Group Project: <u>Sustainability Assessment of Older Established and Newly Constructed Natural Gas Pipelines and Ground Transportation Alternatives</u>

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Authors' Note

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Abstract

Since the 1950s, global fuel consumption had shifted from an oil and coal dominated duopoly to one that was powered by natural gas in addition to oil and coal (Ritchie et al., 2022). This shift was driven by global efforts to reduce greenhouse gas (GHG) emissions as natural gas served as a clean and efficient fuel source for electricity generation (Williams Companies, 2021). Natural gas remained to serve as an intermediary energy source to strengthen the resilience of our electrical grids as the world continued its transition towards renewable energy sources (Williams Companies, 2021). With the demand for natural gas growing, combined with the increasing need to transport gas over long distances from isolated natural gas extraction sites to their customers, the transportation methods for natural gas can be analyzed to improve its efficiency and sustainability. Currently, the most used transportation methods over land are pipelines and ground transportation. These two methods will be analyzed based on the technical, environmental, economic, and societal dimensions of sustainability in this sustainability assessment.

Introduction

In this sustainability assessment, the use of natural gas transmission pipelines and the use of ground transportation to transport natural gas over land is analyzed. The two methods will be assessed based on the four sustainability dimensions mentioned. A streamlined life cycle assessment (SLCA) will be conducted to evaluate the impacts associated with each alternative method. The SLCA is selected by the team instead of conducting a full-scale life cycle assessment (LCA) due to time constraints and the lack of access to expensive software and databases. An SLCA retains the same breadth and approach as a full-scale LCA but with a simplified process that greatly improves its overall efficiency (Reddy et al., 2019). The multicriteria decision analysis (MCDA) matrix is used to rank each alternative against the indicators and dimensions. Finally, an uncertainty analysis will be conducted based on the sequential perturbation approach for calculating uncertainties (Manteufel, 2012). This method is selected because it greatly reduces the tedious nature of the calculations (Manteufel, 2012). In addition, the team is most familiar with this method, as it is commonly applied in thermo-fluid applications. The results gained from this procedure will provide information on uncertainties obtained for the scoring and ranking of various indicators selected by the team for the assessment.

The team recognizes that within the Canadian natural gas transportation network, there are newly constructed pipelines that have been operational since the 1950s (Government of Canada, 2022). Hence, it is expected that the pipelines constructed at different times will vary in performance and construction methods. For example, the methods used for corrosion protection will differ, including the use of coating materials which directly affects the pipeline's ability to resist corrosion, and therefore mitigate pipeline leaks and failure (Senkowski, 2016). To consider these differences in the sustainability assessment, the Canadian Mainline, commenced operations in 1958 (Government of Canada, 2022), and the Nova Gas Transmission Ltd. (NGTL) Grande Prairie South Area Expansion pipeline constructed to commence service in 2021 to 2022 (Press, 2020) are used as the two pipeline transportation alternatives.

Our team selects rail and road liquefied natural gas (LNG) transportation as the ground transportation alternatives to be assessed after reading an investigation carried out by Hart & Morrison (2015). The team learns that ground transportation, including the use of road and rail transport, has been often credited lately by critics as the new preferred energy transportation method as opposed to the use of conventional pipelines for the transportation of fossil fuels (Krosofsky, 2021). Pipelines have also become a controversial topic in Canada with various communities that have been opposed to the construction and development of pipeline projects based on the merit that they can negatively impact the surrounding environment. In this sustainability assessment, the two ground transportation methods will be further analyzed and compared to their pipeline counterparts. This will be achieved by examining the rankings for each alternative transportation method generated from the sustainability assessment.

Project Alternatives

The team selects the Canadian Mainline as the project alternative to represent existing natural gas pipelines currently still in use. The line is approximately 14,120 km long (Government of Canada, 2022a) and up to 48 inches in diameter as shown in Figure 1 in Appendix A1. The line was constructed in the 1950s, and natural gas pipelines constructed during this time used pipeline steel combined with the application of asphalt and polyethylene tape (p-tape) coatings (Wilson, 2020). This line is selected because with an older line to choose from, there is more data and metrics that can be used by the team to compare the differences in the pipeline's performance relative to newer pipelines. For example, key information on the construction, operation, and maintenance of the Canadian Mainline can be obtained from the publicly available Canadian Mainline regulatory documents (facilities) Folder 90715 on the Canada Energy Regulator (CER) webpage (Government of Canada, 2022).

