Environmental Science & Technology

Article

pubs.acs.org/est

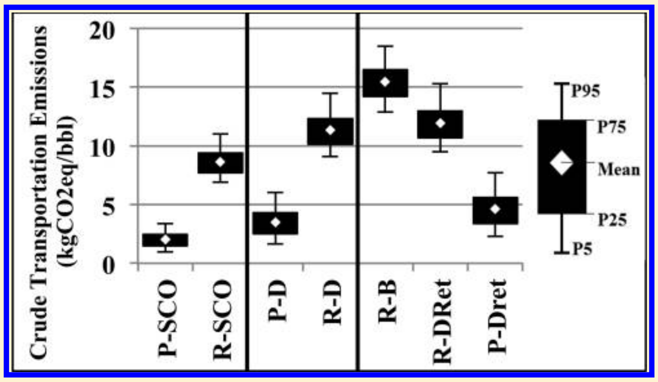
Life Cycle Analysis of Bitumen Transportation to Refineries by Rail and Pipeline

Balwinder Nimana, Aman Verma, Giovanni Di Lullo, Md. Mustafizur Rahman, Christina E. Canter, Babatunde Olateju, Hao Zhang, and Amit Kumar*

Department of Mechanical Engineering, 10-263 Donadeo Innovation Centre for Engineering, University of Alberta, Edmonton, Alberta T6G 1H9, Canada

S *Supporting Information*

ABSTRACT: Crude oil is currently transported primarily by pipelines and rail from extraction sites to refineries around the world. This research evaluates energy use and greenhouse gas (GHG) emissions for three scenarios (synthetic crude oil and dilbit with and without diluent return) in which 750 000 bpd of Alberta's bitumen is transported 3000 km to determine which method has a lower environmental impact. Each scenario has a pipeline and rail pathway, and the dilbit without diluent return scenario has an additional heated bitumen pathway, which does not require diluent. An Excel based bottom-up model is developed using engineering first-principles to calculate mass and energy balances for each process. Results show that pipeline transportation produced between 61% and 77% fewer GHG emissions than by rail. The GHG emissions decreased by 15% and 73% for rail and pipelines as the capacity increased from 100 000 to 800 000 bpd. A Monte Carlo simulation was performed to determine the uncertainty in the emissions and found that the uncertainty was larger for pipelines (up to ±73%) and smaller for rail (up to ±28%). The uncertainty ranges do not overlap, thus confirming that pipelines have lower GHG emissions, which is important information for policy makers conducting pipeline reviews.



1. INTRODUCTION

Oil sands operations are a significant source of GHG emissions. Alberta, the location of one of the world's largest oil sands industries in western Canada, generates approximately 123 $MtCO_2eq$ emissions per year from its oil and gas sector.[1] Crude transportation, which emitted an estimated 1.7−29.4 $MtCO_2eq/y$ in 2014,[2,3] has a significant impact on oil sands industry emissions. Currently, pipelines and rail are responsible for 58% and 31%, respectively, of crude transportation for crude refined in the U.S.[4] Although pipelines have lower transportation costs, public concern has made the permitting process, especially for new pipeline construction, difficult, time-consuming, and expensive for the oil industry.[2,5,6] As a result, there has been significant focus on rail transportation recently.[2,5,6] In order to help reduce emissions, it is necessary to understand the difference in the construction and operating GHG emission intensities of pipeline and rail crude transport and to identify potential areas for emissions reduction.

Crude oil is a generic term for liquid hydrocarbons. Alberta's bitumen is a viscous and dense crude oil with an API of less than 12 degrees (986 kg/m^3).[7,8] Due to bitumen's high viscosity, it cannot be directly transported to a refinery by pipeline. To reduce the viscosity, the feedstock is either upgraded to synthetic crude oil (SCO), mixed with a diluent (dilbit), or mixed with SCO (synbit). Naphtha or natural gas (NG) condensate can also be used as a diluent. At the refinery, the diluent can either be processed into gasoline or returned to the extraction site and reused.[9] An advantage of rail transport is that it can use less diluent as the viscosity only needs to be low enough to pump the crude in and out of the tank car and transport it short distances. The higher viscosity dilbit transported by rail is commonly referred to as railbit.[6]

There have been both academic and industry life cycle assessments (LCAs) analyzing oil sands technologies.[2,9−21] However, none of these studies performed a detailed analysis of crude oil transportation emissions via pipeline and rail. Existing research uses aggregated data,[16] examines small-diameter short distance pipelines,[17] or analyzes nonapplicable industries[18−21] to produce point estimates. A detailed model that accounts for product-specific density and viscosity for dilbit, SCO, and bitumen is needed to fill the data gap in the literature. The objective of this study has two parts. The first is to create a bottom-up model that can analyze specific situations rather than industry averages; the model will be flexible, allowing it to model specific pipeline and rail systems in the future. The second is to

Received: June 21, 2016
Revised: November 15, 2016
Accepted: November 18, 2016
Published: November 18, 2016

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

perform an uncertainty analysis that will allow us to determine if it is possible to state with reasonable certainty that one transportation method, pipeline or rail, has higher emissions than another.

There have been studies, which looks at the well-to-wheel (WTW) emissions of SCO, dilbit, or pure bitumen with very limited assessment of transportation emissions.[9,11,22−24] These studies also found that the SCO pathway had higher WTW GHG emissions. While the transportation emissions represent only 2−4% of the WTW emissions, they are still relevant to policy makers when examining crude pipeline and rail terminal projects.

This study is not calculating the WTW emissions of SCO, dilbit, and bitumen. This study's LCA focuses on the construction and operation emissions of the rail and pipeline systems, not the WTW emissions of the transported product. Determining whether SCO, dilbit, or pure bitumen has lower WTW emissions is outside the scope of this work. However, the product being transported by the rail and pipeline systems will affect their design and emission intensity, which is why product specific scenarios are examined. This study will also determine how a system's daily capacity affects the emission intensity. Finally, the emissions for transportation are analyzed and compared to previous work in this area.[2,16]

The findings of this study will be significant to those in industry and government who make decisions on pipeline and rail terminal project proposal reviews. In the face of carbon limits and taxes, both policy makers and industry leaders need accurate results with quantified uncertainty to make informed decisions.

An analysis of marine crude transportation is included in section S6 of the Supporting Information (SI). Although Alberta's crude is not currently transported by marine vessels, future infrastructure development has the potential to increase Alberta's market access, which would result in a demand for marine transportation.[25−27]

2. METHODOLOGY

The methodology used in this study follows the LCA framework, which has four parts: goal and scope definition, life cycle inventory, life cycle impact assessment, and results and discussion.[28] This study creates an Excel based model for the LCA using the equations shown in the SI; the system boundaries and a high-level overview are shown in Figures 1 and 2. The uncertainty analysis is performed using the ModelRisk Excel add-in by Vose.[29]

2.1. Goal and Scope Definition. This study focuses on the assessment and comparison of the life cycle GHG emissions from transporting bitumen in the form of bitumen, dilbit, and SCO (northern Alberta crudes) by rail and pipeline The assessment was conducted based on a functional unit of one U.S. barrel of crude, where "crude" is SCO for the SCO scenarios, and bitumen for the dilbit scenarios. The aim is to compare the transportation system emissions, rail and pipeline, and not the various crude forms (i.e., SCO, bitumen, dilbit) with each other. Three scenarios were developed, and each scenario has two to three pathways (Table 1). Although the heated bitumen pathway is not currently in use it is included as it does not require diluent, which is in limited supply.[30] The heated bitumen pathway is included in the dilbit with return scenario since the diluent starts and ends at the loading terminal for all the three pathways.

Due to the aggregated nature of publically available data, it is not possible to determine how much SCO and dilbit is transported by rail vs pipeline. Alberta has the capacity to export 177 kbpd via rail with an additional 322 kbpd capacity proposed.[31] Meanwhile a total of 723 and 862 kbpd of SCO and dilbit was exported to the US in 2015.[32] The current rail and pipeline system capacities range from 20 to 65 kbpd and 74−796 kbpd,[31,33] respectively. However, a 750 kbpd system is examined in this study as currently purposed pipelines range from 525 to 1100 kbpd.[34]

The system boundaries for the two transportation methods are shown in Figure 1. The starting point for each transportation system is at the rail or pipeline terminal. For SCO, it is assumed the upgrader is located near the terminal and that no additional transportation is required. In order to focus on the transportation stage only, we have not included gathering lines from the extraction sites. The boundary end point for all scenarios is the refinery terminal. For the dilbit scenarios, the diluent recovery unit (DRU) at the refinery is not included as it is part of the refining process; the bitumen needs to be heated anyway. In any event, the diluent recovery energy added within the refinery atmospheric distillation tower is recovered by a heat exchanger; the effect on the overall emissions will be a change of less than 1.0%, according to preliminary calculations shown in section S3.8 of the SI. For the heated bitumen pathway, the DRU unit is at the loading terminal and the heat added to the bitumen is lost as it will cool in the tank car during transit; hence, the DRU unit is included. Diluent upstream emissions are not considered, as these should be examined in a well-to-wheels analysis where it is possible to include the diluent fate as well. Fugitive, flaring, and venting emissions are not included either due to the lack of quality data.

