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Comparative Life Cycle Assessment of Road and Multimodal Transportation Options - A Case Study of Copperwood Project

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COMPARATIVE LIFE CYCLE ASSESSMENT OF ROAD AND MULTIMODAL TRANSPORTATION OPTIONS – A CASE STUDY OF COPPERWOOD PROJECT

By

Sumanth Kalluri

A REPORT

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This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Civil Engineering.

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Abstract

Freight transportation of goods and commodities is a necessity and often accounts for a significant portion of the overall investment in the industrial development, especially in the natural resource industry. The economic costs of developing an infrastructure have long been factored into the project costs, but environmental and/or social impacts have received less attention. In addition, alternative transportation modes are rarely compared from both economic and environmental perspectives. This project uses a case study to assess the environmental impacts (emissions) of different transportation options for transporting ore between a planned mine and a processing plant, and concentrate from the processing plant to an intermediate location (Escanaba, MI). The ore transportation options include truck only option and two multimodal (truck-rail) options, while the concentrate transportation options include truck only, rail only and one multimodal (truck-rail) option.

Environmental impact assessment is done by a process called Life Cycle Assessment (LCA) using SimaPro Version 8 software and includes all aspects related to the construction, operation, and maintenance (stages) of transportation infrastructure and equipment required for the project. The end of life stage was excluded from the analysis. The different processes that occur during the three stages are identified and data for each process is either collected from local sources or from datasets available in SimaPro. The analysis is conducted for four alternative mine lives, ranging from ten to thirty years.

The output of the LCA is provided in the overall Global Warming Potential (GWP) in terms of kilogram equivalents of CO_2 (kg CO_{2eq}) and the emissions generated by each transportation option are compared on the basis of one ton (US ton) of ore/concentrate transported. Overall, the results suggest that multimodal options generate the lowest emissions among all alternatives, for both ore and concentrate transportation. Operations stage accounts for the majority of the emissions for all six options, regardless of the life of the mine, but there are large differences in the operational emission quantities from truck only vs. multimodal options. It is also revealed that the construction emissions can be significant, especially for short mine lives, but emissions from maintenance activities remain fairly low for all options and all mine lives.

In addition to quantifying the emissions from each alternative, the integration of results into economic analysis is investigated. An overview of Life Cycle Cost Analysis (LCCA) for freight transportation options is discussed and the emission results from LCA are converted to dollar value for transporting one ton of ore/concentrate using costs of carbon from literature.

Introduction

1.1 Background

Freight transportation commonly occurs between the major steps of a production system and is very important in a product's life cycle. Energy consumed by the transportation sector is one of the major sources of emissions and tailpipe emissions from transportation accounted for 27% of the total greenhouse gas (GHG) emissions in the United States (US) in 2013 (Figure 1). Almost one quarter (23%) of these emissions were from the medium and heavy duty vehicles [1] and forecasts indicate that the fuel consumption by heavy duty vehicles will increase by 25% from 2013 to 2040, even though the consumption of light duty vehicles is currently declining [2].

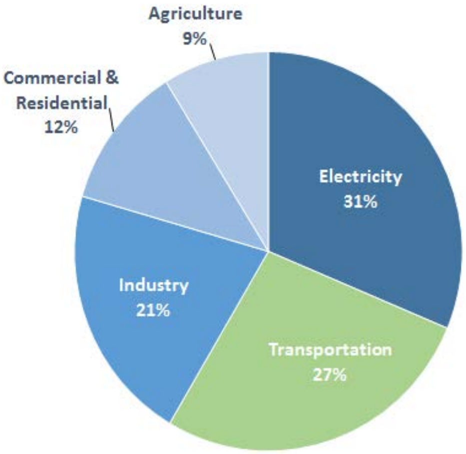


Figure 1: Total U.S. Greenhouse gas emissions by economic sector in 2013 (Source: United States Environmental Protection Agency. Sources of Greenhouse Gas Emissions: Transportation Sector Emissions[1])

Due to the forecast of an increase in heavy duty vehicle emissions, it is essential that new freight transportation projects take up measures to minimize fuel consumption/emissions throughout the project life cycle. To initiate the process, in June 2015 the EPA proposed a phase two rulemaking process for reduction of greenhouse gas emissions and fuel consumption standards of medium and heavy duty engines and vehicles. The EPA also published Tier 4 emission standards in 2008 to control the emissions from off road vehicles and locomotives built after 2015 [3]. These standards regulate the emissions from idling locomotives and target the reduction of particulate matter (PM) by as much as 90% and the NOx emissions by 80 % [4]. With these regulations in place, the CO_2 emissions and fuel consumption of heavy duty vehicles would decrease by 24% of the current values, instead of the increases predicted above [5].

While operational (tailpipe) emissions are well understood and accounted for, the construction and maintenance activities of roads, railroad tracks, and various other transport infrastructure are also significant contributors to project level emissions. To minimize the overall impacts of a project to the environment, it is essential that all contributing activities throughout the project life cycle be considered. To secure this, quantification and comparison of emissions between different project alternatives should be a standard procedure during the development. This is commonly done to compare the economic attributes of roads/highways to determine the preferred project alternatives for developing new infrastructure [6]. It may also be done for cases where different modal alternatives can be considered (such as rail versus road), but detailed environmental (emissions) comparison between those alternatives have rarely been conducted. Life Cycle Analysis (LCA) looks at the overall environmental impacts and emissions released by a product or project over its life time.

1.2 Study Objectives and Report Structure

The objective of the study was to use a process called Life Cycle Assessment (LCA) to conduct environmental impact assessment for different transportation alternatives considered for the Copperwood Project, a planned copper mine and processing plant in the Upper Peninsula of Michigan (Figure 2). The study will investigate transportation alternatives for both ore and concentrate transportation movements and will consider four different mine lives for the analysis. Specific objectives of the study are

- Review the concept of LCA and past literature on its applications in transportation projects. This includes reviewing past studies on transportation infrastructure construction, maintenance and operations, and those related to equipment construction maintenance and operations.
- Perform impact assessment for the ore and concentrate transportation options of the Copperwood project.
    - Identify, develop and collect necessary parameters and related data for each option
    - Interpret and summarize the LCA emission results of alternatives.
- Investigate the economic methodologies for analyzing transportation system investments and integration of LCA results into the analysis.
- Perform conversion of emissions to dollar values using available costs of carbon.

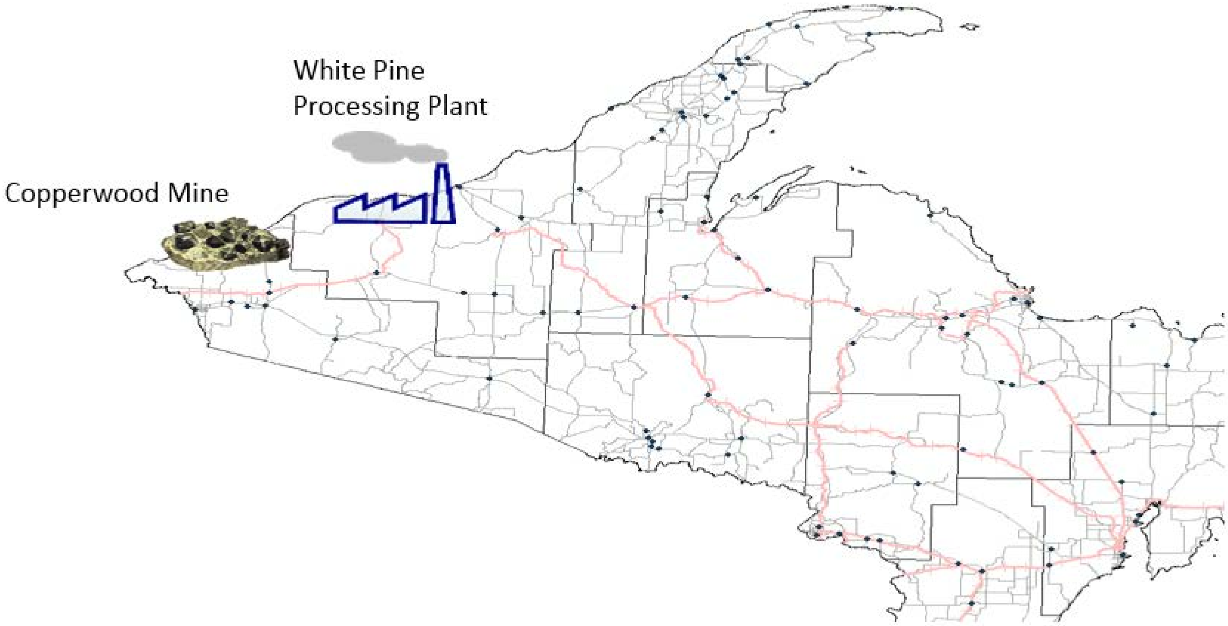


Figure 2: Copperwood Mine and White Pine Processing Plant in Wester Upper Peninsula of Michigan

The report is broken down to seven chapters. Chapter two will start by defining LCA and reviewing its past applications in transportation projects. We also discuss a brief outline of the LCA process in this chapter. Chapter three introduces the case study and related transportation alternatives investigated in the project and in Chapter four we review the data and tool for the LCA analysis. In Chapter five, the results for the LCA are provided and discussed in detail. The current methodologies for transportation investment decision making and the integration of emission results into overall decision making by converting them to costs is discussed in Chapter six. The final chapter includes project conclusions and next research steps.

2 Life Cycle Assessment (LCA)

2.1 Background

Life Cycle Assessment (LCA) is a method of assessing environmental impacts over a product or process life cycle, ideally from raw material extraction to the final end of life stage. The demand for sustainable products has encouraged the development of LCA in order to quantify potential impacts of product changes. The history of LCA dates back to 1969 when Coca-Cola first conducted a LCA study to compare the impact of different beverage container materials on the environment [7]. Since then LCA became a commonly used process and several technical societies established guidelines and standards for conducting an LCA. In 1993, the International Organization for Standardization (ISO) began the standardization of the LCA process. The outcome was the initial Principles and Frameworks of LCA – ISO 14040 in 1997 [8] and the framework defined a method for performing a simple LCA process and listed all the terms and principles. Numerous revisions were made to these guidelines before the final ISO 14040 – LCA Requirements and Guidelines was compiled in 2006 [9]. This framework described more elaborate methodology to perform LCA for a product or a process.

2.2 LCA Phases

The phases of LCA outlined by ISO 14040:2006 [9] include all the processes and methodology to perform LCA for a typical product life cycle. According to the outline, LCA is performed in four different phases: Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. Figure 3 shows a general outline of LCA phases.

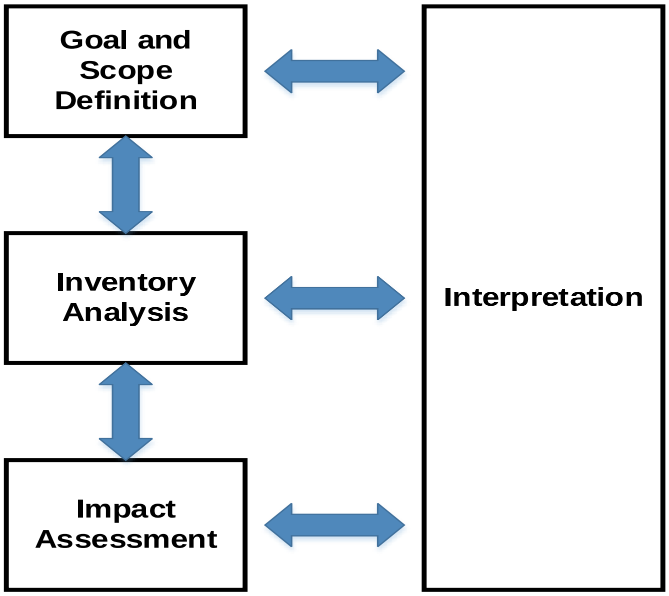


Figure 3: LCA Phases Outline (Source: ISO 14040)

2.2.1 Goal and Scope

In this phase the primary goal of the LCA is identified, and the functional unit and boundaries for performing LCA are set. The functional unit can be used as a reference to compare two or more competing methods or systems. Boundary definition includes identifying the stages of the product life cycle included in the LCA. All the processes that are included and excluded from the LCA are defined in the boundary. For example, if there are any repetitive processes when performing comparative LCA of two products, we can define in the boundary if we want to include or exclude the repetitive process. Also the time frame for LCA and the environmental impacts to be assessed are defined in this phase.

2.2.2 Inventory Analysis

Identifying the inputs to the processes that occur during the life cycle of a product is done in the inventory analysis phase. This includes defining all of the primary material and energy inputs of a process based on the defined boundary, as well as the secondary inputs of energy, material and transport processes that are required for all the primary inputs. The data for the secondary inputs is typically included in the lifecycle inventory databases. If the data for any of the primary or secondary inputs does not meet the required process or flow, then custom datasets are created in the databases by collecting the necessary information of the process. All material data and custom databases are validated with the help of different existing databases and scientific values.

2.2.3 Impact Assessment

In an impact assessment, the method for analysis is selected to produce the desired output of the LCA. Methods can include calculating the total energy consumed over the life of a product, calculation of total resource consumption over the product life cycle, calculating the total greenhouse gas emissions in terms of CO_2 equivalents, quantifying human health impacts and resource consumption among many other methods available. They are often developed by a team of researchers after careful study of the relevant literature; and are updated as necessary, to reflect new information of life cycle inputs and related environmental impacts. A more detailed discussion on different impact assessment methods is presented in section 2.6.

2.2.4 Interpretation

In this phase, impact assessment results are analyzed based on the desired output of the LCA. Sensitivity analysis and uncertainty analysis for the parameters are also done in this phase. Based on the outcomes, recommendations can be made to revise the data inputs and/or the system boundary to perform the LCA iteratively. The results of the iteratively performed LCA can be used to compare alternatives with different input values and also help identify the processes with most impacts in the life cycle of the product.

2.3 Life Cycle of a Product

Since all of the processes that release emissions into the environment during the life of a product are measured, LCA is considered a “cradle to grave analysis”. The basic stages of a life cycle are manufacturing/construction of the product (including gathering of raw materials), use/consumption, and finally the end of life stage which include the products disposal and return of materials to earth. The different processes under each stage are categorized separately before performing LCA, so that the amount of emissions or environmental impact from each process of the product’s life cycle can be identified. Figure 4 shows an example of different stages and the processes that occur in the life cycle of a product, followed by discussion of each key stage to our case study.

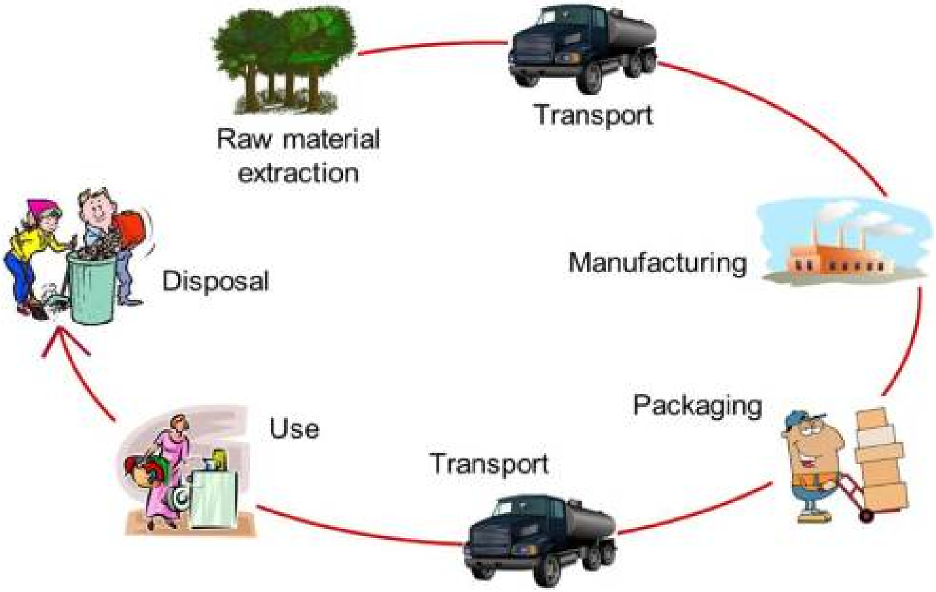


Figure 4: Stages of LCA – Cradle to Grave (Source: [10])

2.3.1 Construction/Manufacturing Stage

The processes that are undertaken to develop, construct or manufacture a product are part of the construction/manufacturing stage of an LCA. This includes the use of required resources like raw materials, intermediate and / or finished products. The input data also includes the energy consumption, the transport of the materials and other secondary level processes involved in the construction. For example, the construction, or manufacturing stage of a light bulb includes the glass production, energy consumed for the production of glass and other materials, transport of the materials and the process for forming the shape of the bulb along with packaging. Here the primary processes are glass production and packaging. The secondary level processes are energy consumed for production of glass, transport to the market and packaging cardboard manufacturing process.

2.3.2 Use/Operations Stage

This includes all the processes that are involved during the use of the product, or operation or maintenance of the product. Commonly, operations and maintenance of the product are all part of the operations stage. As an example, for a light bulb's LCA, the use/operations stage includes the consumption of electricity and the production of this electricity. However, for our case study, we considered the operations stage and maintenance stage separately, as we wanted to be able to quantify the operations vs. maintenance born emissions in more detail.

2.3.3 End of Life

The end of life stage of the LCA includes the different materials that are disposed of or recycled after the use of the product or a process. Considering the same example of the light bulb, the end of life includes the disposal and/or recycling of the glass and metal components of the bulb. End of life was excluded from our case study analysis, due to the uncertainty of actions at the end of project.

2.4 LCA in Transportation

Use of life cycle assessment in the transportation sector has gained prominence during the last decade and the development of reliable datasets and guidelines has enhanced its capabilities to explore the impacts of transportation on the environment. The earlier datasets and LCA methods included the impacts caused by transport of goods, raw materials and other processed materials over an average distance, but considered only the tail pipe emissions of the transport process. The study by Facanha and Horvath was one of the few to include all the infrastructure, vehicle and fuel life cycle phases [11]. LCA analysis on complete highway freight transport project was first performed in Germany by Marheineke in a study which included the production, use, and end of life for trucks, along with related road construction and maintenance.

LCA is typically performed using process flow analysis, but Marheineke also used a hybrid model of Input-Output analysis [12]. Spielmann used European data to develop a similar life cycle inventory for the transport of goods by road, rail, and water [13]. His inventory is considered to be one of the few which include complete life cycle stages of infrastructure, vehicles and fuel on multiple modes [11]. Based on Spielmann's approach, Facanha and Horvath tried to develop an inventory with US data that can calculate the emissions of all the processes in transportation, including the fuel life cycle, infrastructure provision, production and end of life of the rolling stock [11]. The comparison of their LCA results with that performed for only tail pipe emissions indicate that life cycles of vehicles and transportation infrastructure account for a significant amount of total emissions. Argonne National Laboratory in the US has been conducting several studies on the life cycle analysis of long distance freight transport over land. One of them highlighted the emissions during the manufacturing of vehicles and extraction and combustion of fuels during the freight transport process of a vehicle. It also compared the emissions from alternative fuels over the life cycle [14]. In the early 2000's, Argonne developed the Greenhouse gases, Regulated Emissions, and Energy use in Transport (GREET) model as a tool for estimating the greenhouse gas emissions from the transportation life cycle, including fuel and vehicle stages. This model is currently applicable to passenger cars and light duty truck life cycles only [15].

The previous studies on the LCA process for road, trucks, railroad tracks, locomotives and rail cars mostly discuss all off the data inputs necessary to conduct LCA for the equipment (trucks and rail rolling stock), but the data requirements for conducting infrastructure LCA have not been detailed in any comparative study. Past studies that apply the LCA for road infrastructure exist, but the boundaries and conditions differ from case to case [16]. For example, a study on pavement construction scenarios included the different materials for construction of pavement, but considered the construction equipment emissions static between cases [17]. LCA analysis on rail infrastructure had similar differences in system boundaries and most of them relate to passenger train infrastructure, partially due to their origination in Europe [18, 19]. A study by the New Zealand transport agency on the lifetime liabilities of road and rail infrastructure attempted to enhance the understanding of the emissions over the life of the infrastructures, but it only considered the construction stage of the infrastructure and limited maintenance aspects while neglecting the end of life considerations and maintenance of other critical parts [20].

Modal comparisons are difficult to find in literature. A study by Kim [21] looked at emissions between truck only and truck-rail intermodal systems in Europe. The study initially identified that truck and rail based systems are not directly comparable due to the door to door service provided by the trucks. A conceptual model was created in which the rail based intermodal and truck only system offered similar service levels. From the results it was found that the emissions from the rail based intermodal system were lower than from the truck only system, but the proportion changed depending on the source of energy for the trains.

The LCA of trucks and railroad rolling stock (trains) over their life cycle in freight transportation are not as complicated as the infrastructure LCA and the procedures and inventories are outlined to some extent in the past studies [11, 22, 23]. These inventories include all the stages of construction, maintenance and the fuel use and emissions during their life. They are used as a basis for the equipment life cycle inventory developed for this study.

2.5 LCA Databases and Software

Analyzing the life cycle of a product involves various steps and processes that occur during its useful life. Databases of the common products and their major life cycle processes have been developed over the years to help perform the LCA. These databases are frequently provided with updates, as scientific agencies and technical societies continue their development. A few commonly used databases are the ecoinvent, US Life Cycle Inventory, and GaBi database developed for GaBi tool. LCA tools and software integrate these databases with a user interface for performing the LCA.

SimaPro, OpenLCA, GaBi, Umberto and the GREET model are major tools for performing LCA. The tools mainly differ in the type of interface and the impact assessment methods available; and may only allow use of some of the databases listed above. The GREET model is mostly used for transport related LCA and includes LCA of fuels and related transport processes. The tool calculates the emissions, as well as other criteria pollutants that result from transportation life cycles. OpenLCA is an open source software platform that primarily uses the ecoinvent and GaBi tool databases. The software is run and managed by the Green Delta company of Germany, and can be downloaded from their website.

SimaPro 8.0 software was used to perform the LCA in this study. SimaPro is a European software that relies on European databases. The main database is the ecoinvent v3.1 that has more than 10,000 processes and flows in areas like chemicals, agriculture, transport, and metals. It is one of the most extensive databases in the world [24]. SimaPro also includes the US Life Cycle Inventory database (USLCI) and the U.S. ecoinvent database is currently being added into the software.

2.6 Impact Assessment Methods

As described earlier, the output of LCA is determined based on the impact assessment method selected for the analysis. Table 1 shows the three impact assessment methods available in SimaPro.

Table 1 Impact Assessment Methods in SimaPro

Method	Output
Cumulative Energy Demand	Total process and embodied energy required in kJ or BTU
Eco Indicator 95 Method	Impacts of different pollutants and resource consumption.
IPCC 2013 GWP 100a	kg CO_2 eq. of all the greenhouse gases.

