure 11. The limited sensitivity of the rail transportation cost to the loading/unloading time may appear counterintuitive given the sensitivity of rail costs to process lead times. However, the limited insensitivity in this case is because the loading/unloading time has a relatively small contribution to the transit time. In similar fashion, the insensitivity of transportation costs to the rail track construction cost (despite the significant capital expenditure that it incurs) is due to the prolonged service life of the tracks, which in this case is 50 years.

4.3.2 Oil by pipeline – Generalized Sensitivities

The sensitivity analysis results shown in Figure 12 are based on scenario 2, with a base case production capacity of 750,000 bpd and a market distance of 3000 km. As illustrated, the velocity and material cost of pipeline (capital cost subset) are the two most influential parameters on the transportation cost. In addition, lifetime of the pipeline, and pump efficiency have a relatively moderate effect on the cost estimates compared to the velocity and material cost. Furthermore, electricity cost has a relatively minute effect on the transportation cost. As depicted in Figure 12, the transportation cost is more sensitive to the material cost rather than the pipeline velocity. This is because material cost of the pipeline is a major constituent of the total capital cost. In the case of velocity, its non-linear effect on cost is due to the non-linear relationship between the Reynolds number of the pipeline flow and the friction factor, which influence the head loss due to friction. An increase in the pipeline velocity increases the transportation cost. This is because, although the pipeline diameter becomes smaller (which lowers cost), the effect of this is counter-balanced by an increase in pressure losses due to the increased level of friction caused by a higher velocity. The effect of the increased pressure loss on the cost estimates surpasses that of the decrease in diameter, resulting in an overall increase in costs. To put this in context, a 25% change in velocity leads to a 10% change in diameter and a 57% change in the number of booster stations required. To add to this, during the base case lifetime of the pipeline (20 years), the pumps at the booster stations will be replaced twice, due to their significantly shorter service life of 10 years. As a result, the significant impact of the velocity can be appreciated.

4.3.3 Multiplicity of rail tracks

For all the scenarios involving the transport of oil via rail, the use of one track has been assumed in this study. As a result, the impact of multiple tracks on the estimated transportation cost is worthy of investigation. This is especially true when considering the potential for decreased levels of track congestion that could be achieved. As shown in Figure 13, in the case of a two-track system, the economies of scale are more pronounced and extensive, as they are realized for the entire capacity range considered in this study. This is because the two-track system negates the need for sidings; which eradicates the cost incurred due to congestion. Furthermore, although the additional cost of an extra track is significant, this is compensated for by the elimination of time wastage due to sidings, which, in turn, decreases the number of trains required for continuous operation. Consequently, for a two-track system, a reduced number of trains are required to transport a given capacity relative to a one-track system. Hence, even though the transportation cost of the two-track system is higher than the one-track system for smaller capacities, the benefits of the reduced number of trains along with the mitigation of track congestion are realized particularly at larger scales; which is where the two-track system is more cost effective than its one-track counterpart.

4.3.4 Cost of diluent

In the transportation cost estimates presented in Figures 9 and 10, the cost of the diluent needed to transport bitumen was not considered. The results shown in Figure 14 illustrate the impact of the diluent cost (estimated to be $110/bbl on average [47]) on all scenarios involving the transportation of dilbit or raw bitumen. In the case of bitumen transport in insulated rail cars, the bitumen is likely to be transported from the site of production to the rail terminals in the form of dilbit via pipeline feeder networks. Thus, the use of a diluent and its accompanying cost is also included in this scenario. Upon arrival at the terminal, the diluent is separated from dilbit using a diluent recovery unit (DRU), leading to the loading of raw bitumen in the insulated rail cars.

As seen in Figure 14, for a transportation distance and production scale of 3000 km and 750,000 bpd respectively, the effect of the diluent cost is limited to a relatively small increase in the unit transportation cost of pipeline and rail. The results show that pipeline remains the more cost efficient option in comparison to rail ($10.49/bbl vs. $12.76/bbl). It is worth adding that the relatively small magnitude of the diluent cost is because, in this study, it is assumed to be a one-time cost paid by the operator, as opposed to being an ongoing operational cost. Furthermore, a 99% recovery rate of the diluent is assumed in this study [48] - which prolongs the useful life of the diluent extensively.

4.3.5 Rail and pipeline – Integrated operation

The transportation cost incurred when both modes are integrated with one another for the transportation of crude oil to a given market, is worthy of investigation. The integrated operation considered here involves the use of a pipeline or train that transports 750,000 bpd of SCO from an upgrader, to a distant hub located 2000 km away. From the hub, the transportation volume is split into three equivalent capacities of 250,000 bpd and distributed to three different refineries by rail or pipeline within a distance of 1 -1000 km from the hub (see Figure 15). The aggregate cost incurred for the integrated option of 'pipeline with rail' against 'pipeline with pipeline' and 'rail with rail' is shown in Figure 15. The results show that the 'pipeline with pipeline' mode is significantly more cost effective in comparison to the 'rail with rail' alternative. More importantly, 'pipeline with rail' is cheaper than 'rail with rail', and is only slightly more expensive than 'pipeline with pipeline.' The reason for the cost efficiency of 'pipeline with rail' is that the improved competitiveness of rail at smaller production volumes and shorter distances. As a result, in the absence of distribution pipelines, the integrated operation can be quite compelling for operators, especially considering circumstances where the distribution of relatively small product volumes is needed from storage hubs to refineries in close proximity.

4.3.6 Future Prospects, key challenges and market dynamics

As long as the construction of (new) pipeline projects remain an increasingly uncertain, rigorous and time consuming endeavor for the oil industry, a degree of risk will be ascribed to the ability of oil industry operators to get their products to market. This degree of risk is consolidated further, when operators consider the need for flexibility and responsiveness to evolving market dynamics (e.g. new production regions and demand centers, supply bottlenecks, price differentials etc.) in the North American oil market. Driven by the need to hedge these aforementioned risks and remain competitive in all circumstances encountered in the energy market, industry operators will likely diversify their supply chain portfolio with the adoption of oil via rail. In this regard, the adoption of oil by rail by industry operators is likely to be a prudent and strategic measure; as it increases confidence in market accessibility and limits exposure to supply constraint risks. As a result, oil by rail is likely to have short-term, mid-term and long-term relevance in the oil industry. However, there are some caveats and subtleties concerning the viability of rail in the North American market that are worth elaborating upon. These caveats and subtleties are dependent upon localized industry factors and inextricably linked to pipeline development.

First, in the US portion of the North American market, the viability of oil via rail is primarily driven by two interrelated factors, namely arbitrage opportunities and pipeline constraints. As a result, depending on pipeline developments (i.e. the expansion of existing pipelines and permitting of new projects), the current supply glut which has plagued the market and contributed to arbitrage opportunities may be mitigated. Consequently, the likelihood of oil via rail being a long-term market trend is adversely affected by this scenario and may be limited to a short-term transient.

Contrastingly, in the Canadian oil sands industry, the viability of oil by rail is complemented by the current market drivers in the US, but remains independent of them. This is because in the business as usual economics of bitumen transport, there is a strong potential for a paradigm shift; as the transport of bitumen in insulated rail cars has been shown to be more cost competitive relative to pipeline (under certain conditions). This notion is supported by the increased investment in oil sands industry rail infrastructure that has occurred in recent times. Apart from this, the fact that 60% of rail car manufacturing orders are of the insulated type [9], further buttresses this point. Hence, it becomes evident that the tendency for oil via rail to maintain market relevance in the mid and long term is higher in the oil sands industry and relatively lower in the general US oil industry.

5 Conclusion

The techno-economic analysis carried out in this study has provided insight into some of the nuances, complexities, and trade-offs associated with rail and pipeline transportation of crude oil. Furthermore, this study provides an independent, specific, and quantitative portrayal of the cost competitiveness of rail and pipeline transportation of different crude grades.

Compared to rail, pipelines have superior cost efficiency at large production scales. This is due to the strong economies of scale inherent to the cost structure of pipelines; economies of scale are relatively weak in rail transport. However, at smaller production capacities, rail becomes more cost effective. This is due to the relatively inelastic nature of rail costs with changes in transportation scale. In more specific terms, the competitive margins of both transportation modes for the different crude grades considered are as follows:

For a fixed distance of 3,000km, the transportation of SCO via rail is the more economical option for production volumes below 100,000 bpd, with pipeline being the mode of choice for volumes exceeding 100,000 bpd. In addition, for the transportation of dilbit without diluent return, the competitive range of rail over pipeline is 100,000-200,000 bpd; transportation capacities over 200,000 bpd will shift cost competitiveness to pipelines. Furthermore, for the transportation of dilbit with diluent return, the competitiveness of rail expands to a range of 100,000-400,000 bpd, with pipeline being the mode of choice for capacities greater than 400,000 bpd. Lastly, the cost efficiency of insulated rail cars against pipelines, for the transport of raw bitumen, holds true for the widest capacity range of 100,000-520,000 bpd.

For a fixed large-scale production capacity of 750,000 bpd, compared to rail, pipelines incur lower costs for the transport of SCO and dilbit (with and without diluent return), for distances ranging from 1-3,000 km. Furthermore, considering the use of insulated rail cars for the transportation of raw bitumen, pipelines remain more cost effective than rail for the entire range of transportation distances.

In general, the use of insulated rail cars for the transport of raw bitumen is the area with greatest potential for cost competitiveness against pipelines, and is likely to be the area of concentration for investment, research, and development efforts. It is important to stress that the use of insulated rail cars introduces a potential for a paradigm shift in the business-as-usual economics of bitumen transport in the oil industry. This potential is independent of some of the market dynamics with a significant degree of mid/long term uncertainty (e.g., price differentials/arbitrage opportunities, pipeline project delays, etc.) that contribute to the current usage of rail in the broader North American oil market. As a result, oil by rail is likely to have short-term, mid-term and long-term relevance in the North American oil industry, particularly in the Canadian oil sands industry.

