LIFE CYCLE ASSESSMENT OF THE LIGHT RAIL TRANSIT CONFEDERATION LINE STAGE 1

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TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

CA - Canada
DV - Diesel Vehicle
EOL - End of Life
EV - Electric Vehicle
EPD - Environmental Product Declaration
FHWA - US Federal Highway Association
FTA - Federal Transit Administration
GHG - Greenhouse Gas
GV - Gasoline Vehicle
GWP - Global Warming Potential
HVAC - Heating, Ventilation, and Air Conditioning
HSR - High Speed Rail
LCA - Life Cycle Assessment
LRT - Light Rail Transit
LRV - Light Rail Vehicle
ON - Ontario

1. Abstract

According to the 2011 Canadian National Household Survey, around four out of five Canadians use private cars for work commute. One out of five uses other means such as biking, walking or public transit [1]. In 2011, approximately 20% of Ottawa inhabitants took public transit as their primary means of transportation for work commuting. Raising concerns about environmental issues and equity of access to transportation encourage cities to develop public transportation systems. The O-train is the light rail transit system of Ontario. This work will focus on the first stage of the Confederation line (also called Line 1). In 2019, it was estimated that 159,000 passengers transited daily via the Confederation line [2]. Accounting for the life-cycle assessment of the train system including rails, stations and wagons, the number of passengers needed to make the use of the Confederation line more environmentally friendly than driving private cars on a time scale of 30 years is 18,024. This number depends on the lifetime of the rail system; A lifetime of 60 years requires 11,667 passengers to transition, and a lifetime of 90 years requires 8,851.

2. Executive Summary

The goal of a life cycle assessment (LCA) is to holistically evaluate the cradle-to-grave impact of a product. In our case, our project aims to better understand the total environmental impact of electric urban rail. The project case study of Ottawa's Confederation line, opened in September 2019, gives good insight into the present-day cost and benefits of an urban rail project. Older systems contain perhaps more data and literature but this project aims to illuminate as close to a present-day project as possible. This project will present the data as divided into three individual categories: rails and track, stations and infrastructure, and the trains themselves.

Tracks include rails, ties, rock ballast, land use, and all other emissions and impacts related with manufacture and construction. Beginning with the land use and clearing, the process involves the smelting and transport of steel, the quarrying and distribution of rock and the carbon intensity of all construction operations and machinery. As the line increases its length and capacity, its carbon footprint due to the track itself increases. Another portion of the system's impact can be attributed to stations and support facilities including maintenance yards. In addition to the overall impact of construction, these require constant energy inputs for light, equipment and heating especially during Ottawa's winters. The trains themselves are the final element of the assessment. These account for between 11 and 25% of the overall raw material and manufacturing impacts as well as continuous energy use for a time scale between 30 and 90 years. For an extended-duration analysis, these are largely dependent on the intensity of Ottawa's electric grid.

One other element to be considered however difficult to quantify is the social impact of the rail systems and what effects it will have beyond its immediate life-cycle. Being in direct competition with other modes of transit, it could be argued that reduction or increase of other modes could be a factor as people's mode of transit is a binary decision. Potential reduction of cars and subsequently parking lots, gasoline refining, tire manufacturing, etc. are all indirect lifestyle impacts of rail travel that are non-negligible. Similarly, time-frame is crucial to gaining a complete understanding of the total impact throughout the life-span of the system and determining economic and environmental payback period.

Given the time constraints of the project and the limited information on such a new rail line, we took strategic approaches to maximize our findings. We chose to highlight the most crucial metrics by which to assess the impact of the Confederation line. CO2e/passenger-km has been a common metric in many LCAs of transportation so we have chosen to focus quantitatively on this while acknowledging that there are other impacts to be accounted for. Where information was missing or unavailable, we drew the best possible parallels from other more well-researched rail lines to achieve the closest approximation possible. Though in a perfect assessment, other pollutants as well as land use and biodiversity loss would also be considered, we have chosen to focus our research on carbon emissions. Parallels can be drawn to the real-world fight against climate change, where the measures with the greatest impact must be selected given limitations of time and resources. This paper will present the best representation of the holistic impact of Ottawa's new Confederation line using metrics such as CO2e/passenger-km and acknowledging other environmental impacts and trends wherever possible as pertaining to each specific sector of the project.