The IPCC 2013 GWP 100a method was used to quantify the equivalent amount of CO_2 released over the life of the process. The global warming potential (GWP) of the different greenhouse gas emissions released during the life cycle of a product are calculated in this method. All non-carbon dioxide gas emissions are converted to equivalents of CO_2 emissions and the final output will be in equivalents of carbon dioxide (kg CO_2 eq.). In GWP, the potential of a gas or atmospheric pollutant is calculated for 20, 100, and 500 year time intervals. GWP of a gas is defined as the ability to absorb energy from the earth that would otherwise escape into space, resulting in heating up of the atmosphere. The gases that can be quickly removed from the atmosphere will have a higher potential over short time horizons and lower potential over longer time horizons. The 100a indicates a 100 year time period over which the potential of a particular gas is calculated. Since all the greenhouse gas emissions can be quantified in terms of CO_2 equivalents, the IPCC method was selected for the analysis in this project.

3 Copperwood Project

3.1 Introduction

Highland Copper is a Canadian firm focused on exploring and developing copper mining projects in the Western Upper Peninsula (U.P.) of Michigan Figure 5 [25]. In 2014 the company acquired the copper deposits of Copperwood, White Pine North and Keweenaw “projects” and it has completed the feasibility studies for potential copper ore mining at each project location, and for the development of a processing facility at White Pine to convert the ore to copper concentrate.

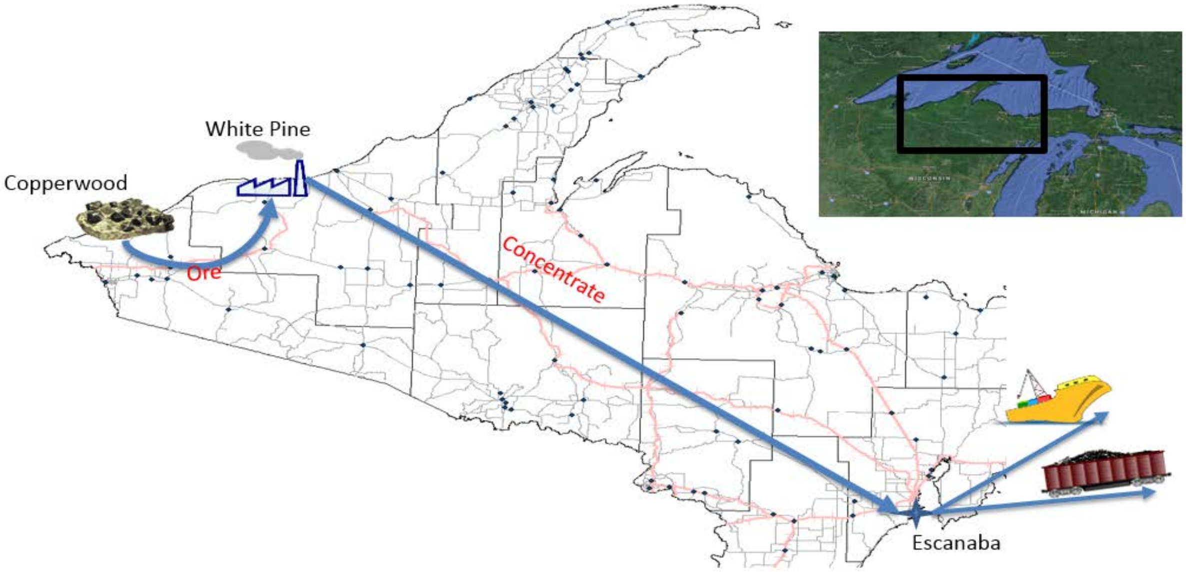


Figure 5: Location Map of Copperwood, White Pine and Escanaba

It is estimated that about 2.7 million tons of ore will be produced annually (7,000 tons per day) at the Copperwood mine site that is located in Gogebic County, approximately 20 miles west of the White Pine (as the crow flies). The ore is then transported to the processing plant in White Pine where it is converted to concentrate. The quantity of concentrate produced after processing is 10% of the ore volume, or approximately 270,000 tons annually. The remaining 90% of the ore (tailings) will be placed in the existing tailings pond near the processing plant. The concentrate is transported from White Pine to a currently unidentified location for further processing. It is expected that the concentrate transportation will travel through Escanaba, which is a regional transportation hub with good ship and rail connectivity Figure 6.

Figure 6: Movements Analyzed in the Study

Since the final destination for concentrate has no effect on the ore transportation decisions from the mine to White Pine and on the concentrate transportation from White Pine to Escanaba, this study concentrates on evaluating the alternatives for those two movements Figure 5. After Escanaba, Highland Copper will have the choice of selecting the most economic mode available for the final leg of concentrate transportation.

The different options for transporting ore and concentrate are discussed in following sections. For all options, the overall environmental effects will be evaluated using LCA tools and from the results of the LCA, a preferred option for the transportation of ore and concentrate from environmental perspective will be identified.

3.2 Ore Transportation Options

As mentioned above, the ore mined in Copperwood is to be transported to the processing plant in White Pine (Figure 7). As the Copperwood site is only two miles from the South Boundary Road of the Porcupine Mountain state park, specific consideration is placed in avoiding the use of that road and thus minimizing the effects of the project on park activities.

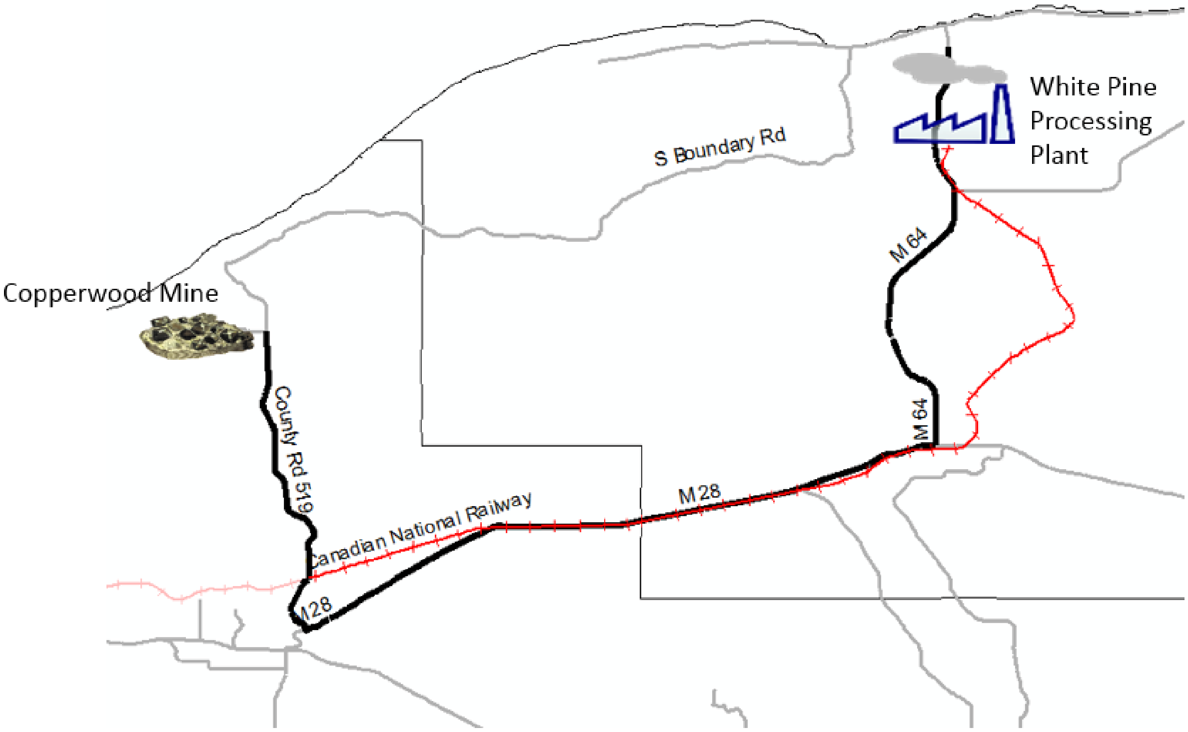
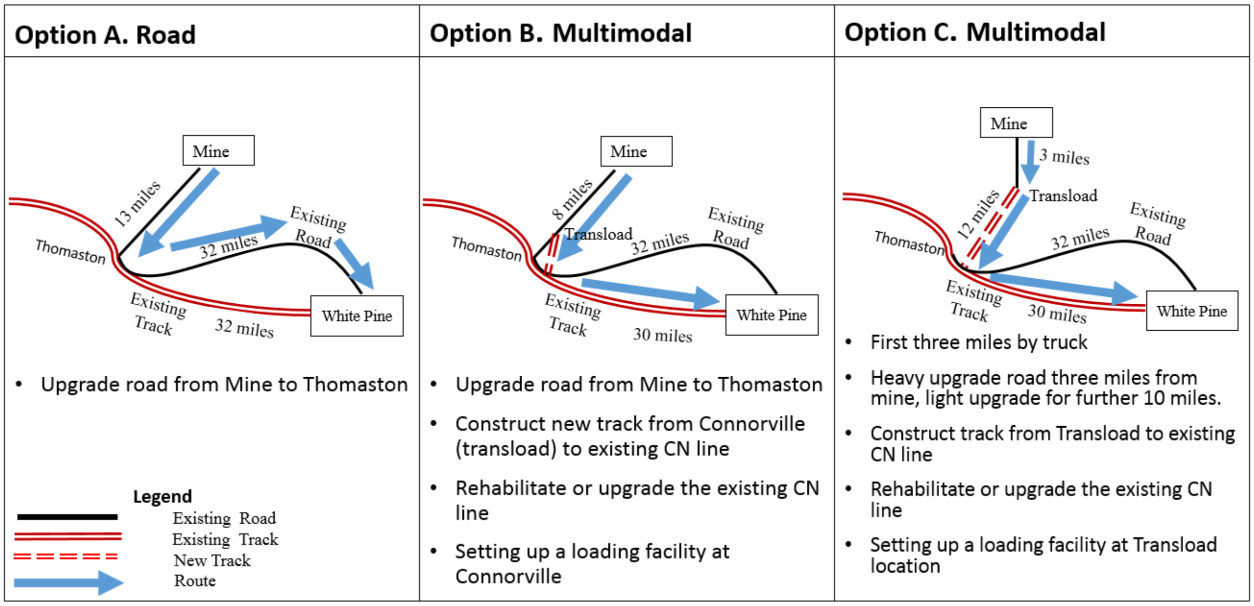


Figure 7: Ore Transportation, Location of Copperwood and White Pine (Road = Black, Track = Red)

Highland Copper is looking at three alternative routes that partially rely on existing road and rail infrastructure, and use either single or multimodal transportation. The options are shown in Figure 8 and discussed in the following sections.



Option A. Road	**Option B. Multimodal**	**Option C. Multimodal**
• Upgrade road from Mine to Thomaston	• Upgrade road from Mine to Thomaston • Construct new track from Connorville (transload) to existing CN line • Rehabilitate or upgrade the existing CN line • Setting up a loading facility at Connorville	• First three miles by truck • Heavy upgrade road three miles from mine, light upgrade for further 10 miles. • Construct track from Transload to existing CN line • Rehabilitate or upgrade the existing CN line • Setting up a loading facility at Transload location

Figure 8: Infrastructure and Route Comparison of Ore Transportation options between Mine and White Pine

3.2.1.1 *Option A: Road Transportation*

In this option, the ore is transported from the mine to the processing plant by trucks. The route for this option travels south from the mine for *13 miles* on County Road 519 until the road meets M 28, follows M 28 east *19 miles* and turns north at Bergland onto M 64 for *13 miles* until reaching the processing plant in White Pine. (Figure 9). The state highways are currently all season roads capable of handling the ore trucks, but the county road must be upgraded to facilitate the 24/7 movement of trucks throughout the year. County road upgrade includes heavy reconstruction of the full *13 miles*. The total length of one way road trip from the mine to White Pine in Option A is *45 miles*.

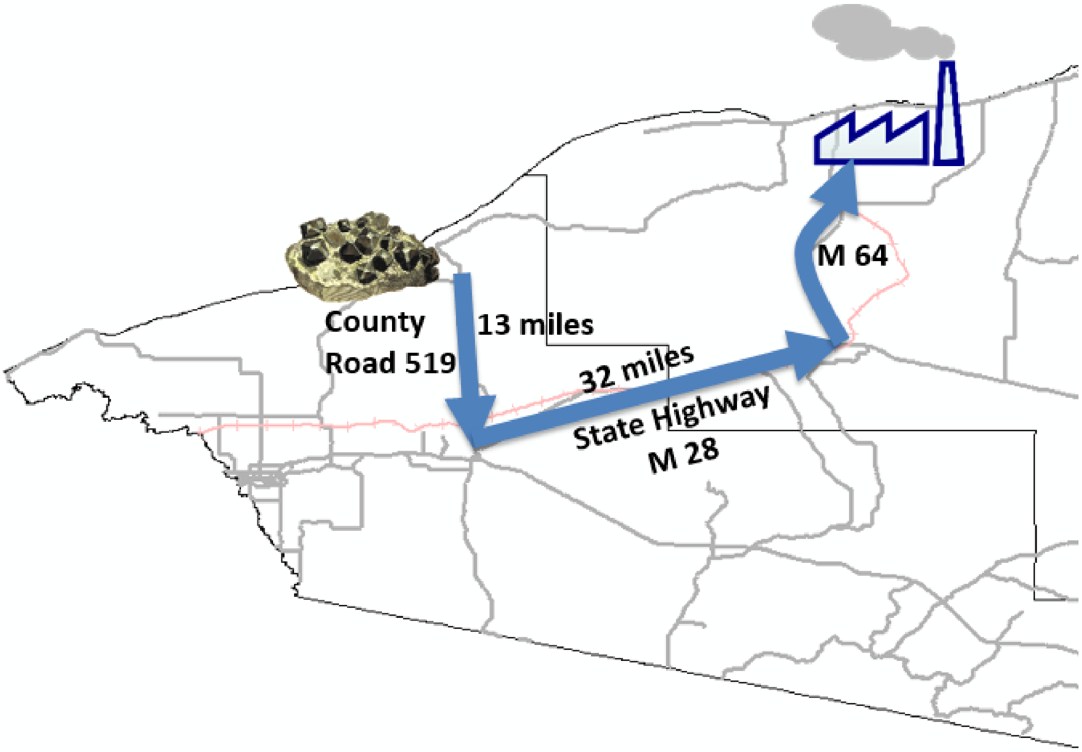


Figure 9: Ore Transportation Option A Road - Route Characteristics

3.2.1.2 *Option B: Multimodal Transportation (Road – 8 miles)*

This is a multimodal option in which the first *8 miles* from the mine to Connorville location is by truck on County Road 519. A transload facility will be constructed at Connorville and the ore will then be transported *34 miles* by train to White Pine in hopper style rail cars. The county road in this option has to be reconstructed heavily for *full 13 miles.* For the rail movements, there is an existing CN railway line from Thomaston to White Pine, which hasn't been used since 2010, and requires rehabilitation of track structure and the subgrade. The track from Connorville to the existing CN line must be constructed on an old track subgrade. For Option B, the length of road trip is *8 miles,* followed by *34 miles* for one way train movement (Figure 10).

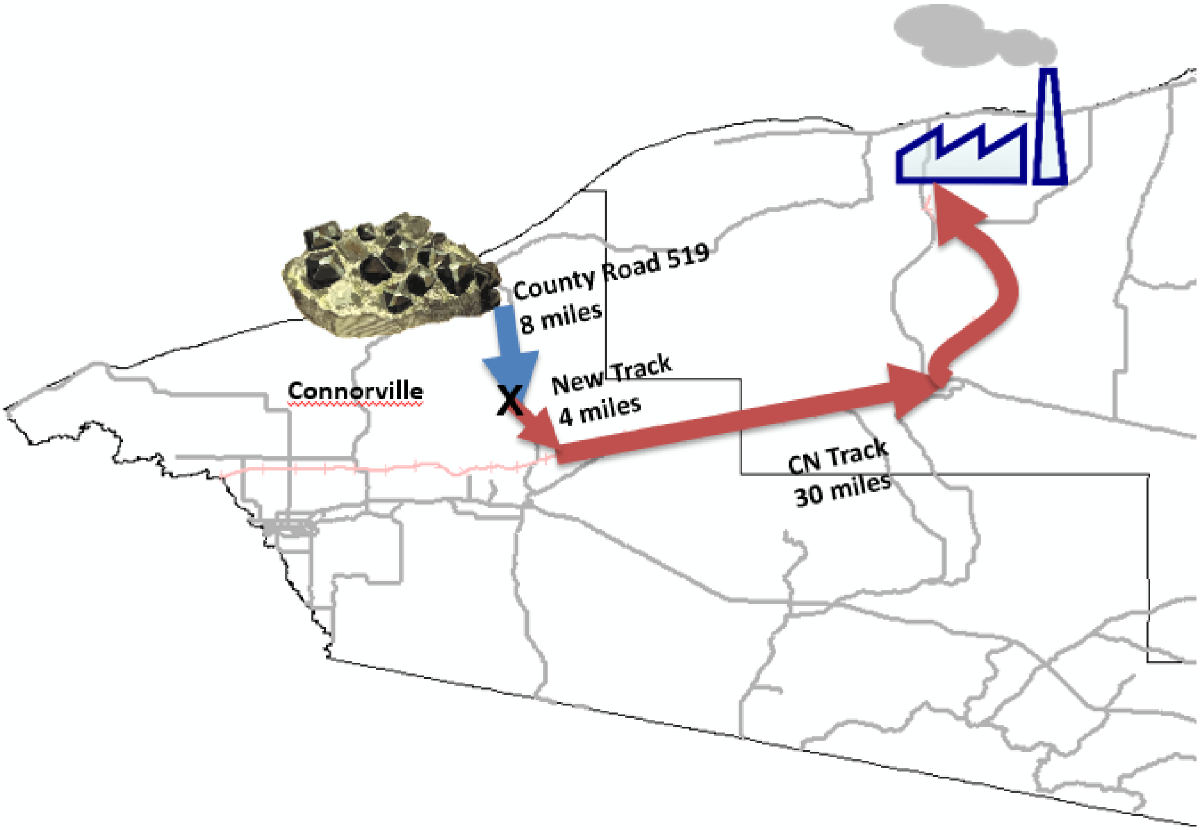


Figure 10: Ore Transportation Option B Multimodal (Road – 8 miles) - *Route Characteristics*

3.2.1.3 *Option C: Multimodal Transportation (Road – 3 miles)*

The third option is also a multimodal option in which the ore will be trucked for the first *three miles* and then it is transloaded into hopper cars and transported by train *42 miles* to White Pine. First three miles must be trucked due to high grades and land constraints which make it very expensive to build new track all the way to the mine. In the analysis, three miles of heavy reconstruction was considered for the county road, while the remaining 10 miles requires light upgrade for service vehicles. However, per Highland Copper, it is plausible that heavy reconstruction is required for the full 13 miles. The rail route from the transload facility to the existing CN track follows an old track and requires 12 miles of new track construction on existing subgrade. Rehabilitation (same as Option B) is required for the existing CN track. A transload facility must be constructed three miles south of the mine to load the rail cars. In this option, the length of one way truck trip is *three miles* and length of train transport is *42 miles (*Figure 11).

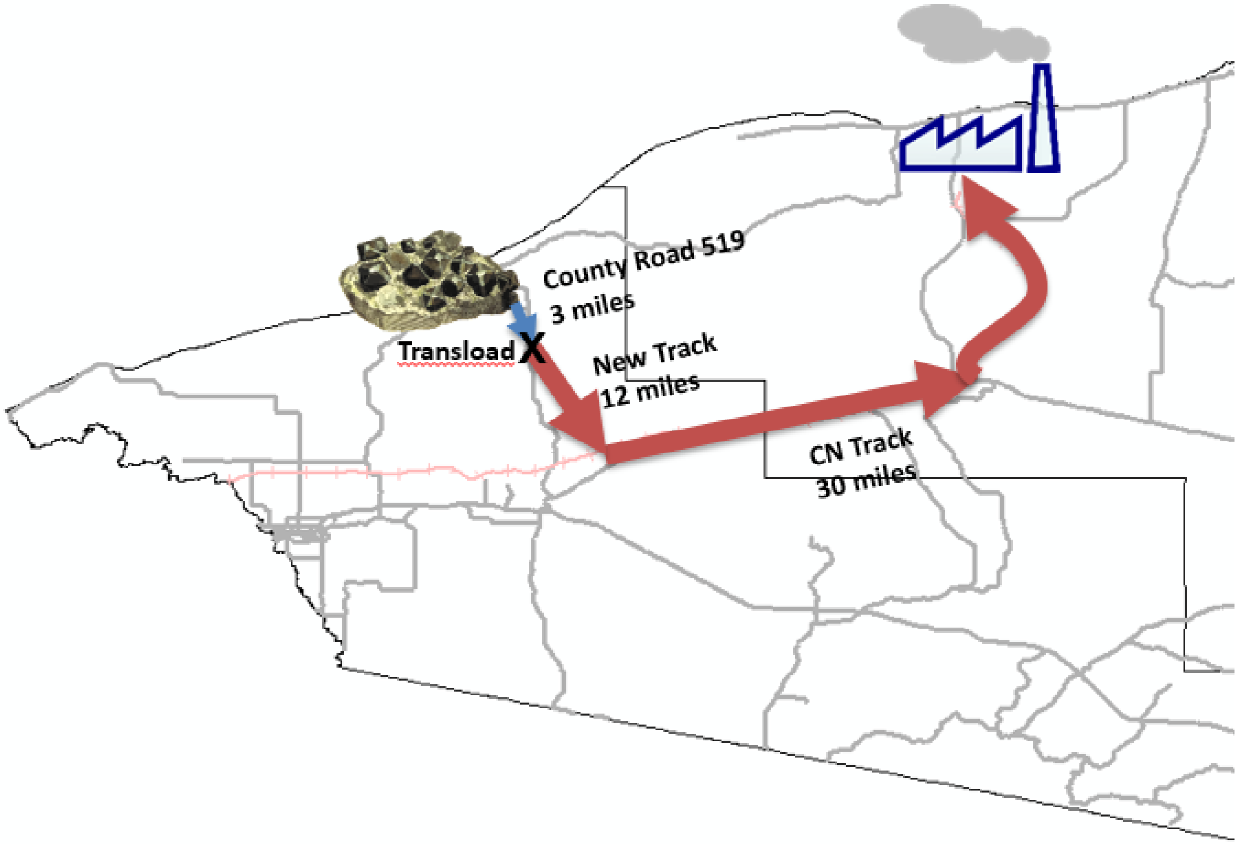


Figure 11: Ore Transportation Option C Multimodal (Road – 3 miles) - Route Characteristics

Table 2 shows the comparison of infrastructure requirements for each ore transportation option.

Table 2: Infrastructure Requirements for Ore Transportation

	Option A	Option B	Option C
Transport by Road (miles)	45	8	3
Transport by Rail (miles)	N/A	34	42
Road Heavy Reconstruction miles	13	13	3
Light Road Upgrade miles	0	0	10
New Track Construction on Existing Track Bed (miles)	N/A	4	12
Track Upgrade (miles)	N/A	30	30
Transload construction	No	Yes	Yes

3.2.2 Ore Transportation – Operational Characteristics

The data for truck and rail equipment and operations was provided by Highland Copper, MHF services (project consultant for Highland Copper), and M.J. VanDamme trucking. The trucks used for the ore transport are Michigan 11-axle tractor-trailer trucks with a gross weight of 164,000 lbs. (82 tons). They have a carrying capacity of 51 tons, and will be operated 24/7 throughout the year. 140 round trips are required per day. Due to confidentiality, the total number of trucks is not disclosed in the report.