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Appendix A

Equation 1: Continuity Equation: $A_1v_1 = A_2v_2$

Equation 2: Head loss (m/m): $h_f/L = fv^2/2gD$

Equation 3: Power of each Pump (Pa), $P = \Delta P * Q/\eta$

Equation 4: Distance between booster stations (m), $d = \Delta P / ((h_f/L) * \rangle * g)$

Equation 5: Number of booster stations, $N = L/d$

<u>Equation 6:</u>

[illegible] ([illegible]$_1$) [illegible] = [illegible]$_1$+ [illegible]$_1$+ [illegible]$_1$+ [illegible]$_1$+ ([illegible]$_1$+ [illegible]$_1$+ [illegible]$_1$+ [illegible]$_1$+ [illegible]$_1$)* [illegible]

Where,

[illegible]$_1$= [illegible] (10 [illegible]) / [illegible]

[illegible]$_1$= [illegible], [illegible] (40 [illegible]) / [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

$\square_1 =$ [illegible]

Where,

A = Area of cross section for the pipe (m^2)

ΔP = Pump pressure differential (Pa)

Q = Volume flow rate of each pump (m^3/s)

ŋ = Efficiency of the pump

h_f/L = Head loss due to friction per unit length (m/m)

f = Friction factor

v = Velocity of flow (m/s)

g= Gravitational acceleration (m^2/s)

D= Inside diameter of pipe (m)

L= Total length of pipe (m)

ρ = Density of commodity (kg/m^3)

Appendix B

All Time Units are in days, Distance Units are in km

<u>Equation 1</u>

$$\text{[illegible]} = \frac{\text{[illegible] ([illegible])}}{\text{[illegible] ([illegible])}}$$

<u>Equation 2</u>

$$\text{□□□□□□ □□□□□□□□□ □□□□□}$$

$$= \text{□□□□□□□ □□□□□} \ (\text{□□□} - \text{□□□}) + \text{□□□□□□□□ □□□□□} + \text{□□□□□□□□□□□ □□□□□}$$

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Where,

$$\text{□□□□□□□ □□□□□} \ (\text{□□□} - \text{□□□}) = \frac{\text{□□□□□□□□□□}(\text{□□□} - \text{□□□})}{\text{□□□□□□□□ □□□□□□ □□ □□□□□□} \ (\frac{\text{□□}}{\text{□□}}) \ \text{□} \ 24}$$

$$\text{□□□□□□□□ □□□□□} = \text{□□□□□□□□ □□□□□} + \text{□□□□□□□□□ □□□□□}$$

$$\text{□□□□□□□□□□□ □□□□□} = \text{□□□□□□□□ □□□□□} + \text{□□□□□□□□ □□□□□} + \text{□□□□□□□□□ □□□□□}$$

Heating time is specific to Scenario 7.

Equation 3

$$\text{□□□□□□ □□□□□□□ □□ □□□□□□□ □□□□□□□□□□ □□□ □□□}$$

$$= \frac{\text{□□□□□□□ □□ □□□□□ □□□□□ □□□□□□□□□□ □□□ □□□}}{\text{□□□□□□□ □□ □□□□□ □□□□□ □□□ □□□□□□}}$$

Equation 4

$$\text{□□□□□□ □□□□□□□ □□ □□□□□□□ □□□□□□□□□□ □□□ □□□□□□□□□□□ □□□□□□□□□□□}$$

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Equation 5

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$$= \text{□□□□□□□ □□ □□□□□□□ □□□ □□□□ □} \frac{\text{□□□□□□□ □□□□□□□□ □□□□□ (□□□□□□)}}{24}$$

Number of sidings is calculated based on how many times a train returning back would cross the trains coming from the upgrader.

<u>Equation 6</u>

□□□□□□□ □□ □□□□□□□□□□ □□ □□□□□ □□□□□ □□□(□3)

$$= \frac{\text{(□□□□□□□ □□□□□□□□□□ □□ □□□□□ □□□ (□□) − □□□□□□□ □□ □□□□□□ □□□□□ □□□ (□□))}}{\text{□□□□□□□□ □□ □□□□(}\frac{□□}{□3}\text{)}} \text{□ □□□□□□□□□□ □□□□□□□}$$

<u>Equation 7</u>

$$\text{□□□□ □□□□ □□□□ □□ □□□□□□ (□□/□□□)} = \frac{\text{□ □} \int_{15.6}^{60} \text{□ □ □□ □ □□}}{\text{□□□□□□□ □□ □□□□□□□□□□ □□ □□□□□□ (}\frac{□□}{□□}\text{)}}$$

Bitumen is reported to flow at 60 degree Celsius [40]

Where,

V= Volume flow rate of bitumen (m^3/sec)

ρ, density of bitumen (kg/m^3) is calculated by the following equation [49]:

$$\square = 1013.3 \square (1 - 0.0603 \square \frac{\square - 15}{100})$$

T= Temperature in degree Celsius, up to 260 degree Celsius

Cb, specific heat capacity of bitumen (kJ/kg deg C) is represented by the following formula [50]:

Cb =1.605 + 0.004361 X T - 4.046X10^-6 X T^2

Applicable for 0 < T < 300 degree Celsius

<u>Equation 8</u>

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Where,

$\square_1 = \frac{\text{□□□□□□□□□ □□□□□ □□ □□□□□□□□}}{\text{□□□□□□ □□ □□□□□□□ □□□□□□□□□□□ □□□ □□□□}}$

$\square_2 = \frac{\text{□□□□□□ □□□□□□□□□□□ □□□□□ □□ □□□□□□□□}}{\text{□□□□□□ □□ □□□□□□□ □□□□□□□□□□□ □□□ □□□□}}$

$\square_1 = \frac{\text{□□□□□□□□□ □□□□□ □□ □□□□□□□ □□□□□}}{\text{□□□□□□ □□ □□□□□□□ □□□□□□□□□□□ □□□ □□□□}}$

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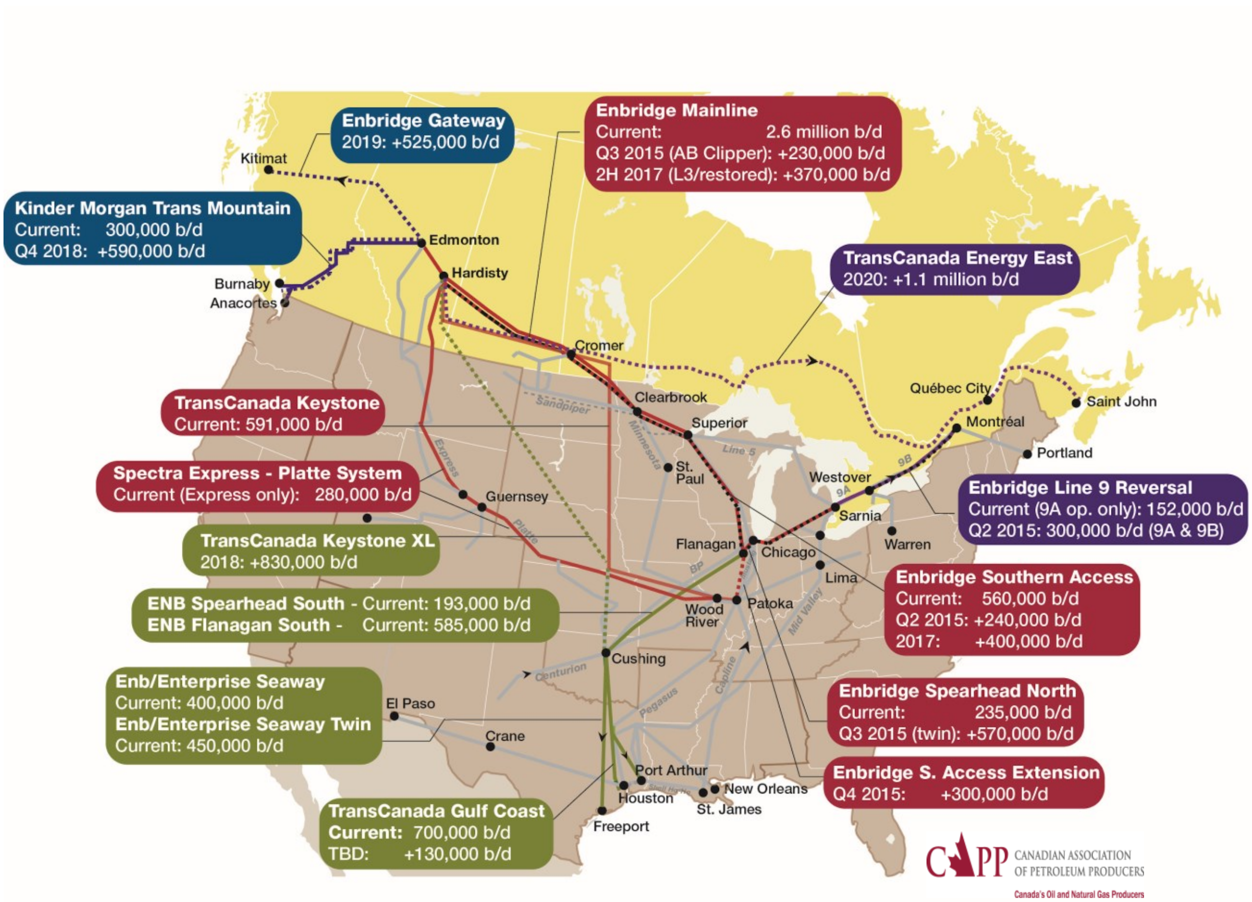

Figure 1: Existing and proposed North American pipeline network [1]. ***Figure reproduced with permission of Canadian Association of Petroleum Producers CAPP.***