From the late 1980s, the use of fusion bonded epoxy (FBE) coatings became more widespread in the pipelines industry (Wilson, 2020). These coatings were found to better adhere to the pipeline steel and thus provided excellent corrosion control (Wilson, 2020). This proved to be a game changer to the pipelines industry as external corrosion was greatly reduced after the application of the coating and hence improved the pipeline's integrity and lifespan (Wilson, 2020). FBE coatings continue to be the preferred option and are still applied to pipelines manufactured today, including the NGTL Grande Prairie South Area Expansion pipeline. By selecting the NGTL Grande Prairie South Area Expansion pipeline as the other pipeline alternative, the option offers the best contrast when comparing to the older Canadian Mainline pipeline alternative. The NGTL Grande Prairie South Area Expansion pipeline is approximately 344 km in length and 48 inches in diameter (TC Energy, n.d.). Like the Canadian Mainline, information related to the construction, operation, and maintenance of the NGTL pipeline can be found from the NGTL regulatory documents Folder 554112 on the CER webpage (Government of Canada, 2022). A map of the pipeline is provided in Figure 2 in Appendix A1 for reference.

For examining the application of ground transportation of natural gas, the team selects the use of rail and road as our two ground transportation alternatives. In both ground transportation methods, the natural gas must first be liquified which will reduce its volume by a factor of 1/600 (Government of Canada, 2020). This allows the gas to be transported in greater volumes over longer distances economically (Government of Canada, 2020). The LNG is then pumped into a chain of tanker rail cars for the purposes of rail transport, or into LNG tanker trucks for road transport, respectively. These two methods of transportation will be compared to the pipeline alternatives in the context of the four sustainability dimensions. The sustainability tools and indicators that will be applied to conduct this analysis will be discussed in the following methodology section.

Methodology

To choose the best alternative amongst the pipeline options and the ground transportation methods, the team has decided to do an SLCA. This is performed on both pipelines, which are the Canadian Mainline and the NGTL Grande Prairie South Area Expansion pipeline, along with the ground transportation alternatives, which are by road and rail. The team opted to create two models and to choose the best option among them by utilizing an SLCA to help model the stages of the pipeline alternatives. This in turn is used to develop the scoring and ranking indicators for the MCDA tables developed further in the assessment. These pipelines are devised into Model 1 for the pipelines, and Model 2 for the ground transportation methods. The SLCA for both models are included in Figures 3 and 4 respectively in Appendix A1. In the SLCA, the transportation efficiency for both alternatives is determined. Furthermore, uncertainty analysis is used to visualize uncertainties in the ranking process.

Based on the team's previous experience, transportation of natural gas, which is predominately methane (CH_4), can be categorized into eight processes which are illustrated in the SLCA. As shown in Figure 3 in Appendix A1, the fluid enters from P1 to P8 and in each process. The gas is then injected into the inlet injection station and into the compressor station, P2. Compressor stations regulate the standard pressure of the natural gas pipeline to achieve the maximum rate of fluid flow. Partial delivery station P3 is used to regulate the partial flow of gas and is then sent off to station P4, which acts as a safety station to control any pipeline leaks. If a leak is detected, the gas flow can be stopped to prevent accidents. If all the safety standards are met up to station P4, then the gas is sent to station P5, which is the regulator station. The regulator station sends the gas out for final delivery, which also serves as the contact point between the consumer and source for the purposes of this assessment.

The indicators for the SLCA are determined by the team based on the effect it poses on the transportation of natural gas through the pipelines. The indicators chosen are the diameter of the pipes, the material used to construct the pipes, the length of the pipelines, the pressure of the pipelines and the flow rate of gas. Diameter is chosen as it can determine the pressure and flow rate of the gas as it is being transported (White, 2016). Typically, smaller diameters will reduce pressure and lessen the flow rate for the same volume of gas transported (White, 2016). Hence, larger pipe diameters can handle higher volumes of gas relative to pipes with smaller diameters at any given instance, however, the stress and strain imposed on the pipe will increase as the pipe is further pressurized (White, 2016).

Older pipelines, such as the Canadian Mainline, are prone to corrosion. Cracks can form over time from pits and manufacturing, which can lead to the leakage of gas and fail the pipe (Cheng, 2013). In newer pipelines, such as the NGTL Grande Prairie South Area Expansion pipeline, cracks can also occur, but more commonly due to manufacturing defects as corrosion is a time dependent process (Cheng, 2013). Based on the team’s experience, the natural gas can also include certain quantities of sulphur, carbon dioxide, and water, which can contribute to corrosion. The combination of the tensile stress exerted by the gas can also lead to environmental induced cracking of the pipeline steel (Cheng, 2013). Hence, the pipeline’s resilience is key to ensuring the preservation of wildlife, mitigating explosions, and safeguarding communities living near the pipeline (Cheng, 2013). Thus, the manufacturing technique used to construct the pipeline must be considered for determining the pipeline’s service life (Cheng, 2013). As natural gas is predominately CH_4, which is a GHG, leaks are reflected in the emissions factor. The length of pipe is also important to be considered so the team can measure each alternative's performance on a per kilometre basis. Thus, the team is assessing pressure, flow rate of gas, the pipe material, emissions factor, pumping capacity, and maintenance as our indicators for the MCDA.