This study focuses on the large sources of energy use and emissions during the construction and operating phases (see Figure 1). The construction phase focuses on fuel use for large equipment and upstream emissions for the main construction material. For the rail pathway, the track emissions have been included as crude train traffic can fully consume the track's capacity. The operating phase focuses on the main equipment only such as the locomotives, pumps, and diluent recovery unit. For the pipeline pathways, drag-reducing agents were not included in the main article due to the lack of industrial data on their real world effectiveness. However, their potential effects are included in supplementary section S7. Blending and storage tanks are not considered because preliminary analysis showed their construction emissions to be less than 0.1% of the total emissions and the number of tanks needed would not vary significantly between scenarios.

Figure 2 provides a high-level overview of the excel model inputs, intermediate variables, and outputs; the full calculations are provided in the SI. This study created a flexible excel based model, which allows the analysis of multiple scenarios.

This analysis reports primarily GHG emissions intensities; however, a high-level net energy ratio is used to determine energy efficiency for each process. Energy use is presented as MJ/GJ-crude, and crude is defined as either SCO or bitumen. The net energy ratio (NER) is calculated and defined in eq 1.

$$\text{NER} = \frac{\text{energy density of crude}}{\text{energy density of crude} + \text{operation energy}} \quad (1)$$

2.2. Life Cycle Inventory. This section describes all of the main processes used in the rail and pipeline base cases to create the mass and energy inventories. The crude properties can be found in Table S1 in section S1. The marine base case design is in section S6.

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

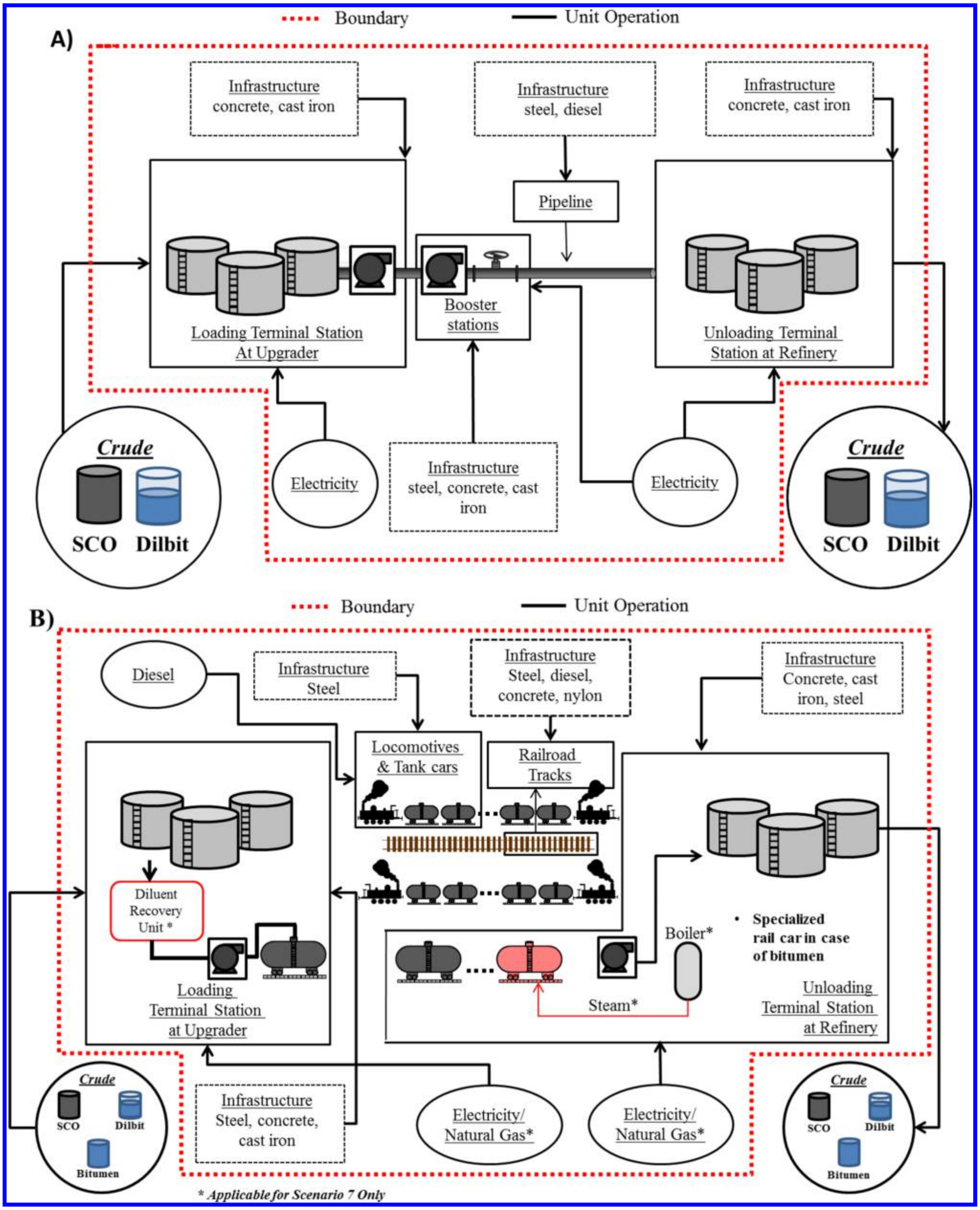


Figure 1. Boundaries for the LCA of Alberta's crudes for pipeline (A) and rail (B).

2.2.1. Pipeline Base Case Design. The pipeline base case inventory is developed by examining the major construction and operating processes. The base case is designed to deliver 750 000 bpd of SCO or bitumen; if diluent is used, the shipped volume increases to 1 054 884 bpd to account for the diluent volume. The diluent ratio is calculated from the bitumen, diluent, and dilbit densities and is found to be 29%. The 3000 km distance represents the approximate distance between Alberta and a refinery in the Gulf Coast. This is the farthest distance Alberta's crude currently travels, and approximately 20% of Alberta's SCO

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

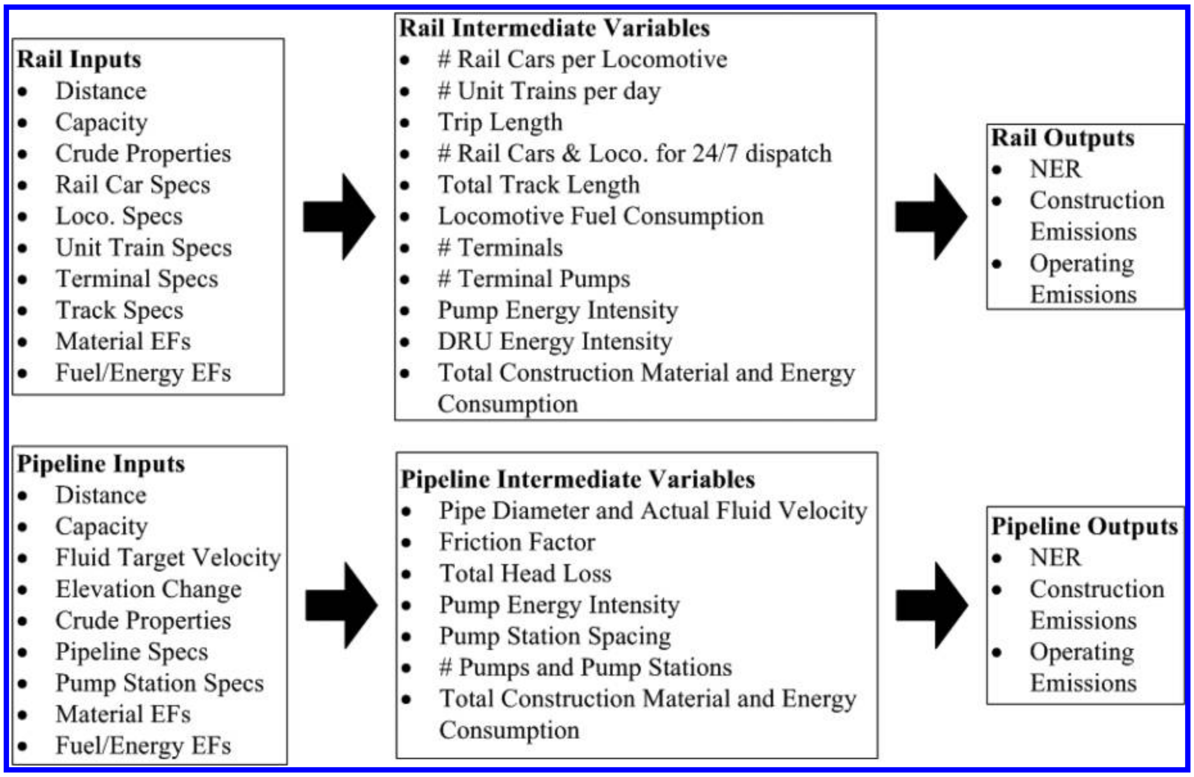


Figure 2. Excel model calculation overview.