Figure 2: Existing North American railway network [11]. ***Figure reproduced with permission of Association of American Railroads (AAR).***

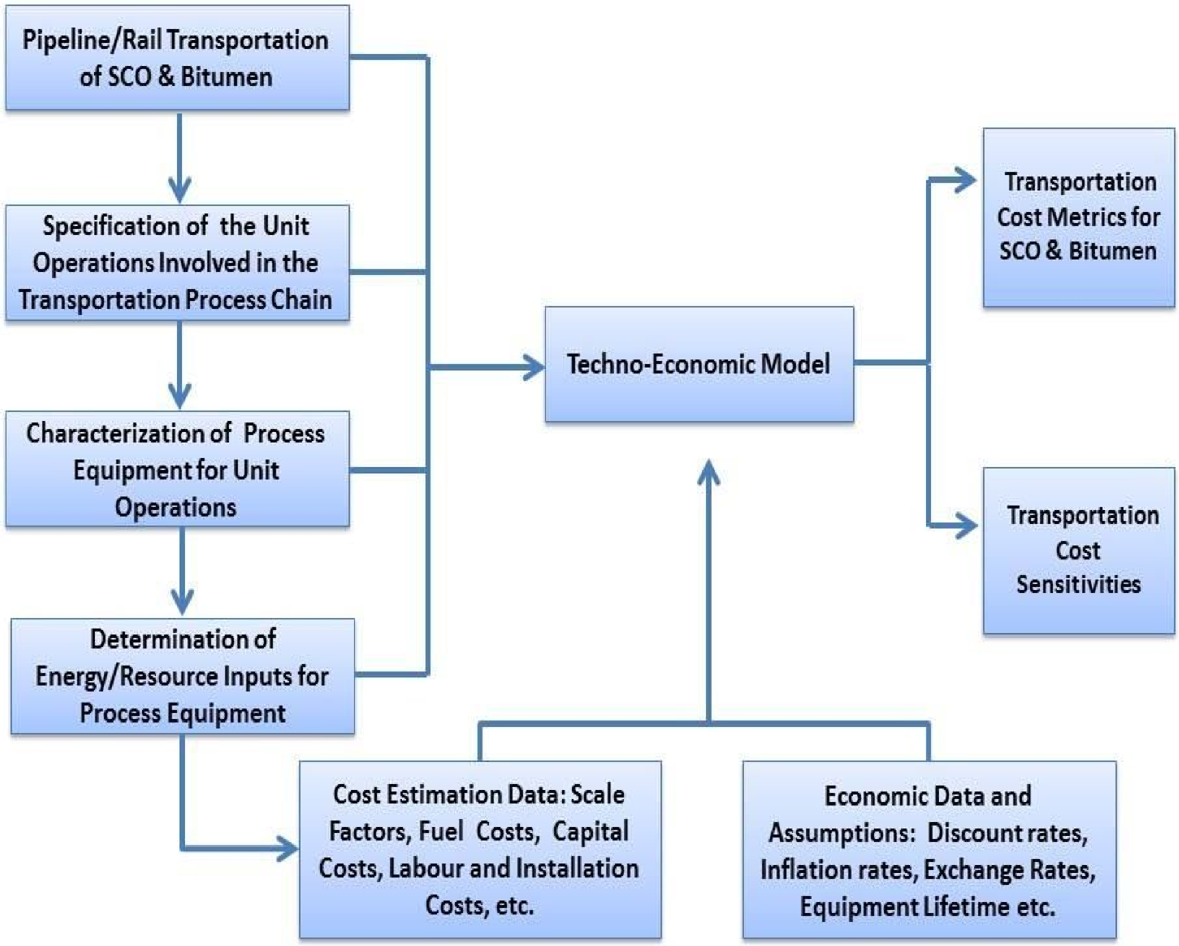

Figure 3: Generalized modeling overview

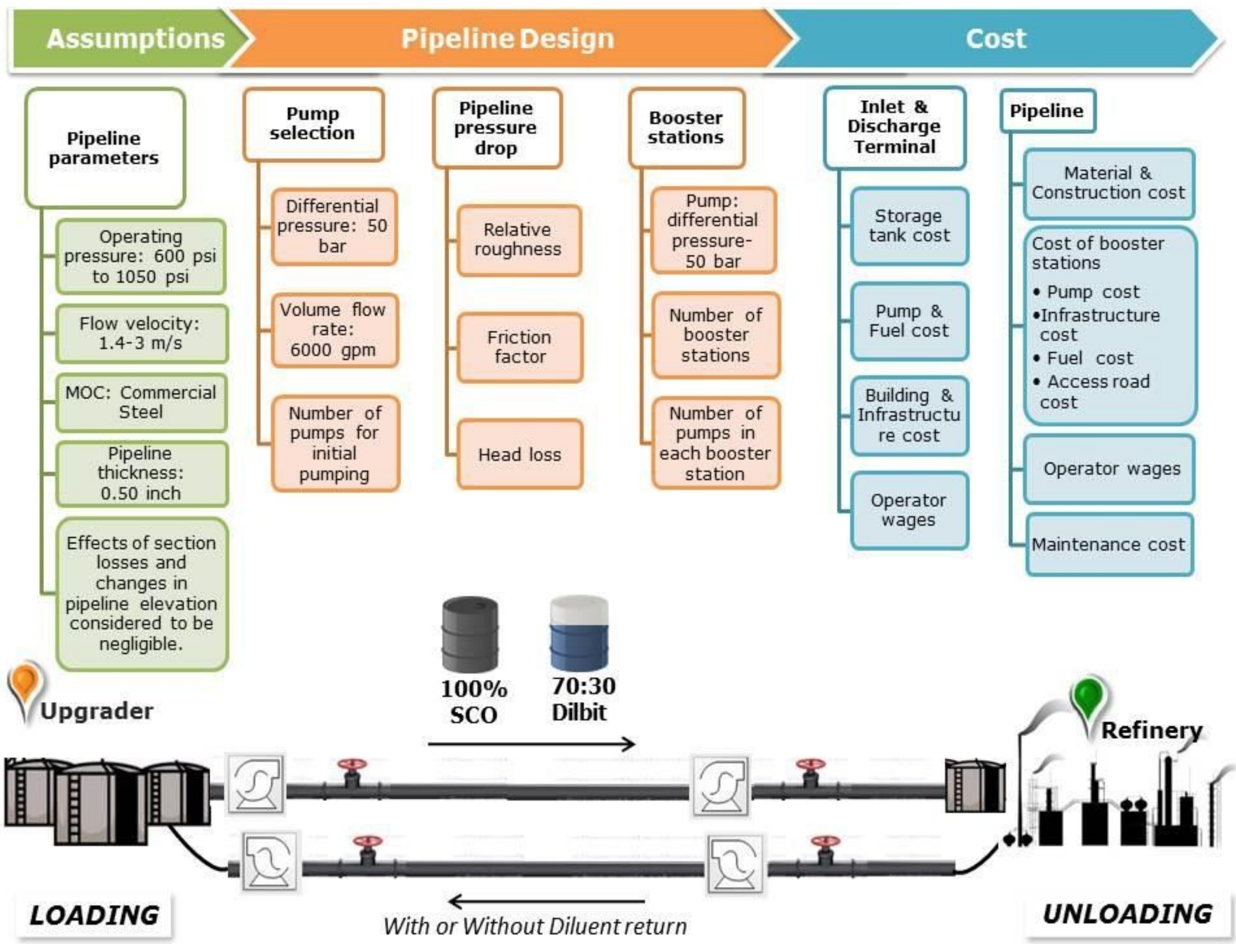

Figure 4: Crude oil transportation via pipeline – modeling methodology

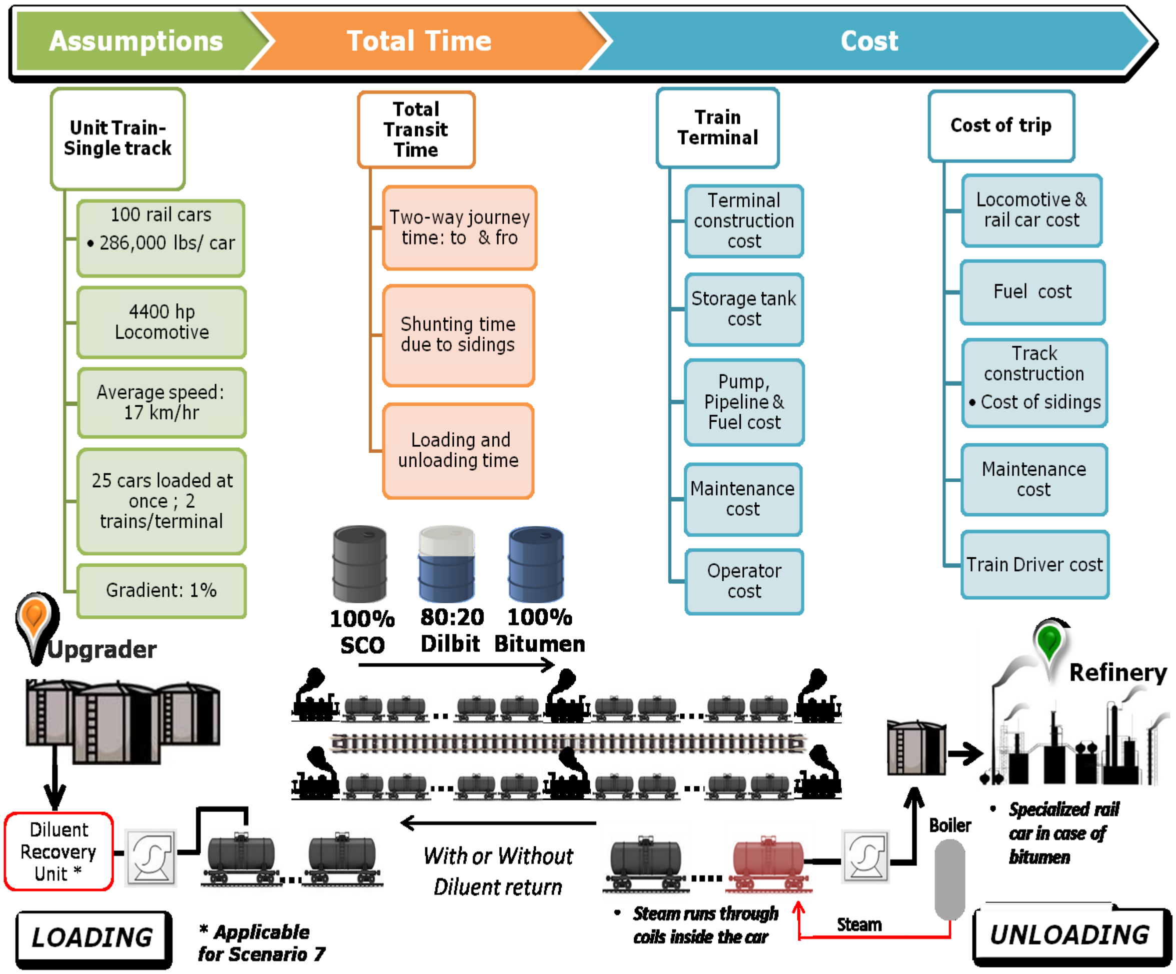

Figure 5: Crude oil transportation via rail – modeling methodology

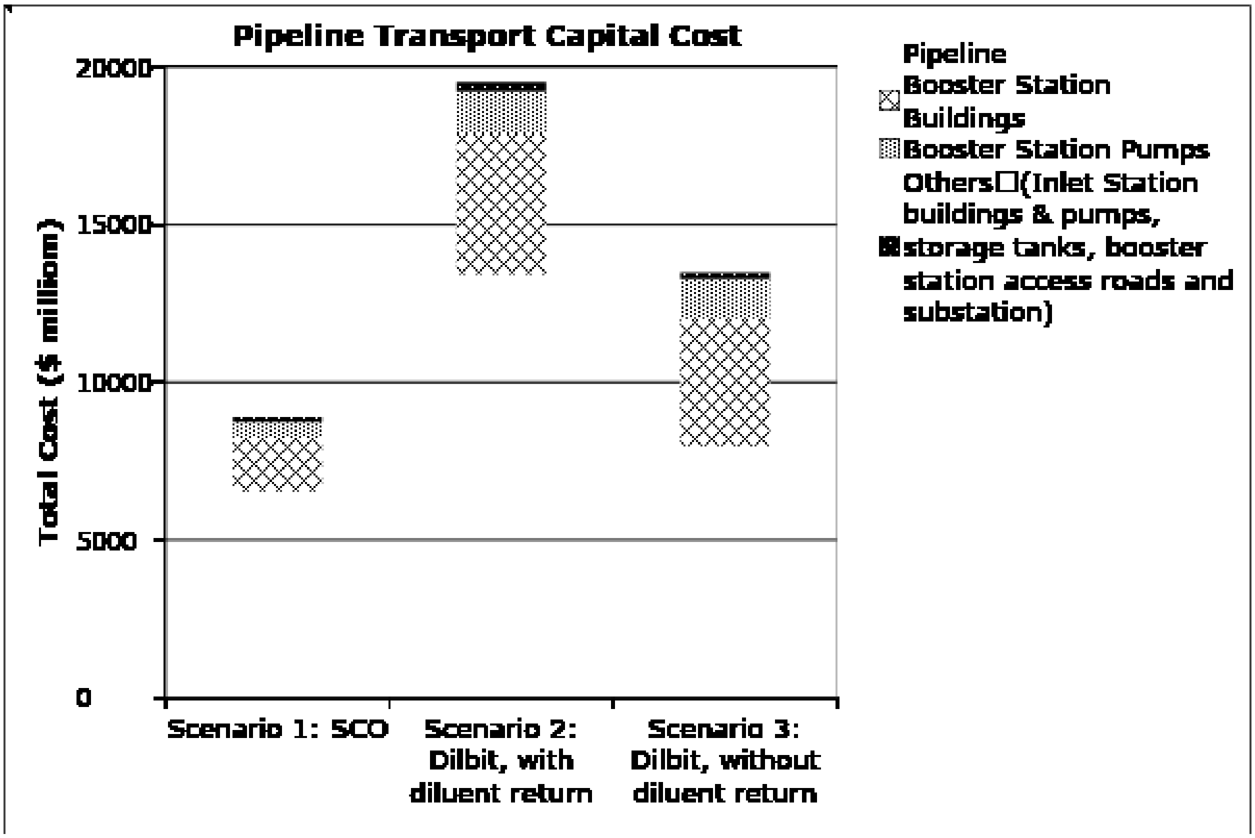

Figure 6: **Capital cost of pipeline transport**

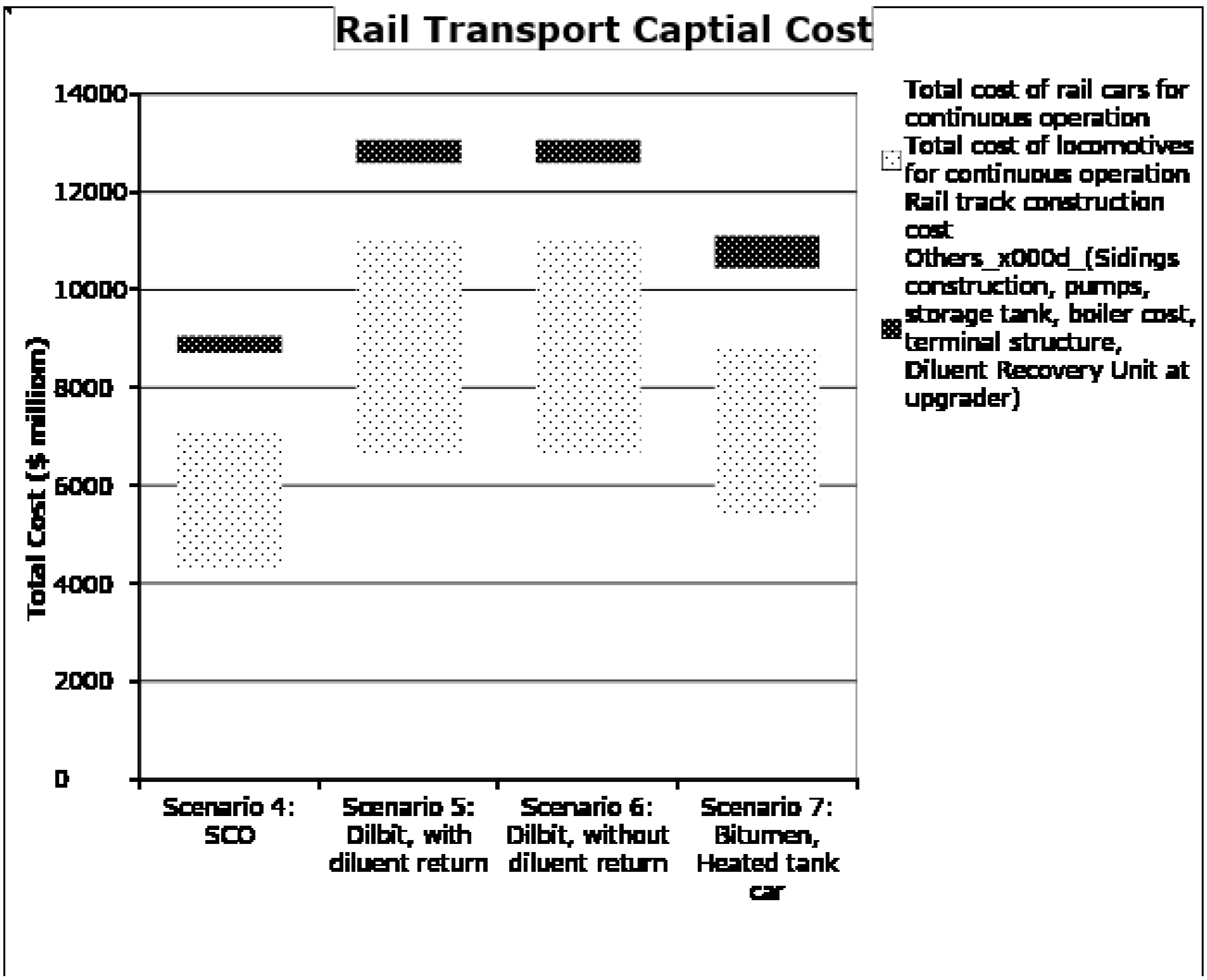