The values corresponding to the indicators mentioned can be determined from fluid dynamics and thermodynamics principles. The steps used to calculate each value is included under Appendix A2. From these relations, the flow rate, velocity of gas and pressure can be deduced based on the data extracted from the CER webpage. By determining the flow rate, we can also determine the type of gas flow, for instance if the flow is laminar or turbulent (White, 2016). The formula for the Reynold's Number can be used to achieve this and is included in Appendix A2 (Engineering Clicks, 2017). Similarly, the hydraulic diameter can be determined using the equation also presented in Appendix A2 (Engineering Clicks, 2017). To assess the parameters, two models are developed. The first model analyzes the indicators and parameters for the Canadian Mainline and the NGTL Grande Prairie South Area Expansion pipelines. The results are tabulated for each stage of the pipeline's development, including the inlet and compressor stations, partial delivery stage, block valve stations, regulator stations, and finally the delivery stations to deliver the gas to consumers. The table is used to assign a preference score to each indicator or category and will be helpful in deducing the best alternative. The results of the MCDA are summarized in Tables 1 and 2 in Appendix A1. From the MCDA table for Model 1, the team can compare both the pipeline alternatives based on the indicators. Model 2 is devised to compare rail and road transportation options for shipping natural gas. Both the pipeline and ground alternatives share a few common indicators such as distance, cost of maintenance, revenue generated and emissions intensity. As the cost of maintenance is directly proportional to the number of compressor stations and the length of the pipeline, this value is qualitatively determined by taking these relationships into consideration. Similarly, emissions intensity is also determined qualitatively based on its proportionality with the number of compressor stations.

Proportionality relationships are also used to determine qualitative values for Model 2. Ground transportation methods also incur additional costs involved with the conversion of natural gas between phases and are also limited by the maximum quantity of natural gas that can be carried per vehicle. In rail and road transport, the natural gas pumped from storage facilities must first be converted into LNG so it can be transported in higher quantities in cylinders. This is performed in process P2 as illustrated in Figure 4 in Appendix A1. After the phase conversion, the LNG is loaded onto trucks or rail cars. Lastly, once loaded onto the truck or rail car, it is distributed to another facility where it will be converted back to a gaseous state. The gas will then be transported further to reach local communities. Once the preferred alternative from both models is found, the two preferred alternatives from each model are compared.

Finally, uncertainty analysis is performed on Models 1 and 2 using the sequential perturbation approach to find the absolute uncertainties for the alternatives. Sensitivity is also found to highlight how each indicator impacts ranking uncertainties. First, the mean values are calculated, followed by calculating the absolute uncertainty of each indicator by multiplying the preference score with its relative uncertainty. A value of 1 to 2 % is used for relative uncertainty, upon which a matrix with the indicators is created. Elements in the matrix not along the diagonal are the mean values, whereas the ones along the diagonal represent the sum of the mean. The variable R is found based on the procedure illustrated in Appendix A2. The difference between all the R values is determined, then squared, and finally summated. The absolute uncertainty for the model or alternative is deduced after taking the square root of the summation. To find the sensitivity for each indicator, the square of the difference between each R value is found and dividing it by the uncertainty gives insight into how much the indicator affects the overall uncertainty. These procedures are performed for alternative 2 of Models 1 and 2 and the results are presented in Tables 3 and 4 in Appendix A1.

Results and Discussion

Merits and Demerits of Each Alternative

Based on the assessment results, the merits, and demerits of each of the project alternatives are discussed and assessed against the technical, environmental, economic, and societal dimensions used in sustainability assessment. The **merits** of each project alternatives when measured against the four sustainability dimensions are discussed below:

The technical dimension merit for the NGTL Grande Prairie South Area Expansion pipeline is that it uses new pipeline steel manufactured using modern steel making processes and the latest construction technologies. These factors reduce the likelihood of manufacturing and construction defects. The Canadian Mainline, however, was constructed using technologies, such as, asphalt coating, and was designed based on non-destructive examination requirements deemed obsolete today. These factors lead to a higher probability of failure as the pipeline is prone to manufacturing and construction defects (Nanney et al., 2012). Therefore, we can use the learnings obtained from each pipeline to find the best solution for addressing the threat of manufacturing and construction defects on existing operational assets. The merit of ground transportation is that it uses pressure vessel technology for transportation and is helpful to assess other pressure vessels on the facilities that are either used to inject or store gas.

The environmental dimension merit for the NGTL Grande Prairie South Area Expansion pipeline is that it will supply gas from the Western Canadian Sedimentary Basin (WCSB) to natural gas markets (TC Energy, n.d. -a), whereas the Canadian Mainline supplies gas to Eastern Canada (TC Energy, n.d. -b). Both projects help Canada decrease our dependence on traditional non-renewable sources of energy, such as, coal and oil, and will thus lower our overall GHG emissions and helping us achieve net-zero emissions by 2050. However, transporting the fuel by truck or rail is found to have a lower carbon footprint and GHG emissions when the gas is transported over shorter distance to rural communities compared to the use of pipelines (Rajnauth et al., 2008).