Snow on the county road 519 must be cleared during winter, so that the operations are not interrupted. Since the snow clearing requirements on the county road must be expanded due to the opening of the mine, the operation of snow plows will have impact on the overall emissions of ore transport. The snow clearing for the *13 miles* of county road will be accounted for in the analysis.

The rail cars used for the ore transport are covered hoppers of net capacity 100 tons per car. 70 rail car loads of ore have to be transported daily from the mine to the processing plant. Two 2,000 horsepower locomotives will be used to haul the trains. The train operation for Option B is one train trip per day, but in Option C, two 35 car trains will be operated from transload near the mine to Connorville where they are combined into one 70 car train to White Pine. This is due to the steep ascent from the mine to the existing CN track that makes two locomotives insufficient for hauling 70 cars at once. In the return, all the 70 cars can be pulled back to the mine transload location.

The rail cars will be loaded at the transload facility using one front end loader. The transload building will be covered and the trucks use side dumps to unload the ore. Table 3 gives a detailed outline of the operational characteristics of ore transportation.

Table 3: Operational Data for Ore Transportation Options.

	Option A	**Option B**	**Option C**
Annual tons of ore	2.7 million		
Net Capacity of trucks	51 tons		
Total number of trucks	XX	YY	ZZ
Truck round trip (miles)	90	16	6
Train round trip (miles)	N/A	68	84
Number of truck trips per day	140		
Number of locomotives	N/A	2 – 2000 HP	2 – 2000 HP
Total number of rail cars	N/A	70	70
Gross(Net) weight of rail cars	130(100) tons		
Cars per train trip	N/A	70	35*
Train roundtrips per day	N/A	1	2*
Transloading Equipment	N/A	Front End Loader	

N/A - Not Applicable, *XX* - No. of trucks in Option A, *YY* - No. of trucks in Option B, *ZZ* - No. of trucks in Option C

* - In option C, two train trips per day from Mine to Connorville, From Connorville to White Pine it is one train.

3.2.3 Ore Transportation – Maintenance

The maintenance of infrastructure and equipment is one of the most important tasks to keep the project running without delays. The major maintenance of road is milling and overlay of the 13 miles of county road in five year intervals. State highway maintenance is excluded, as no change is considered due to mine opening. The track maintenance includes annual inspections and spot repairs. It was assumed that about 20% of the quantities of track construction are required for track maintenance every five years. Also this maintenance is spread across the five year interval with 1/5th every year.

Per MJ VanDamme, the preventive maintenance for trucks is done every 15,000 miles of operations and includes change of hydraulic fluids, engine oil and lubricants. The drive and steer tires have a life of 70,000-80,000 miles and the trailer tires have a life of 130,000 miles. Per

Mineral Range Railroad, the locomotive and rail car maintenance includes the change of lubricants, oil and rail car wheels periodically to keep the equipment in good condition. In the analysis, the maintenance of locomotive includes the change of oils and filters once every month and the rail car maintenance includes a wheel change every 300,000 miles of operations.

3.3 Concentrate Transportation Options

The ore is received at White Pine and processed into higher value copper concentrate. The concentrate will then be transported from White Pine to an as yet to be determined location. Since all routes for concentrate transportation are expected to move through Escanaba, it was selected as the end point of the study. The general route options for concentrate transportation are shown in Figure 12.

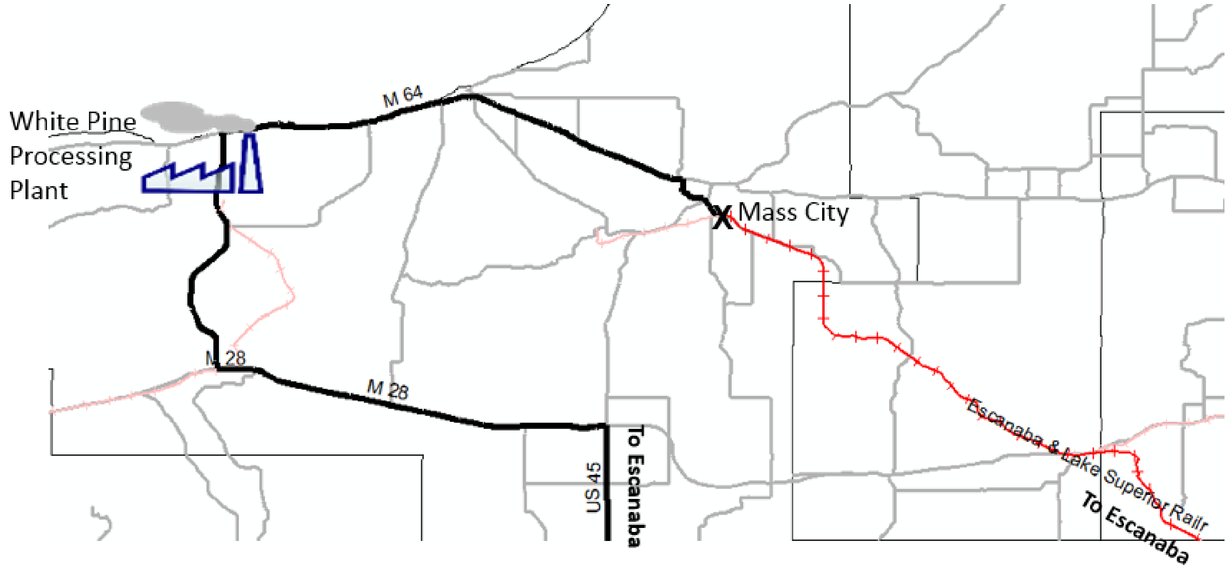
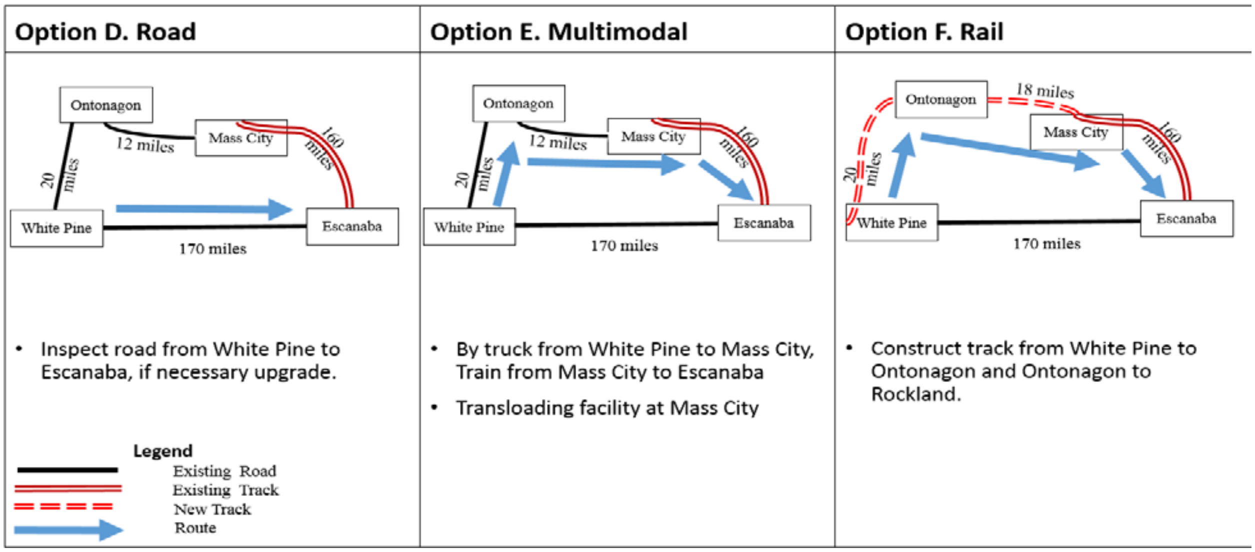


Figure 12: Concentrate Transportation, Location of White Pine and Mass City

Just like for ore transportation, the Highland Copper is considering three alternatives for the concentrate transportation between White Pine and Escanaba. These options are shown in Figure 13 and discussed in the following sections.



- Inspect road from White Pine to Escanaba, if necessary upgrade.

- By truck from White Pine to Mass City, Train from Mass City to Escanaba
- Transloading facility at Mass City

- Construct track from White Pine to Ontonagon and Ontonagon to Rockland.

Figure 13: Infrastructure and Route Comparison of Concentrate Transportation Options between White Pine and Escanaba

3.3.1 Alternatives of Concentrate Transportation

3.3.1.1 *Option D: Road Transportation*

In this option, the concentrate is transported from the processing plant to Escanaba by road. The route follows along M 64 south from White Pine to Bergland for *13 miles*, turns south to US 45 south for *19 miles* from Bergland to Watersmeet and then follows US 2 east until Escanaba for *140 miles*. Since most of the route is existing state highways, there is no need for new road construction or major upgrades and no additional maintenance expenses are considered due to concentrate traffic. The total length of one way trip from the White Pine to Escanaba is *172 miles* (Figure 14).

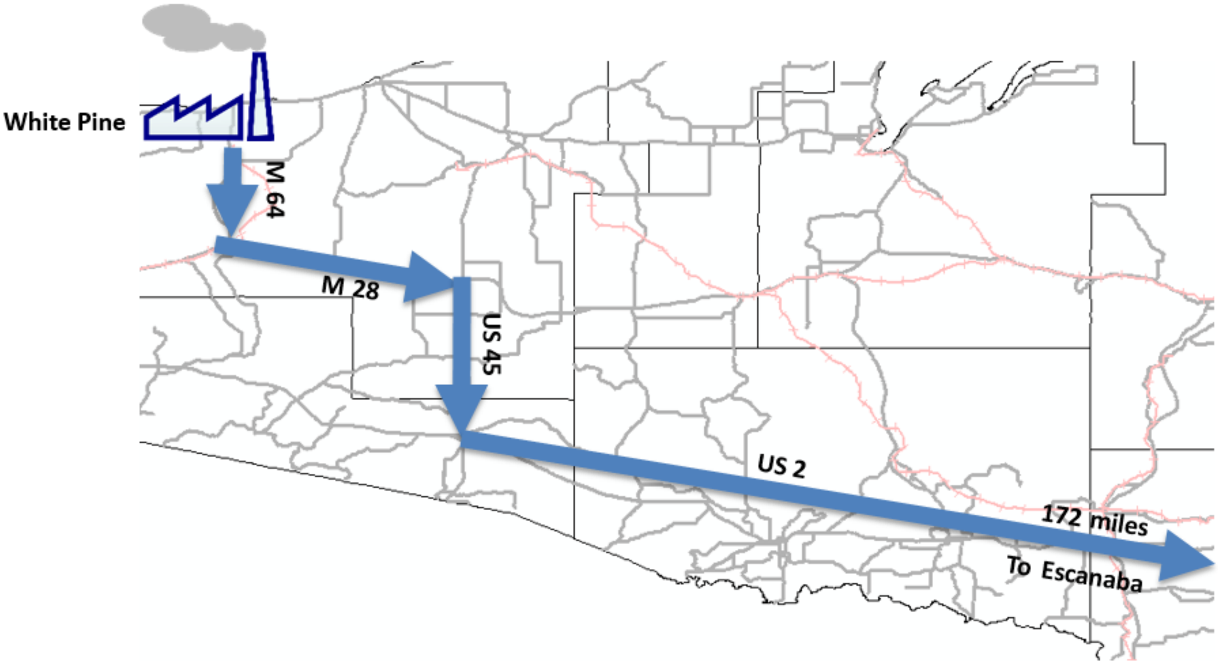


Figure 14: Concentrate Transportation Option D Road - Route Characteristics

3.3.1.2 *Option E: Multimodal Transportation*

This is a multimodal transportation option where trucks move concentrate from the White Pine processing plant to transload facility in Mass City (*33 miles)*. From Mass City the concentrate will be transported *160 miles* to Escanaba by train in covered hoppers. The infrastructure construction and improvements for the road part of the transport are minimal, as this route uses mostly state highways M 64, M 38 and M 26 which are in good condition. There might be a few minor upgrades to the bridges and grade crossings, as necessary. Rail portion uses existing E&LS railway line from Rockland to Escanaba, which passes through Mass City. This line is operational and doesn't require major upgrades. Initially the plan was to setup a transload facility at Rockland, which is further west of Mass City, but due to short rail sidings and land availability issues, the transload location was moved to Mass City. At Mass City, there are existing sidings which can be upgraded and used for transloading, but better infrastructure for concentrate storage and handling must be constructed. The length of one way road trip is *33 miles* and one way train movement is *160 miles* (Figure 15).

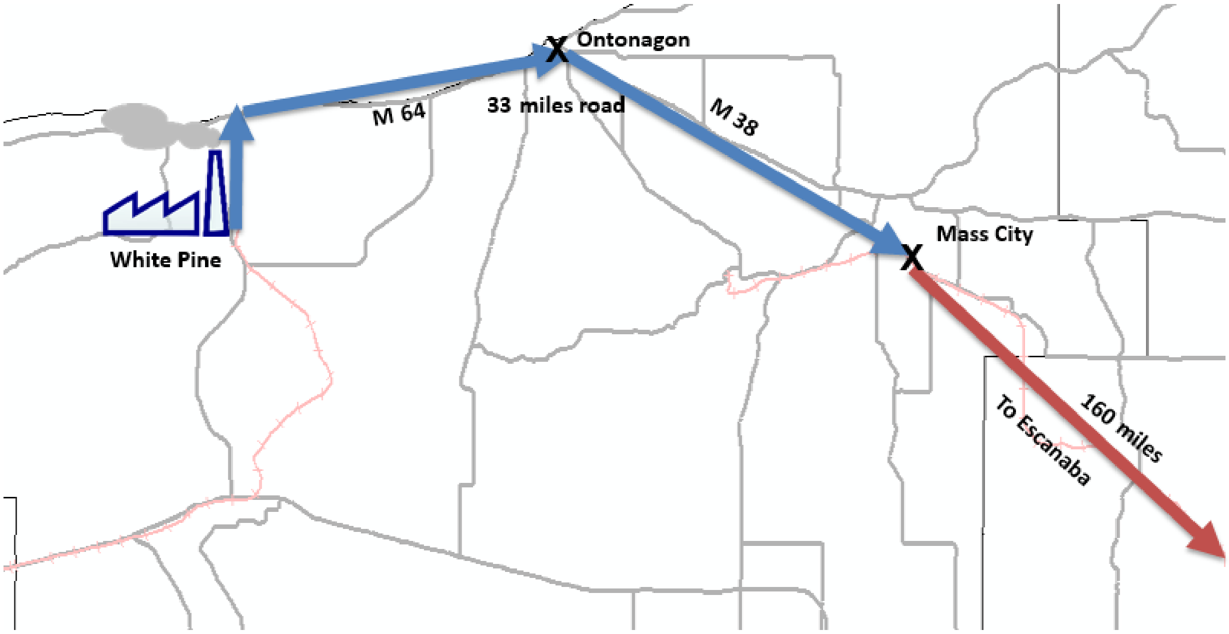


Figure 15: Concentrate Transportation Option E Multimodal - Route Characteristics

3.3.1.3 *Option F: Rail Transport*

The third option is all by rail from the White Pine processing plant to Escanaba in covered hoppers. As noted earlier, operational tracks exist from Escanaba to Rockland (northeast of White Pine). Previously, track existed from west of Rockland to Ontonagon port, but they were recently removed by E&LS and the right-of-way was converted to trails. This section (15 miles) would have to be rebuilt. There is no rail connectivity from the Ontonagon port to White Pine and therefore this part of the track (20 miles) must be newly constructed. The total length from White Pine to Escanaba is *198 miles* (Figure 16).

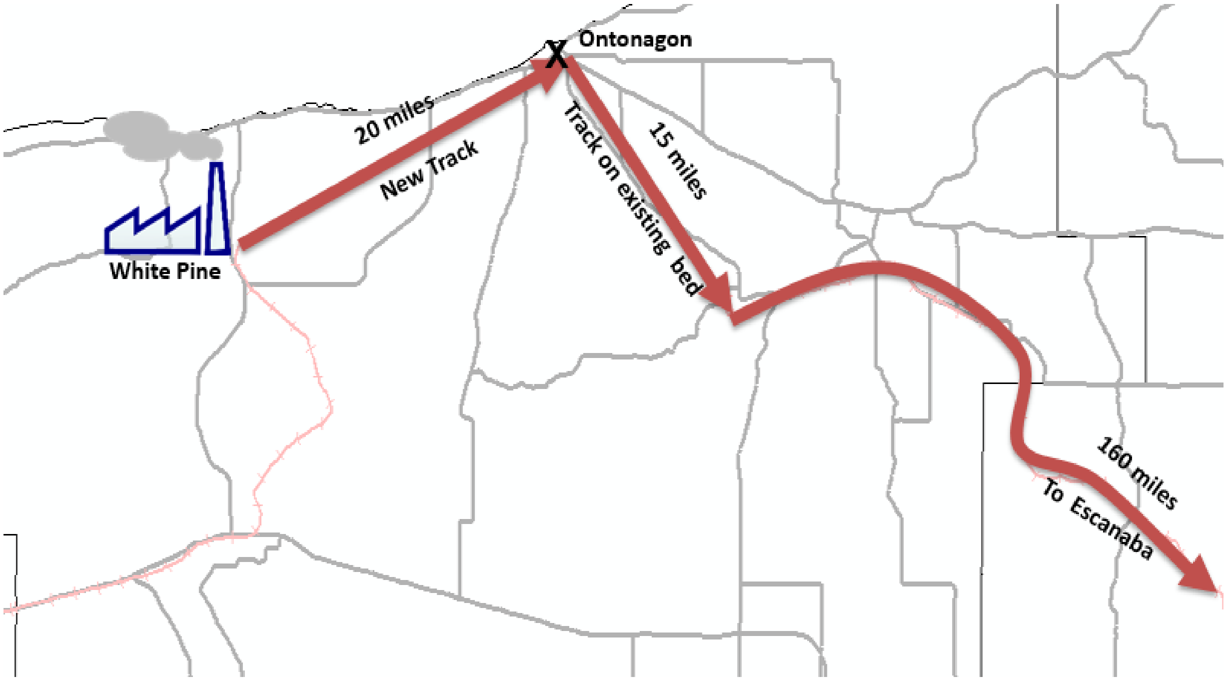


Figure 16: Concentrate Transportation Option F Multimodal - Route Characteristics

Table 4 shows the infrastructure for each concentrate transportation option.

Table 4: Infrastructure Requirements for Concentrate Transportation

	Option D	**Option E**	**Option F**
Transport by Road (miles)	172	33	N/A
Transport by Rail (miles)	N/A	160	195
Road Upgrade miles	0	0	N/A
New Track Construction on Existing Track Bed (miles)	N/A	0	15
Track Construction (miles)	N/A	0	20
Transload construction	No	Yes	No

N/A - Not Applicable

3.3.2 Concentrate Transportation - Operation Characteristics

The quantity of concentrate to be transported is 271,000 tons per year; i.e. approximately 5,000 tons per week. The trucks used for concentrate share similar characteristics with ore trucks. Since all the roads are all-season roads, there is no need for additional snow clearing due to concentrate movements.

For the concentrate transportation, the train consist will be a two locomotive train with 25 rail cars in both Option E and Option F. Since the concentrate cars need to go further from Escanaba, it was estimated that approximately 200 cars are required for the operations, taking into consideration the return time of the cars from the final destination. The rail cars used for the concentrate transport are covered hoppers and will be loaded at the transload facility with a front end loader. The transload facility is similar to the one used for ore transloading. A more detailed data for operations under each option is shown in Table 5.

Table 5: Operational Data for Concentrate Transportation

	Option D	**Option E**	**Option F**
Annual tons of ore	270,000		
Capacity of trucks	51 tons		
Total number of trucks	XX	YY	N/A
Truck round trip (miles)	344	66	N/A
Train round trip (miles)	N/A	320	390
Number of truck trips per day	15		
Number of locomotives	N/A	2 – 3000 HP	2 – 3000 HP
Total number of rail cars	N/A	200	200
Gross(Net) weight of rail cars	130(98) tons		
Cars per train trip	N/A	25	25
Train roundtrips per week	N/A	2	2
Transloading Equipment	N/A	Front End Loader	N/A

N/A – Not Applicable, *XX* – Confidential No. of trucks in Option D,*YY* – Confidential No. of trucks in Option E

3.3.3 Concentrate Transportation – Maintenance

The road maintenance is not accounted for in the analysis, as the routine maintenance for the road is done by the Michigan Department of Transportation (MDOT) irrespective of the project. The maintenance of track in Option E is not accounted for in this project since the track is currently owned and operated by E&LS and will be maintained irrespective of the project for other service. In Option F, the track maintenance for the newly constructed section from White Pine to Rockland is accounted for in the project and is similar to that discussed in ore transportation. The maintenance of trucks and rail rolling stock are the same as in ore transportation, as well as the loader maintenance for Option E.

4 LCA Application

The following section breaks down the application of LCA in this study, according to the guidelines set by ISO 14040:2006 [9].

4.1 Goal and Scope of the Project:

The goal of the project was to conduct LCA for ore and concentrate transportation options for several mine lives. LCA results are then compared to identify the option that releases the least amount of greenhouse gases to the environment.

4.1.1 Functional Unit

The functional unit of the ore stage is one ton of ore moved from Copperwood project site to White Pine processing plant. For the concentrate stage, the functional unit is one ton of concentrate transported from the processing plant to Escanaba.

4.1.2 System Boundary

The system boundary for the ore stage is from the point of loading at the mine to the point of unloading at the processing plant. The initial loading at the origin and final unloading at the destination is excluded, because these activities remain unchanged in all options. System boundary for the concentrate stage also excludes the loading of concentrate at processing plant and unloading of concentrate at Escanaba. All the intermediate loading processes at the transload facility are included in the multimodal options for both ore and concentrate.

The LCA study is performed for assumed mine lives of 10, 20, 25, and 30 years. The analysis includes new rolling stock and added maintenance cycles, as required by the longer mine life.

4.2 Inventory Analysis:

The inventory analysis phase describes the data used for the LCA, including all the quantities of material use and energy consumption during the stages of construction/manufacturing, operations and maintenance. The ecoinvent datasets in SimaPro that were used for all processes under each stage will be detailed in this phase. Most data items in ecoinvent are based on European data, but US based data values are used when available. For the data items not available in ecoinvent, custom datasets were created with material and energy inputs obtained from local industry experts involved in the project. The different processes included in the LCA for both the ore and concentrate transportation are shown in Figure 17.