Figure 7: **Capital cost of rail transport**

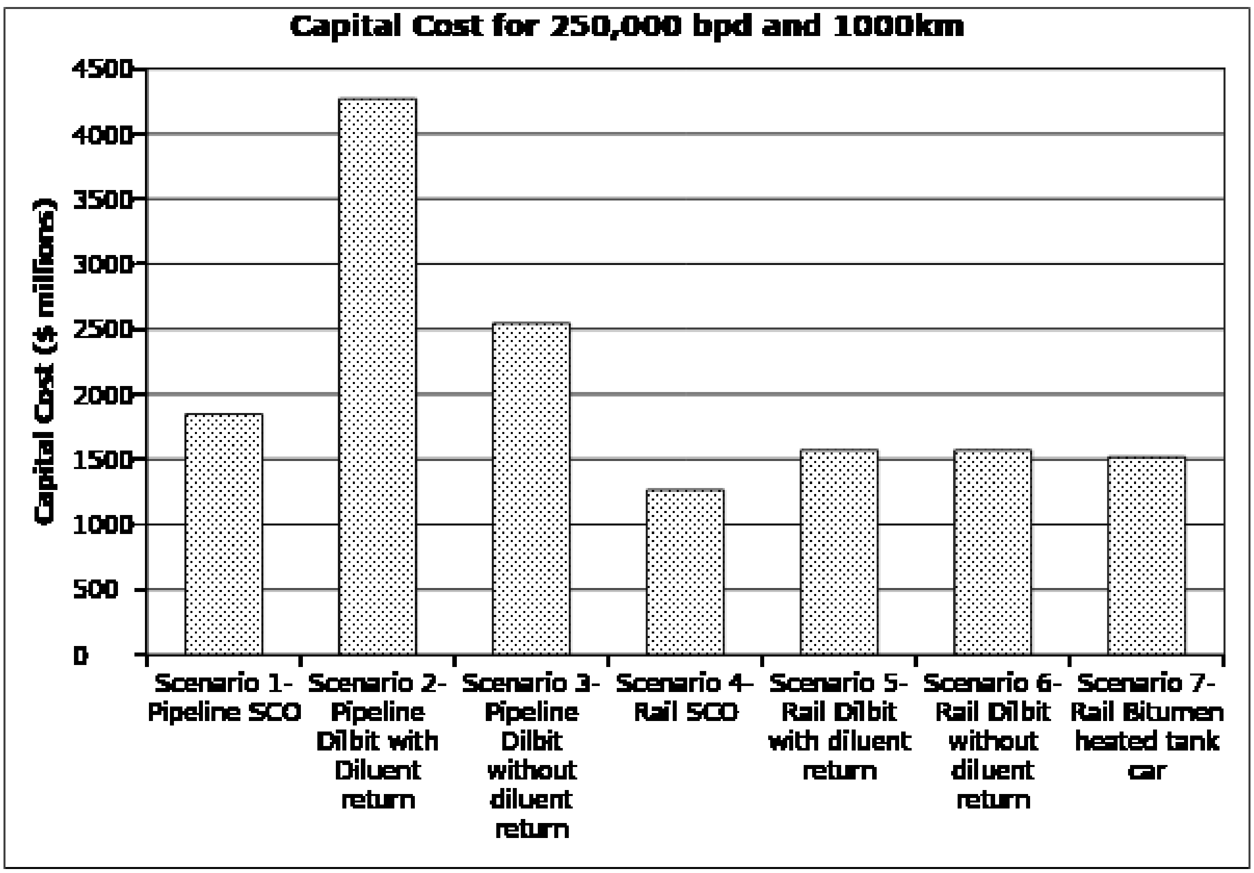
Capital Cost for 250,000 bpd and 1000km
Capital Cost ($ millions)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Scenario 1- Pipeline SCO
Scenario 2- Pipeline Dilbit with Diluent return
Scenario 3- Pipeline Dilbit without diluent return
Scenario 4- Rail SCO
Scenario 5- Rail Dilbit with diluent return
Scenario 6- Rail Dilbit without diluent return
Scenario 7- Rail Bitumen heated tank car

Figure 8: **Capital cost of rail and pipeline scenarios for a production capacity of 250,000 bpd and a market distance of 1000 km.**