Table 1. Alberta's Crude Transportation Assessment Scenarios

scenario	pathway	abbr	comment/assumptions
SCO	pipeline	P-SCO	transportation of SCO via pipeline to downstream refineries
	rail	R-SCO	transportation of SCO via rail to downstream refineries
dilbit without diluent return	pipeline	P-D	transportation of bitumen with diluent (dilbit) via pipeline to downstream refineries; no additional pipeline for diluent return is included; it is assumed that the diluent is used for other purposes by downstream refineries
	rail	R-D	transportation of bitumen with diluent (railbit) via rail to downstream refineries; no diluent return via rail is included; it is assumed that the diluent is used for other purposes by downstream refineries
dilbit with diluent return	pipeline	P-DRet	transportation of bitumen with diluent (dilbit) via pipeline to downstream refineries; a diluent pipeline is also included for the return of the diluent after being recovered by downstream refineries
	railbit	R-DRet	transportation of bitumen with diluent (dilbit) via rail to downstream refineries; the backhaul of diluent by rail after being recovered by downstream refineries is also included
	heated bitumen	R-B	transportation of bitumen via rail in insulated rail cars to downstream refineries; the use of diluent is negated completely in this pathway due to the technology adopted; a diluent recovery plant is needed in this pathway, as bitumen reaches the loading rail terminals from the extraction site in the form of dilbit; thus, the raw bitumen needs to be separated from dilbit

and bitumen is delivered to the Gulf Coast.[32] A second pipeline is included for the diluent return scenario, and it is designed using the same methodology as the delivery pipeline. The diluent return line capacity assumes that 100% of the diluent is recycled.[35] This section is organized in the order in which the calculations are performed.

Pipeline Operating Conditions. Designing the pipeline involves first determining pipeline dimensions and pressure drop. To determine the dimensions, the pipeline velocity is required. Based on currently operating Enbridge pipelines and various sources,[33,36−40] a target velocity of 1.4 m/s was determined for the base case. (See section S5.2 for more detail.) An approximate pipe diameter is determined from the required capacity and velocity. The nearest API 5 L standard diameter pipe is selected and the actual pipeline velocity for the new diameter is calculated.[41] The Reynolds number is calculated from the crude properties and the pipe's relative roughness of 0.000 046 m for new commercial steel.[42] The friction factor is determined using the Haaland and Colebrook correlations. The elevation change and the friction factor are used to determine head loss for each scenario. It is assumed there are no steep declines along the pipe path that would require throttling. Since the pipeline does not pass through mountains, this is a valid assumption. The elevation change of 632 m between Edmonton, AB, and Houston, TX, is used for the base case.[43,44]

The pumping energy intensity is determined from the total head loss, crude specific gravity, and pump efficiency. A pump efficiency of 85% is used for the base case. Additional information is available in section S5.2.[38,40,45−48]

Pumping Station Requirements. The pump station's design includes determining the number of pumps required and the distance between stations. In order to determine station spacing, the pump inlet pressure is assumed to be atmospheric pressure, 1 bar, and the pressure differential is assumed to be 5 MPa. To determine the distance between booster stations, the pump pressure differential is divided by the pressure drop per km. It is assumed that the booster stations are equally spaced. Pumps are selected that can handle the pipeline pressure. The number of

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

pumps required in parallel is then determined from the line's capacity and the pump's flow rate of 22.7 m^3/min (6000 gpm).[45] Preliminary results found that the pipeline pressure and booster station pumps have a negligible effect on the overall emission as they have no effect on the operating emissions and their construction emissions are relatively small; hence, a more in-depth analysis was not done.

Pipeline Construction. For pipeline construction, it is assumed that the pipeline is made of 12.4 mm (0.5 in.) thick virgin steel.[49] The pipe geometry and steel density are used to determine the mass of steel required for each scenario. To determine the fuel use for pipeline construction, it is assumed that trenching will consume most of the fuel, and consequently the trencher is the only piece of construction equipment analyzed. A Vermeer T1255 is considered in our study because it can handle large diameter pipelines.[50] The amount of time required for trenching depends on the soil type.[51] There are reports for similar trenchers that can go through 3.3 m of rock per hour or 65 m of loose soil per hour. An average of the two, 34.2 m/h, is used here.

For terminal construction, it is assumed that for each pump station there is a building to house the equipment. Information was not found on the construction of these buildings, so it is assumed that they are 6.1 m × 6.1 m × 6.1 m (20 ft) with 203 mm (8 in.) thick walls and are constructed with 203 mm × 203 mm × 406 mm concrete bricks weighing 21.0 kg each.[52] Each pump is made from cast iron and stainless steel, and it is assumed that the 4000 kg weight is split evenly between the two materials.[45] Preliminary results showed these assumptions had a negligible effect on overall emissions as the pump construction emissions are relatively small; hence, a more in-depth analysis was not done.

Pipeline Intermediate Results. Table 2 shows a breakdown of the intermediate values to provide further insight into the calculation methodology and final results. For the P-DRet pathway, the delivery line is for the main dilbit pipeline and the return line is for the secondary diluent return pipeline.

Table 2. Pipeline Intermediate Results

variable	unit	P-SCO	P-D	P-DRet delivery line	P-DRet return line
diluent ratio	%vol	0%	29%	29%	29%
shipped volume	bpd	750000	1054884	1054884	304884
pipe inner diameter	in. (m)	45 (1.1)	51 (1.3)	51 (1.3)	29 (0.7)
pipe velocity	m/s	1.35	1.47	1.47	1.32
Colebrook friction factor		0.017	0.034	0.034	0.013
pressure drop (friction)	bar/km	0.115	0.263	0.263	0.106
pressure drop (friction + elevation)	bar/km	0.097	0.244	0.244	0.121
distance between stations	km	514	204	204	412
pumping stations required		6	15	15	8
no. of parallel pumps at each station		4	6	6	2
pumping energy intensity	kWh/bbl	1.51	3.80	3.80	0.77

2.2.2. Rail Base Case Design. A rail base case inventory is developed by examining the major construction and operating processes. The base case rail system is designed to deliver 750 000 bpd of SCO or bitumen. When railbit with 15% diluent is used, the shipped volume increases to 882 353 bpd; this is less than in the pipeline scenario as the railbit only needs to be pumped short distances, which allows for higher viscosities.[6] Typically, a unit train with 100 rail cars operates on a single lane track.[53]

Rail signaling and track switches are not considered in this analysis. A study by Stripple and Uppenberg using electric trains found that the power and signaling system was responsible for only 9% of the infrastructure material.[54] Since this study assumes diesel locomotives are used, high power lines are not required, further reducing the impact from the power and signaling system. Moreover, rail yard activity is not considered; since this study assumes unit trains, there will be minimal rail yard movement. This section is organized in the order in which the calculations are performed.

Tank Car Requirements. The loading capacity of each tank car is determined from the car's weight and volume limits as well as crude properties. The analysis is in section S3.1. SCO and dilbit are transported in lighter, noninsulated and coiled tank cars since they do not need to be heated for pumping; however, the heated bitumen scenario uses heavier insulated and coiled cars. The number of tank cars required per day is determined from the tank car's volume and the system's capacity. The number of unit trains required per day is determined from the number of rail cars required per day divided by the number of cars in a unit train (100 cars/unit train).

Locomotive Requirements. To determine the number of locomotives required, a 0.5% grade is assumed; if the grade becomes steeper, the train can slow down as required.[55] The pulling capacity is determined with the Davis equation, which can be found in section S3.2 along with the GE ES44AC locomotive specifications.[56] All scenarios find that each locomotive can pull 36 tank cars. The number of locomotives required per unit train is found by dividing the number of rail cars per unit train (100 cars/unit train) by the number of cars each locomotive can pull (36 cars/loco) and rounding up to the nearest whole locomotive, which gives 3 locomotives per unit train for all pathways.