The economic dimension merit for the NGTL Grande Prairie South Area Expansion pipeline is that, in addition to the new pipeline, it uses existing infrastructure including facilities, gathering system, and the transmission system, to deliver gas system from the WCSB to natural gas markets efficiently and at a reduced cost. These elements make the construction of the pipeline economically viable. The Canadian Mainline built in 1950s, however, delivers gas from existing markets to the province of Ontario, and rebuilding infrastructure of a similar scale will be one of the largest and most expensive projects to be undertaken in North America. Consequently, the pipeline maintains its economic viability even today. However, transportation by rail and road is also economically viable to some extent as they also use existing infrastructure for transporting gas over short distances (Green et al., 2015).

The societal dimension merit for the NGTL Grande Prairie South Area Expansion pipeline and Canadian Mainline is the tax generation for local municipalities and job creation for locals and indigenous groups. Other societal merits for both the pipeline alternatives are that they can deliver gas to remote local communities which lie along the pipeline's route. This can encourage the communities to transition towards using a less carbon intensive energy source, such as natural gas in place of coal or oil. Similarly, the benefits of transporting natural gas by rail and road are the tax generation benefits for local municipalities and job creation for locals and indigenous groups. An additional benefit of transporting gas by road or rail is the ability to deliver gas in emergency situations to remote communities.

Summarized below are the **demerits** for the project alternatives against the four dimensions:

The technical dimension demerit for the NGTL Grande Prairie South Area Expansion pipeline and the Canadian Mainline are the fact that they are only efficient when transporting natural gas at high pressure for long distances, as additional equipment is required for pressure cut to deliver to facilities along the pipeline route. The technical dimension demerit for ground transportation is the lower throughput allowed as the gas pressure that can be transported over short distances is limited when compared to the use of pipeline transportation (Green et al., 2015).

The environmental dimension demerit for the NGTL Grande Prairie South Area Expansion and the Canadian Mainline are the fugitive emissions release from valves and natural gas releases during a facility blowdown for maintenance activities. Ground transportation options, however, has found to contribute to even higher GHG emissions than both the pipeline alternatives described in the paper when compared based on the per volume of gas transported.

The economic dimension demerit for the NGTL Grande Prairie South Area Expansion and Canadian Mainline, are the large financial capital required to complete a similarly scaled project and the additional cost over-runs in today's environment due to the COVID-19 pandemic and inflation (Nunan, n.d.). The economic dimension demerit for ground transportation is the significant upfront capital cost to procure the rail cars and trucks to transport the same amount of gas when compared to pipelines.

The societal dimension demerit for both pipelines is that public demonstrations have shown society's resentment over the use of liquid pipelines and have also increased the risk of undertaking new natural gas transmission pipeline projects (Paul, 2022). This is despite that natural gas pipelines are known to contribute to a lower risk to the environment when compared to liquid pipelines. Whereas for ground transportation, society demands incidents such as the Lac Magnetic rail disaster be avoided (Murphy, 2018), and thus limits the amount of gas that can be transported at a given time.

Alternative Scoring and Ranking

The team aims to establish a concrete scoring and ranking system between the chosen alternatives of the assessment. This is done using analysis of the sustainability indicators and the four dimensions of sustainability. Sustainability indicators provide key variables and ways to evaluate the degree of sustainability for specific engineering projects or processes (Reddy et al., 2019). It is noted that the sustainability indicators alone are not easily measurable, however, by integrating numerical values or quantitative characteristics, a more accurate and objective assessment can be done (Reddy et al., 2019).

The team has opted for the use of an MCDA, chosen because it combines indicators and metrics from various dimensions into a single indicator or smaller sub-set group of indicators (Thiessen, 2022). As discussed earlier, the assessed pipeline alternatives are the Canadian Mainline, and the NGTL Grande

Prairie South Area Expansion pipeline. Analyzing the aspects of ground transportation by means of rail and road for transporting natural gas are also considered as primary alternatives to discuss along with the four dimensions. When comparing these, there are clear advantages and disadvantages that may exist, for instance, the movement of goods and resources by rail continues to gain prominence as a more efficient, GHG friendly mode of transportation (Railway Association of Canada, 2016). GHG emissions calculated for the example that focuses on a truck that travels 1000 miles with 20 short tons of cargo, is found to emit 3.24 metric tons for one move, while it is found that the average freight truck emits 161.8 grams of carbon dioxide per ton-mile (Environmental Defense Fund, 2021). In Canada, more recent data suggests average rail-truck fuel efficiency ratios of 3.7, with circuity considered, and 3.9 without circuity considered (Railway Association of Canada, 2016). This provides a basis for ranking the alternatives against the environmental dimension and helps quantify the merits in utilizing rail instead of road transportation.