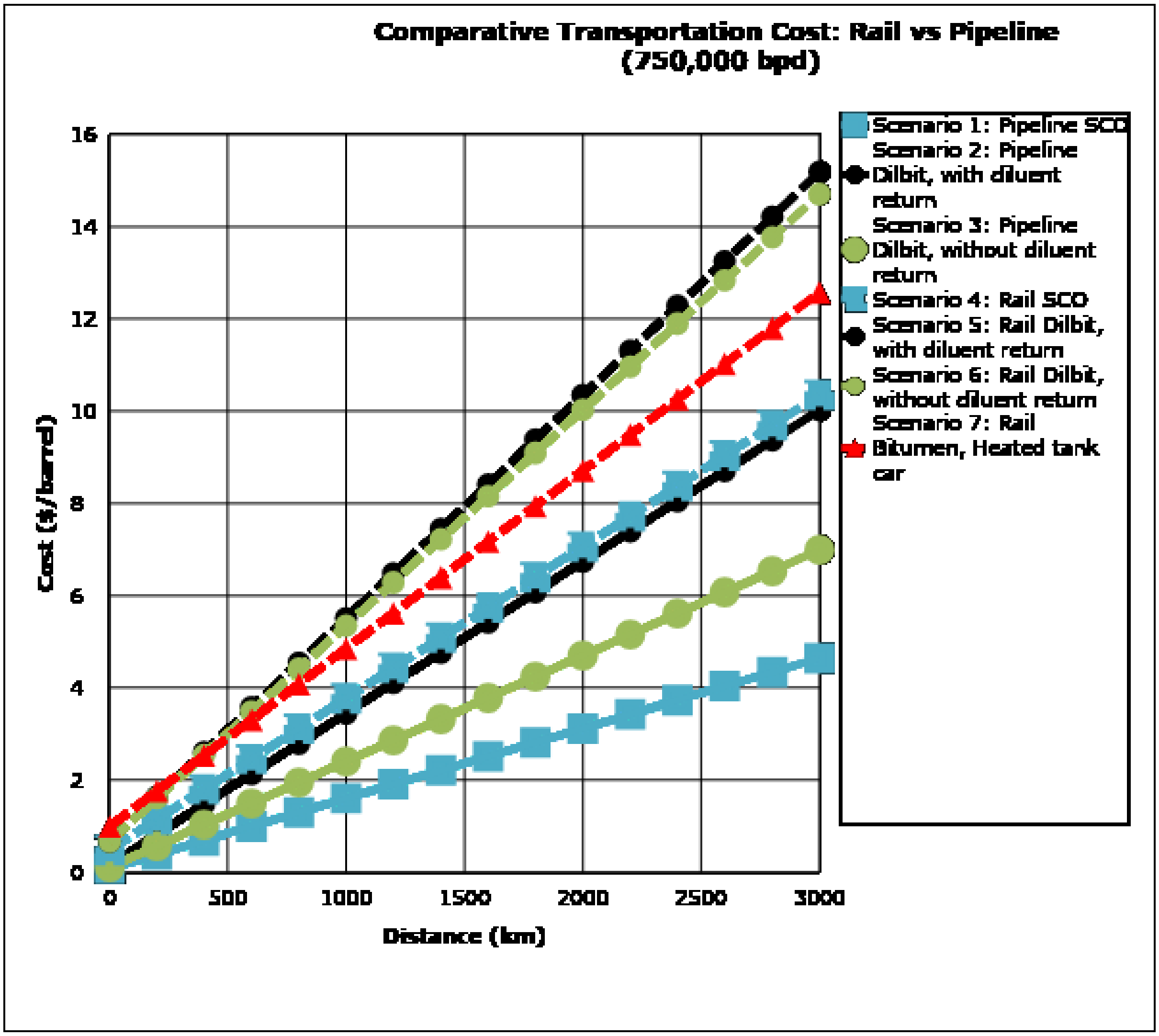

Figure 9: **Impact of market distance on transportation cost**

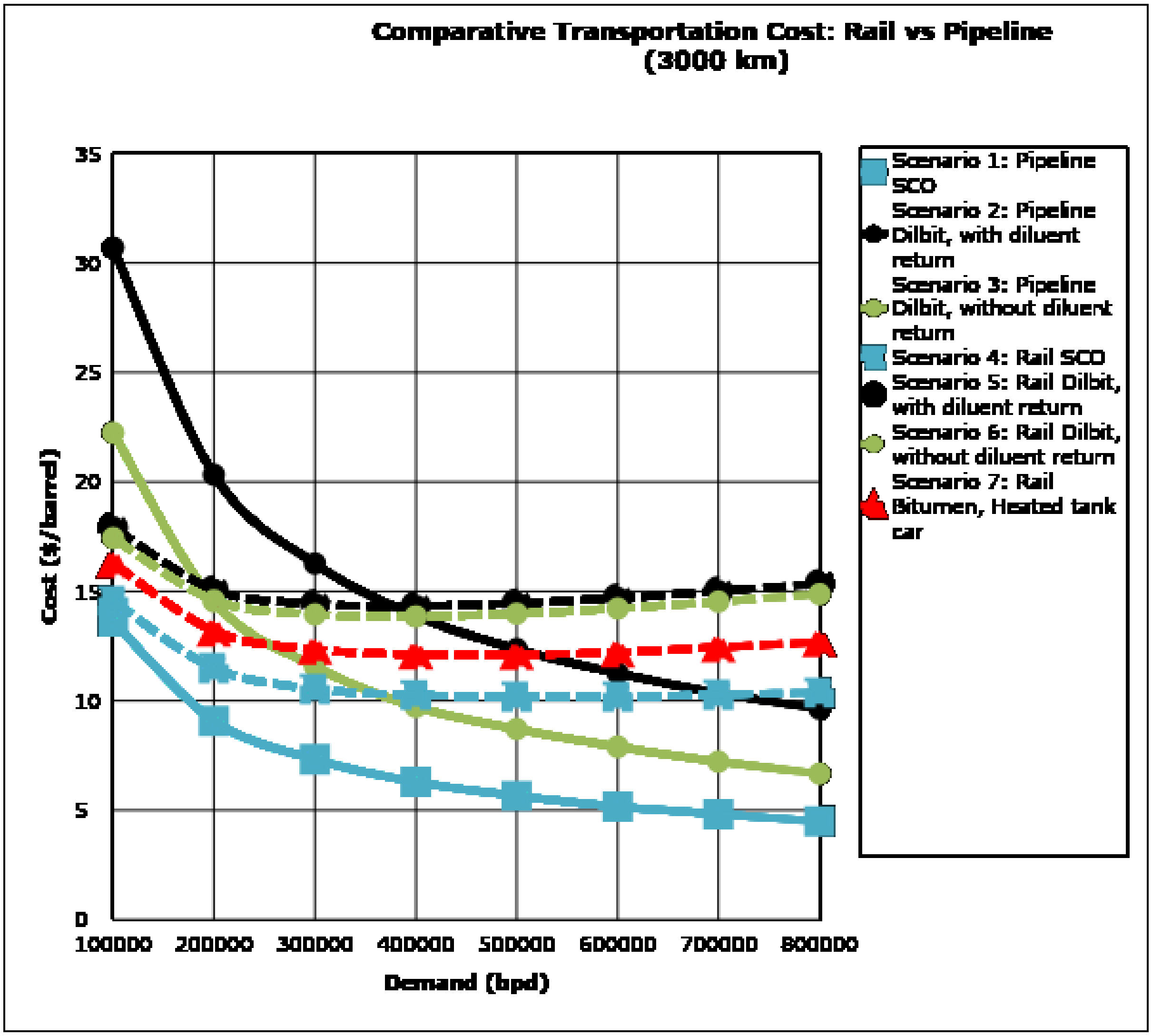

Figure 10: **Impact of production scale on transportation cost**

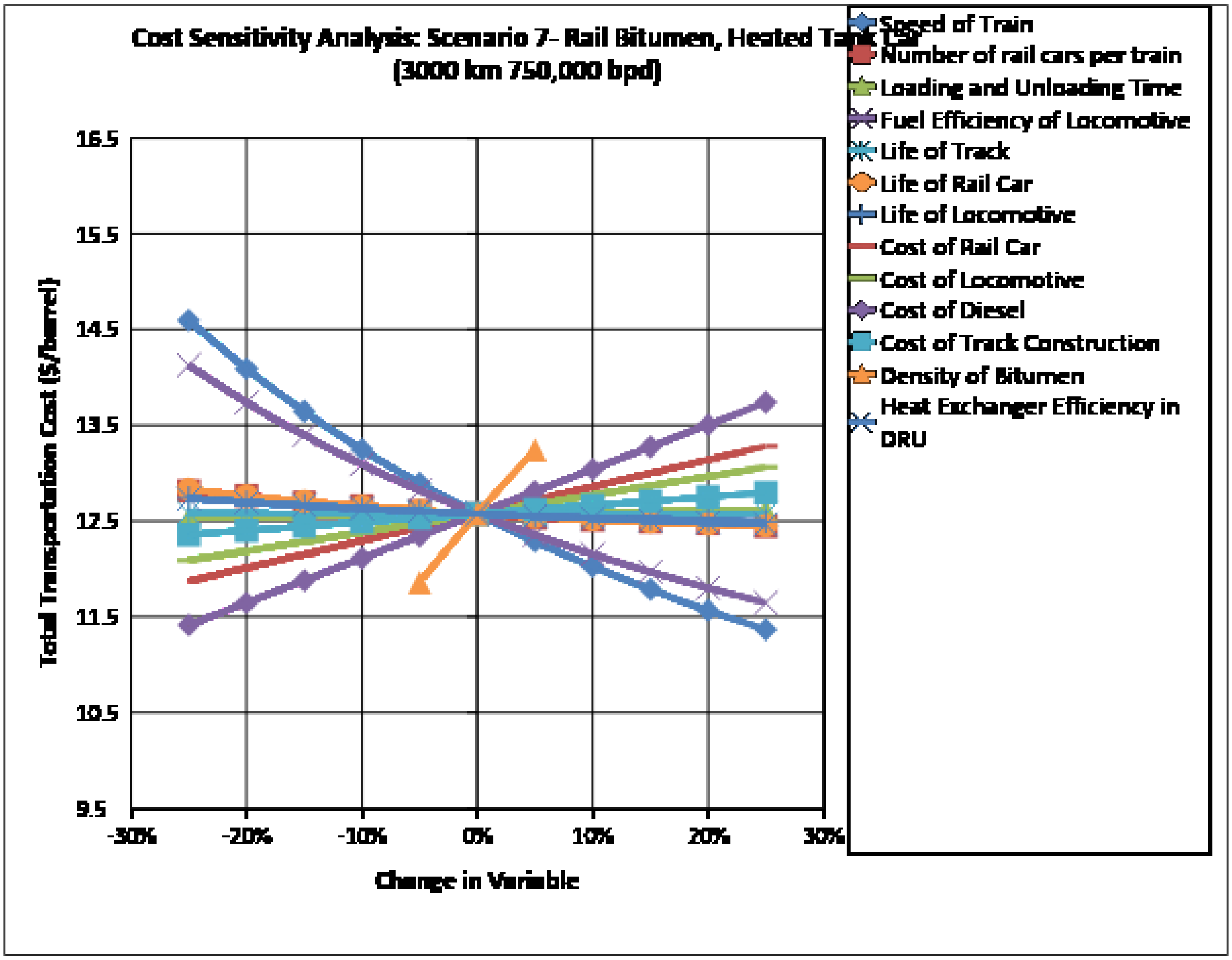