The fuel efficiency of locomotives is difficult to determine using engineering first-principles; hence, aggregated data were used to find fuel consumption. The Statcan database is used in section S3.3 and the 2009 average was found to be 344 gross tonne-km/L, GTK/L, for freight trains.[56] The gross tonne is the weight of the product and the tank car. Fuel consumption, in liters per kilometer, is calculated by dividing the unit trains gross weight (gross tonne) by the fuel efficiency (gross tonne-km/L). The resulting fuel consumption is 37.7 L/km for the up journey and 12.0, 12.0, 12.1, and 14.9 L/km for the return trip for the R-SCO, R-D, R-B, and R-DRet scenarios, respectively. The fuel economy on the return trip varies as the unit trains gross weight depends on the type of rail car used and the amount of diluent being returned to the extraction site, while there is no variation for the up trip as the unit train is fully loaded. Since locomotive fuel efficiency is calculated using aggregated data, the numbers inherently include the effect of elevation changes during a typical trip. Due to the lack of disaggregated data, it is not possible to quantify the effect of elevation on the locomotive fuel efficiency.

Transit Time Requirements. Total transit time is found by determining the loading/unloading times, travel time, and time wastage due to sidings. The total time is shown in equations

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

S30–36 in section S3. The loading/unloading times are determined based on the assumption that 25 cars would be unloaded simultaneously at 2 m^3/min. Preliminary results showed these assumptions had a negligible effect on overall emissions, and a more in-depth analysis was not done. An average velocity of 36 km/h is assumed based on the crude unit train data from the Surface Transportation Board to determine the travel time.[57] Track sidings are required when two-way traffic occurs on a single track. Trains traveling in one direction must travel at reduced speeds along the siding while a train traveling in the opposite direction passes. For the heated bitumen pathway, it is assumed that it takes an additional 45 min to heat the bitumen at the refinery terminal.[58]

Track Construction. Although crude trains can use preexisting rail lines and share the tracks with trains transporting other commodities, track construction is included for completeness. Transporting 750 000 bpd of crude requires 11–15 trains per day, and a single-track system can only handle 20–48 trains per day, depending on the control system used.[59] Additionally, a track should operate below 70% of the rated capacity to reduce the risk of delays.[59] Thus, the trains transporting crude will make up a significant portion of the track's use. Additionally, existing rail lines will need to be replaced as the heavy crude trains will wear out the track. The results of this study found that track emissions contributed less than 3% of the total (discussed in detail in section 3.1.2), so the effect of including them is minimal. The track construction calculations are shown in section S3.9.

Terminal Requirements. The number of terminals required was determined from the number of trains required per day and the loading and unloading times. It is assumed that each terminal could unload two trains at once. The terminal length is assumed to be 50% of the train length. This allows 25 rail cars to be loaded or unloaded at the same time. It is also assumed that each terminal has a 1.8 m (6 ft) wide and 203 mm (8 in.) thick concrete slab. The pumps are assumed to be made of 50% stainless steel and 50% cast iron; the desired flow rate of 2 m^3/min is compared to the pump's designed flow rate to determine if parallel pumps are required. The selected pumps can provide 1 MPa at 2.3 m^3/min (600 usgpm) and weigh 600 kg each.[45] The pumping power is determined from the desired flow rate, pump pressure, and pump efficiency. Pumps are assumed to have 85% efficiency.[38,40,45–48] These assumptions proved to be negligible based on the results from section 3.3.1.

For the R-B pathway that is, bitumen in a heated rail car, the bitumen arrives at the export (Alberta) terminal as dilbit. The diluent is then removed in a separation process, and for this analysis it is assumed that the process would be similar to the process used in an upgrader's diluent recovery unit. The diluent recovery process was analyzed in detail for upgrading, which included material and energy flows of the system.[35]

The diluent recovery unit (DRU) analysis is in section S3.8. The DRU uses 53.1 MJ of NG/bbl of bitumen to produce heat and steam for the process. To determine the DRU infrastructure materials, only the flash drums are modeled, due to a lack of information on the sizing of the other unit operations (heat exchangers, pumps). The DRU analysis determined that 2,349 tonnes of stainless steel are required for the R-B base case.

In order to unload the bitumen, the cargo must be reheated, and this is done using steam. It is assumed the bitumen will reach atmospheric temperature during transit. Data from an Altek heated tank car design showed the bitumen starts at 15.4 °C and is heated to 60 °C before being pumped out. It is assumed that a 75% efficient NG boiler would be used to generate the required steam.[58,60–63]

Train Construction. It was assumed that the train is constructed of 100% steel. In order to determine the amount of steel needed, the number of trains needed for 24 × 7 service is required. This number is calculated by multiplying the total transit time by the number of trains required.

Rail Intermediate Results. Table 3 shows a breakdown of the intermediate values to provide further insight into the calculation methodology and results.

Table 3. Rail Intermediate Results

high level	units	R-SCO	R-D	R-B	R-Dret
shipped volume	bpd	750000	882353	750000	882353
diluent returned	bpd	N/A	N/A	N/A	132353
shipped density	kg/m^3	859	967	1011	967
Rail Cars and Locomotives					
rail car volume	bbl/car	647.8	575.6	547.6	575.6
number of rail cars required per day	cars/day	1157.8	1532.9	1369.6	1532.9
no. of locomotives required per day	loc/day	34.7	46.0	41.1	46.0
number of trains required per day		11.6	15.3	13.7	15.3
total transit time	days	10.4	11.3	11.0	11.3
Rail Requirements					
no. of trains for 24 × 7 dispatch		120	174	151	174
no. of rail cars for 24 × 7 dispatch		11,991	17,317	15,071	17,317
no. of locomotives for 24 × 7 dispatch		360	520	453	520
loading terminals needed		2	2	2	2
unloading terminals needed		2	2	2	2
Additional Data					
total track length	km	3,147	3,194	3,174	3,194
pumping electricity consumption	kWh/m^3	0.327	0.327	0.327	0.327
Fuel Consumption					
diesel consumption delivery journey	L/km	37.7	37.7	37.7	37.7
diesel consumption return journey	L/km	12.0	12.0	12.1	14.9

2.2.3. Base Case Inventories. The base case inventory is divided into construction and operating inventories. Section S6.3 has the marine base case inventory. Table 4 shows the results for the pipeline and rail pathways. For the pipeline pathways, P-DRet (D) refers to the main delivery pipeline and P-DRet (R) refers to the diluent return pipeline. The mass and energy densities used are provided in Table S2. Tables S4–S6 in the SI shows all of the model inputs and additional intermediate values determined in the model for reference.

2.3. Life Cycle Impact Assessment. *2.3.1. Amortizing Construction Emissions.* Amortized emissions (gCO_2eq/bbl) were found by dividing the construction emissions by the component's lifetime and the crude transported per year. For the rail pathway, it is assumed that the locomotives, tank cars, and tracks have a 20-y lifetime[64] and a DRU has a 10-y lifetime. For pipelines, the pump station's life is assumed to be 40 y,[64] and the pipeline is expected to last 33 y.[65,66] The pumps are assumed to last 10 y, which is typical for rotating equipment.

2.3.2. Emission Factors. GHG emission factors (EF) for all materials and fuels are summarized in Table S3. The electricity

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680–691

Table 4. Pipeline Construction and Operating Inventories

		Pipeline			
construction inventory	units	P-SCO	P-D	P-DRet (D)	P-DRet (R)
pipe steel	t	1085069	1228156	1228156	703507
pump stainless steel	t	48	180	180	32
pump cast iron	t	48	180	180	32
station concrete	t	339	849	849	453
construction diesel	L	10571707	10571707	10571707	10571707
operating inventory	units	P-SCO	P-D	P-DRet (D)	P-DRet (R)
pump electricity	kWh/bbl	1.51	3.80	3.80	0.77
		Rail			
construction inventory	units	R-SCO	R-D	R-Dret	R-B
locomotive steel	t	70543	101895	101895	88766
tank car steel	t	494951	714792	714792	628920
sleeper steel	t	40003	40597	40597	40349
clip steel	t	8496	8622	8622	8570
rail steel	t	212318	215466	215466	214150
sleeper nylon	t	651	661	661	657
sleeper concrete	t	1084038	1100112	1100112	1093389
terminal concrete	t	2454	2454	2454	2483
pump stainless steel	t	60000	60000	60000	60000
pump cast iron	t	60000	60000	60000	60000
DRU stainless steel	t	N/A	N/A	N/A	2349
construction diesel	L	10342383	10495734	10495734	10431598
operating inventory	units	R-SCO	R-D	R-Dret	R-B
DRU NG	MJ/bbl	N/A	N/A	N/A	53.1
tank car heating NG	MJ/bbl	N/A	N/A	N/A	15.1
locomotive diesel	L/bbl	2.30	3.05	3.22	2.73
electricity	kWh/bbl	0.104	0.122	0.122	0.104

EFs were determined from eGrid[67] data for the U.S. and National Inventory data for Canada.[68] For the pipeline pathway, a distance-weighted average was used across Alberta, Saskatchewan, and the MROW, SPNO, and SPSO eGrid regions with weights of 0.05, 0.2, 0.35, 0.2, and 0.2 respectively. The MROW, SPNO, and SPSO electrical grid regions cover the central United States along the pipelines path. For the rail pathway, it is assumed that 50% of the electricity is consumed at the Alberta export terminal and 50% at the Texas import terminal. Thus, the EF is determined from an average of the Alberta and the SPSO eGrid region electricity EFs.[69] Section S6.2 provides the marine-specific EF. The steel EF assumes that 40% of the steel is recycled and 60% is virgin steel as 40% of global steel production is recycled steel.[70]

This study uses a 100-y time horizon and global warming potential factors from the IPCC Fifth Assessment Report of 1, 34, and 298 for CO_2, CH_4, and N_2O, respectively, to find CO_2eq emissions.[71]

2.4. Uncertainty Analysis. In order to determine whether rail or pipeline transportation has higher emissions, it is important to compare probable ranges rather than use deterministic point estimates. This can be accomplished by performing an uncertainty analysis through a Monte Carlo (MC) simulation.