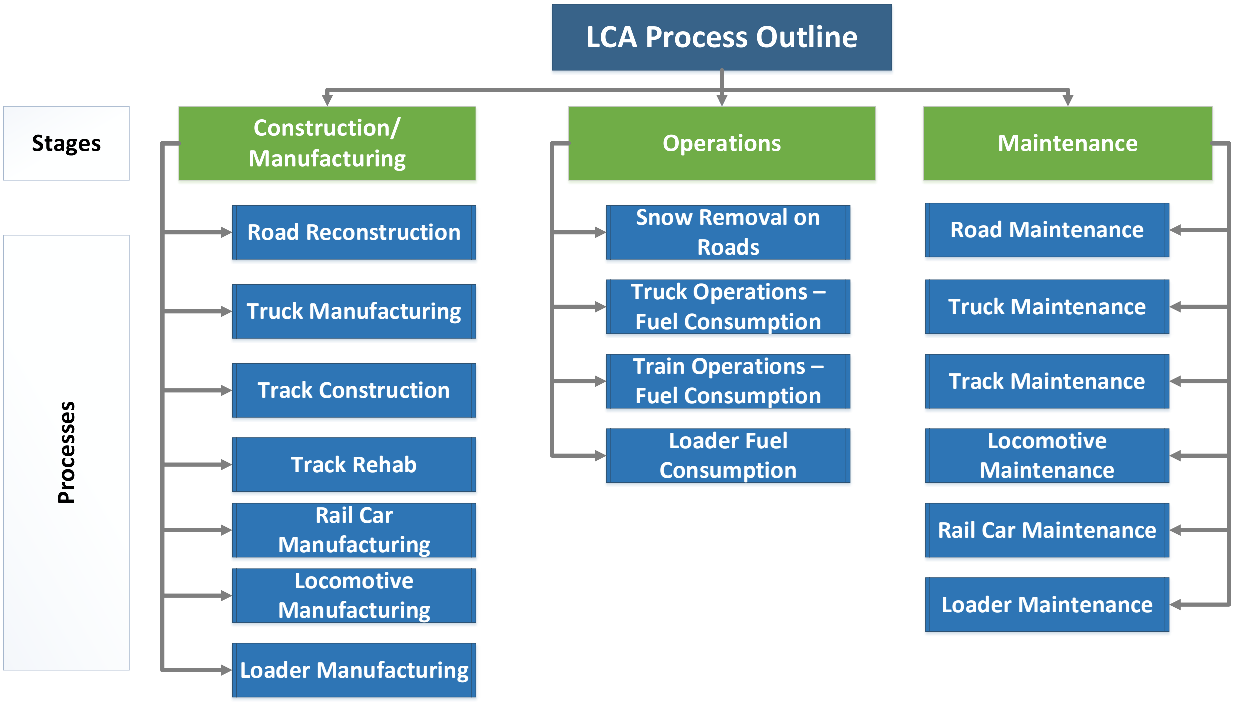


Figure 17. LCA Process Outline

The results are presented for all six transportation options analyzed in the research (three each for both ore and concentrate transportation), but the breakdown of data and calculations is presented only for one option and one mine life (20 years) in the report body. Data and calculations for the remaining alternatives are included in *Appendix -A: Quantities of different process used for SimaPro datasets*. The alternative selected for detailed description was Option B of ore transport, as it is one of the multimodal options that has truck, train and transloading activities. The 20 year mine life was selected due to its consistency with currently planned operation horizon by Highland Copper (based on feasibility studies).

The different processes under the stages of construction/manufacturing, operations and maintenance are discussed in following sections. Each process has different data items which are either existing datasets of ecoinvent or custom datasets that were created from local data. For the custom datasets, there are sub items as inputs from ecoinvent database. After introducing the datasets, the different quantities applicable to Option B are listed for all the processes.

4.2.1 *Manufacturing or Construction*

The process included in the manufacturing/construction stage are infrastructure construction and rolling stock manufacturing.

4.2.1.1 *Infrastructure Construction*

Table 6 shows the ecoinvent or custom datasets that were used to create the processes for infrastructure construction in SimaPro. Each dataset was obtained from ecoinvent database, unless otherwise noted in the comments. The table is followed by a more detailed breakdown of each process.

Table 6: Datasets of Processes under Infrastructure Construction

Infrastructure Construction				
Process	***Unit***	**Item**	**Dataset**	**Comments**
Road Reconstruction	*Per mile*	Hot Mix Asphalt (HMA)	LCA Highland Copper HMA	*Custom Dataset*, Created using the quantities of gravel and asphalt present in HMA (see Table 7)
		Gravel	Gravel, crushed (GLO)| market for | Alloc Def, U	
		Sand	Sand (GLO)| market for | Alloc Def, U	
		Fuel	Diesel production and emissions from diesel burned	The quantities of fuel consumed per mile of road construction were calculated using literature values.
Track Construction	*Per mile*	Gravel	Gravel, crushed (GLO)| market for | Alloc Def, U	For ballast
		Steel	Steel, low-alloyed, hot rolled (GLO)| market for | Alloc Def, U	For rail, spikes and tie plates
		Timber	Sawn timber, hardwood, planed, air/kiln dried, u=10% at plant/US- US-EI U	For ties
		Fuel	Diesel production and emissions from diesel burned	The quantities of fuel consumed per mile of track construction were calculated using literature values.

Road Reconstruction Process

For ore transportation, the road reconstruction process includes heavy reconstruction of the county road 519 for ore trucks in all three options and light reconstruction for service vehicles in Option C. In addition to ecoinvent datasets, the process required the development of a custom dataset for Hot Mix Asphalt (HMA), using data from Gogebic County Road Commission and Marquette County Road Commission. Inputs of HMA custom dataset are shown in Table 7.

Table 7 Hot Mix Asphalt (HMA) Custom Dataset – Quantities and Calculations

Sub Item	**Unit**	***Quantity***	***Source/Calculations/Comments***
LCA Highland Copper HMA Data			
Percent of Bitumen by volume in unit of HMA	%	8	NCHRP Report 673 - A manual for Design of hot mix asphalt with Commentary
Percent of Aggregates by volume in unit of HMA	%	88	NCHRP Report 673 - A manual for Design of hot mix asphalt with Commentary
Density of Bitumen	*Lbs./cu.ft*	45	
Density of Aggregates	*Lbs./cu.ft*	95	
Tons of Bitumen per Cu ft. of HMA	*tons*	0.0018	Calculation - 1 cu ft. of HMA *percent of bitumen by volume in 1 cu ft. of HMA * density of bitumen / 2,000 lbs. (1 ton)
Tons of Aggregates per Cu ft. of HMA	*tons*	0.042	Calculation - 1 cu ft. of HMA *percent of aggregates by volume in 1 cu ft. of HMA * density of bitumen / 2,000 lbs. (1 ton)

The quantity data used in SimaPro for HMA, gravel, sand, and the related calculation formulas are given in Table 8. Since specific data was not available on the different construction activities for the road reconstruction, the most common activities like milling, gravel surfacing, compaction, etc. were assumed and all quantitative data was obtained from the estimates provided by the Gogebic County Road Commission and Marquette County Road Commission. The unit was one mile of road and it included the emissions from construction activity which were included in terms of fuel consumed per mile of construction. Table 8 lists all the data for heavy reconstruction of road. For light reconstruction, only resurfacing the existing county road was included. An estimate of 2,130 tons/mile of HMA was used for light reconstruction based on the data obtained from Gogebic County Road Commission

Table 8: Road Reconstruction (Heavy) Process – Quantities and Calculations per mile

Item	**Unit**	***Quantity***	***Source/Calculations/Comments***
Road Reconstruction (Heavy) – Data			
Depth of sand leveling	*feet*	2	Gogebic county road commission and Marquette county road commission road section sheets
Aggregate depth	*inches*	12	
HMA depth	*inches*	6	
Width of sub base	*feet*	40	
Width of HMA	*feet*	28	
Density of Aggregates	*Lbs./cu.ft*	95	
Density of Sand	*Lbs./cu.ft*	100	
Road Reconstruction (Heavy) – Calculations			
Volume of sand per mile	*Cu.ft/mile*	422,400	Calculation - depth* width* 5,280 ft. (1mile)
Volume of aggregate per mile	*Cu.ft/mile*	211,200	Calculation - depth* width* 5,280 ft. (1mile)
Road Reconstruction (Heavy) – Values for SimaPro Datasets			
Volume of HMA per mile	*Cu.ft/mile*	73,920	Calculation - depth* width* 5,280 ft. (1mile)
Weight of sand per mile	*tons*	21,120	The volume from calculations is converted to tons using the density value
Weight of aggregate per mile	*tons*	10,032	
Fuel	*Gal / mile*	9696	The total fuel consumption per mile of road reconstruction

Track Construction and Track Rehabilitation Processes

Track work for ore transportation includes improvements to the existing CN line and constructing track on an old track bed between the CN line and the two potential transload locations. Track upgrade and new track construction processes are created in SimaPro using ecoinvent datasets and the quantities were obtained from a similar track rehabilitation work done by the Mineral Range Railroad (MRR) and from MHF services. Table 9 and Table 10 show the quantities, their source and calculations for the track construction and rehabilitation processes on a per mile basis.

Table 9: Track Construction Process – Quantities and Calculations per mile

Item	**Unit**	***Quantity***	***Source/Calculations/Comments***
Track Construction on Existing Track Bed – Data			
Number of ties per mile	*Each*	2,947	21.5" c/c tie spacing, MHF services
Quantity of wood per tie	*cu ft.*	3.7	7" * 9" * 8.5' (Tie dimensions) http://www.rta.org/faqs-main
Weight of tie plate	*Lbs.*	17.87	6" width rail, AREMA plan 10 http://harmersteel.com/hs/wp-content/catalog/cache/harmer-steel-catalog-2014/48.pdf
number of spikes per 200 lbs. keg	*Each*	360	standard spike size is 5.5 in long http://sizes.com/tools/spikes_railroad.htm
Type of rail	*Lbs./yd.*	136	MHF Services
Volume of ballast per mile	*tons*	10,000	MHF Services
Track Construction on Existing Track Bed– Values entered into SimaPro Datasets			
Weight of Steel for rail, per mile	*tons/mile*	240	Calculation - conversion of lbs./yd. to tons/mile * two rails
Volume of timber for ties per mile	*Cu.ft./mile*	11,000	Calculation - number of ties per mile * volume of wood per tie
Weight of steel for tie plates per mile	*tons/mile*	53	Calculation - Number of ties per mile * 2 plates per tie / 2,000 lbs. (1 ton)
Weight of steel for spikes	*tons/mile*	3.3	Calculation - Number of ties per mile * 4 spikes per tie / spikes per keg * weight of one keg/2,000lbs (1 ton)
Fuel	*Gal/mile*	4909	The total fuel consumption per mile of track construction (Clearing, track bed and ballast)

Table 10: Track Rehabilitation Process – Data and Calculations

Item	**Unit**	***Quantity***	***Source/Comments***
Track Rehabilitation – Data			
Number of ties per mile	#	1,200	40 % of ties upgraded
Quantity of wood per tie	*cu ft*	3.7	7" * 9" * 8.5' (Tie dimensions) http://www.rta.org/faqs-main
Volume of ballast per mile	*tons*	5,000	50% of new track construction, confirmed with MHF services
Track Rehabilitation – Values entered into SimaPro Datasets			
Weight of Steel for rail, per mile	*tons/mile*	240	Calculation - conversion of lbs./yd. to tons/mile * two rails
Volume of timber for ties per mile	*Cu.ft/mile*	4,500	Calculation - number of ties per mile * volume of wood per tie
weight of steel for tie plates per mile	*tons/mile*	21	Calculation - Number of ties per mile * 2 plates per tie / 2,000 lbs. (1 ton)
Weight of steel for spikes	*tons/mile*	1.3	Calculation - Number of ties per mile * 4 spikes per tie / spikes per keg * weight of one keg/2,000lbs (1 ton)

4.2.1.2 *Rolling Stock Manufacturing*

Table 11 shows ecoinvent datasets used in SimaPro for rolling stock manufacturing process

Table 11: Datasets for Processes under Rolling Stock Manufacturing

Process	**Unit**	***Item***	***Dataset***
Truck Manufacturing and *Loader Manufacturing*	*Per truck*	Steel	Steel, low-alloyed, hot rolled (GLO)| market for | Alloc Def, U
		Aluminum	Aluminium, cast alloy (GLO)| market for | Alloc Def, U
		Manufacturing Process	Metal working, average for metal product manufacturing (RER)| processing | Alloc Def, U
Truck Tire manufacturing	*Per Tire*	Rubber	Acrylonitrile-butadiene-styrene copolymer (RER)| production | Alloc Def, U
		Processing	Injection moulding (GLO)| market for | Alloc Def, U
Locomotive Manufacturing and *Rail car manufacturing*	*Per Unit*	Steel	Steel, low-alloyed, hot rolled (GLO)| market for | Alloc Def, U
		Manufacturing Process	Metal working, average for metal product manufacturing (RER)| processing | Alloc Def, U

Truck Manufacturing Process

The trucks used to haul ore and concentrate are 11 axle tractor-trailers and the quantities of steel, aluminum and tire components are calculated for each truck using data from M J VanDamme (Table 12). The process includes all of the materials and energy inputs required for one truck. Tire manufacturing was created as a separate dataset to make it easier to account for the tires replaced over the life of the study. The number of trucks and tires varied between options and were given as input into the SimaPro modules for each option separately.

Table 12: Truck Manufacturing Process – Quantities and Calculations per Truck

Item	**Unit**	***Quantity***	***Source/Comments***
Truck Manufacturing – Data			
Loaded Truck Weight	*tons*	82	Van Damme trucking, Michigan maximum truck weight, 164,000 lbs. (82 tons)
Capacity of truck	*tons*	51	Van Damme trucking,
Empty truck weight	*tons*	31	
Number of tires per truck	*#*	42	Van Damme trucking
Weight of tires	*Lbs.*	130	Weight of each tire, Size of tire from Van Damme trucking, weight from Michelin tire website
Total weight of tires	*tons*	2.73	
Weight of truck without tires	*tons*	28.27	
Truck Manufacturing – Values entered into SimaPro Datasets			
Quantity of steel	*tons*	18.38	Assuming 65% truck components are steel
Quantity of aluminum	*tons*	7.07	Assuming 25% truck components are aluminum
Weight of tire in tons	*tons*	0.065	

Loader Manufacturing Process

A transload facility with a single front end loader is required in Option B and Option C of ore transportation, and for Option E in concentrate transportation. The loader construction process includes items for quantities of steel and rubber for tires. MHF services provided the details on the type of loader, and the quantities of steel and rubber for the loader were obtained from the specifications sheet from the loader manufacturer’s website. Table 13 lists the quantities for manufacturing process of loader.

Table 13: Loader Manufacturing Process – Quantities and Calculations

Item	**Unit**	***Quantity***	***Source/Comments***
Loader Construction – Data			
Empty Loader weight	*tons*	56.28	Source: Caterpillar performance handbook, CAT 988K Front loader
Weight of tires	*tons*	2.38	1,191.22 lbs. per tire * 4 tires. Source: Tire type from performance handbook, tire weight from Heuver tires website.
Weight of loader without tires	*tons*	53.90	
Loader Construction – Values entered into SimaPro Datasets			
Quantity of steel	*tons*	35.04	Assuming 65% components are steel
Quantity of aluminum	*tons*	13.48	Assuming 25% components are aluminum

Locomotive and Rail Car Manufacturing Processes

MHF services and Highland Copper provided the data on the locomotive type and number of rail cars that are required for each option involving rail. The train consist for ore transportation includes two 2,000 HP locomotive hauling 70 rail cars from the mine to White Pine in Option B. In Option C, two 35 car trains will be hauled from the mine to Connorville, where the train will be built to a 70 car unit train and moved further to White Pine. For the concentrate transportation scenario, the train consist will be a two locomotive train with 25 rail cars in both Option E and Option F. Since the concentrate cars need to go further from Escanaba, it was estimated that approximately 200 cars are required for the operations, taking into consideration the return time of the cars from the final destination. For locomotive and rail car manufacturing, the major component used in the analysis is steel and weights are obtained from public rolling stock databases. The data for one locomotive and one rail car manufacturing processes are shown in Table 14.

Table 14: Locomotive and Rail Car Manufacturing Process - Quantities and Calculations per unit

Item	**Unit**	***Quantity***	***Source/Comments***
Locomotive Manufacturing – Data			
Locomotive Weight	*tons*	125	GATX website
Locomotive Manufacturing – Values entered into SimaPro Datasets			
Quantity of steel	*tons*	112.5	90% of locomotive is made of steel
Rail Car Manufacturing – Data			
Gross weight of Rail car	*tons*	131.5	weight of car + load, Data from MHF suggested 263,000 lbs. operations
Net Weight of Rail car	*tons*	100	MHF Data
Empty Rail car weight	*tons*	31.5	
Rail Car Manufacturing – Values entered into SimaPro Datasets			
Quantity of steel per rail car	*tons*	31.5	Assuming complete steel for rail car

4.2.2 Use/Operations

The energy consumption during the use/operations stage of infrastructure is limited to the snow removal on the county road 519. Since the county road is currently not accessible in winter, the snow has to be cleared after the mine becomes operational and as such, the fuel consumed for 136 days of snow removal per year is considered. This is the average days of snow removal annually, as provided by the Gogebic County Road Commission. The snow removal on railroad tracks can be done by attaching a snow plow to the front of the locomotive and hence is not considered as a separate item in the analysis.

Under the operation stage, the major variable for equipment is the truck and locomotive fuel consumption. The operations are assumed to take place 24/7 throughout the year (Table 3 and 5 in Section 3).

The average truck fuel consumption for the 51 ton capacity trucks is approximately 3.5 mpg (loaded and unloaded), obtained from M J VanDamme. The total number of trucks needed varies between options, due to variation in round trip distance and the number of truckloads per day. The number was obtained from a trucking rates proposal by M J VanDamme, but is considered confidential (values not included in the table).

For train operations, data on number of rail cars and type of locomotive was obtained from MHF services and Escanaba and Lake Superior Railroad (E&LS). The consumption of fuel per train round trip in each option was calculated in Rail Traffic Controller (RTC) software, as described in Section 4.2.2.1.

For the transload operations, the fuel consumption required by the loader for loading ore and concentrate is obtained from the loader specification sheet as 11.80 gallons/hour (see details in Appendix -A: Quantities of different process used for SimaPro datasets).

The fuel consumption of trucks and trains was calculated for each option and mine life. In SimaPro, the emissions from fuel were included in two parts; The first is the quantity of diesel produced for the operations/use, which is calculated from the average fuel consumption of trucks and train. The second is the amount of carbon dioxide emitted from burning 1 kg of diesel. This value was obtained from the GREET model [26] and the stoichiometric calculations resulted in an approximate 3.2 kg of CO_2 emitted per kg of diesel burnt. The emissions from the total fuel consumed over life are estimated in this step

4.2.2.1 *Train Fuel Consumption Calculation – Rail Traffic Controller (RTC)*

RTC was used to calculate the locomotive fuel consumption, based on the actual vertical profiles of the tracks. The profile for the new track in ore transportation was provided by MHF services. For the CN existing track, profile was developed from Google Earth. Track elevations for the proposed track between Ontonagon and White Pine (option F) were obtained from an old project proposal for the line. RTC used actual train configurations and weights and all trains were operated at 25 mph. Figure 15 shows an example of the RTC simulation graph.

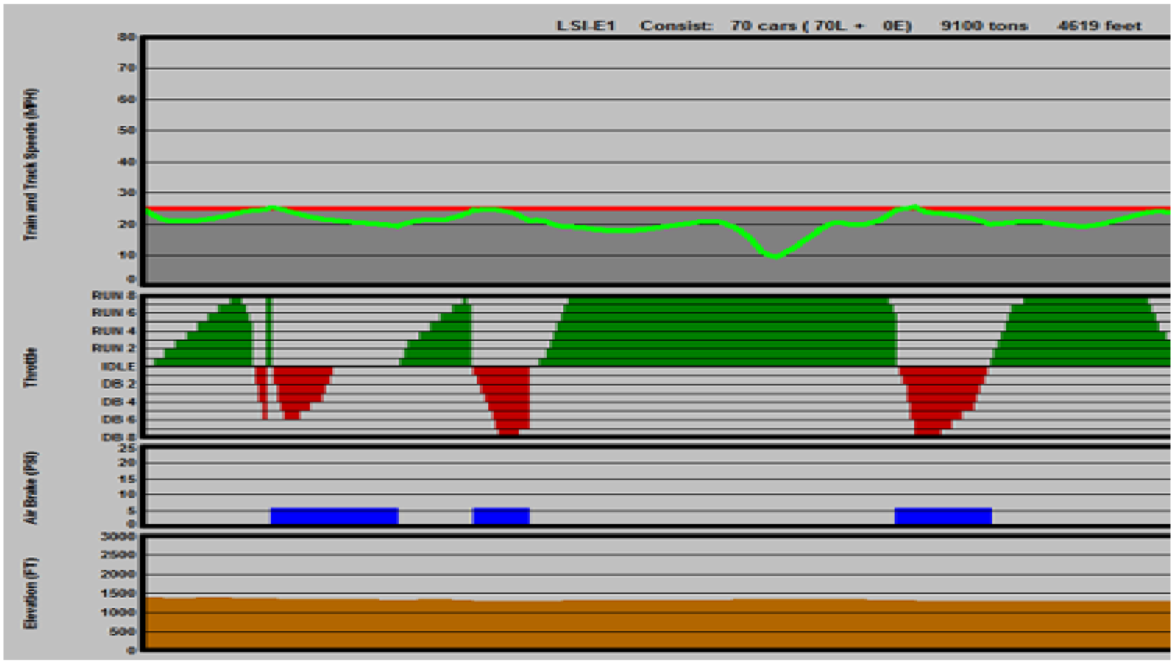


Figure 18: Screen shot of RTC Simulation including the Train Speed, Throttle, Braking and the Track Elevation from Top to Bottom

A) *Ore Transportation*

In the ore transportation, Options B and C include rail transportation. In Option B, a 70 car unit train is operated every day from Connorville to White Pine. Due to grade limitations, two 35 car trains are moved from the transload near the mine to Connorville every day in Option C and then combined into one 70 car unit train to White Pine. In return all 70 cars can be pulled to the mine in a single train. The round trip fuel consumption and trip duration for Option B and Option C are shown in Table 15. It should be noted that in Option B, the fuel consumption of the returning empty train is higher than the loaded train, mainly due to prominent uphill during the return trip.

Table 15: Ore Transportation – RTC Simulation Data

	Direction	**Option B**	**Option C**
Travel Time (HH:MM)	**Loaded Outbound**	01:37	03:28
	Empty Return	01:35	02:00
Fuel Consumption (gallons)	**Loaded Outbound**	202.5	470.3
	Empty Return	211	242

B) *Concentrate Transportation*

50 car loads of concentrate will be transported weekly from White Pine to Escanaba. This is done in two 25 car unit trains for Options E and F, each using either two GP 38-2 or SD 40-2 locomotives by E&LS Railroad. From RTC analysis, the higher fuel consumption was observed in GP 38-2 and the results of these locomotives are used for the analysis so that the worst case scenario is modeled. Table 16 shows the round trip travel time and fuel consumption of Option E and Option F.

Table 16: Concentrate Transportation – RTC Simulation Data

	Direction	**Option E**	**Option F**
Travel Time (HH:MM)	**Loaded Outbound**	09:02	10:50
	Empty Return	08:50	10:20
Fuel Consumption (gallons)	**Loaded Outbound**	782.6	999.8
	Empty Return	346.2	453.9

4.2.3 Maintenance

4.2.3.1 *Infrastructure Maintenance*

The maintenance required for infrastructure and rolling stock contribute to the life cycle emissions of the system. Table 17 details the ecoinvent datasets used for the maintenance of infrastructure.