The metrics are summarized in an MCDA, with indicators for pressure, flow rate, pipeline material, pipe length, emissions intensity and pumping capacity used as the main indicators of ranking the pipeline alternatives. For road and rail, indicators include the distance, emissions intensity, cost of phase conversion, and maximum quantity of LNG for each truck or train car. Due to the differences in the chosen indicators between the alternatives, two models are created, one for the pipeline alternatives, and the other for the ground transportation. Scoring is performed on a scale out of 5 to allow for the selection of the most optimal alternative from both models. This scale was chosen because it offers a shorter range of values to help classify the indicators (e.g., 1=poor, 2=limited, 3=satisfactory, 4=good, and 5=excellent). The scores are assigned qualitatively based on the respective values in Tables 1 and 2. The total scores are added for each indicator and alternative, with a summation index calculated. The alternative that is found to have a higher index score is chosen to be the preferred option.

For the economic dimension, it is important to compare the metrics related to the costs associated with each pipeline. As an insight, the NGTL expansion project experienced an estimated investment of $1.3 billion (Verdict Media Limited, n.d.). Being one of the biggest natural gas transmission systems operated by TC Energy, the organization aims at adding 130 kilometres in pipeline in five separate sections throughout Alberta (Verdict Media Limited, n.d.). In Model 1 of the MCDA, revenues for each pipeline are tabulated in Table 1 of Appendix A1, which helps to provide an insight into the influences of the pipeline's productions from an economic perspective. Costs will play a big role when it comes to Model 2 as well, where the costs to convert between the gas phases, and maintenance costs, are assessed in a more subjective manner. The indicators are categorized by their impacts on the source to consumers, and the percentage of GHG produced per factor. Instead of obtaining concrete values for the indicators, they are assigned as either having a 'more', 'less', or a negligible amount, due to the limitations of obtaining more accurate and up-to-date cost information. The results are summarized in Table 2 of Appendix A1.

From the technical and environmental perspective, it shall be noted that LNG, when discussing the scalability of shipping and transportation, assumes each ton of payload transported via rail or road to hold a value of 2.36 cubic metres of LNG (Riviera, n.d.), as shown in Table 2 in Appendix A1. According to the article published by the Railway Association of Canada (2016), each truck load is assumed to transport 16,000 tonnes of LNG, which is equivalent to just less than 38,000 cubic metres of natural gas. Table 2 summarizes emission intensity as a parameter to assess the environmental impacts from ground transportation. For assigning a score, information is obtained which assumes moving freight by rail instead of truck will have a positive effect on emissions, where 75% of GHG emissions are reduced (Twin Cities & Western Railroad Company, 2019). This is reflected in Table 2, where the average emission intensity of grams of carbon dioxide per kilometre for rail is chosen as 112 grams (Nicolai, 2020), and the value for transportation by truck is calculated as 75% of the rail value, resulting in 84 grams of carbon dioxide per kilometre. Lastly, in Table 1, the emissions from the NGTL pipeline for instance are much higher due to quantity of compressor stations, whereas for rail transportation in Table 2, the emissions are reduced.

For the societal dimension, the ranking focuses on health and safety as primary indicators to rank for the alternatives. In the study by Hart & Morrison (2015), the societal risk of transporting LNG by road and rail is compared to those associated with the transportation of liquefied petroleum gas (LPG). Hart & Morrison (2015) concluded that the risk profiles for transporting the LNG and LPG via the two transportation methods were similar. However, rail transportation was found to yield a higher safety risk than road transportation due to the greater volumes of tank cars used (Hart & Morrison, 2015). For the pipeline alternatives, an important consideration deals with findings from the transportation safety board (TSB) of Canada. Statistical summaries taken over a 10-year period revealed 111 average yearly number of occurrences involving pipelines (Green & Jackson, 2015). Thus, it is important to include these indicators in Table 1, which addresses emission intensity as being higher or lower when comparing the Mainline and NGTL pipeline to assign a score. This directly impacts societal aspects, as pipeline leaks and GHG emissions to the surroundings are detrimental to those living in proximity. When combined with the other previously summarized indicators for pipeline characteristics such as flow rate, pressure, distance, diameter, and transportation capacity, this will help to address the societal dimension in the MCDA.

Conclusion

In conclusion, a sustainability assessment is conducted with the primary goal of implementing various sustainability engineering tools and methods to evaluate alternatives in selecting a preferred natural gas pipeline and method for ground transportation. An older, more established pipeline, in this case, the Canadian Mainline, is compared with a current, newly developed pipeline, the NGTL Grande Prairie South Area Expansion project. An SLCA, which helped to organize the key indicators and metrics to assign for each alternative, is done. An MCDA is chosen as the optimal scoring and ranking tool to assess which alternative is the most preferred when ranked against the four dimensions. Results are compiled in Tables 1 and 2, for the pipelines and ground transportation methods, respectively. The methodology, merits, demerits, and scoring techniques are discussed along with the dimensions.