To perform a MC simulation, a distribution of possible values is required for each input. Only inputs that have a significant effect on the model results were included. To determine which inputs should be included in the MC simulation, a sensitivity analysis was performed on all of the model inputs by varying them ±25% from the base case.

Once the key inputs were identified, distributions for each were determined. A conservative approach was taken to determine the distributions in order to ensure that worst case scenarios were included in the output distribution. When only low quality data were available, triangle or uniform distributions were used. When high quality data were available, ModelRisk data fitting tools were used to determine the input distributions. A detailed analysis for each distribution can be found in section S5.

3. RESULTS AND DISCUSSION

This section focuses on the breakdown of the energy used and emissions generated from transportation. The base case was analyzed and broken down into construction and operating emissions. The effect of the transportation system's capacity on the total emissions was then examined, after which an uncertainty analysis was conducted. The marine pathway results are in section S6.3.

3.1. Base Case Results. *3.1.1. Transportation Energy Use.* Energy use for both rail and pipeline is shown in Table 5. For rail, diesel is the most used energy source as diesel locomotives are used; little grid electricity is used as the terminal pumps only need to transport the crude a short distance. For pipeline transport, all of the energy is from grid electricity for the pumps. The diluent scenario electricity consumption is larger than the SCO scenarios as the shipped volume increases when diluent is added. Pipeline transportation has NERs over 99%, and the rail NER is 1.8% lower. The NER shows how energy efficient each process is at transporting crude. The results tell us that pipelines are more energy efficient than rail.

3.1.2. Transportation Emissions. Total Emissions. Emissions totals for the rail pathways were 7982, 10 495, 11 041, and 14 623 gCO_2eq/bbl for the R-SCO, R-D, R-DRet, and R-B, respectively. For the pipeline pathways, emissions were significantly lower at

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

Table 5. Pipeline and Rail Net Energy Ratios (NER)

	Rail Transport (MJ/GJ-Crude)			
	R-SCO	R-D	R-DRet	R-B
diesel	17.61	21.02	22.23	18.83
natural gas	0.00	0.00	0.00	14.53
electricity	0.08	0.09	0.09	0.07
total	17.70	21.10	22.31	33.44
NER	98.26%	97.93%	97.82%	96.76%
	Pipeline Transport (MJ/GJ-Crude)			
	P-SCO	P-D	P-DRet	
electricity	1.17	2.65	3.18	
NER	99.88%	99.74%	99.68%	

1572, 3321, and 4184 gCO_2eq/bbl for the P-SCO, P-D, and P-DRet, respectively. The heated bitumen pathway has higher emissions than both diluent return scenarios due to the amount of NG required to heat the bitumen in the DRU and at the unloading terminal. Figure S22 in section S6.3 shows the emissions broken down into the construction and operating phases. Construction emissions are less than 9% of the total for the rail scenarios. For the pipeline scenarios, construction emissions are responsible for up to 29% of the total emissions. Although a direct comparison between SCO and dilbit is not possible, the main reason the dilbit scenarios have higher emissions is because they are required to transport both the diluent (304 884/132 353 bpd for pipeline/rail) and the bitumen (750 000 bpd).

Operating Emissions. The operating emissions are shown in Figure 3. Due to process variations outside the scope of this work, results cannot be compared across crudes. For pipelines, the operating emissions are from the electricity used for the pumps. These emissions are split between the delivery and diluent return pipeline when applicable. There are five sources of rail operating emissions. Most of the diesel is consumed in route (from Alberta to Texas and back). The electricity used to operate the terminal pumps is negligible compared to the diesel consumption due to the short pumping lengths. For the heated bitumen scenario, it was assumed that NG is consumed at the Alberta terminal in the DRU to remove the diluent and again at the Texas terminal to reheat the bitumen in the tank cars (with steam) so it can be unloaded. The NG consumption for the DRU is 3.5 times larger than for unloading since the DRU has to heat the bitumen to 450 °F (232 °C) to separate the diluent, while the steam only has to heat the bitumen to 100 °C to pump it out of the rail car. The results show that the heated bitumen scenario generates more emissions through heating the bitumen than is saved on locomotive fuel. For the pipeline scenarios, the dilbit scenarios use more electricity since the transported volume was higher.

Construction Emissions. The infrastructure emissions are shown in Figure 3. The pipeline emissions are broken down into delivery pipe steel, return line pipe steel, and "other." The other category represents the pump station buildings and pumps as well as diesel used during construction. The other emissions account for less than 1% of the construction emissions; as a result, further analysis was not done. For rail, the track-specific emissions include all material and diesel used to build the track. The other category includes the terminal construction as well as the DRU stainless steel. The analysis of the terminal stations and DRU is simplistic but captures the major emissions sources; since the other category accounts for fewer than 11% of the construction emissions, this is an acceptable approach.

It can be argued that crude is not the only commodity transferred on the rail tracks or that it will use existing rail lines, as mentioned in section 2.2.2. The track construction emissions were found to be 30−36% of the construction emissions but only 1.6−3.3% of the total. Since the trains are responsible for a portion of the track emissions, the effect from allocating all of the track emissions to the crude will be small.

The track emissions can be broken down into rail steel (55.3%), sleeper concrete (31.1%), sleeper steel (8.7%), clip steel (2.2%), construction diesel (2.3%), and sleeper nylon (0.4%). The share of track emissions is the same for all scenarios as the track emissions are a function of the track lengths.

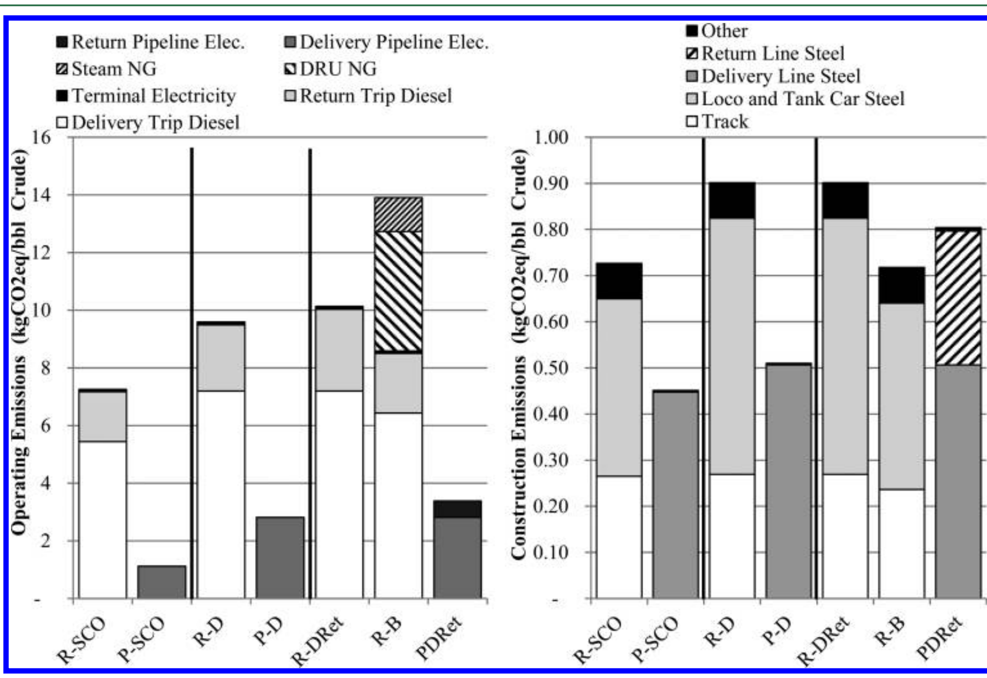


Figure 3. Rail and pipeline operating emissions (left) and construction emissions (right).