Table 17: Datasets of Processes under Infrastructure Maintenance

Infrastructure Maintenance

Processes	***Unit***	**Item**	**Datasets**	**Comments**
Road Maintenance	*Per mile*	HMA	LCA Highland Copper HMA	Custom Dataset
Track Maintenance	*Per mile*	Gravel	Gravel, crushed (GLO)| market for | Alloc Def, U	For ballast
		Steel	Steel, low-alloyed, hot rolled (GLO)| market for | Alloc Def, U	For rail, spikes and tie plates
		Timber	Sawn timber, softwood, planed, air dried, at plant/US- US-EI U	For ties

Road Maintenance Process

The road maintenance process includes a mill and overlay of the county road once every five years to prevent the road from deteriorating. The Gogebic County Road Commission provided a value of 18,480 cu. feet of HMA per mile of overlay (1.5 inches depth of mill and overlay). The road maintenance process for one mile was created in SimaPro using this quantity of HMA. The total quantity of maintenance used the appropriate lengths for each option.

Track Maintenance Process

For rail infrastructure, inspections at regular intervals and spot maintenance were included. The quantity of materials and energy consumption for this maintenance was estimated to be at 20% of the full construction quantity in five year intervals. Since track maintenance is not done all at once but is done in spot maintenances over life, the maintenance is assumed to be performed every year and the quantity of track maintained every year is one fifth of the 20% which equals 4% of the full construction quantity annually. The values of track maintenance per mile are shown in Table 18.

Table 18: Track Maintenance Process– Quantities and Calculation per mile

Item	**Unit**	***Quantity***	***Source/Comments***
Track Rehabilitation – Data			
Number of ties per mile	#	600	20 % of ties per mile of track upgraded with spot fixes within a five year period
Quantity of wood per tie	*cu ft*	3.7	7" * 9" * 8.5' http://www.rta.org/faqs-main
Volume of ballast per mile	*tons*	2,000	20% of quantities of new track construction every five years, assumed value
Track Rehabilitation – Values entered into SimaPro Datasets			
Volume of timber for ties per mile	*cuft/mile*	2220	Calculation - number of ties per mile * volume of wood per tie
weight of steel for tie plates per mile	*tons/mile*	11	Calculation - Number of ties per mile * 2 plates per tie / 2,000 lbs. (1 ton)
Weight of steel for spikes	*tons/mile*	0.7	Calculation - Number of ties per mile * 4 spikes per tie / spikes per keg * weight of one keg/2,000lbs (1 ton)

4.2.3.2 *Rolling Stock Maintenance*

Rolling stock maintenance is one of the crucial tasks to keep the operations running without delays. Table 19 shows ecoinvent datasets used in SimaPro for rolling stock maintenance processes.

Table 19: Datasets for Processes under Rolling Stock Maintenance

Processes	**Unit**	***Item***	***Datasets***
Truck , Loader and Locomotive maintenance	*Per cycle*	Lubricating oil	Lubricating oil (GLO)| market for | Alloc Def, S
Truck Tire maintenance	*Per Tire*	Rubber	Acrylonitrile-butadiene-styrene copolymer (RER)| production | Alloc Def, U
		Processing	Injection moulding (GLO)| market for | Alloc Def, U

Truck Maintenance Process

For the trucks, routine maintenance, such as change of oils and other filters performed at regular mileage intervals of 15,000 miles was included. The number of tires required varies based on the mine life and is included in the tire manufacturing process. The life of a truck is considered to be 20 years, as provided by MHF services. Table 20 shows the details of truck maintenance and the inputs for the truck maintenance process in SimaPro.

Table 20: Truck Maintenance Process – Quantities and Calculations per mile

Item	**Unit**	***Quantity***	***Source/Comments***
Truck Maintenance – Oil Replacement Data			
Quantity of oil replaced per maintenance cycle	*gal*	11.00	Van Damme trucking
Density of oil	*kg/l*	0.85	
quantity of oil in liters	*lit*	41.64	
Distance travelled by truck in one day	*miles*	320	For option B, round trip 16 miles, Calculation - 140 truck trips per day *16/number of miles
Distance travelled by truck in one year	*miles*	116,800	
number of maintenance cycles per year	*#*	7.79	Calculation – distance travelled per year / 15,000 miles (maintenance interval)
Truck Maintenance – Oil Replacement Values entered into SimaPro Datasets			
Weight of oil per maintenance cycle	*kg*	35.39	Calculation – Quantity of oil in liters per maintenance cycle * density of oil
Truck Maintenance Cycles over life	*#*	1,090	Calculation – number of maintenance cycles per year * number of trucks * life

Train (Rolling Stock) Maintenance

A schedule of routine maintenance of locomotives was assumed. Locomotives undergo maintenance once every month where oils are changed and filters are replaced. This was used in the analysis for emissions from locomotive maintenance. The wheels of the rail car were assumed to be changed for every 300,000 miles, per a rail car manufacturing company. Change of locomotive wheels was excluded, as there were only two locomotives and also there was no reliable data for locomotive wheel changes.

Loader Maintenance

Loader maintenance includes oil changes, oil filter and routine maintenance every year. From the specification sheet of the loader, it was observed that the hydraulic oil needs to be changed 14 times for every 2,000 hours of operations. The quantity of oil changed for every cycle is 206.5 gallons. The loader maintenance process included these quantities per maintenance cycle and the total number of maintenance cycle over life for each option was included in the SimaPro module of each option. The replacement of loader was not considered in any option, since there was no data available on the maximum operational loader life.

4.2.4 End of Life

In the end of life, the road is left in place after the mine closes, so there is no disposal or recycle of material from road infrastructure. For the rail infrastructure, the rail and the ties can be salvaged and reused in a different project. Similarly, the locomotive and rail cars might be rebuilt and then reused, but the trucks which are past their life can be scrapped. Due to high level of uncertainty for the end of life quantities and values, the stage was excluded from the LCA analysis.

5 Results and Discussion

5.1 LCA Results for Primary Input Units

As mentioned earlier, this project uses the IPCC 2013 100a method for calculating Global Warming Potential (GWP), which calculates the amount of greenhouse gases released during the complete life cycle process in terms of equivalents of carbon dioxide (kg CO_{2eq}). The output of the LCA will be in GWP equivalent measures of kg $CO_{2eq,}$ which can be normalized on the basis of our functional unit for comparison of different transportation options. Table 21 illustrates the Global Warming Potential (GWP) results on unit basis for different infrastructure and rolling stock processes. In the table, the LCA results obtained from SimaPro per ton of product transported from each option are multiplied with the total volume of the product shipped over the selected mine life to obtain total emissions per process for the option. Then each item is divided with the quantity of the selected unit to get comparable values for activities or processes across the alternatives. For example, all infrastructure processes are normalized to determine the quantity of emissions for kg CO_{2eq}/mile, and most operations for kg CO_{2eq}/ton-mile. The table is followed by a short discussion of each primary input category.

Table 21 Global Warming Potential in kg CO_{2eq} per Unit for Primary Inputs

Item	Amount	Unit	Comments
Infrastructure			
Road Reconstruction	6.79×10^5	kg CO_{2eq}/mile	
Road Maintenance	5.02×10^4	kg CO_{2eq}/mile	
Rail Upgrade	6.67×10^5	kg CO_{2eq}/mile	
Rail New Construction	8.55×10^5	kg CO_{2eq}/mile	
Rail Maintenance	7.41×10^4	kg CO_{2eq}/mile	
Rolling Stock			
Truck Manufacturing	1.22×10^5	kg CO_{2eq} / truck	Includes 42 new tires
Truck Maintenance	1.40×10^{-1}	kg CO_{2eq} / truck-mile	New tires, oil changes
Locomotive Manufacturing	4.40×10^5	kg CO_{2eq} / Locomotive	
Rail Car Manufacturing	1.23×10^5	kg CO_{2eq} /Railcar	
Locomotive Maintenance	1.12×10^4	kg CO_{2eq} / year	Oil changes
Rail Car Maintenance	1.69×10^4	kg CO_{2eq} / wheel change per car	
Loader Manufacturing	2.02×10^5	kg CO_{2eq} / Loader	
Loader Maintenance	2.02×10^4	kg CO_{2eq} / year	Hydraulics and lubricant changes (for ore scenario)
Operations			
Truck Operations	0.13	kg CO_{2eq}/ton-mile	
Rail Operations (Ore)	0.02-0.027	kg CO_{2eq}/ton-mile	For options B and C, respectively (different capacity, track routes)
Rail Operations (Concentrate)	0.015-0.016	kg CO_{2eq}/ton-mile	For options E and F, respectively (different capacity, track routes)
Transload Operations	0.19	kg CO_{2eq}/ton	For options B, C and F.

5.1.1 Construction/Manufacturing

The construction or rehabilitation of track, construction of track on existing subgrade, road reconstruction-heavy and road reconstruction-light are all compared on emissions per mile basis. The emissions from road reconstruction and track construction on existing subgrade per mile are similar, but the track upgrade emissions are somewhat lower than the track construction on existing subgrade due to lower quantities of materials required for upgrade.

Truck construction has lower impact than train construction, which can be expected based on the difference between their size and hauling capacity. The emissions from locomotive manufacturing are much higher than from truck manufacturing.

5.1.2 Operations

A clear difference in operational impacts can be seen between truck and rail transportation. Rail transport generates 5-10 times lower emissions per ton-mile, depending on the specific configuration of the train. The loader fuel consumption for loading one ton of ore/concentrate into the railcars is included in the analysis, but it has only minor effect on overall results.

5.1.3 Maintenance

Train and truck maintenance are not directly comparable, as truck maintenance is based on mileage, while the locomotive maintenance is on a monthly basis regardless of distance operated. The rail car maintenance is on a 300,000 mile intervals. The emissions per unit for track maintenance are higher than for road maintenance due to the larger quantities of materials replaced per mile (road maintenance is only mill and overlay).

5.2 LCA Results – Ore Transportation

This section discusses the LCA results of the ore transport on the basis of per ton of ore transported from Copperwood to the processing plant at White Pine. In the first part, the emissions for each option for the base case (20 year mine life) are analyzed, followed by the results of other mine lives. Finally, an activity level breakdown for the 20 year ore transport option is provided.

5.2.1 Ore Transportation – 20 Year Mine Life

Figure 19 shows the total GWP in kg CO_{2eq} per ton of ore of each option for the 20-year mine life. In Option A, where trucks are the only method of transportation, small percentage of GHG emissions are attributed to construction of road infrastructure, while over 90% of the total emissions are due to truck operations. Option B shows a large decrease in emissions from operations due to the use of the more fuel-efficient rail mode for 80% of the route distance. This large decrease in operations emission exceeds the increase in infrastructure related emissions due to rail line upgrade. The resulting GWP per ton of ore in option B is 53% lower than Option A (6.3 vs 2.95 kg CO_{2eq}/ton ore for Options A and B, respectively). In Option C, emissions due to construction stay relatively constant, due to offsetting burdens of increased new track construction and decreased heavy road reconstruction. Operations burdens continue to decrease in Option C, as even higher percentage of total transportation is by rail, resulting in an overall GWP of 2.66 kg CO_{2eq}/ton ore. In all options, GWP emissions related to maintenance of infrastructure and rolling stock are minor contributors and stay relatively constant.

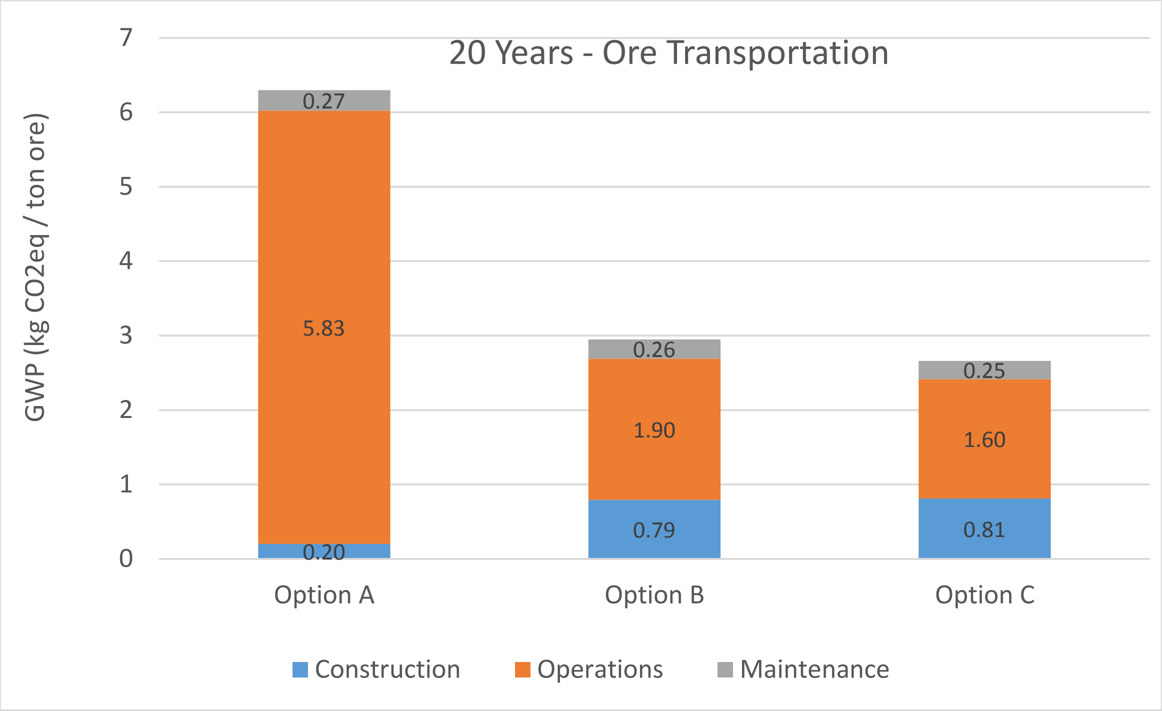


Figure 19 Global Warming Potential (GWP) of Different Ore Transport Options, for 20 years Mine Life.

5.2.2 Ore Transportation – All Mine Lives

Figure 20 shows the overall GWP emissions per ton of ore for all investigated mine lives (20-year values match with Figure 16). GWP from maintenance of infrastructure and rolling stock have minor effect on the overall emissions and stay relatively constant between transport options and different mine lives. This is logical, as maintenance activities occur on a regular time and/or mileage intervals, so these stay constant for different operating time frames when we normalize the impacts on the basis of each ton of transported ore. Similarly, the burden of operation activities remains fairly constant, as average emissions from diesel combustion have low variability on per ton basis.

Construction emissions, which include infrastructure construction and rolling stock manufacturing, show the largest variation between mine lives. In option A, road and truck construction burdens remain the same for 10 and 20 year mine lives while the ore production doubles, decreasing the per ton construction impacts by approximately 50%. The same scenario takes place for road and rail infrastructure/rolling stock for the 10 and 20-year time frame in options B and C. As the life of the mine passes 20 years, a new fleet of trucks is needed to replace the initial set of trucks, which adds to the total construction burden and offsets the continuing decrease of infrastructure emissions when normalizing to an increasing time horizon. This effect is even clearer in options B and C, where the decrease in construction emissions continues throughout the increasing time horizon. Regardless of the mine life, option C results in the lowest overall GWP emissions, ranging from 3.36 to 2.42 kg CO_{2eq}/ton ore.

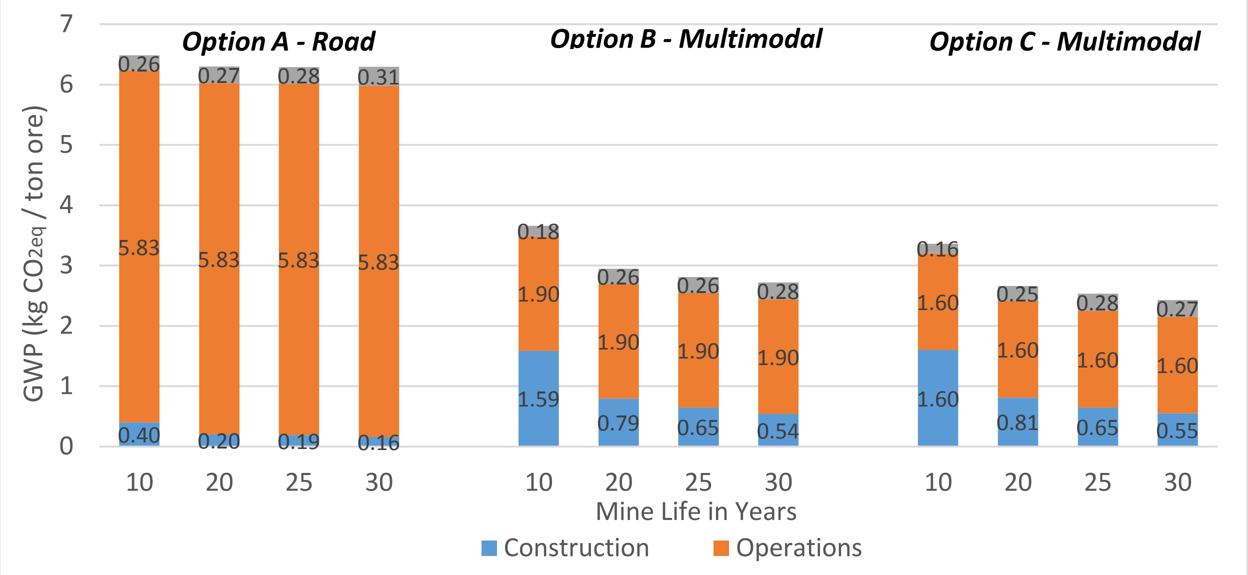


Figure 20 kg of CO_{2eq} per ton of Ore Transported in Different Options for all Mine Lives.

5.2.3 *Ore Transportation – Breakdown of Activities for 20 year Mine Life*

Figure 21 shows the breakdown of activities within the three main categories for the Option B and 20 year mine life. Option B was selected for demonstration, as it offers the most balanced need for rail and road infrastructure upgrades and distance of trucking and rail transportation and 20 years is the currently expected operating life by Highland Copper. As evident in the figure, the operations stage accounts for 64% of the overall life cycle emissions. Even though the trucking distance is only 8 miles compared to the 34 miles of rail transport, the emissions from the trucking operations are 20% higher than those from the rail operations. Transloading accounts for the remaining 10%.

While construction accounts for only 27% of the total lifecycle emissions, the breakdown of construction stage clearly depicts that the GWP emissions from rail related activities account for more 77% of the total construction/manufacturing stage (49% of the total emissions).

The infrastructure maintenance constitutes over 71% of the total maintenance emissions (6% of total). This is due to the needed spot maintenance for the tracks and a mill and overlay for the road. The remaining 29% of maintenance emissions (2.5% of total) are a combination of train, truck and loader maintenance.

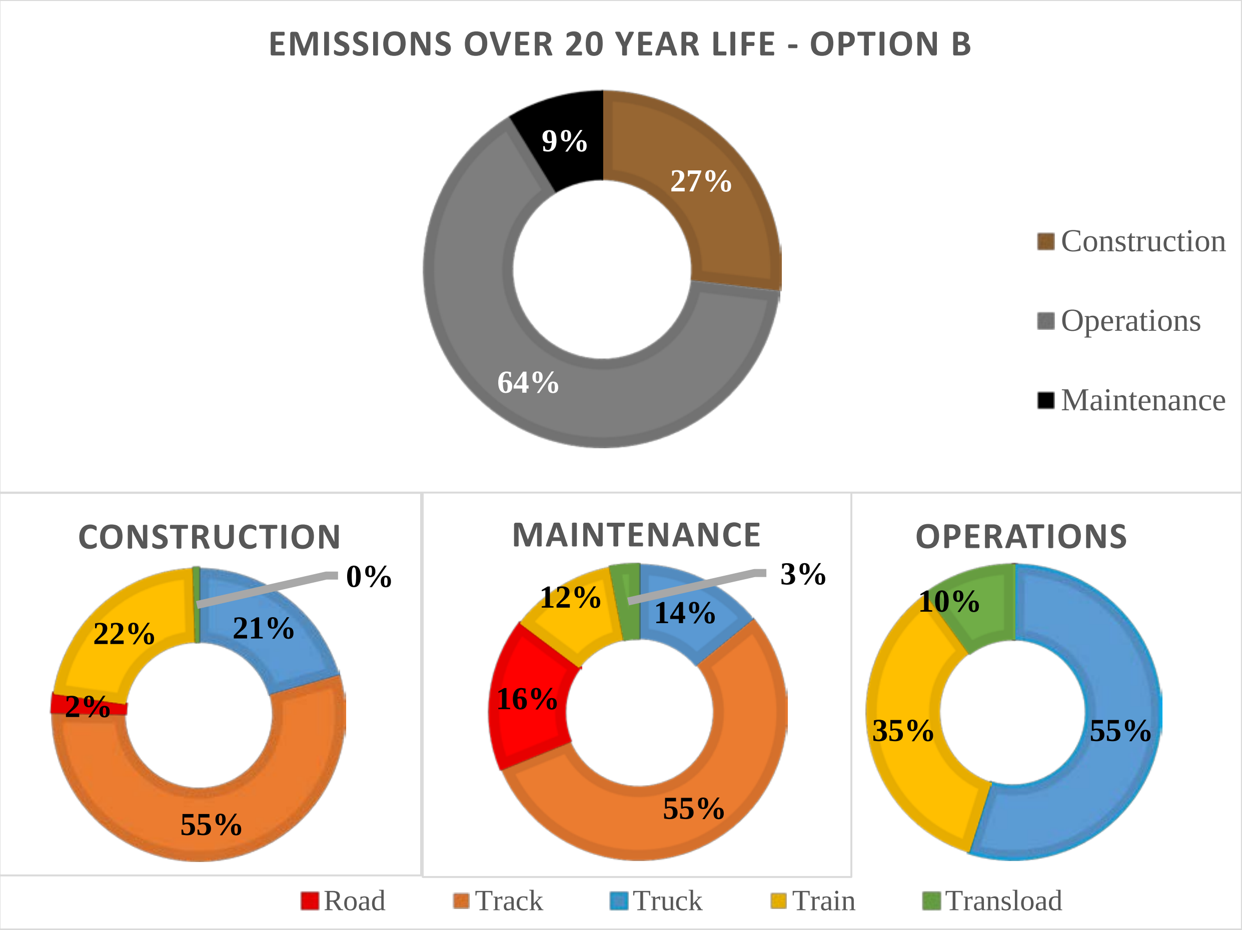


Figure 21 Breakdown of GWP Emissions of Different Stages in Option B Ore Transport for 20 Years Mine Life

5.3 LCA Results – Concentrate Transportation

The following includes results of the concentrate transport scenario from the processing plant at White Pine to Escanaba (Options D, E and F). The discussion is outlined similar to the ore transportation, the first part analyzing the results for each option for the base case of 20 years, followed by the overall results for the different mine lives. Finally, an activity level breakdown for the 20 year mine life (Option E) is provided.