3. Introduction

The increasing urgency of climate change mitigation has led to investigation and innovation in the sectors principally responsible for greenhouse gas (GHG) emissions; electricity and heat, agriculture, and transportation. Globally, transportation is responsible for 14% of GHG emissions ([3] US EPA, 2016). In Canada, passenger vehicles accounted for 16% of this fraction in 2021 - approximately 26 megatonnes of CO_2e ([4] Canada, 2021). While many wealthy regions are calling for the transition to greener transportation through the transition from internal combustion engines to a fleet of electric passenger vehicles, this solution demands costly infrastructure and large scale access to renewable energy. Furthermore, this alternative maintains a reliance on independent transportation, and thus high energy consumption, high land use for vehicle storage, and high consumption of materials for vehicle construction ([5] Kenworthy & Laube, 1996). A more communal green transport technology to explore is that of urban electric light rail systems.

Light rail transit (LRT) systems are comprised of urban, electric short trains with lighter passenger capacities than longer distance vehicles ([6] *Light-Rail Transit (LRT)*, 2016) and can be categorized as either First or Second Generation. First Generation systems are those built upon the foundations of previous trolley or tramway lines, while Second Generation systems are newly designed and constructed. North America operates seven First Generation systems, and numerous Second Generation systems. The majority of future LRT implementation is expected to be new and Second Generation. LRT physical capital can be assorted into three sectors: Infrastructure, rolling stock and fixed equipment. Infrastructure includes rail tracks, stations, tunnels, bridges, and storage facilities. Rolling stock consists of the fleet of railcars which transport passengers. Fixed equipment is generally comprised of the energy supply to the system, communications, and operations and maintenance ([7] *This Is Light Rail Transit*, 2000) .

While in operation, LRT produces 62% less GHG emissions per passenger kilometer than the average single passenger vehicle ([8] U.S. Department of Transportation, 2010) - a reduction from 251 gCO_2 to 95 gCO_2 per kilometer ([9] US EPA, 2016). However, this value is not representative of the emissions incurred during construction, nor does it account for the variability of passenger density. Cervero & Guerra (2011) demonstrate that LRT systems require a population density of 7400 people per km^2 surrounding stations to be "[placed] in the top one-quarter of cost-effective rail investments in the U.S.". Further, Winston and Maheshri (2007) [10] report that the benefits exceed the costs for only one of twenty-five rail systems in the U.S. ([11] Cervero & Guerra, 2011). These studies highlight two key barriers to LRT implementation: location and cost. If there is insufficient ridership in a city, an LRT system will be costly both economically and environmentally. Therefore, it is imperative to understand the boundaries of ridership in typical urban environments such that LRT can be effectively scaled across commuting countries.

One of these environments is Ottawa, Canada. In 2021, Ottawa recorded a metropolitan population of 1,488,307 and a population density of 364.9 inhabitants per km^2. As reported in a 2016 census, 30% of commuters in Ottawa commuted sustainably with either public transit, walking or biking. The other 70% (approximately 220,000 commuters) drove, with 82% of this population driving a passenger vehicle alone. A third of these car commuters drove over 30 minutes per trip ([12] Government of Canada, 2017). This transit behavior resulted in passenger vehicles accounting for 40% of Ottawa transportation emissions. At the time of this survey, the public transit landscape in Ottawa included a city-wide bus system and a diesel light rail transit pilot project. In 2019, the city opened the first stage of a large-scale LRT system.

The Confederation line is a 12.5 km east-west LRT line running through the downtown core ([13] *Ottawa, Ontario, BRT Case Study*) with 13 stations. Each two-car train can accommodate 600 passengers and runs every 5 minutes at peak service for a capacity of 10,700 passengers per hour, each way. Four of the city stations are below ground level, along a 2.5km tunnel section of the line ([14] *O-Train Line 1 | OC Transpo*). The railcars are fully electric Alstom Citadis Spirit cars, manufactured in Hornell, NY and assembled in Belfast Yard and Brampton, ON. The vehicles are also in use in Nantes and Lyon, France, with a 100% low-floor LRV configuration and a top speed of 100 km/h. The line also includes a storage facility at Belfast Yard within Ottawa; the yard has a capacity of 66 LRVs to accommodate the completed Stage 1 and eventual expansion of the Stage 2 line. The facility contains a storage shed, maintenance facilities and an administrative office. Within the 51 major census neighborhoods in Ottawa, one is above the population density recommended by Cervero & Guerra (2011). Four of the Confederation line stations are within this high density neighborhood ([15] Government of Canada, 2022), with the remaining nine located in areas below this suggestion. As a city with a historically independently commuting population, mid-to-low population density, and a recent investment in LRT, Ottawa provides an relevant and applicable study for the environmental Life Cycle Assessment of a rail system.