For the MCDA, scoring is done on a scale out of 5, with cumulative index scores calculated for each alternative. Results are obtained based on a combination of concrete and assumed values assigned to the various indicators. The team deduces that the NGTL pipeline is the best alternative for Model 1 because it has a higher cumulative index score of 35, as opposed to the Canadian Mainline, with a score of only 26. Furthermore, the method of rail transportation which has a total index score of 22 is determined to be the better alternative when compared to the index score of 18 for road transportation. These results confirm that sustainability practices continue to become paramount in the field of pipeline development and natural gas transportation, as newer developments, and a shift to more conventional methods continue to show positive trends. This is supported through calculations done on pipeline transportation efficiency shown in Appendix A2, with an efficiency of 52% and 70% for the Mainline and NGTL pipeline, respectively. For the road and rail alternatives, the team concludes that they are the best means of transportation of LNG as this is easily achieved over shorter distances. The transportation efficiencies for road and rail are 51% and 63%, respectively, where the discrepancy is explained by factors such as the loading and unloading of containers, and longer durations taken to deliver products by road. By using a combination of these two transportation alternatives in Canada, the overall impact of GHG emissions can be reduced with the aim to also improve the transportation efficiencies in the future.

Finally, uncertainty and sensitivity analyses are done using sequential perturbation. In Model 1, the Mainline has an absolute uncertainty of 0.4358, whereas the NGTL pipeline has an absolute uncertainty of 0.37. For Model 2, road and rail transportation have uncertainties of 0.34 and 1.02, respectively. Together with the scoring and efficiency metrics calculated, this confirms that the NGTL pipeline, and rail transportation, are the most optimal alternatives determined through the assessment of natural gas transportation via pipelines and by ground transportation alternatives.

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Appendix

A1 – Tables and Figures

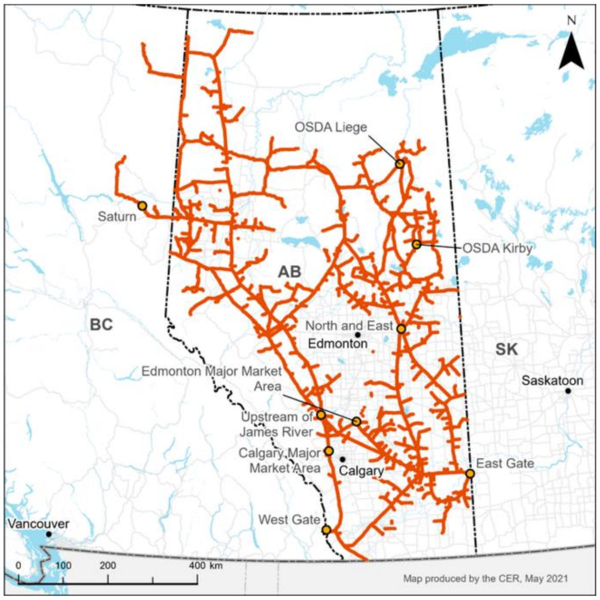
Figure 1

Canadian Mainline Pipeline Map

Adapted from *Pipeline Profiles: TC Canadian Mainline,* by Government of Canada C. E. R., 2022 (https://www.cer-rec.gc.ca/en/data-analysis/facilities-we-regulate/pipeline-profiles/natural-gas/pipeline-profiles-transcanadas-canadian-mainline.html). In the public domain.

Figure 2

NOVA Gas Transmission Ltd. (NGTL) Pipeline Map



Adapted from *Pipeline Profiles: NOVA Gas Transmission Ltd. (NGTL),* by Government of Canada C. E. R., 2022 (https://www.cer-rec.gc.ca/en/data-analysis/facilities-we-regulate/pipeline-profiles/natural-gas/pipeline-profiles-ngtl.html). In the public domain.

Figure 3

SLCA for Model 1 – Transportation through pipelines

Alternative 1: Canadian Mainline

Alternative 2: NGTL pipeline

- P1 • Inlet Injection Station
- P2 • Compressor Station
- P3 • Partial Delivery Station
- P4 • Block Valve Station
- P5 • Regulator Station
- P6 • Delivery Station
- P7 • Consumer
- P8 • Feedback

Figure 4

SLCA for *Model 2 - Ground transportation*

Alternative 1: By road

Alternative 2: By rail

- P1 • Storage
- P2 • Conversion of phases
- P3 • Loading onto trucks/rail
- P4 • Distribution to consumer
- P5 • Unload and conversion of phases
- P6 • Further distribution to local communities