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

3.2. Effect of System Capacity on GHG Emissions. The models input capacity was varied from 100 to 800 kbpd to generate Figure 4. For rail, there is a relatively small decrease in emissions (15%) with increased capacity. This is because all of the trains are fully loaded and as capacity increases more trains are added which increases the infrastructure requirements without a significant change in transportation efficiency. For pipeline transportation, there is a significant decrease in emissions (73%) as capacity increased due to the change in pipe diameter. The great reduction in emissions has to do with the fact that the cross-sectional area of the pipe is related to the squared diameter of the pipe. Diameter increases with capacity, and when the target velocity is maintained at 1.4 m/s, the Reynolds number increases, causing the friction factor to decrease, which decreases the pump energy intensity (kWh/bbl). The curve is not perfectly smooth because standard pipe diameters are assumed; in industry, the pipeline flow rate would be optimized for the chosen diameter based on economics by varying the velocity. The results show that pipelines have lower emissions for all SCO and dilbit capacities above 100 kbpd. The effect of uncertainty on the crossover point is included in Figures S16–S18 in section S5.5.

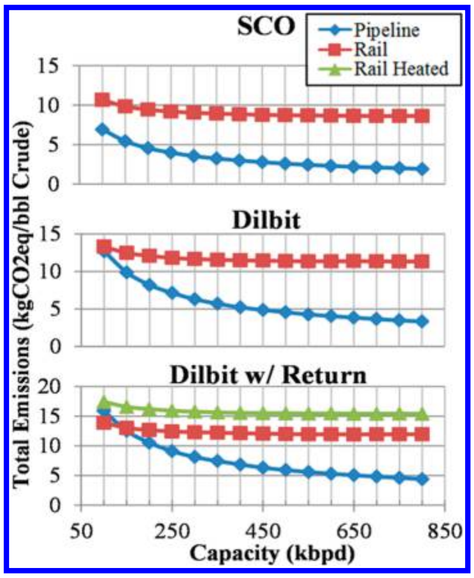


Figure 4. Effect of capacity on the total GHG emissions.

3.3. Uncertainty and Sensitivity Analysis. *3.3.1. MC Results.* The MC uncertainly simulation is performed using the key variables determined from the sensitivity analysis. The simulation produces a most likely estimate for the transportation emissions based on the uncertainty in the key model inputs. Table 6 shows the key inputs used for the MC simulation, Table S7 in the SI shows the distributions used and their data sources. The distribution are determined using conservative triangle distributions when there is a lack of quality data, full justifications for each input is in section S5.

Figure 5 shows the results of the MC analysis. The P5 and P95 values give a wide range (from ±17% to ±73%) from the mean values. However, even with the large ranges, the pipeline pathways clearly have lower emissions than the rail pathways for all scenarios. The pipeline pathways are 87%, 69%, and 61% lower than the rail pathways for SCO, dilbit without and with return, respectively. The difference between the rail and pipeline pathways is highest for SCO; this is primarily due to the lower viscosity of SCO, which reduces the pipeline pumping energy intensity. When diluent is returned, the difference between the pathways shrinks since the pipeline pathway requires a complete second pipeline. The effect on the rail pathway is less significant since the trains still have to return empty for the diluent without returned pathways. For rail with diluent return versus rail with

Table 6. MC Key Inputs

rail	units
diluent ratio	% vol
loco EF	gCO_2eq/L
loco fuel eff	t km/L
train speed	km/h
tank car life	y
track life	y
noninsulated tank car LW	lbs
insulated tank car LW	lbs
HEX eff	%
bit HR intlet	°C
bit HR outlet	°C
boiler eff	%
dilbit inlet	°C
dilbit outlet	°C
pipeline	**units**
SCO ν	m^2/s
dilbit ν	m^2/s
diluent ν	m^2/s
dilbit API	API
electricity EF	g/kWh
pipeline steel	kg/m^3
target velocity	m/s
elev change	m
wall thickness	in
pump eff	
pipeline life	y
both	units
bitumen API	API
SCO density	kg/m^3
diluent density	kg/m^3
steel EF	gCO_2eq/kg

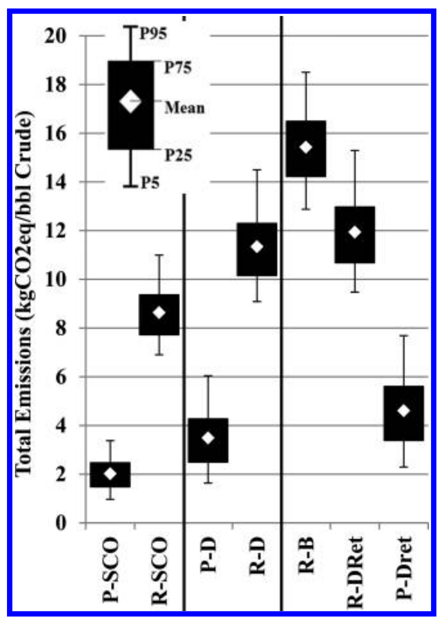


Figure 5. MC rail and pipeline total emissions distributions.

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680–691

heated bitumen, the results are less clear. Due to the high uncertainty around locomotive fuel consumption and diluent recovery emissions, it is not possible to confidently state that one method has lower emissions than the other.

The tornado diagrams from ModelRisk are in section S5.4. The results show that for the pipeline pathways, the target velocity is the dominant source of uncertainty; this is due to the high sensitivity as well as the large range of velocities analyzed (from 0.75 to 2.0 m/s). Ideally, pipelines should aim to minimize fluid velocity to reduce their emissions; however, a reduced velocity will decrease the pipeline capacity affecting the pipeline economics. For the rail scenario, the locomotive efficiency and diesel EF are the dominant sources of uncertainty, a result of high sensitivity and a wide range of values.

3.4. Comparison to Published Literature. We compared our results to those from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) and Tarnoczi models;[2,16] however, due to the different distances and capacities used, it is difficult to directly compare the results. For pipelines, the GREET model uses an aggregated pumping intensity of 404 BTU/(t mi) for all pipelines regardless of product properties, it did not consider infrastructure emissions ("t" (ton) refers to the mass of SCO/bitumen transported).[16] The energy intensity is compared to simplify the comparison and remove variation from the EF used. This study's results, converted to British thermal units per ton miles, are 25 and 49 BTU/(t mi) for the SCO and dilbit pipelines, respectively which are significantly lower than the GREET value. Further investigation found that a 100 kbpd SCO pipeline with a fluid velocity of 2.63 and 3.82 m/s had an energy intensity of 375 and 923 BTU/(t mi). Furthermore, a 100 kbpd Dilbit pipeline with a fluid velocity of 1.77 and 3.02 m/s had an energy intensity of 263 and 919 BTU/(t mi). Hence, this study's results are lower than GREET's since GREET uses aggregated data which includes lower capacity and higher velocity pipelines. The Tarnoczi dilbit pipeline energy intensities ranged from 220 to 650 BTU/(t mi). The higher ranges are a result of the higher pipeline velocities assumed. The pipelines examined carry a range of products from light crude to heavy dilbit and their specified flow rate represents the average flow rate. When we examined pipeline velocities, we found that the heavier crude pipelines operated at lower velocities, which is why the velocities are lower in this study.

For rail, GREET determines a transportation energy intensity of 274 BTU/(t mi) compared to this study's results of 276, 325, and 492 BTU/(t mi) for SCO, dilbit, and bitumen, respectively ("ton" refers to the mass of SCO/bitumen transported). The bitumen scenario is significantly higher because of the NG consumed in the DRU and at the unloading terminal. The results from Tarnoczi are lower (146−196 BTU/(t mi)) because of lower locomotive fuel use.

This studies result for P-SCO and R-B are 0.34 and 2.85 gCO_2eq/MJ. Nimana et al. found that crude transportation emissions were 1.8 and 4.3 gCO_2eq/MJ for the SCO and dilbit with diluent return scenarios, respectively, and were responsible for less than 4% of the WTW emissions.[24] While the transportation emissions are a small portion of the WTW emissions these results are still significant to regulatory bodies responsible for the approval of pipelines and crude rail systems.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b02889.

List of inputs, calculations, sensitivity analysis results, Monte Carlo input distributions and justifications, tornado plots, marine transportation methods and calculations, and drag reducing agent analysis (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Tel.: +1-780-492-7797. E-mail: Amit.Kumar@ualberta.ca (A.K.).