5.3.1 *Concentrate Transportation – 20 Year Mine Life*

Figure 22 shows the total GWP in kg CO_{2eq} per ton of concentrate for each option of the 20-year mine life. There is no need for road construction or maintenance in any of the concentrate transportation options. In Option D, truck manufacturing, operations and maintenance account for the emissions, and 95% of them are being attributed to truck operations. In Option E, a large decrease in emissions from operations can be observed due to the use of the more fuel-efficient rail mode. The construction emissions remain low, as there is no need for track/road infrastructure upgrade in Option E, leaving only construction of train, trucks and transloading equipment. The resulting GWP per ton of concentrate in option E is 37% lower than option D (24.97 vs 15.69 kg CO_{2eq}/ton concentrate for options D and E, respectively). In option F, emissions due to construction are relatively high, due to added burdens of increased new track construction and track upgrade. Since Option F is only using rail, the operations burdens continue to decrease, resulting in an overall GWP of 19.22 kg CO_{2eq}/ton concentrate. Option F has somewhat higher maintenance related emissions due to added track infrastructure. Overall, option F has higher overall GWP emissions compared to the net GWP of Option E (multimodal), but lower than Option D.

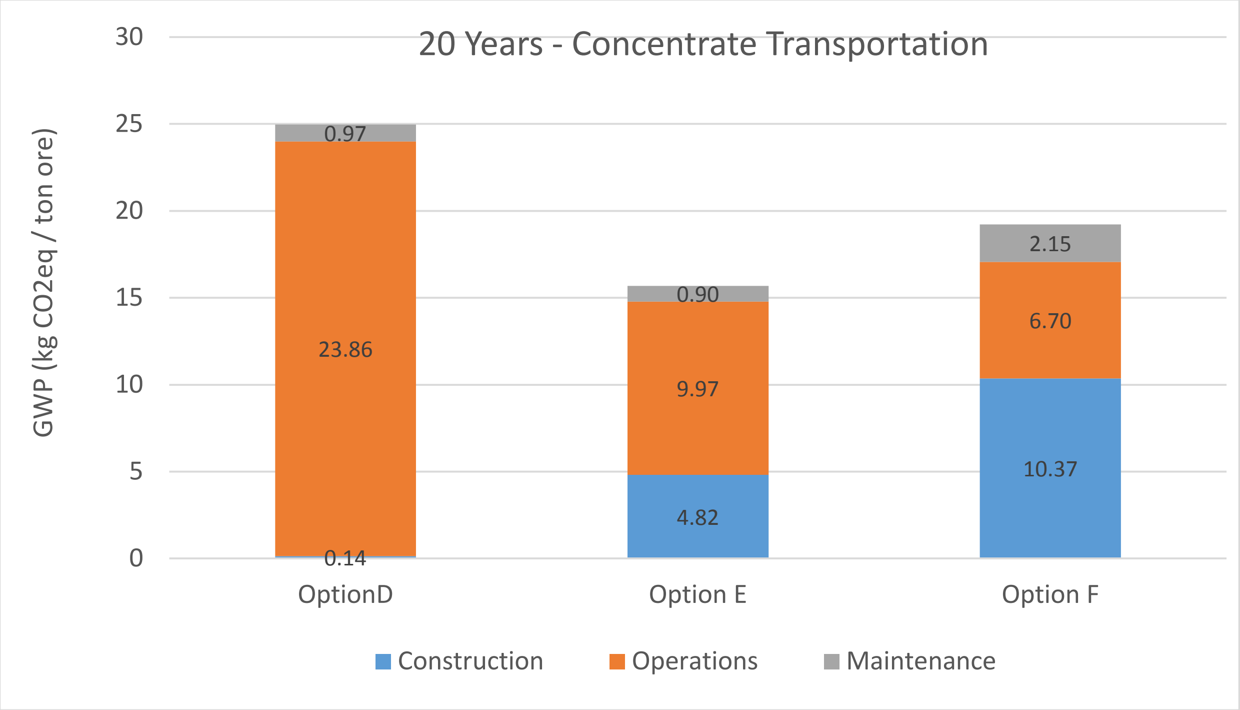


Figure 22 Global Warming Potential (GWP) of Different Concentrate Transport Options, for 20 years Mine Life.

5.3.2 Concentrate Transportation – All Mine Lives

Figure 23 shows the overall GWP emissions per ton of concentrate for all investigated mine lives (20-year values match with Figure 19). Similar to ore transport results, GWP due to maintenance of infrastructure and rolling stock is a minor contributor to the overall emissions. For Options E and F, a significant increase in the maintenance emissions can be observed as the mine life increases because a higher number of rail car wheels must be changed after every 300,000 miles. Similarly, the burden of operation activities is constant in each option regardless of the mine life, as average emissions from diesel combustion have low variability per ton basis.

Construction emissions, which include infrastructure construction and rolling stock manufacturing, show the largest change between mine lives, especially for options E and F. In option D, since construction includes only truck manufacturing, a 50% decrease in emission burdens can be observed between 10 and 20 year mine lives. To offset the construction due to new fleet of trucks after 20 years, a jump in the emissions can be observed between the 20 and 25 year mine lives. Across all time horizons, option E results in the lowest overall GWP emissions, ranging from 19.87 to 14.31 kg CO_{2eq}/ton concentrate.

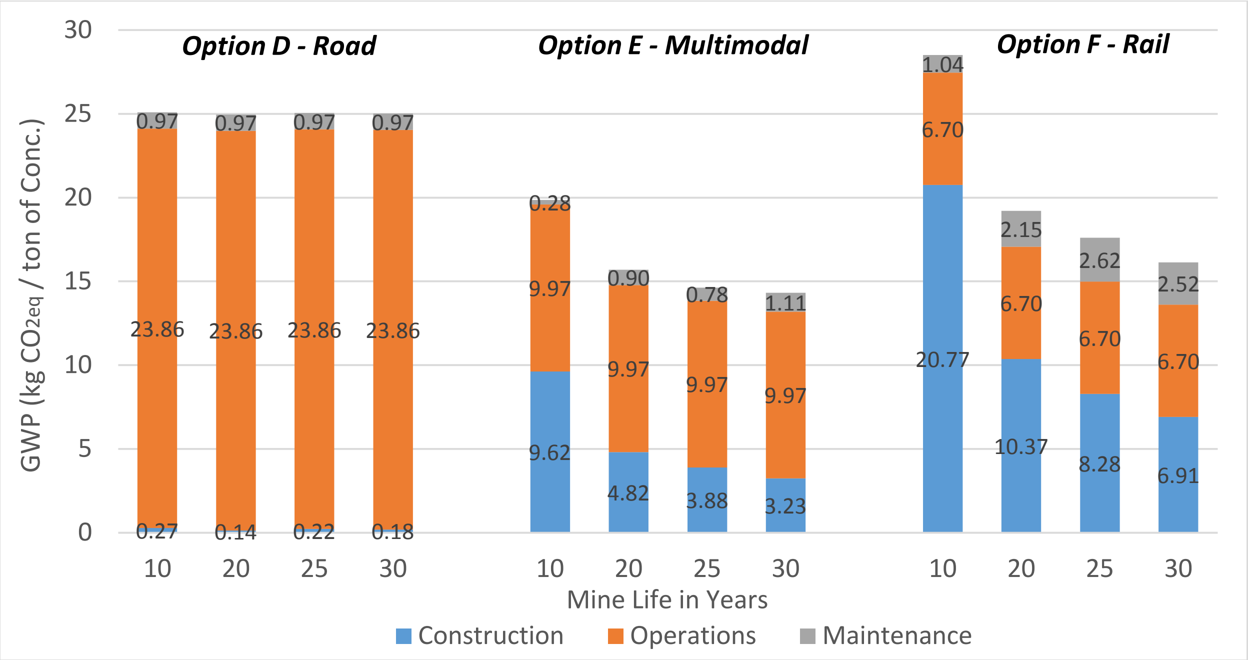


Figure 23 kg of CO_{2eq} per ton of Concentrate Transported in Different Options for All Mine Lives.

5.3.3 Concentrate Transportation – Breakdown of Activities for 20 Year Mine Life

Figure 24 shows the breakdown of activities within the three main categories for the Option E and 20 year mine life. Option E was selected as it included both truck and rail transportation. As it was the case in ore transport, operations burden dominates the emissions of concentrate transportation as well, accounting for 63% of the overall life cycle emissions. Even though the trucking distance is only 33 miles compared to 160 miles of rail transport, the emissions from rail operations are only 6% higher than those from the truck operations. The transloading operations account to 2% of the total operation emissions.

The breakdown of construction stage depicts that the GWP emissions from train construction is 98% of the total construction stage emissions because it includes construction of 200 rail cars and 2 locomotives. The truck and transloading equipment manufacturing contributes for only 1% each to the emissions. In the maintenance stage breakdown, the train maintenance constitutes about 78% of the total maintenance emission (5% of overall emissions) which is due to the large number of rail cars. Truck maintenance contributes 21% (1.2% overall) even though there are very few trucks required

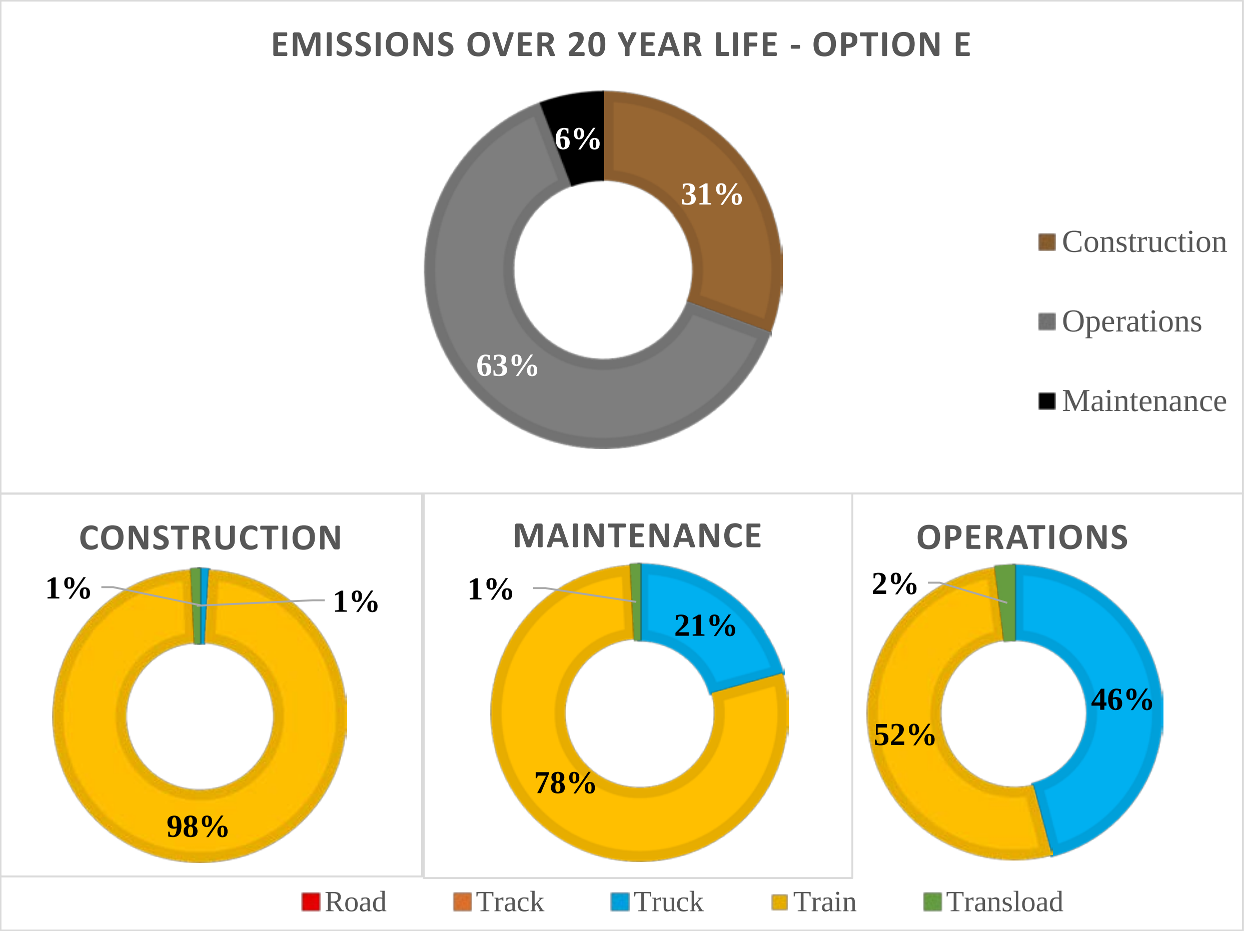


Figure 24 Breakdown of GWP Emissions of Different Stages in Option E Concentrate Transport for 20 Years Mine Life

6 Integration of LCA into Economic Analysis

While the main objective of this study was quantification of emissions through (LCA), a future objective would be to incorporate those emissions in the economic analysis, as transportation and related infrastructure/equipment investment decisions often depend on economics. When conducting economic analysis, there is a need to evaluate the cost of maintenance, operations, and replacement, in addition to determining the initial capital costs[27]. There are several methodologies that are used to evaluate transportation investments, such as the Benefit Cost Analysis (BCA), Economic Impact Analysis (EIA) and Life-Cycle Cost Analysis (LCCA). The methodology used depends on the study objectives and in some cases more than one of these alternatives are included in the analysis. Figure 25 highlights the similarities and differences between BCA (or B/C) and EIA analysis.

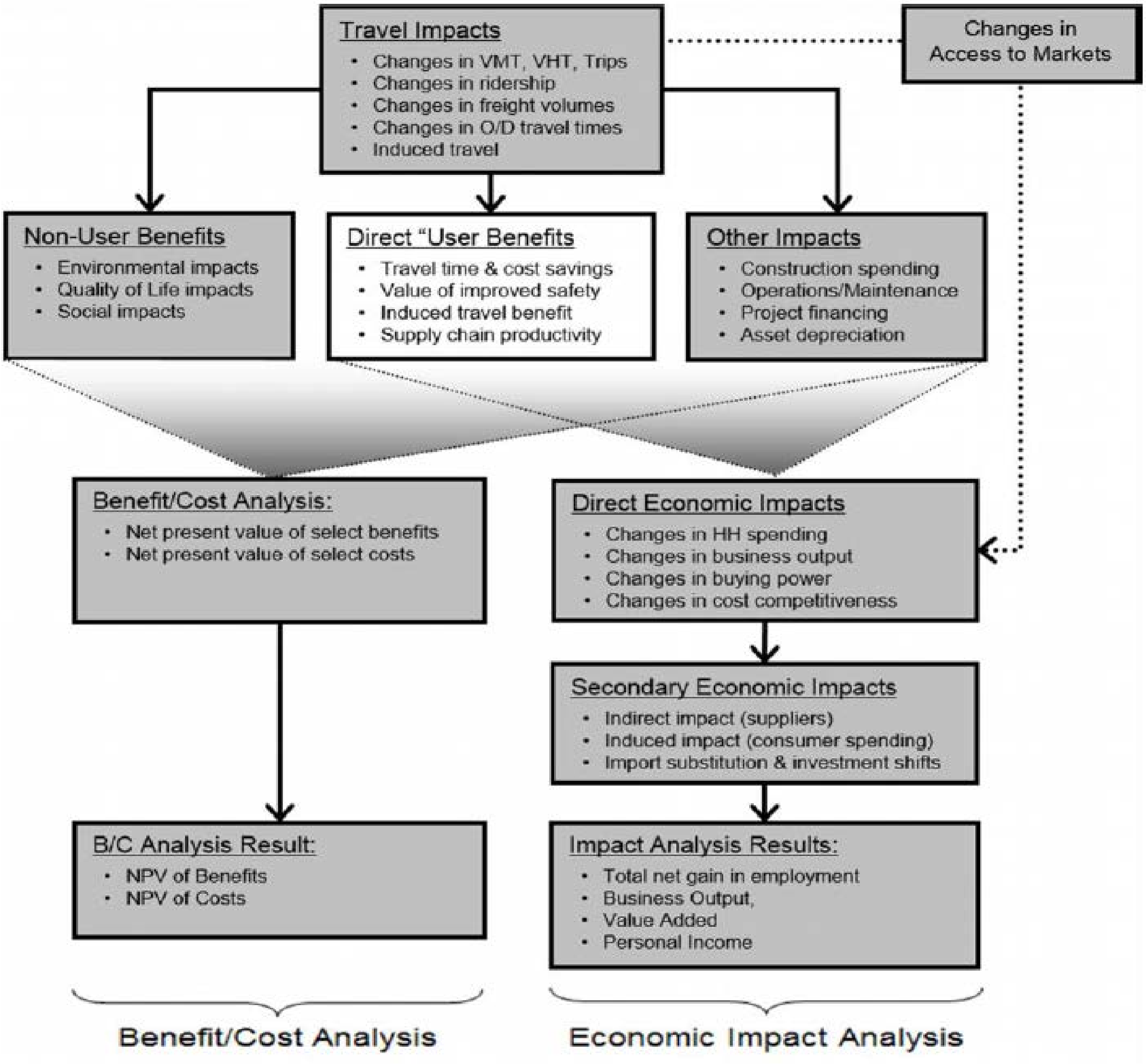


Figure 25: Overview of Benefit Cost Analysis and Economic Impact Analysis (Source: [28])

As described in the figure, both BCA and EIA use similar inputs, but the objectives (results) are different. While BCA calculates the different costs and benefits over the lifetime of a project, EIA provides an overview of short term and long term effects on the regional economy due to the transportation project. Both methods can be used to compare the project alternatives.

LCCA is a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment [29]. Performing LCCA for a project in the pre planning stages helps in the comparison of alternatives in the decision making process. The inclusion of social and environmental costs in the LCCA, such as safety, user delay, comfort and emissions, depend on the project objectives and the tools used. Costs are calculated by using relevant factors to convert them into a dollar value, which is then incorporated in the overall LCCA. In the following sections, LCCA is investigated in more detailed as the methodology to integrate emissions costs in the analysis.

6.1 LCCA in Transportation

Although LCCA is a very powerful economic tool [30], its use in transportation field has been much more prolific in the private sector where companies often have their own internal LCCA tools to evaluate cost allocation and decision making, Then financial investments with the highest potential for a return are selected [27]. For example, private freight railroads in the United States have their own set of economic theories and principles that were originally developed in the early in 20th century [31].

Conducting LCCA for decision making on transportation infrastructure investments in the public sector is gaining interest. The National Highway System (NHS) designation Act of 1995 requires all states to perform life cycle cost analysis to evaluate alternatives for projects costing more than $25 million [32]. The US DOT has guidelines for conducting LCCA [32] and many state DOT’s have their own set of principles and guidelines, such as Life Cycle Cost Analysis Procedure Manual by Caltrans [33], or LCCA process steps in Pavement Design and Selection Manual by Michigan DOT (MDOT) [34]. More recently, a report by the American Society of Civil Engineers (ASCE) recommended that federal agencies should standardize LCCA in the capital programming process by introducing state level legislation, partnering with the private sector, and improving data resources.[6]

6.2 Methodology

Although guidelines to perform LCCA differ, the steps are similar. For example, the main steps in the Federal Highway Administration’s manual on Life Cycle Cost Analysis in Pavement Design [32] are:

- Establish alternative pavement design strategies for the analysis period.
- Determine performance periods and activity timing.

- Estimate agency costs.
- Estimate user costs.
- Develop expenditure stream diagrams.
- Compute net present value.
- Analyze results.
- Reevaluate design strategies.

The Federal Energy Management Program also identifies similar steps in its life cycle costing manual [30].

6.3 Calculation of Costs

Calculation of costs over the life of a project is the primary objective of LCCA. To compare the costs over a long period, it is necessary to convert them to a common reference value. FHWA methodology requires the conversion of all costs to current value through Net Present Value (NPV) calculations. In NPV the future costs are made comparable by bringing them back to today's value using an interest or discount rate. The calculation of NPV uses a simple formula:

$$NPV = Future\ Cost\ \frac{1}{(1+i)^n}$$

Where i = discount rate or interest rate
n = year of expenditure

.

6.4 Integration of LCA into Economic Analysis

Calculating the social costs of carbon emissions allows agencies to estimate the carbon dioxide reduction benefits and include them in their cost analysis in terms of economic, social and complete environmental impacts [35]. The carbon emissions from different sources have various short term and long term impacts and in general have an adverse effect on the public health, wildlife, natural resources, forests and the environment. Since we performed LCA for the stages of construction/manufacturing, operations and maintenance, performing LCCA for the similar scope could identify all the costs along all the stages. Conducting full LCCA for the project was out of scope for this study, but the LCA emissions were converted into costs in terms of NPV for demonstration purposes. The major items for the conversion included identifying the cost of kg of CO_2, selecting a discount rate for calculating the NPV's, and the breakdown of emissions to annual contributions over the different mine lives. Figure 23 shows the basic outline of integrating the emission costs to the life cycle cost.

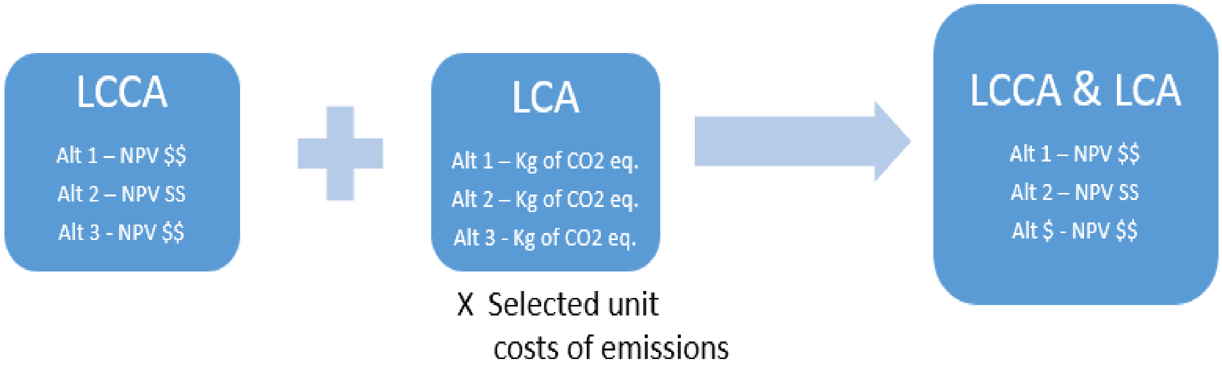


Figure 26 Integration of LCCA into LCA

6.5 Cost of Carbon

There are several options for quantifying the social costs of carbon. Mathews and Lave looked at the literature available to make comparisons of benefits from reduced emissions. They found four previous studies where the costs of GWP in CO_2 equivalents ranged from $2 to $23 /ton [36]. Tol claimed that there is large uncertainty in the social costs of carbon. He reviewed about 28 studies that assessed the marginal damage costs of carbon and found the best "guess" to be around $5/ ton of carbon with the mean being $104/ ton. He stated that it is unlikely for costs of carbon to exceed $50/ ton [37]. In our calculations, we used the social carbon unit costs published by U.S. Environmental Protection Agency (EPA) [38].

Table 22 shows the cost estimates of CO_2 emissions over multiple time horizons with different discount rate applied. The values in the table are the average of three different models that EPA uses to quantify the emissions. For this study, the 3% average value is used as the discount rate, which is identified as the most likely value by EPA[39]. The cost for each year of analysis was obtained through interpolation of the five year interval costs provided in Table 22.