Table 1

MCDA for *Model 1 – Transportation through pipelines*

Alternative 1: Canadian Mainline

Alternative 2: NGTL pipeline

Model #1 - Pipelines	Inlet Station	Compressor stations	Partial Delivery	Block Valve Stations	Regulator Stations	Delivery station to consumer	Preference score (ñ) out of 5
Canadian Mainline							
Diameter (in.)	48	48	48	48	48	48	3
Distance (km)	-	-	-	-	-	14,082	2
Pressure (kPa)	-	8619	-	-	-	9000	2
Flow rate	-	381	-	-	-	Dependent on pressure difference (Lower)	2
Emissions intensity	-	-	-	-	-	More than NGTL	4
Pumping Capacity (millions m3/day)	171.73	171.73	171.73	171.73	171.73	171.73	2
Cost for maintainance	-	-	-	-	-	Higher than NGTL	2
Number of compressor stations (40MW)	-	19	-	-	-	-	4
Revenue in millions ($) (2020)	-	-	-	-	-	3586	3
Capacity of CH4 transportation (millions barrels/day)	-	-	-	-	-	2.5	2
							∑ Index =26
NGTL pipeline							
Diameter (in.)	48	48	48	48	48	48	3
Distance (km)	-	-	-	-	-	24,494	4
Pressure (kPa)	-	8702	-	-	-	12000	4
Flow rate	-	3298	-	-		Higher	5
Emissions intensity	-	-	-	-	-	Less than the Mainline	4
Pumping Capacity (millions m3/day)	329.51	329.51	329.51	329.51	329.51	329.51	3
Cost for maintainance	-	-	-	-	-	Lower than Mainline	4
Number of compressor stations (30 MW)	-	6	-	-	-	-	2
Revenue in millions ($) (2020)	-	-	-	-	-	2534	2
Capacity of CH4 transportation (trillion ft3/day)	-	-	-	-	-	4.2	4
							∑ Index =35

Table 2

MCDA for *Model 2 – Ground Transportation*

Alternative 1: By road

Alternative 2: By rail

Model #2 - Ground Transportation	Source to Consumer	GHG % produced per factor	Preference score out of 5
Road Transport			
Distance	less	more	2
Emission intensity (grams of CO2 per km)	112	higher	2
Cost of converting phases for gas	if same quantity then same cost	negligible	3
Maximum quantity of LNG per vehicle (m3)	2.36	-	4
Cost for maintainance	less	less	2
Revenue	less	less	2
Safety	more	-	3
			∑ Index =18
Rail Transport			
Emissions intensity (grams of CO2 per km)	84	less	5
Distance	more	less	2
Cost of Converting phases for gas	same quantity, same cost	negligible	3
maximum quantity of LNG per train (m3)	2.36	-	2
Cost for maintainance	more	less	4
Revenue	more	-	4
Safety	less	-	2
			∑ Index =22

Table 3

Uncertainty Analysis Matrix and Sensitivity for *Model 1 – Transportation through pipelines*

Alternative 1: Canadian Mainline

1	2	3	4	5	6	7	8	9	10
Diameter (in.)	Distance (km)	Pressure (kPa)	Flow rate	Emissions intensity	Pumping Capacity (millions m3/day)	Cost for maintainance	Number of compressor stations (40MW)	Revenue in millions (2020)	Capacity of CH4 transportation (millions barrels/day)
3	3	3	3	3	3	3	3	3	3
2	2.02	2	2	2	2	2	2	2	2
2	2	2.02	2	2	2	2	2	2	2
2	2	2	2.04	2	2	2	2	2	2
4	4	4	4	4.08	4	4	4	4	4
2	2	2	2	2	2.02	2	2	2	2
2	2	2	2	2	2	2.04	2	2	2
4	4	4	4	4	4	4	4.08	4	4
3	3	3	3	3	3	3	3	3.03	3
2	2	2	2	2	2	2	2	2	2.04

0.19	**0.4375**	**0.44253**	**0.430971**	**0.4375**	**0.4375**	**0.4375**	**0.4375**	**0.4375**	**0.4375**	**0.4375**
	2.5E-05	4.3E-05	0	0	0	0	0	0	0	0.19140625
sensitivity for indicators	0.00013	0.00022	0	0	0	0	0	0	0	1.007401316

Alternative 2: NGTL pipeline

1	2	3	4	5	6	7	8	9	10
Diameter (in.)	Distance (km)	Pressure (kPa)	Flow rate	Emissions intensity	Pumping Capacity (millions m3/day)	Cost for maintainance	Number of compressor stations (30 MW)	Revenue in millions (2020)	Capacity of CH4 transportation
3.03	3	3	3	3	3	3	3	3	3
4	4.08	4	4	4	4	4	4	4	4
4	4	4.04	4	4	4	4	4	4	4
5	5	5	5.1	5	5	5	5	5	5
4	4	4	4	4.04	4	4	4	4	4
3	3	3	3	3	3.06	3	3	3	3
4	4	4	4	4	4	4.12	4	4	4
2	2	2	2	2	2	2	2.02	2	2
2	2	2	2	2	2	2	2	2.04	2
4	4	4	4	4	4	4	4	4	4.04

	0.26431	**0.27287**	**0.256968**	**0.2639**	**0.263889**	**0.263888889**	**0.263888889**	**0.263888889**	**0.263888889**	**0.263888889**
0.14	0.07	0.07	0.00	0.00	0.00	-	-	-	-	-
sensitivity of indicators	0.19	0.20	0.00	-	0.00	-	-	-	-	-