Figure 11: **Sensitivity analysis of crude oil transport via rail**

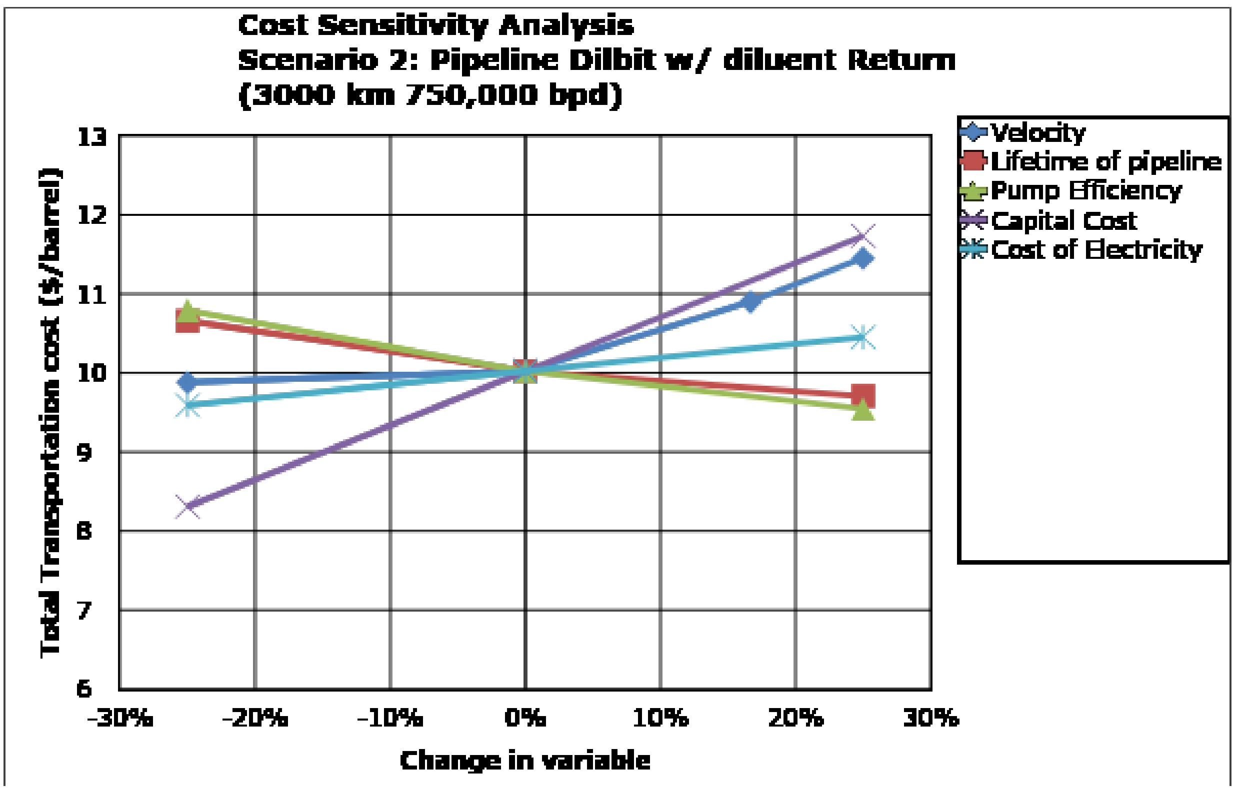

Figure 12: **Sensitivity analysis of crude oil transport via pipeline**

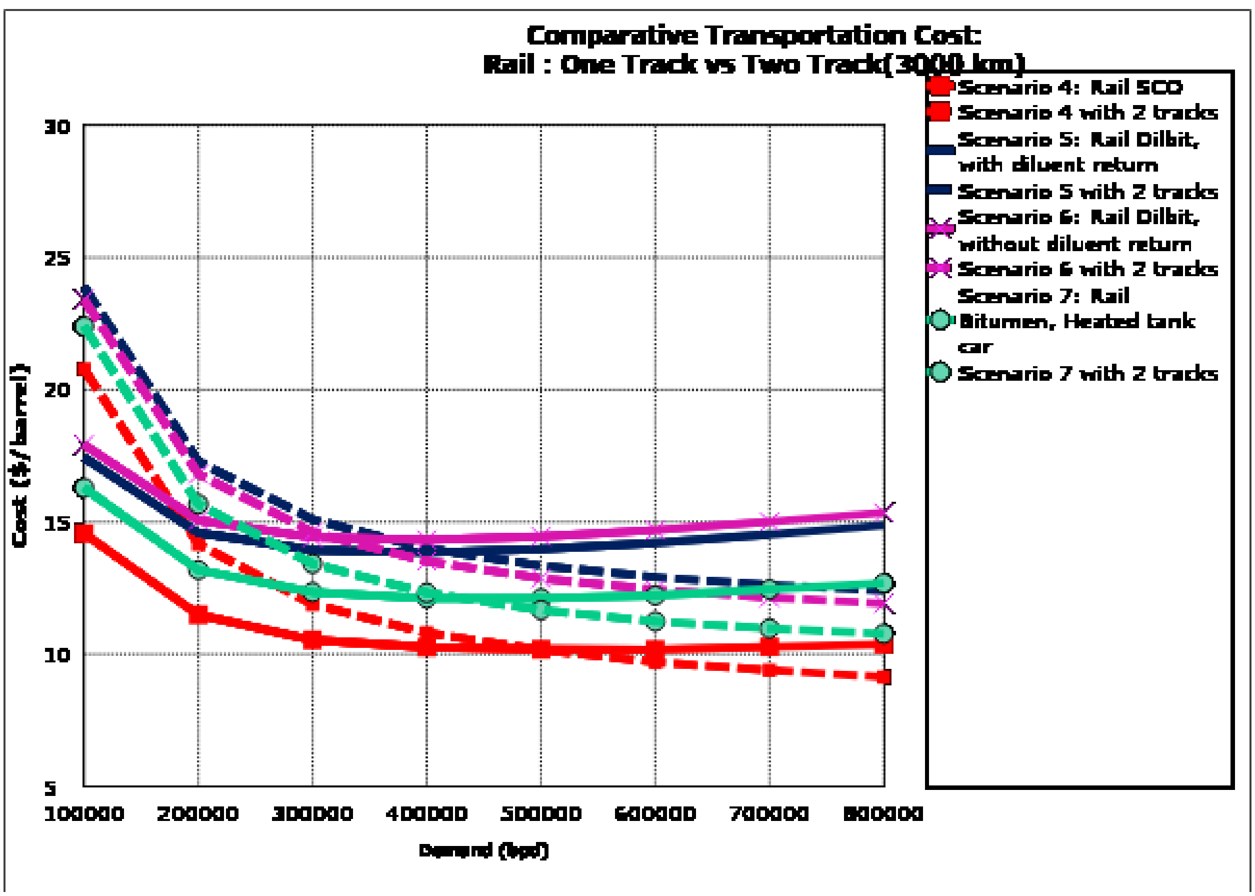

Figure 13: **Impact of multiple tracks on rail transportation costs**