Table 22: Social Cost of Carbon Dioxide in 2014 dollars per metric ton CO_2 (Source: EPA Website)

	Discount Rate and Statistic			
Discount Year	**5% average**	**3% average**	**2.5% average**	**3% 95th percentile**
2015	$12	$40	$62	$120
2020	$13	$47	$69	$140
2025	$16	$51	$76	$150
2030	$18	$56	$81	$170
2035	$20	$61	$87	$190
2040	$23	$67	$93	$200
2045	$26	$71	$99	$220
2050	$29	$77	$110	$240

As mentioned before, the LCA results for ore and concentrate transportation were calculated by SimaPro per ton of material transported. The quantity of emissions from all processes under each life cycle stage was calculated by multiplying the emissions in kg of CO_2 per ton of material transported with the total quantity transported over the mine lives and the emissions for each process were assigned to the year they occurred (Table 23). For example considering Option B for the 30 year mine life, the construction emissions were assigned to year zero, before the start of operations. The annual maintenance and operations emissions were assigned to every year, beginning at year one of the project. The road maintenance emissions were assigned once every five years and the railcar maintenance emissions were assigned to the year the rail cars achieved mileage necessitating maintenance (years 13 and 26). The processes that occurs at a certain interval are highlighted in bold in Table 23. A detailed breakdown of emissions for each activity are shown in Appendix –B: Emission Cost Calculation

Table 23: Emissions breakdown of Option B (Ore Transportation) for 30 years Mine Life

Year	Emissions Assigned for the Year
0	***Construction of infrastructure and equipment.***
1-4	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
5	***Road maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
6-9	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
10	***Road maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
11-12	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
13	***Rail Car Maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
14	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
15	***Road maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
16-19	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
20	***Truck Construction, Road maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
21-24	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
25	***Road maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
26	***Rail Car Maintenance**, Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*
27-30	*Truck maintenance, Track maintenance, loader maintenance, locomotive maintenance, Truck operations, Train operations*

6.6 Calculation of Emission costs

Once the emissions were obtained from the results of LCA, the average annual emissions for each option of ore and concentrate transportation were calculated according to the following process:

- The average annual per ton (ore/concentrate) emissions were then broken down between major processes taking place that year.
- Emission costs in Table 22 were interpolated for 30 years from 2016, which is the highest mine life in the LCA analysis. Then these yearly costs were converted to NPV.
- The annual emissions from each process were then multiplied by NPV emission cost during that year according to the assumptions made in the breakdown of emissions
- The total emission costs for different mine lives were added up and then divided by the total quantity of ore or concentrate transported over the life time to calculate cost per ton.

Figure 27 shows a process flow of the calculation of emission costs.

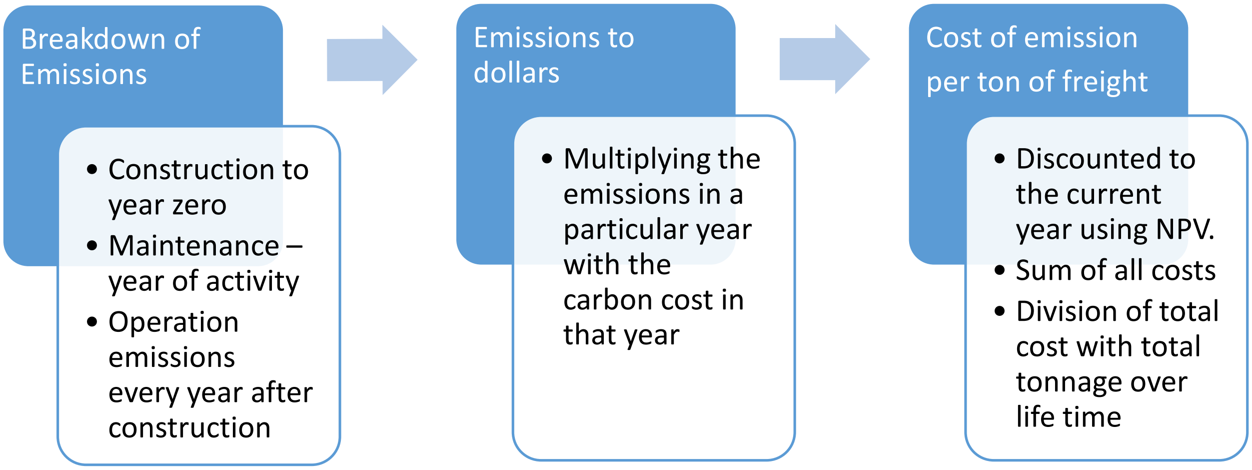


Figure 27: Calculation of Emission Costs

6.7 Emission Cost Results

The cost of CO_2 emissions per ton of ore or concentrate transported are calculated and the results are presented in Figure 28 and 29. Figure 28 shows the emission costs of transporting one ton of ore from the mine to the processing plant. Since the emissions in Option A are higher across all mine lives, the costs of emissions are also the highest for this option among all the ore transport options. Just like with emission quantities per ton of ore transported, the cost of emissions per ton also decrease with increase in mine life for all alternatives.

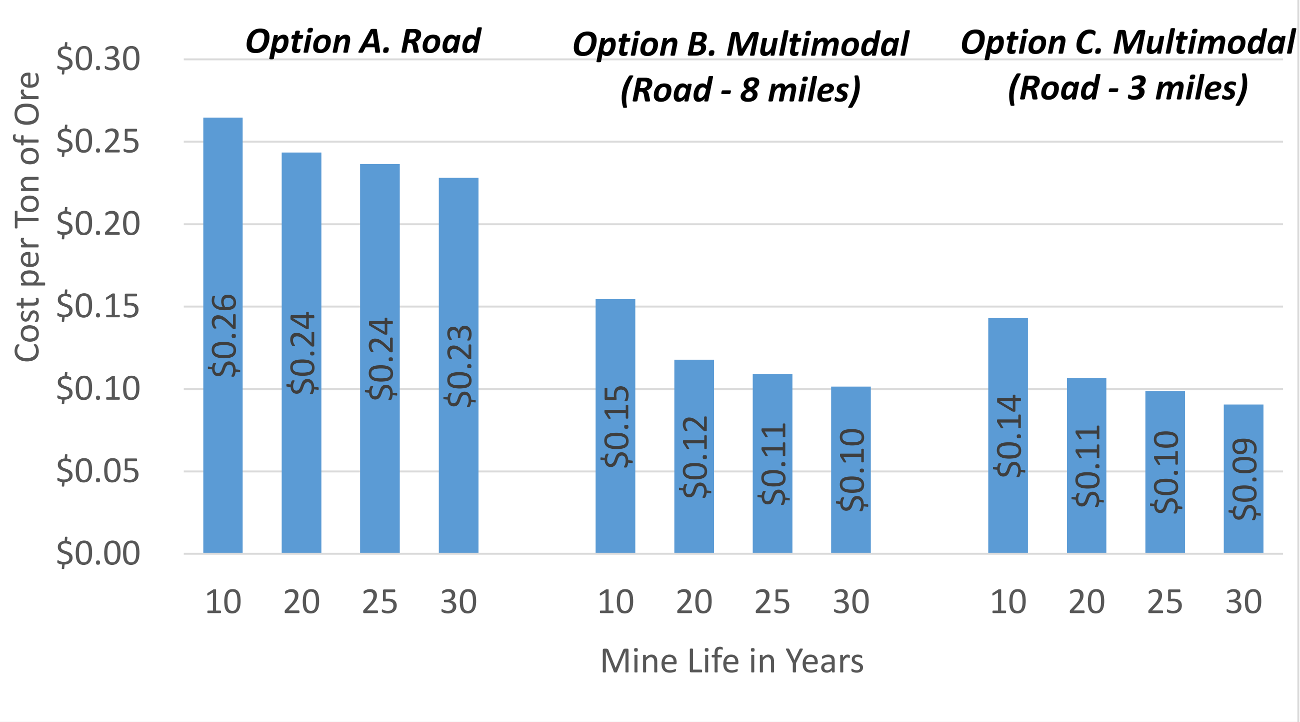


Figure 28 Emission Costs per ton of Ore Transported

Figure 29 shows the emissions costs per ton of concentrate transportation. Option F has the highest costs for the 10 year mine life due to the track construction emissions. For 20, 25 and 30 mine lives, the emission costs are higher for Option D. The emissions from Option E were the lowest in the LCA results, and thus the costs are also lowest for Option E.

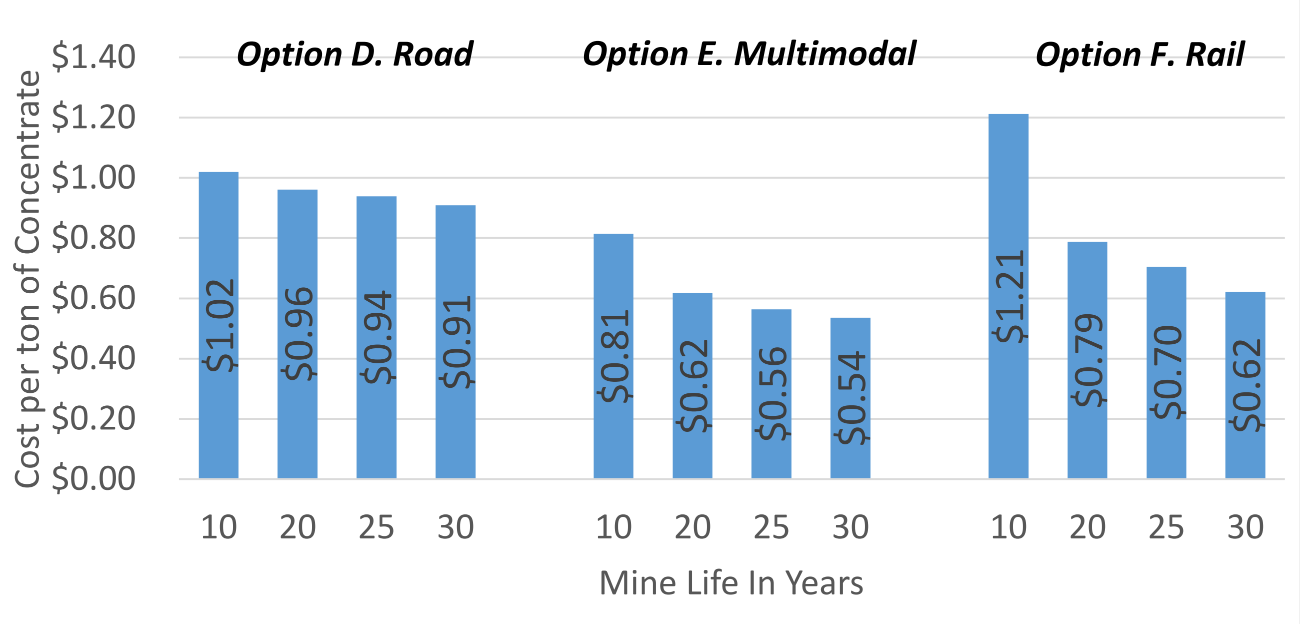


Figure 29 Emission Costs per Ton of Concentrate Transported

7 Conclusions and Recommendations for Future Research

7.1 Conclusions

This project introduced the concept of LCA as outlined by ISO 14040:2006 and the processes that occur during the life of a product. It also reviewed its past applications in transportation and applied these concepts to the case study of Copperwood project to analyze emissions from ore and concentrate transportation. The analyses used SimaPro tool to perform the LCA for calculating the global warming potential over the life of the mine in terms of kg of CO_2 equivalents per ton of ore / concentrate transported. The data was obtained from ecoinvent database or from locally collected custom datasets and the analysis was performed for 10, 20, 25 and 30 year mine lives to compare the impact of lifespan on the mode of transportation.

The study also outlined the concepts of economic analysis for comparing transportation system alternatives and investigated the integration of emission costs in the LCCA analysis for identifying the option that is most cost effective from a socio economic perspective. For the integration, the LCA results were converted to dollar values using unit cost of CO_2 emissions

The main conclusions of the study include:

- The literature review revealed that the use of LCA in transportation is often directed towards a specific goal of the project or case study. There were few studies available for general freight comparisons, especially where multiple modes were present. For example GREET model is geared towards transportation related LCA, but mainly focuses on passenger transport.
- Performing LCA requires very extensive data and datasets that include all the parameters to perform LCA for transportation systems are not available or are case specific. The case study used data available in ecoinvent database and complimented it with custom data sets that were collected from local sources and then formatted to match the requirements of SimaPro.
- LCA was performed for the ore and concentrate transportation option of Copperwood Project. The impact assessment results indicate the following:
    - Significantly lower GWP emissions are observed from multimodal transportation options
    - Operations of truck and trains (fuel usage) account for the majority of emissions in most alternatives, across mine lives.
    - For short mine lives, new track construction emissions contribute significantly.
    - Maintenance and transloading emissions have minor effect in all the options.

- As expected, the emission costs calculated from the LCA results identified that the road only options have higher prices per ton of freight transported. These costs can be included in the LCCA results to include them in the overall economic analysis. Since the scope didn’t include complete LCCA analysis, the significance of emissions costs in the overall project selection could not be quantified.

7.2 Recommendations for Future Research

There are several potential research areas in the use of LCA and LCCA for transportation project development. Some of the potential topics for future research include:

- Development of improved database for transportation emissions analysis. The major challenge for this study was to generate a relevant parameter list and database for the analysis. A predefined list of parameters for performing LCA and LCCA for different modes of freight transportation should be prepared for the US environment, as some of the values used were developed to the European markets. As the traffic characteristics differ in urban and rural areas, creating separate lists for each environment would be beneficial. The database should be integrated in the current LCA tools and applicable to multiple modes, include custom datasets based on national averages and allow for use of local data for regional modelling.
- Sensitivity analysis of operational emissions. This study used the current fuel economy of trucks and locomotives across all mine lives. Considering the fact that operations accounted for the majority of emissions in most options, reliable data and estimates on fuel economy changes and emission guidelines for the coming years would be beneficial to perform a sensitivity analysis on operational emissions. Also a scenario analysis using hybrid engines in future years would provide interesting insight on the opportunities to reduce operational emissions.
- For meaningful economic impact analysis, area or region specific tools are needed on a micro scale. The tool should include single scenario analysis and comparative analysis of single or multiple mode alternatives. It should also include the conversion of the life cycle emissions into costs.
- Directions to compare the different modes of freight transportation from an economic, social and environmental perspective. Such guidelines don’t seem to be currently available which forces public agencies to depend on non-data based approaches when comparing the project’s worth from public perspective, or when comparing the public benefits of project alternatives. Such guidelines should also include incorporation the socio-economic analysis into decision-making process of transportation projects (apart from benefit cost analysis).

References

1. United States Environmental Protection Agency. *Sources of Greenhouse Gas Emissions: Transportation Sector Emissions*. 2014 [cited 2014 September 21]; Available from: http://www.epa.gov/climatechange/ghgemissions/sources/transportation.html.
2. U.S. Energy Information Administration, *Annual Energy Outlook 2015 - with projections to 2040*. 2015.
3. Agency, U.S.E.P. *Locomotives*. Transportation and Air Quality 2104 [cited 2015; Available from: http://www3.epa.gov/otaq/locomotives.htm#info.
4. OfficeofTransportationandAirQuality, *Emission Factors for Locomotives*, U.S.E.P. Agency, Editor. 2009. p. 9.
5. NHTSA, *Cutting Carbon Pollution, Improving Fuel Efficiency, Saving Money, and Supporting Innovation for Trucks - Overview*, EPA, Editor. 2015.
6. Eno Center for Transportation, *Maximizing the Value of Investments Using Life Cycle Cost Analysis*. 2014.
7. PEInternational. *A Brief History of Life Cycle Assessment (LCA)*. 3/15/2015]; Available from: http://www.pe-international.com/america/company/newsroom/news-detail/article/a-brief-history-of-life-cycle-assessment-lca/.
8. Standardization, I.O.f., *ISO 14040:1997(en)*, in *Environmental management - Life cycle assessment - Principles and framework*. 1997. p. 20.
9. Standardization, I.O.f., *ISO 14040:2006(en)*, in *Environmental management — Life cycle assessment — Principles and framework*. 2006.
10. Hanafiah, M.M. *Life Cycle Assessment (LCA)*. November 5, 2015]; Available from: https://mhmarlia.wordpress.com/research-interests/life-cycle-assessment-lca/.
11. Facanha, C. and A. Horvath, *Environmental Assessment of Freight Transportation in the U.S. (11 pp).* The International Journal of Life Cycle Assessment, 2006. **11**(4): p. 229-239.
12. Marheinek, T., R. Friedrich, and W. Krewitt. *Application of a Hybrid-Approach to the Life Cycle Inventory Analysis of a Freight Transport Task*. in *Total Life Cycle Conference and Exposition*. 1998. Graz, Austria: SAE International.
13. Spielmann, M. and R.W. Scholz, *Life Cycle Inventories of Transport Services: Background Data for Freight Transport.* The International Journal of Life Cycle Assessment, 2005. **10**(1): p. 85-94.
14. Stodolsky, F., et al. *Lifecycle Analysis for Freight Transport*. in *Total Life Cycle Conference and Exposition*. 1998. Graz, Austria: SAE International.
15. Argonne National Laboratory, *GREET 2014 Life-Cycle Model*. 2014, Center for Transportation Research, Energy System Division.

16. Santero, N., E. Masanet, and A. Horvath, *Life Cycle Assessment of Pavements: A Critical Review of Existing Literature and Research*. 2010, Portland Cement Association, Skokie, Illinois, USA,. p. 81 pages.
17. Celauro, C., et al., *Environmentally appraising different pavement and construction scenarios: A comparative analysis for a typical local road.* Transportation Research Part D: Transport and Environment, 2015. **34**: p. 41-51.
18. Vihermaa, L., M. Lettenmeier, and A. Saari, *Natural resource consumption in rail transport: A note analysing two Finnish railway lines.* Transportation Research Part D: Transport and Environment, 2006. **11**(3): p. 227-232.
19. Stripple, H. and S. Uppenberg, *Life cycle assessment of railways and rail transports - Application in environmental product declarations (EPDs) for the Bothnia Line*. 2010, IVL Swedish Environmental Research Institute Ltd.
20. Mithraratne, N. *Lifetime Liabilities of Land Transport Using Road and Rail Infrastructure*. 2011. 100.
21. Kim, N.S. and B. Van Wee, *Assessment of CO2emissions for truck-only and rail-based intermodal freight systems in Europe.* Transportation Planning and Technology, 2009. **32**(4): p. 313-333.
22. Facanha, C. and A. Horvath, *Evaluation of Life-Cycle Air Emission Factors of Freight Transportation.* Environmental Science and Technology, 2007. **41**(20): p. 7138-7144.
23. Motzl, H., *Life Cycle Assessment of Means of Transport for Goods Traffic*. 2009, Austrian Institute for Healthy and Ecological Building.
24. Consultants, P. *SimaPro: Reliable Databases and Methods*. June 15, 2015]; Available from: http://www.pre-sustainability.com/databases.
25. HighlandCopperCompany. *Home*. 2015 [cited 2015 March 25]; About Highland Copper]. Available from: http://www.highlandcopper.com/s/home.asp.
26. Argonne National Laboratory, *GREET 2015 Life-Cycle Model*. 2015, Center for Transportation Research, Energy System Division.
27. A.S.C.E., Eno Centre for Transportation, *Maximizing the Value of Investments Using Life Cycle Cost Analysis.* 2014.
28. *TREDIS Techincal Document - Benefit Cost Module*. 2014, Economic Development Research Group
29. *Improving Transportation Investment Decisions Through Life Cycle Cost Analysis*. 8/3/2015 [cited 2016; Available from: https://www.fhwa.dot.gov/infrastructure/asstmgmt/lccafact.cfm.
30. US Department of Commerce, *Life Cycle Costing Manual for Federal Energy Management Program*. 1995.
31. Calvert, B., James. *Arthur Mellen Wellington's Railway Location*. 1999 [cited 2016; Available from: http://mysite.du.edu/~jcalvert/railway/wellingt.htm.
32. Federal Highway Administrataion, *Life-Cycle Cost Analysis in Pavement Design*. 1998, US Department of Transportation. p. 123.

33. *Life-Cycle Cost Analysis Procedures Manual*. 2013, State of California Department of Transportation.
34. *Pavement Design and Selection Manual*. 2012, Michigan Departement of Transportation.
35. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis*. 2015.
36. Matthews, H.S. and L.B. Lave, *Applications of Environmental Valuation for Determining Externality Costs†*. Environmental Science & Technology, 2000. **34**(8): p. 1390-1395.
37. Tol, R.S.J., *The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties*. Energy Policy, 2005. **33**(16): p. 2064-2074.
38. *The Social Cost of Carbon*. [cited 2015 November]; Available from: http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html.
39. *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis*. 2010.