ORCID

Amit Kumar: 0000-0002-1746-7139

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank the NSERC/Cenovus/Alberta Innovates Associate Industrial Research Chair Program in Energy and Environmental Systems Engineering and the Cenovus Energy Endowed Chair Program in Environmental Engineering for funding the research project. The authors would like to thank the Technical Advisory Committee (TAC) for their constant input and feedback during the term of the project. The TAC included: Craig Stenhouse (Cenovus Energy Inc.), Eddy Isaacs (Alberta Innovates−Energy and Environmental Solutions), Edwin Ma (Suncor Energy), Prit Kotecha (Suncor Energy), Scott Smith (Cenovus Energy Inc.), Stan Blade (Alberta Innovates−Bio Solutions), Steve Price (Alberta Innovates−Bio Solutions), Surindar Singh (Alberta Innovates−Energy and Environmental Solutions). The authors are grateful to Eusebio Palmisano and Tim Koskowich from Cenovus Energy Inc. for their comments and opinions during the course of the study. The authors would like to thank James Auld (Canadian National), Jesse White (Canadian National), Phil Ireland (Jexi Inc.), Steve Smith (Torq Transloading Inc.), Stacy Terlecki (Canadian Pacific Railways Ltd.), Mark Stefani (GE Capital), Doug Reece (Procor Ltd.), R. Philipenko, and A. Wan (both from Enbridge Pipelines Inc.) for their help with data verification and useful inputs in various forms. The authors are thankful to Astrid Blodgett for editorial assistance in this paper. All conclusions are those of the authors and are not endorsed by either the financial sponsor of this work or the many people who offered comments and suggestions.

■ REFERENCES

(1) Government of Alberta. Alberta's current emissions. http://www.alberta.ca/climate-current-emissions.cfm (accessed December 9, 2016).

(2) Tarnoczi, T. Life cycle energy and greenhouse gas emissions from transportation of Canadian oil sands to future markets. *Energy Policy* **2013**, *62*, 107−117.

(3) Energy Resources Conservation Board. *Alberta's Energy Reserves 2012 and Supply/Demand Outlook 2013*−*2022*; 2013; http://www.aer.ca/documents/sts/ST98/ST98-2013.pdf.

(4) U. S. Energy Information Administration. *U.S. Refinery Receipts of Crude Oil by Method of Transportation*; EIA: Washington, DC, 2014; https://www.eia.gov/dnav/pet/pet_pnp_caprec_dcu_nus_a.htm.

(5) Johnson, T. Pipes vs. trains: Which is better for moving oil? *CBC News* March 10, 2015; http://www.cbc.ca/news/business/pipelines-vs-trains-which-is-better-for-moving-oil-1.2988407.

(6) Fingas, M. Diluted bitumen (dilbit): A future high risk spilled material. Presented at the Interspill, Amsterdam, March 23−26, 2015.

(7) Canadian Association of Petroleum Producers. *Canada's Oil Sands Overview and Bitumen Blending Primer*; Segato102312; U.S. National Academy of Science, 2012; http://onlinepubs.trb.org/onlinepubs/dilbit/Segato102312.pdf.

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

(8) Canadian Heavy Oil Association. Heavy Oil 101. Presented at the Heavy Oil Confrence & Exhibition, Latin America, 2013.
(9) Keesom, W.; Unnasch, S.; Moretta, J. *Life Cycle Assessment Comparison of North American and Imported Crudes prepared for Alberta Energy Research Institute*; AERI 1747; Jacobs Consultancy: Chicago, IL, 2009; eipa.alberta.ca/media/39640/life%20cycle%20analysis%20jacobs%20final%20report.pdf.
(10) Choquette-Levy, N.; MacLean, H. L.; Bergerson, J. A. Should Alberta upgrade oil sands bitumen? An integrated life cycle framework to evaluate energy systems investment tradeoffs. *Energy Policy* **2013**, *61* (0), 78−87.
(11) Bergerson, J. A.; Kofoworola, O.; Charpentier, A. D.; Sleep, S.; MacLean, H. L. Life cycle greenhouse gas emissions of current oil sands technologies: surface mining and in situ applications. *Environ. Sci. Technol.* **2012**, *46* (14), 7865−7874.
(12) Brandt, A. R. *Upstream Greenhouse Gas (GHG) Emissions from Canadian Oil Sands as a Feedstock for European Refineries*; Stanford University: Stanford, CA, 2011; https://circabc.europa.eu/d/d/workspace/SpacesStore/db806977-6418-44db-a464-20267139b34d/Brandt_Oil_Sands_GHGs_Final.pdf.
(13) Rosenfeld, J.; Pont, J.; Law, K.; Hirshfeld, D.; Kolb, J. *Comparison of North American and Imported Crude Oil Lifecycle GHG Emissions - Final Report Prepared for Alberta Energy Reseach Institute*; TIAX Case No. D5595; TIAX LLC: Cupertino, CA, 2009; http://eipa.alberta.ca/media/39643/life%20cycle%20analysis%20tiax%20final%20report.pdf.
(14) Lattanzio, R. K. *Canadian Oil Sands: Life-Cycle Assessments of Greenhouse Gas Emissions*; R42537; Congressional Research Service: Washington, DC, 2014; https://www.fas.org/sgp/crs/misc/R42537.pdf.
(15) Brandt, A. R. Variability and uncertainty in life cycle assessment models for greenhouse gas emissions from Canadian oil sands production. *Environ. Sci. Technol.* **2012**, *46* (2), 1253−1261.
(16) *GREET1*; Argonne National Laboratory: Argonne, IL, 2013; https://greet.es.anl.gov/.
(17) Pootakham, T.; Kumar, A. A comparison of pipeline versus truck transport of bio-oil. *Bioresour. Technol.* **2010**, *101* (1), 414−421.
(18) Giannouli, M.; Samaras, Z.; Keller, M.; deHaan, P.; Kallivoda, M.; Sorenson, S.; Georgakaki, A. Development of a database system for the calculation of indicators of environmental pressure caused by transport. *Sci. Total Environ.* **2006**, *357* (1−3), 247−270.
(19) Horvath, A. Environmental assessment of freight transportation in the U.S. *Int. J. Life Cycle Assess.* **2006**, *11* (4), 229−239.
(20) Craig, A. J.; Blanco, E. E.; Sheffi, Y. Estimating the CO2 intensity of intermodal freight transportation. *Transportation Research Part D: Transport and Environment [Online]* **2013**, *22*, 49−53.
(21) Facanha, C.; Horvath, A. Evaluation of life-cycle air emission factors of freight transportation. *Environ. Sci. Technol.* **2007**, *41* (20), 7138−7144.
(22) Gordon, D.; Brandt, A.; Bergerson, J.; Jonathan, K. *Know Your Oil: Creating a Global Oil-Climate Index*; Carnegie Endowment for International Peace: WA, 2015; http://carnegieendowment.org/files/know_your_oil.pdf.
(23) Cai, H.; Brandt, A. R.; Yeh, S.; Englander, J. G.; Han, J.; Elgowainy, A.; Wang, M. Q. Well-to-Wheels greenhouse gas emissions of Canadian oil sands products: Implications for U.S. petroleum fuels. *Environ. Sci. Technol.* **2015**, *49* (13), 8219−8227.
(24) Nimana, B.; Canter, C.; Kumar, A. Life cycle assessment of greenhouse gas emissions from Canada's oil sands-derived transportation fuels. *Energy* **2015**, *88*, 544−554.
(25) TransCanada. Energy East Pipeline Project. http://www.transcanada.com/energy-east-pipeline.html (accessed January 7, 2016).
(26) Goverment of Canada. *Estimated Canadian Crude Oil Exports by Type and Destination*; National Energy Board: Ottowa, ON, 2014; https://apps.neb-one.gc.ca/CommodityStatistics/Statistics.aspx?language=english.
(27) Goverment of Canada. *2014 Canadian Crude Oil Exports - By Export Transportation System Summary - 5 year trend*; National Energy Board: Ottowa, ON, 2015; https://www.neb-one.gc.ca/nrg/sttstc/crdlndptrlmprdct/stt/cndncrdlxprttrnsprttnsstm5yr/2014/cndncrdlxprttrnsprttnsstm5yr2014-eng.html.
(28) International Organization for Standardization. *Environmental management--Life cycle assessment--Principles and framework*, ISO 14040; 2006; http://www.iso.org/iso/catalogue_detail?csnumber=37456.
(29) *ModelRisk Software*, 5.3; Vose: Belgium, 2015; http://www.vosesoftware.com/.
(30) Lewis, J. Diluent shortages could make for sticky situation for Alberta bitumen. *National Post* May 23, **2013**; http://www.nationalpost.com/m/wp/tag/blog.html?b=business.financialpost.com/m/m/2013/05/23/diluent-shortages-could-make-for-sticky-situation-for-alberta-bitumen.
(31) Canadian Association of Petroleum Producers. *Transporting Crude Oil by Rail in Canada*; CAPP: Calgary, Canada, 2014; www.capp.ca/~/media/capp/customer-portal/documents/242427.pdf.
(32) Goverment of Canada. *Estimated Canadian Crude Oil Exports by Type and Destination*; National Energy Board: Ottowa, ON, 2015; www.capp.ca/~/media/capp/customer-portal/documents/242427.pdf.
(33) Enbridge Pipelines Inc. *Q2 2015 Service Levels On the Enbridge Liquids Pipeline Mainline Network*; Enbridge: Calgary, AB, 2015; http://www.enbridge.com/~/media/www/Site%20Documents/Delivering%20Energy/Shippers/Enbridge_Mainline_Service_Levels.pdf?la=en.
(34) Regulator, A.E., ST98: Pipelines. https://www.aer.ca/data-and-publications/statistical-reports/pipelines (accessed Oct. 26, 2016).
(35) Netzer, D. *Alberta Bitumen Processing Integration Study*; 158261; The Alberta Energy Institute: Edmonton, AB, 2006; http://www.assembly.ab.ca/lao/library/egovdocs/2006/alet/158261.pdf.
(36) Transportation Research Board. *Effects of Diluted Bitumen on Crude Oil Transmission Pipelines*; TRB Special Report 311; National Academy of Sciences: Washington, DC, 2013; https://www.nap.edu/catalog/18381/trb-special-report-311-effects-of-diluted-bitumen-on-crude-oil-transmission-pipelines.
(37) Xing, X.; Dou, D.; Wu, C. Engineering-economic analysis of pipeline transportation of waxy crude oil in China. Presented at the International Conference on Pipelines and Trenchless Technology, Beijing, China, October 26−29, 2011.
(38) Nesbitt, B. Flow of Liquids. In *Handbook of Pumps and Pumping: Pumping Manual International*; 1st ed.; Elsevier Science: Oxford, U.K., 2006; pp 95−124.
(39) Sutherland, B.; Van Vliet, D.; Dohan, K.; Moodie, T. *Interfacial Mixing in Viscous Pipe Flows Final report to Imperial Oil*; Department of Mathematical Sciences, University of Alberta: Edmonton, AB, 2000; http://www.ualberta.ca/~bsuther/papers/pipe/finalrep.pdf.
(40) Abdel-Aal, H. K.; Aggour, M. A.; Fahim, M. A. *Petroleum and Gas Field Processing*; 2nd ed.; CRC Press: Baco Raton, FL, 2015.
(41) American Petroleum Institute. *API 5L: Specification for Line Pipe*; 49 CFR 192.113; American Petroleum Institute: Washington, DC, 2004; https://law.resource.org/pub/us/cfr/ibr/002/api.5l.2004.pdf.
(42) White, F. M. *Fluid Mechanics*; 7th ed.; McGraw-Hill: New York, 2011.
(43) Wikipedia, Houston. https://en.wikipedia.org/wiki/Houston (accessed December 4, 2015).
(44) Wikipedia. Edmonton. https://en.wikipedia.org/wiki/Edmonton#cite_note-6 (accessed December 4, 2015).
(45) Colfax. *Crude Oil Transport Pumps*; BR000CTP_04; Colfax: Monroe, NC. http://www.imo-pump.com/brochures/BR000CTP_04.pdf (accessed December 9, 2016).
(46) Campell, J. M. *Gas Conditioning and Processing*; Campell Petroleum Series: Norman, OK, 1984; Vol. 2: The Equipment Modules.
(47) *Pipeline Transportation Pumps*; Bulletin FPD-8d (E); Flowserve: Irving, TX, 2015; http://www.flowserve.com/files/Files/Literature/ProductLiterature/Pumps/fpd-8-e.pdf.
(48) Karassik, I. J.; Messina, J. P.; Cooper, P.; Heald, C. C. 2.1 Centrifugal Pump Theory. In *Pump Handbook [Online]*, 4th ed.; McGraw Hill Professional: New York, 2015; http://accessengineeringlibrary.com/browse/pump-handbook-fourth-edition.
(49) Manning, F. S.; Thompson, R. E. *Oilfield Processing of Petroleum: Crude Oil*; PennWell Books: Tulsa, OK, 1995; Vol. 2.