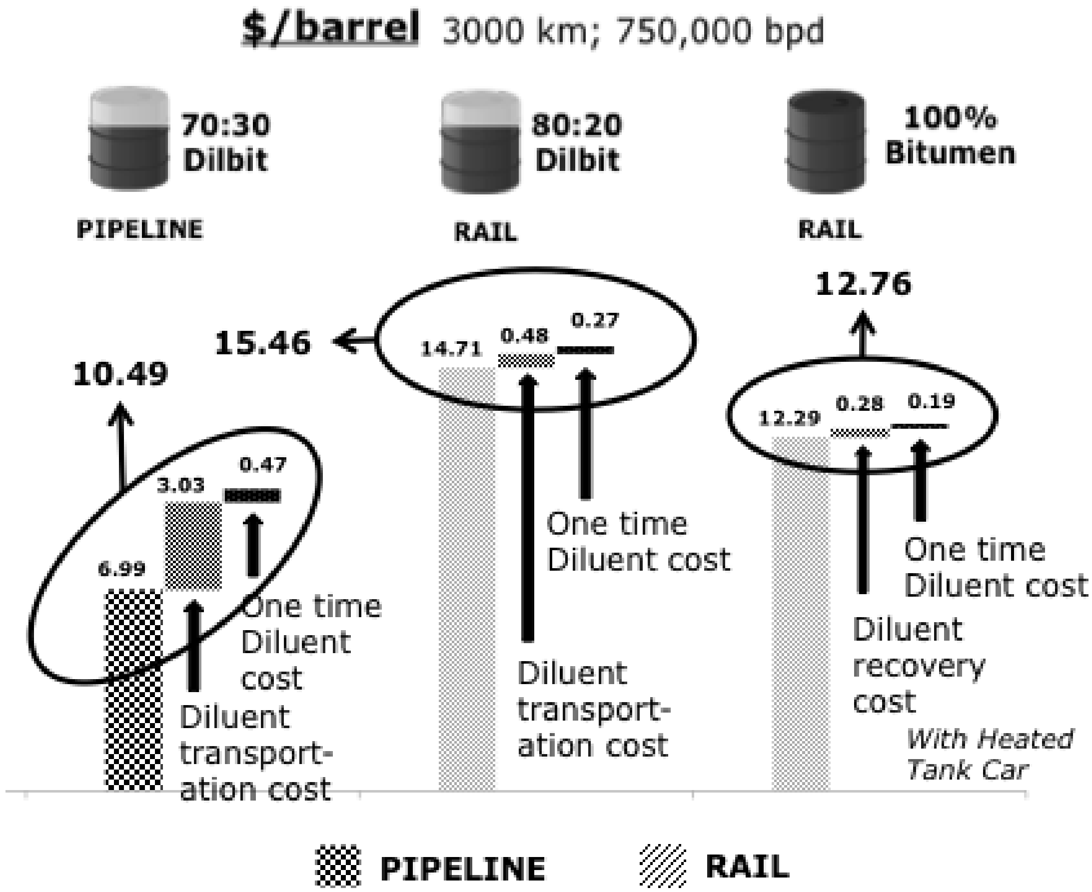

Figure 14: **Impact of diluent cost on the transportation cost of rail and pipeline (scenarios 2, 3, and 5)**

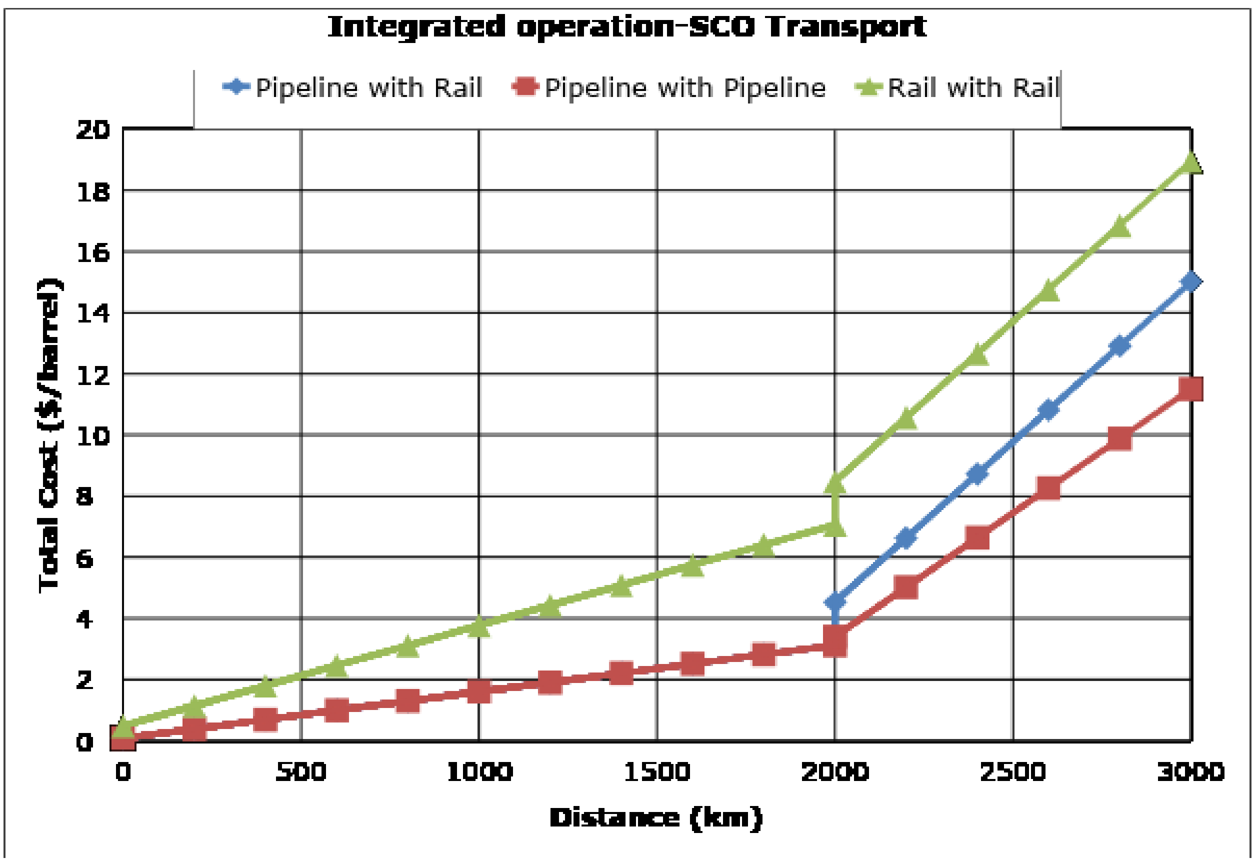

Figure 15: Pipeline and rail integrated transportation cost.