4. Problem Statement

The proportion of people using public transit for work commute in Ottawa is approximately 20%, with another 70% using a car, truck or van [1]. More than 90% of those using cars, trucks or vans are drivers, meaning at least 8 out of 9 of the vehicles driven for work commute only have one passenger on board. Development of public transportation could help reduce the number of people using private motorized vehicles to commute to work and hence reduce associated carbon emissions. However, building a public transit system can be costly and have an important environmental impact (rolling material, infrastructure). While planning a transportation system, it is important to study its scale: it is counter-productive to build a rail system if the construction and use of the line are not balanced by the number of people shifting their transportation mode from private vehicles to public transit.

The balance can be found either by encouraging people to shift their transportation mode (e.g. advertising, incentives for taking the train compared to using the car) or by adapting the functioning model of the trains (e.g. changing the frequency). If correctly sized, the rail system can allow reductions in CO2 emissions and thus have environmental benefits.

In most cases, when it is claimed that trains are less greenhouse gas intensive than cars, only the emissions due to energy consumption in the use phase of the vehicle are considered. To have a clear view of the issue it is necessary to know the impact over the entire life of the vehicle, which is why we are conducting a life cycle analysis from construction to end of life of the Ottawa Confederation Line.

This study of the Confederation line aims at knowing whether the break-even point - for which the train system is environmentally more beneficial than the use of cars - has been reached or not under the current conditions of use and if not what levers could be driven to achieve this point.

5. Questions to Answer

This work focuses on the break-even point to make, from an environmental point of view, the Confederation line of Ottawa more sustainable than the use of private cars, via the establishment of a life-cycle assessment of Ottawa's line 1. This break-even point takes as input variable the period of use and gives as an output the number of passengers. In a first step, other parameters such as frequency of the trains are taken as they are today in Ottawa. In a second step, some parameters are changed to study their impact on the break-even point and to build different scenarios to understand what conditions can make the Confederation line less 'polluting' than private cars.

Some questions to answer will be:

- What are the different parameters that could have an impact on the break-even point?
- What is the potential impact of these parameters?
- Should the system be resized?
- How many passengers are needed to make the Confederation line more environmentally profitable than private cars?

6. Literature review

The paper *Life-cycle Environmental Inventory of Passenger Transportation in the United States* ([16] Chester, 2008) adopts a hybrid model for the study - combining a process-based LCA with an EIO-LCA. The LCA modeling software used in this example is SimaPro. We should note that the train manufacturing data for SimaPro stems from Switzerland, and Germany. Since process-based LCAs are more comprehensive and accurate, this study should minimize the EIO-LCAs conducted. Nevertheless, this mentions where LCAs were conducted, and where EIO-LCAs were chosen instead (see figure 1). Within this project, some sources of data will be different to those chosen in the paper - as such, where Process-based LCAs can be conducted, and where EIO-LCAs will have to suffice, will vary.