Appendix

Appendix -A: Inputs to SimaPro datasets

Ore Transportation - Road Quantity Inputs

		Option A				**Option B**				**Option C**			
LIFE in Years		**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**
Construction													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Length of Road reconstruction (Heavy)	miles	13	13	13	13	13	3	13	13	3	3	3	3
Length of Road reconstruction (Light)	miles	0	0	0	0	0	0	0	0	10	10	10	10
Operations													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Snow plowing years	year	10	20	25	30	10	20	25	30	10	20	25	30
Maintenance													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Length of road maintenance	miles	13	13	13	13	13	13	13	13	13	13	13	13
times of road maintenance	#	1	3	4	5	1	3	4	5	1	3	4	5

Ore Transportation - Track Quantity Inputs

		Option A				Option B				Option C			
LIFE in Years		**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**
Construction													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Miles of Track construction on existing trackbed	miles	0	0	0	0	4	4	4	4	12	12	12	12
Miles of Track Rehabilitation	miles	0	0	0	0	30	30	30	30	30	30	30	30
Maintenance													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Length of track maintenance	miles	0	0	0	0	34	34	34	34	42	42	42	42
times of track maintenance	#	0	0	0	0	1	3	4	5	1	3	4	5

Concentrate Transportation - Track Quantity Inputs

		Option D				Option E				Option F			
LIFE in Years		**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**	**10**	**20**	**25**	**30**
Construction													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Miles of Track construction on existing track bed	miles	0	0	0	0	0	0	0	0	35	35	35	35
Miles of Track Rehabilitation	miles	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance													
Item	**Units**	**Quantity**				**Quantity**				**Quantity**			
Length of track maintenance	miles	0	0	0	0	0	0	0	0	35	35	35	35
times of track maintenance	#	0	0	0	0	0	0	0	0	1	3	4	5

Ore Transportation Option B - Train Quantity Inputs

		Option B			
Input Parameters					
Round trip miles		68			
Train trips per week		7			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of locomotives	#	2	2	2	2
number of rail cars	#	70	70	70	70
Operations					
Item	**Units**	**Quantity**			
Fuel consumption per Trip	gal	413.3	413.3	413.3	413.3
Fuel consumption over life	gal	1,504,412	3,008,824	3,761,030	4,513,236
Maintenance					
Item	**Units**	**Quantity**			
Total maintenance cycles of locomotives	miles	240	480	600	720
Distance travelled by rail car per year	miles	24,820	24,820	24,820	24,820
Distance travelled by rail cars over life	miles	248,200	496,400	620,500	744,600
Number of times wheelsets changed over life	#	0	1	1	2
Number of wheel sets changed	#	0	280	280	560

Ore Transportation Option C - Train Quantity Inputs

		Option C			
Input Parameters					
Round trip miles		84			
Train trips per week		7			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of locomotives	#	2	2	2	2
number of rail cars	#	70	70	70	70
Operations					
Item	**Units**	**Quantity**			
Fuel consumption per Trip	gal	712.3	712.3	712.3	712.3
Fuel consumption over life	gal	2,592,772	5,185,544	6,481,930	7,778,316
Maintenance					
Item	**Units**	**Quantity**			
Total maintenance cycles of locomotives	miles	240	480	600	720
Distance travelled by rail car per year	miles	30,660	30,660	30,660	30,660
Distance travelled by rail cars over life	miles	306,600	613,200	766,500	919,800
Number of times wheelsets changed over life	#	0	1	2	2
Number of wheel sets changed	#	0	280	560	560

Concentrate Transportation Option E - Train Quantity Inputs

		Option E			
Input Parameters					
Round trip miles		320			
Train trips per week		2			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of locomotives	#	2	2	2	2
number of rail cars	#	200	200	200	200
Operations					
Item	**Units**	**Quantity**			
Fuel consumption per Trip	gal	1,128.871	1,128.871	1,128.871	1,128.871
Fuel consumption over life	gal	1,174,026	2,348,052	2,935,065	3,522,078
Maintenance					
Item	**Units**	**Quantity**			
Total maintenance cycles of locomotives	miles	240	480	600	720
Distance travelled by rail car per year	miles	27,600	27,600	27,600	27,600
Distance travelled by rail cars over life	miles	276,000	552,000	690,000	828,000
Number of times wheelsets changed over life	#	0	1	1	2
Number of wheel sets changed	#	0	800	800	1600

Concentrate Transportation Option F - Train Quantity Inputs

		Option F			
Input Parameters					
Round trip miles		390			
Train trips per week		2			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of locomotives	#	2	2	2	2
number of rail cars	#	200	200	200	200
Operations					
Item	**Units**	**Quantity**			
Fuel consumption per Trip	gal	1,453.687	1,453.687	1,453.687	1,453.687
Fuel consumption over life	gal	1,511,834	3,023,669	3,779,586	4,535,503
Maintenance					
Item	**Units**	**Quantity**			
Total maintenance cycles of locomotives	miles	240	480	600	720
Distance travelled by rail car per year	miles	28,800	28,800	28,800	28,800
Distance travelled by rail cars over life	miles	288,000	576,000	720,000	864,000
Number of times wheelsets changed over life	#	0	1	2	2
Number of wheel sets changed	#	0	800	1,600	1,600

Ore Transportation Option B and Option C - Loader Quantity Inputs

		Option B and Option C			
Input Parameters					
Cars to load per day		70			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of loaders	#	1	1	1	1
Operations					
Item	**Units**	**Quantity**			
Total cars loaded over life	#	254,800	509,600	637,000	764,400
Time in hours to load the cars over life	hours	36400	72,800	91,000	109,200
Fuel consumption over life	gal	429,520	859,040	1,073,800	1,288,560
Maintenance					
Item	**Units**	**Quantity**			
number of maintenance cycles over life of loader	#	255	510	637	764
total oil over life	gallons	52,616	105,232	131,541	157,849

Concentrate Transportation Option E - Loader Quantity Inputs

		Option B			
Input Parameters					
Cars to load per week		50			
LIFE in Years		**10**	**20**	**25**	**30**
Construction					
Item	**Units**	**Quantity**			
Number of loaders	#	1	1	1	1
Operations					
Item	**Units**	**Quantity**			
Total cars loaded over life	#	26,000	52,000	65,000	78,000
Time in hours to load the cars over life	hours	3,714	7,429	9,286	11,143
Fuel consumption over life	gal	43,829	87,657	109,571	131,486
Maintenance					
Item	**Units**	**Quantity**			
number of maintenance cycles over life of loader	#	26	52	65	78
total oil over life	gallons	5,369	10,738	13,423	16,107

The quantities for truck are not given in the appendix due to the confidentiality of the values.

Appendix –B: Emission Cost Calculation

Interpolation of Carbon Costs for 30 years

The social costs of carbon according to EPA is provided for every five year intervals. The cost for every year is calculated the five year costs

Year y	Cost in Year y
2015	$ 40.00
2016	$ 41.40
2017	$ 42.80
2018	$ 44.20
2019	$ 45.60
2020	$ 47.00
2021	$ 47.80
2022	$ 48.60
2023	$ 49.40
2024	$ 50.20
2025	$ 51.00
2026	$ 52.00
2027	$ 53.00
2028	$ 54.00
2029	$ 55.00
2030	$ 56.00
2031	$ 57.00
2032	$ 58.00
2033	$ 59.00
2034	$ 60.00
2035	$ 61.00
2036	$ 62.20
2037	$ 63.40
2038	$ 64.60
2039	$ 65.80
2040	$ 67.00
2041	$ 67.80
2042	$ 68.60
2043	$ 69.40
2044	$ 70.20
2045	$ 71.00
2046	$ 72.20

Breakdown of Emissions for Ore Transportation

Option A: Road Transportation

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	0.39933	5.82503	NA	0.2378	0.02409	NA	
Total emissions	**10781910**	157275810	NA	6420600	**650430**	NA	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**15727581**	NA	**642060**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	0.18878	NA	NA	NA	
Total emissions			12742650	NA	NA	NA	
Emissions from new trucks			**1960740**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Option B: Multimodal Transportation (Road 8 miles)

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	1.586296	1.89803	NA	0.058032	0.11729	0.0219	
Total emissions	**42829992**	51246810	NA	1566864	**3166830**	**1182600**	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**5124681**	NA	**156686.4**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	0.6474284	NA	NA	NA	
Total emissions			43701417	NA	NA	NA	
Emissions from new trucks			**871425**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Option C: Multimodal Transportation (Road 3 miles)

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	1.5985	1.60383	NA	0.026293	0.132538	0.0219	
Total emissions	**43159500**	43303410	NA	709911	**3578526**	**1182600**	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**4330341**	NA	**70991.1**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	0.64515	NA	NA	NA	
Total emissions			43547625	NA	NA	NA	
Emissions from new trucks			**388125**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Breakdown of Emissions for Concentrate Transportation

Option D: Road Transportation

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	0.2708	23.86	NA	0.9726	NA	NA	
Total emissions	**731160**	64422000	NA	2626020	**NA**	NA	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**6442200**	NA	**262602**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	0.2162	NA	NA	NA	
Total emissions	NA		1459350	NA	NA	NA	
Emissions from new trucks	NA	NA	**728190**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Option E: Multimodal Transportation

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	9.6211	9.9677	NA	0.2773	NA	0.627	
Total emissions	**25976970**	26912790	NA	748710	**NA**	**3385800**	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**2691279**	NA	**74871**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	3.88214	NA	NA	NA	
Total emissions			26204445	NA	NA	NA	
Emissions from new trucks			**227475**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Option F: Rail Transportation

	Construction	Operations	New Trucks	Annual Maintenance	Periodic Maintenance	Rail Car Maintenance	Comments
Emissions per ton for 10 years life	20.7663	6.7	NA	0.0829	0.96	0.627	
Total emissions	**56069010**	18090000	NA	223830	**2592000**	**3385800**	Emission per ton from results * annual tons of ore * Time in years
Total emissions per year	NA	**1809000**	NA	**22383**	NA	NA	Total emissions / life
Emissions per ton for 25 years life	NA	NA	NA	NA	NA	NA	
Total emissions			NA	NA	NA	NA	
Emissions from new trucks			**NA**	NA	NA	NA	Total emissions from 25 years life - Emissions from 10 year life

Calculation of Emission Costs - Ore Transportation

Option A Road – All Mine Lives

Year (y)	Price in Year y	Option A	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 446,371.07	$ 446,371.07
2017	$ 42.80	$ 700,620.63	$ 680,214.21
2018	$ 44.20	$ 723,538.13	$ 682,004.08
2019	$ 45.60	$ 746,455.63	$ 683,112.64
2020	$ 47.00	$ 769,373.13	$ 683,578.06
2021	$ 47.80	$ 813,559.39	$ 701,783.48
2022	$ 48.60	$ 795,564.55	$ 666,272.79
2023	$ 49.40	$ 808,660.27	$ 657,514.80
2024	$ 50.20	$ 821,755.98	$ 648,701.76
2025	$ 51.00	$ 834,851.69	$ 639,844.31
2026	$ 52.00	$ 885,043.69	$ 658,555.63
2027	$ 53.00	$ 867,590.97	$ 626,766.18
2028	$ 54.00	$ 883,960.61	$ 619,992.19
2029	$ 55.00	$ 900,330.26	$ 613,081.09
2030	$ 56.00	$ 916,699.90	$ 606,046.62
2031	$ 57.00	$ 970,144.05	$ 622,698.55
2032	$ 58.00	$ 949,439.18	$ 591,659.11
2033	$ 59.00	$ 965,808.82	$ 584,330.22
2034	$ 60.00	$ 982,178.46	$ 576,926.33
2035	$ 61.00	$ 998,548.10	$ 569,458.03
2036	$ 62.20	$ 1,058,648.42	$ 586,147.96
2037	$ 63.40	$ 1,162,146.16	$ 624,710.82
2038	$ 64.60	$ 1,057,478.81	$ 551,890.26
2039	$ 65.80	$ 1,077,122.38	$ 545,769.02
2040	$ 67.00	$ 1,096,765.95	$ 539,536.17
2041	$ 67.80	$ 1,153,960.81	$ 551,138.11
2042	$ 68.60	$ 1,122,957.37	$ 520,709.41
2043	$ 69.40	$ 1,136,053.09	$ 511,438.67
2044	$ 70.20	$ 1,149,148.80	$ 502,266.23
2045	$ 71.00	$ 1,162,244.51	$ 493,194.23
2046	$ 72.20	$ 1,181,888.08	$ 486,922.24

Total Cost for 10 years	$ 8,345,794.17	**$ 7,147,952.82**
Total Cost for 20 years	$ 17,839,142.93	**$ 13,145,059.10**
Total Cost for 25 years	$ 23,386,617.03	**$ 15,958,103.49**
Total Cost for 30 years	$ 29,138,908.88	**$ 18,472,634.26**

Option B Multimodal (Road - 8 miles) – All Mine Lives

Year (y)	Price in Year y	Option B	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 1,773,161.67	$ 1,773,161.67
2017	$ 42.80	$ 226,042.52	$ 219,458.76
2018	$ 44.20	$ 233,436.44	$ 220,036.23
2019	$ 45.60	$ 240,830.35	$ 220,393.89
2020	$ 47.00	$ 248,224.27	$ 220,544.05
2021	$ 47.80	$ 403,823.84	$ 348,341.99
2022	$ 48.60	$ 256,674.46	$ 214,960.82
2023	$ 49.40	$ 260,899.55	$ 212,135.21
2024	$ 50.20	$ 265,124.64	$ 209,291.84
2025	$ 51.00	$ 269,349.74	$ 206,434.15
2026	$ 52.00	$ 439,306.26	$ 326,885.12
2027	$ 53.00	$ 279,912.47	$ 202,214.73
2028	$ 54.00	$ 285,193.84	$ 200,029.22
2029	$ 55.00	$ 355,518.21	$ 242,090.60
2030	$ 56.00	$ 295,756.57	$ 195,529.94
2031	$ 57.00	$ 481,547.25	$ 309,086.86
2032	$ 58.00	$ 306,319.31	$ 190,888.07
2033	$ 59.00	$ 311,600.68	$ 188,523.53
2034	$ 60.00	$ 316,882.04	$ 186,134.80
2035	$ 61.00	$ 322,163.41	$ 183,725.29
2036	$ 62.20	$ 525,477.88	$ 290,944.36
2037	$ 63.40	$ 390,087.04	$ 209,691.00
2038	$ 64.60	$ 341,176.33	$ 178,057.37
2039	$ 65.80	$ 347,513.97	$ 176,082.46
2040	$ 67.00	$ 353,851.62	$ 174,071.55
2041	$ 67.80	$ 572,787.78	$ 273,566.64
2042	$ 68.60	$ 443,428.16	$ 205,615.30
2043	$ 69.40	$ 366,526.90	$ 165,006.40
2044	$ 70.20	$ 370,751.99	$ 162,047.08
2045	$ 71.00	$ 374,977.09	$ 159,120.16
2046	$ 72.20	$ 381,314.73	$ 157,096.62

Total Cost for 10 years	$ 4,616,873.74	**$ 4,171,643.72**
Total Cost for 20 years	$ 8,097,245.40	**$ 6,360,811.11**
Total Cost for 25 years	$ 10,102,662.15	**$ 7,372,280.14**
Total Cost for 30 years	$ 12,039,661.02	**$ 8,221,165.69**

Option C Multimodal (Road - 3 miles) – All Mine Lives

Year (y)	Price in Year y	Option C	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 1,786,803.30	$ 1,786,803.30
2017	$ 42.80	$ 188,377.01	$ 182,890.30
2018	$ 44.20	$ 194,538.88	$ 183,371.55
2019	$ 45.60	$ 200,700.74	$ 183,669.61
2020	$ 47.00	$ 206,862.61	$ 183,794.75
2021	$ 47.80	$ 381,437.22	$ 329,031.09
2022	$ 48.60	$ 213,904.74	$ 179,141.85
2023	$ 49.40	$ 217,425.81	$ 176,787.08
2024	$ 50.20	$ 220,946.87	$ 174,417.50
2025	$ 51.00	$ 224,467.94	$ 172,035.98
2026	$ 52.00	$ 414,952.62	$ 308,763.72
2027	$ 53.00	$ 295,948.40	$ 213,799.42
2028	$ 54.00	$ 237,671.93	$ 166,698.31
2029	$ 55.00	$ 242,073.27	$ 164,840.11
2030	$ 56.00	$ 246,474.60	$ 162,948.75
2031	$ 57.00	$ 454,851.91	$ 291,952.13
2032	$ 58.00	$ 255,277.26	$ 159,080.35
2033	$ 59.00	$ 259,678.59	$ 157,109.82
2034	$ 60.00	$ 264,079.93	$ 155,119.12
2035	$ 61.00	$ 268,481.26	$ 153,111.11
2036	$ 62.20	$ 496,347.17	$ 274,815.40
2037	$ 63.40	$ 378,628.42	$ 203,531.43
2038	$ 64.60	$ 284,326.05	$ 148,387.64
2039	$ 65.80	$ 289,607.65	$ 146,741.81
2040	$ 67.00	$ 294,889.25	$ 145,065.97
2041	$ 67.80	$ 541,034.38	$ 258,401.03
2042	$ 68.60	$ 301,931.38	$ 140,003.99
2043	$ 69.40	$ 305,452.45	$ 137,511.35
2044	$ 70.20	$ 308,973.51	$ 135,045.14
2045	$ 71.00	$ 312,494.58	$ 132,605.94
2046	$ 72.20	$ 317,776.18	$ 130,919.58

Total Cost for 10 years	$ 4,250,417.74	**$ 3,860,706.74**
Total Cost for 20 years	$ 7,271,302.06	**$ 5,760,181.27**
Total Cost for 25 years	$ 9,059,787.82	**$ 6,662,309.15**
Total Cost for 30 years	$ 10,606,415.92	**$ 7,338,395.15**

Calculation of Emission Costs - Concentrate Transportation

Option D Road – All Mine Lives

Year (y)	Price in Year y	Option D	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 30,270.02	$ 30,270.02
2017	$ 42.80	$ 286,965.53	$ 278,607.31
2018	$ 44.20	$ 296,352.25	$ 279,340.42
2019	$ 45.60	$ 305,738.97	$ 279,794.47
2020	$ 47.00	$ 315,125.69	$ 279,985.10
2021	$ 47.80	$ 320,489.54	$ 276,457.09
2022	$ 48.60	$ 325,853.38	$ 272,897.07
2023	$ 49.40	$ 331,217.22	$ 269,309.91
2024	$ 50.20	$ 336,581.06	$ 265,700.20
2025	$ 51.00	$ 341,944.90	$ 262,072.29
2026	$ 52.00	$ 348,649.70	$ 259,428.12
2027	$ 53.00	$ 355,354.51	$ 256,715.66
2028	$ 54.00	$ 362,059.31	$ 253,941.11
2029	$ 55.00	$ 368,764.11	$ 251,110.41
2030	$ 56.00	$ 375,468.91	$ 248,229.18
2031	$ 57.00	$ 382,173.71	$ 245,302.76
2032	$ 58.00	$ 388,878.52	$ 242,336.23
2033	$ 59.00	$ 395,583.32	$ 239,334.41
2034	$ 60.00	$ 402,288.12	$ 236,301.87
2035	$ 61.00	$ 408,992.92	$ 233,242.95
2036	$ 62.20	$ 417,038.68	$ 230,904.21
2037	$ 63.40	$ 471,251.69	$ 253,321.01
2038	$ 64.60	$ 433,130.21	$ 226,047.41
2039	$ 65.80	$ 441,175.97	$ 223,540.22
2040	$ 67.00	$ 449,221.73	$ 220,987.33
2041	$ 67.80	$ 454,585.58	$ 217,112.60
2042	$ 68.60	$ 459,949.42	$ 213,276.12
2043	$ 69.40	$ 465,313.26	$ 209,478.94
2044	$ 70.20	$ 470,677.10	$ 205,722.02
2045	$ 71.00	$ 476,040.94	$ 202,006.24
2046	$ 72.20	$ 484,086.70	$ 199,437.31

Total Cost for 10 years	$ 3,239,188.26	**$ 2,753,862.00**
Total Cost for 20 years	$ 7,095,790.37	**$ 5,191,280.81**
Total Cost for 25 years	$ 9,345,155.55	**$ 6,332,289.38**
Total Cost for 30 years	$ 11,701,222.98	**$ 7,362,210.01**

Option E Multimodal – All Mine Lives

Year (y)	Price in Year y	Option E	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 1,075,446.56	$ 1,075,446.56
2017	$ 42.80	$ 118,391.22	$ 114,942.93
2018	$ 44.20	$ 122,263.83	$ 115,245.39
2019	$ 45.60	$ 126,136.44	$ 115,432.71
2020	$ 47.00	$ 130,009.05	$ 115,511.36
2021	$ 47.80	$ 132,221.97	$ 114,055.83
2022	$ 48.60	$ 134,434.89	$ 112,587.10
2023	$ 49.40	$ 136,647.81	$ 111,107.17
2024	$ 50.20	$ 138,860.73	$ 109,617.94
2025	$ 51.00	$ 141,073.65	$ 108,121.21
2026	$ 52.00	$ 143,839.80	$ 107,030.32
2027	$ 53.00	$ 326,053.35	$ 235,547.88
2028	$ 54.00	$ 149,372.10	$ 104,766.59
2029	$ 55.00	$ 152,138.25	$ 103,598.75
2030	$ 56.00	$ 154,904.40	$ 102,410.06
2031	$ 57.00	$ 157,670.55	$ 101,202.73
2032	$ 58.00	$ 160,436.70	$ 99,978.85
2033	$ 59.00	$ 163,202.85	$ 98,740.41
2034	$ 60.00	$ 165,969.00	$ 97,489.30
2035	$ 61.00	$ 168,735.15	$ 96,227.30
2036	$ 62.20	$ 172,054.53	$ 95,262.42
2037	$ 63.40	$ 189,795.83	$ 102,024.61
2038	$ 64.60	$ 178,693.29	$ 93,258.69
2039	$ 65.80	$ 182,012.67	$ 92,224.32
2040	$ 67.00	$ 185,332.05	$ 91,171.09
2041	$ 67.80	$ 187,544.97	$ 89,572.52
2042	$ 68.60	$ 422,023.77	$ 195,690.20
2043	$ 69.40	$ 191,970.81	$ 86,423.16
2044	$ 70.20	$ 194,183.73	$ 84,873.19
2045	$ 71.00	$ 196,396.65	$ 83,340.20
2046	$ 72.20	$ 199,716.03	$ 82,280.36

Total Cost for 10 years	$ 2,399,325.95	**$ 2,199,098.52**
Total Cost for 20 years	$ 4,169,862.83	**$ 3,334,322.79**
Total Cost for 25 years	$ 5,093,241.63	**$ 3,802,574.01**
Total Cost for 30 years	$ 6,297,532.62	**$ 4,335,181.12**

Option F Rail – All Mine Lives

Year (y)	Price in Year y	Option F	
		Cost of emissions in year y per ton of ore	Emissions in NPV of 2016
2015	$ 40.00		
2016	$ 41.40	$ 2,321,257.01	$ 2,321,257.01
2017	$ 42.80	$ 78,383.19	$ 76,100.19
2018	$ 44.20	$ 80,947.13	$ 76,300.43
2019	$ 45.60	$ 83,511.06	$ 76,424.45
2020	$ 47.00	$ 86,075.00	$ 76,476.52
2021	$ 47.80	$ 211,437.71	$ 182,388.02
2022	$ 48.60	$ 89,005.21	$ 74,540.47
2023	$ 49.40	$ 90,470.32	$ 73,560.65
2024	$ 50.20	$ 91,935.43	$ 72,574.67
2025	$ 51.00	$ 93,400.53	$ 71,583.73
2026	$ 52.00	$ 230,015.92	$ 171,153.44
2027	$ 53.00	$ 276,510.70	$ 199,757.21
2028	$ 54.00	$ 98,894.68	$ 69,362.74
2029	$ 55.00	$ 100,726.07	$ 68,589.55
2030	$ 56.00	$ 102,557.45	$ 67,802.55
2031	$ 57.00	$ 252,132.83	$ 161,834.47
2032	$ 58.00	$ 106,220.21	$ 66,192.93
2033	$ 59.00	$ 108,051.60	$ 65,372.99
2034	$ 60.00	$ 109,882.98	$ 64,544.67
2035	$ 61.00	$ 111,714.36	$ 63,709.14
2036	$ 62.20	$ 275,134.42	$ 152,335.26
2037	$ 63.40	$ 330,769.40	$ 177,804.85
2038	$ 64.60	$ 118,307.34	$ 61,743.71
2039	$ 65.80	$ 120,505.00	$ 61,058.89
2040	$ 67.00	$ 122,702.66	$ 60,361.58
2041	$ 67.80	$ 299,905.37	$ 143,236.47
2042	$ 68.60	$ 125,632.87	$ 58,255.30
2043	$ 69.40	$ 127,097.98	$ 57,218.12
2044	$ 70.20	$ 128,563.09	$ 56,191.94
2045	$ 71.00	$ 130,028.19	$ 55,176.99
2046	$ 72.20	$ 132,225.85	$ 54,475.30

Total Cost for 10 years	$ 3,456,438.52	**$ 3,272,359.60**
Total Cost for 20 years	$ 4,998,263.82	**$ 4,251,861.11**
Total Cost for 25 years	$ 5,990,453.59	**$ 4,756,066.62**
Total Cost for 30 years	$ 6,634,001.58	**$ 5,037,384.27**