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691

(50) Vermeer. T1255 COMMANDER 3 Track Trencher. http://www.vermeer.com.au/new-equipment-details.php?ProductID=152&CategoryID=66 (accessed January 26, 2016).

(51) Cherrington, M. Vermeer Trencher Help Keeps Queensland Pipeline Ahead. http://www.vermeer.com/TrenchlessEquipment/JobStoriesModel.jsp?PrdlnID=3604&ModID=14449&NewsID=10929 (accessed September 17, 2013).

(52) Stocker Concrete Company, 8 in. Concrete Blocks. http://www.stockerconcrete.com/new8inchblock.htm (accessed September 23, 2015).

(53) UnionPacific, Union Pacific Crude Oil Origin Facilities. http://www.up.com/customers/chemical/crude/origin_facilities/index.htm (accessed December 15, 2015).

(54) Stripple, H.; Uppenberg, S. *Life Cycle Assessment of Railways and Rail Transports*; B1943; Swedish Environmental Research Institute: Göteborg, 2010; http://www.ivl.se/download/18.343dc99d14e8bb0f58b75d4/1445517456715/B1943.pdf.

(55) Nicolussi, M. L. *A Brief Introduction to Locomotive Application*; vNERR, 2000; http://www.vnerr.com/training/intro_loco_app.pdf.

(56) Transportation Division: Multimodal Transport Section. *Rail in Canada*; 52-216-X; Statistics Canada: Ottowa, ON, 2009; http://www.statcan.gc.ca/pub/52-216-x/52-216-x2009000-eng.pdf.

(57) Surface Transportation Board. *STB Consolidated Rail Service Performance Data Spreadsheet*; EP 724; U.S. Department of Transportation: Washington, DC, 2015; http://www.stb.dot.gov/stb/railserviceissues/rail_service_reports.html#loaded.

(58) Molaro, G.; Perry, G. F. Dual Purpose Bitumen/Diluent Railroad Tank Car. Patent US20100122641 A1, May 20, 2010.

(59) Cambridge Systematics Inc. *National Rail Freight Infrastructure Capacity and Investment Study prepared for Association of American Railroads*, AAR2007; Cambridge Systematics Inc: Cambridge, MA, 2007; http://www.nwk.usace.army.mil/Portals/29/docs/regulatory/bnsf/AAR2007.pdf.

(60) Stark, C. *Reducing Energy Cost Through Boiler Efficiency*; Department of Poultry Science North Carolina State University: Raleigh, NC, 2015; https://www.ncsu.edu/project/feedmill/pdf/E_Reducing%20Energy%20Cost%20Through%20Boiler%20Efficiency.pdf.

(61) Energy Technology Systems Analysis Program. *Industrial Combustion Boilers*; International Energy Agency: Paris, FR, 2010; http://iea-etsap.org/E-TechDS/PDF/I01-ind_boilers-GS-AD-gct.pdf.

(62) Council of Industrial Boiler Owners. *Energy Efficiency & Industrial Boiler Efficiency: An Industry Perspective*; Council of Industrial Boiler Owners: Warrenton, VA, 2015; https://www.energyvortex.com/files/EnergyEfficiencyWhitePaper_3-25-03.pdf.

(63) *Boiler Efficiency Guide: Facts about Firetube Boilers and Boiler Efficiency*; Cleaver Brooks: Thomasville, GA, 2010; http://www.cleaver-brooks.com/reference-center/insights/boiler-efficiency-guide.aspx.

(64) Baumgartner, J. P. *Prices and Costs in the Railway Sector*; Laboratoire d' ntermodalité des Transports Et de Planification: Bâtiment, GC, 2001; http://litep.epfl.ch/files/content/sites/litep/files/shared/Liens/Downloads/Divers/Baumgartner_Couts_chf_2001_e.pdf.

(65) Humphreys, S. Economic outlook brightens For pipeline coating developments. *Pipeline & Gas J.* **2010**, *237* (6), 1. http://www.pipelineandgasjournal.com/economic-outlook-brightens-pipeline-coating-developments.

(66) *The State of the National Pipeline Infrastructure*, PHC_103111; U.S. Department Of Transportation: Washington DC, 2015; http://opsweb.phmsa.dot.gov/pipelineforum/docs/Secretarys%20Infrastructure%20Report_Revised%20per%20PHC_103111.pdf.

(67) *eGRID 2012 Summary Tables*; US EPA: Washington, DC, 2012; http://www.epa.gov/energy/egrid-2012-summary-tables.

(68) *National Inventory Report: Part 3*; Goverment of Canada: Ottowa, ON, 2015; http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8812.php.

(69) Olateju, B.; Canter, C.; Radpour, S.; Nimana, B.; Verma, A.; Rahman, M.; Vaezi, M.; Kumar, A. *Transportation of Bitumen/SCO by Rail and Pipeline*; Department of Mechanical Engineering, University of Alberta: Edmonton, AB, 2013.

(70) SteelConstruction.info, Recycling and reuse. http://www.steelconstruction.info/Recycling_and_reuse (accessed December 15, 2017).

(71) Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; Nakajima, T.; Robock, A.; Stephens, G.; T, T.; Zhang, H. Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., V, B., Midgley, P. M., Eds.; Cambridge University Press: Cambridge and New York, 2013; http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf (accessed Nov. 15, 2016).

DOI: 10.1021/acs.est.6b02889
Environ. Sci. Technol. 2017, 51, 680−691