Table 4

Uncertainty Analysis Matrix for *Model 2 – Ground Transportation*

Alternative 1: By road

1	2	3	4	5	6	7
Distance	Emission intensity (grams of CO2 per km)	Cost of converting phases for gas	Maximum Quantity of LNG per vehicle (m3)	Cost for maintainance	Revenue	Safety
2.02	2	2	2	2	2	2
2	2.02	2	2	2	2	2
3	3	3.06	3	3	3	3
4	4	4	4.12	4	4	4
2	2	2	2	2.02	2	2
2	2	2	2	2	2.04	2
3	3	3	3	3	3	3.03

	0.172	0.173725714	0.163699093	0.171428571	0.171428571	0.171428571	0.171429
0.12	3.2653E-07	0.030180624	0.03108201	0.029387755	0.029387755	3.26531E-07	5.28E-06
sensitivity of indicators	0.00	0.09	0.09	0.09	0.09	0.00	

Alternative 2: By rail

1	2	3	4	5	6	7
Distance	Emission intensity (grams of CO2 per km)	Cost of Converting phases for gas	maximum quantity of LNG per train (m3)	Cost for maintainance	Revenue	Safety
5.1	0	4	4	4	4.12	4
0	2.02	2	2	2	2	2.02
0	0	3.06	2	2	2	2
0	0	3	2.022	3	3	3
0	0	0	0	4.08	0	0
0	0	0	0	0	4.12	0
0	0	0.172	0.173725714	0.163699093	0.171429	2.022

1.02	0	0.6375	0.51005	0.218265458	0.5	0.5	0.5075
1.05	0.06612245	0.40640625	0.260049003	0.04763981	0.25	0.01890625	6.5E-06
sensitivity for each indicator	0.06302597	0.387374441	3.932839853	0.117222139	0.961357273	0.396858216	2.6E-05

A2 – Theory, Equations, and Calculations

Calculations for determining pressure and flowrate:

The Bernoulli equation is as follows:

$$P_1 + \rho v_1 + \rho g h_1 = P_2 + \rho v_2 + \rho g h_2$$

Where: P= pressure, ρ=density of gas (CH_4), g=9.8m/s^2, h=elevation of the pipe

To determine the flow rate, the following relation is developed from the Bernoulli equation assuming, that $H_1 = H_2 = 0$ (neglecting elevation changes) and assuming laminar flow:

$$P_1 + \rho v_1 = P_2 + \rho v_2$$

Applying the 2nd Law of Thermodynamics yields:

$$A_1V_1 = A_2V_2 = Q$$

The flow rate is calculated using the relation: $A_1V_1=A_2V_2$, where A_1 and A_2 are the entrance and exit areas for pipeline, normal to the flow of gas. V_1 and V_2 are the inlet and outlet velocities, respectively. Substituting values of V_1 and V_2 into the Bernoulli equation gives:

$P_1 + \rho Q_1 = P_2 + \rho Q_2$, and hence, $Q_1 = (p_2 - p_1/\rho) + Q_2$

From this equation, the team determines that the flow rate is directly proportional to the difference between the pressure differences at each station:

$$Q \geq \Delta(p_2 - p_1)$$

Where: P is the pressure, ρ is the density of the natural gas (CH_4), g is 9.8m/s^2, h is the pipe elevation

Calculations for determining the Reynolds Number and Hydraulic Diameter:

$$Re = [(Q)(DH)]/[(v)(A)]$$

Where: Q is the fluid flow rate, DH is the hydraulic diameter, v is the kinematic viscosity, and A is the pipe cross-sectional area

$$DH=(4A)/P$$

Where: P is the area that contacts the fluid flow

Calculations for determining efficiency amongst the alternatives:

Pipeline transportation efficiency under consideration of the four dimensions for sustainability:

Efficiency = ∑Index/ Total preference score

Alternative 1 (Canadian Mainline) = 26/50 = 52%

Alternative 2 (NGTL pipeline) = 35/50 = 70%

Ground transportation efficiency under consideration of the four dimensions for sustainability:

Efficiency = ∑Index/ Total preference score

Alternative 1 (By Road) = 18/35 = 51%

Alternative 2 (By Rail) = 22/35 = 63%

Calculations for uncertainty analysis:

To find the absolute uncertainty of each indicator, the R value is obtained using the following equation:

$$R = (a+b^2)/(8+c^3)$$

Where: a = 2.00 +/- 0.04, b = 3.00 +/- 0.03, and c = 2.00 +/- 0.03

$$R = R_{mean} + U_r\ (+/-\ F_R\%)$$

Where: R_{mean} is the mean value of R, U_r is the relative uncertainty, and F_R% is a fractional uncertainty

The absolute uncertainty of the output is found using the relations:

$$U_r = \{((\partial R \cdot u_a)/\partial A)^2 + ((\partial R \cdot u_b)/\partial b)^2 - ((\partial R \cdot u_c)/\ \partial c)^2\}^{1/2}$$

$$U_r = \sum ((\partial R \cdot u_{xi})/\partial x_i)^2$$