Table 1: **Transportation scenarios for crude oil via rail and pipeline**

Scenario	Transportation Mode	Commodity	Description	
1	Pipeline	SCO	Transportation of SCO via pipeline to downstream refineries located within a range of 1 – 3000 km.	
2	Pipeline	Dilbit	Transportation of bitumen via pipeline (with diluent (dilbit)) to downstream refineries located within a range of 1 – 3000 km. A diluent pipeline is also included for the return of the diluent after being recovered by downstream refineries.	of bar
3	Pipeline	Dilbit	Transportation of bitumen via pipeline (with diluent (dilbit)) to downstream refineries located within a range of 1 – 3000 km. No additional pipeline for diluent return is included – the diluent is assumed to be utilized for other alternative purposes by downstream refineries.	of bar
4	Rail	SCO	Transportation of SCO via rail to downstream refineries located within a range of 1 – 3000 km.	
5	Rail	Dilbit	Transportation of bitumen via rail (with diluent (dilbit)) to downstream refineries located within a range of 1 – 3000 km. The backhaul of diluent by rail after being recovered by downstream refineries is also included.	of bar
6	Rail	Dilbit	Transportation of bitumen via rail (with diluent (dilbit)) to downstream refineries located within a range of 1 – 3000 km. No diluent return via rail is included – the diluent is assumed to be utilized for other alternative purposes by downstream refineries. .	of bar
7	Rail	Bitume n	Transportation of bitumen via rail in insulated rail cars to downstream refineries located within a range of 1 – 3000 km. The use of diluent is negated completely in this scenario due to the technology adopted.	is r bitu ter pro of bitu sep

Table 2: **Key pipeline techno-economic parameters**

Parameters	Scenario 1	Scenario 2*	Scenario 3	Sources/Comments
Transportation Scale (bpd)	750,000	1,071,429 & 321,429	1,071,429	Base case production capacities.
Pump Selection				
ΔP (bar)	50	50	50	Both pipelines in scenario 2 have the same value [28].
Flow rate (U.S. gpm)	6,000	6,000	6,000	Both pipelines in scenario 2 have the same value [29].
Number of pumps	4	6 & 2	6	
Pump efficiency	70%	70%	70%	Based on report writer's knowledge and typical values.
Power (hp/pump)	3,325	3,166 & 2,850	3166	Calculated from engineering principles. See Appendix A, Eq. 3
Pipeline Specifications				

Length (km)	3,000	3,000 & 3,000	3,000	Long distance to market indicated
Inner diameter (in)	33	40 & 28	40	Calculated from engineering principles assuming pipeline velocity to be in the range of 1.5-3.0 m/s
Thickness (in)	0.5	0.5	0.5	Both pipelines in scenario 2 have the same value.
Absolute roughness (mm)	0.046	0.046	0.046	Both pipelines in scenario 2 have the same value [30].
<u>Booster Station Specifications</u>				
Distance between stations (km)	100	70 & 285	70	Calculated from engineering principles. See Appendix A, Eq. 4.
Number	31	52& 11	52	Assuming equal distance between booster stations. See Appendix A, Eq. 5.
<u>Pipeline Costs</u>				
Cost ($1,000s/mile)	3,508	4,284 & 2914	4284	Based on a model provided by [31].
Lifetime (yr)	20	20	20	

Inlet pump cost ($1,000s)	16,600	24,182 & 7,567	24,182	Estimates for inlet pumps are based on data provided by [30].
Storage tank cost ($1,000s)	46,930	59,174 & 27,056	59,174	Storage tank cost is based on a 5 day storage capacity and a scale factor 0.65 [32].
Booster station cost ($1,000s)	72,302	102,575 & 48,064	102,575	Cost refers to a single booster station and includes: pump, building, substation and access road costs [32].
Economic Parameters				
Discount rate (%)	12	12	12	
Inflation rate (%)	6.6	6.6	6.6	The relatively high inflation rate is intended to reflect the significant rise in the upstream capital cost index (UCCI) [33] and the elevated costs of energy infrastructure projects, particularly in Canada
Operating, Maintenance and Labour Costs				
Pump maintenance ($1,000s/yr)	15936.1	38449 & 2724	38449	Estimated to be 3% of the capital cost [32].
Pipeline maintenance($1,000s/mile/yr)	17.7	21.4 & 14.6	31.4	Estimated to be 0.5% of the capital cost
Wages ($1,000s/mile/yr)	3.8	3.8	3.8	Assuming 2 operators per 100 km and an hourly wage of $35/hr. Both pipelines in scenario 2 have the same

				value
Electricity consumption ($1,000s/yr/km)	60.3	144.5& 8.8	144.5	Assuming an average Alberta cost of electricity of 0.07/kWh [34].

***Note**: Scenario 2 consists of two pipelines, one for dilbit transportation and the other for diluent return. The first value mentioned in the column for scenario 2 is for the dilbit pipeline, whereas the second value mentioned is for the diluent return pipeline.

Table 3: Key rail techno-economic parameters

Parameters	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Sources/Comments**
Type of Train	Unit train	Unit train	Unit train	Unit train	
Average train speed (km/hr)	17	17	17	17	North American Class 1 freight rail car average speed [35]
Transit time (days)	24	28	28	26	The transit times are different because an increased number of trains are required in scenarios 5, 6, and 7. In the case of scenarios 5 and 6, recall that to deliver 750,000 bpd of bitumen, 937,500 bpd of dilbit must be transported (as a result of the 80:20 bitumen to diluent ratio for

					rail). For scenario 7, the increased number of trains is due to the higher density for bitumen in comparison to SCO, which reduces the loading capacity, as it is governed by weight, not by volume.
Daily number of trains	13	17	17	15	Appendix B, Eq. 3
Total number of trains	308	477	477	373	Appendix B, Eq. 4
Rail Track					
Gradient	1%	1%	1%	1%	Typically track gradients are less than 3% [36]
Number of sidings	93	127	127	107	Appendix B Eq. 5
Lifetime (yr)	50	50	50	50	Based on estimates given by [37]
Rail Car					
Capacity (barrels/car)	592	542	542	517	The loading capacity of the rail car is limited by weight and not by volume [9].

					Thus, the amount of crude that can be loaded into a given rail car decreases as the density of the crude increases. A capacity factor of 88% assumed. See Appendix B, Eq. 6
Total Number (cars/day)	1,267	1,729	1,729	1,451	Appendix B, Eq. 1
Lifetime (yr)	20	20	20	20	Based on estimates given by [37]
<u>Locomotive</u>					
Pulling capacity (cars/locomotive)	47	47	47	47	[36]
Fuel efficiency (tonne-km/L)	170	170	170	170	Used data provided by [38]
Lifetime (yr)	20	20	20	20	[37]
<u>Terminal Stations</u>					
Loading/unloading time (hours)	7.6/7.6	7.2/7.2	7.2/7.2	7.4/10.4	Based on a loading rate of 25 rail cars per pump, at a flow rate of 2m^3/min. Furthermore, terminal shunting takes place at a speed of 2km/hr [39, 40]. For the insulated rail car, each tank car is heated for 45 minutes by running steam in the rail cars

					(through coils). This is done for 25 rail cars at once .Steam is produced by a natural gas run boiler with an average life 25 years and an assumed boiler efficiency of 70% [39, 41, 42]
<u>Economic Parameters</u>					
Discount rate (%)	12	12	12	12	
Inflation rate (%)	6.6	6.6	6.6	6.6	The relatively high inflation rate is intended to reflect the significant rise in the upstream capital cost index (UCCI) [33] and the elevated costs of infrastructure projects, particularly in Canada
Rail track construction cost (in $1,000s)	1,599,769	1,599,769	1,599,769	1,599,769	Cost estimates for the rail track and siding track are based on data provided by [43]
Total cost of rail cars for continuous operation (in $1,000s)	4,250,621	6,580,199	6,580,199	5,375,671	Based on 24x7 continuous operations. Rail car and locomotive costs are based on data provided by [37, 44, 45]
Total cost of locomotives for continuous	2,859,596	4,413,026	4,413,026	3,460,895	

operation (in $1,000s)					
Sidings construction cost (in $1,000s)	229,797	313,680	313,680	263,271	
Terminal station construction cost (in $1,000s)	13,509	18,440	18,440	15,477	Terminal construction cost is based on a service life of 40 years [43].
Storage tank cost (in $1,000s)	46,623	46,623	46,623	46,623	Storage tank cost is based on a 5-day storage capacity and a scale factor 0.65 [32].
Pump cost (in $1,000s)	60,325	90,250	90,250	66,025	The pump cost data were provided by [32].
Boiler cost & diluent recovery unit cost (in $1,000s)	-	-	-	275,905	This includes the boiler at the upgrader (loading station) and the refinery (unloading station). Boiler cost estimate is based on a steam pressure and flow rate of 10.3 bar and 1.3kg/sec. A 25-year boiler service life and a scale factor of 0.65 were used in estimating costs. Diluent recovery unit cost estimate was based on data provided by [46].
Operating, maintenance and labour costs (All costs are in $1000s)					
Diesel fuel cost ($1,000s/yr)	1,111,3 86	1,648,2 37	1,517,0 74	1,273,2 75	Includes both up journey and down journey travel of the train.
Wages at terminal ($1,000s/yr)	29,915	40,834	40,834	34,272	Assuming 16 workers per terminal @ $33.7/hr

Electricity cost ($1,000s/yr)	9,247	15,777	15,777	10,594	Electricity is consumed by pumps at the inlet station and outlet station.
Locomotive driver salary ($1,000s/yr)	298,225	459,002	459,002	360,558	Assuming one driver for each locomotive @ $50/hr
Rail track maintenance cost ($1,000s/yr)	54,887	57,403	57,403	55,891	3 % of capital cost [43]
Maintenance cost of locomotives ($1,000s/yr)	57,192	88,261	88,261	69,218	2% of capital cost [43]
Maintenance cost of rail cars ($1,000s/yr)	42,506	65,802	65,802	53,757	1% of capital cost [43]
Storage tank maintenance cost($1,000s/yr)	1,865	1,865	1,865	1,865	2% of capital cost [43]
Terminal pipeline maintenance ($1,000s/ yr)	63.7	79.0	79.0	68.8	3% of the capital cost [32]
Pump maintenance cost($1,000s/yr)	3,614	4,934	4,934	4,141	3% of the capital cost [32]
Terminal structure maintenance cost($1,000s/yr)	270	369	369	310	2% of capital cost [43]
Boiler and DRU maintenance Cost($1,000s/yr)	-	-	-	5,486	2% of capital cost [42]

Natural gas cost ($1,000s/yr)	-	-	-	46,655	Based on the amount of steam required to heat the bitumen to 60 degrees Celsius. See Appendix B, Eq. 7