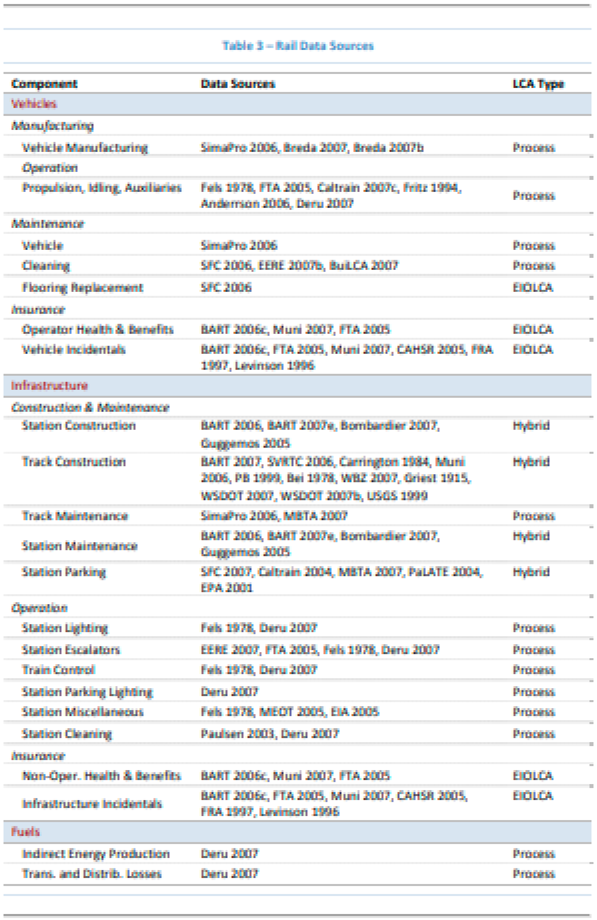


Table 3 – Rail Data Sources

Component	Data Sources	LCA Type
Vehicles		
Manufacturing		
Vehicle Manufacturing	SimaPro 2006, Breda 2007, Breda 2007b	Process
Operation		
Propulsion, Idling, Auxiliaries	Fels 1978, FTA 2005, Caltrain 2007c, Fritz 1994, Andersson 2006, Deru 2007	Process
Maintenance		
Vehicle	SimaPro 2006	Process
Cleaning	SFC 2006, EERE 2007b, BuiLCA 2007	Process
Flooring Replacement	SFC 2006	EIOLCA
Insurance		
Operator Health & Benefits	BART 2006c, Muni 2007, FTA 2005	EIOLCA
Vehicle Incidentals	BART 2006c, FTA 2005, Muni 2007, CAHSR 2005, FRA 1997, Levinson 1996	EIOLCA
Infrastructure		
Construction & Maintenance		
Station Construction	BART 2006, BART 2007e, Bombardier 2007, Guggemos 2005	Hybrid
Track Construction	BART 2007, SVRTC 2006, Carrington 1984, Muni 2006, PB 1999, Bei 1978, WBZ 2007, Griest 1915, WSDOT 2007, WSDOT 2007b, USGS 1999	Hybrid
Track Maintenance	SimaPro 2006, MBTA 2007	Process
Station Maintenance	BART 2006, BART 2007e, Bombardier 2007, Guggemos 2005	Hybrid
Station Parking	SFC 2007, Caltrain 2004, MBTA 2007, PaLATE 2004, EPA 2001	Hybrid
Operation		
Station Lighting	Fels 1978, Deru 2007	Process
Station Escalators	EERE 2007, FTA 2005, Fels 1978, Deru 2007	Process
Train Control	Fels 1978, Deru 2007	Process
Station Parking Lighting	Deru 2007	Process
Station Miscellaneous	Fels 1978, MEOT 2005, EIA 2005	Process
Station Cleaning	Paulsen 2003, Deru 2007	Process
Insurance		
Non-Oper. Health & Benefits	BART 2006c, Muni 2007, FTA 2005	EIOLCA
Infrastructure Incidentals	BART 2006c, FTA 2005, Muni 2007, CAHSR 2005, FRA 1997, Levinson 1996	EIOLCA
Fuels		
Indirect Energy Production	Deru 2007	Process
Trans. and Distrib. Losses	Deru 2007	Process

Figure 1: Examples of data sources and LCA types in Passenger Transportation LCA [16]

We should also note that the EIO-LCA data is based on 2002 economic data. This can be used, only if the processes and technologies used in the EIO-LCA have not changed in the period since the last model was published. This will have to be analyzed in the context of this project.

The Chester and Horvath Paper focusing on the LCA of California High Speed rail focuses, amongst other things, on sulfur dioxide as the environmental impact, as emissions tend to be higher than carbon dioxide emissions in the case of transportation infrastructure. Furthermore, the paper discusses how life cycle assessment of new rail systems is difficult, because calculating the environmental impact is passenger dependent. As a result, the paper recommends using a wider range of ridership estimates to provide for a more realistic assessment of the environmental impact. In our case, the ridership data available only covers one year, which makes it a source of uncertainty. Moreover, ridership data, which is from 2019, dates back to before the pandemic - it is unclear if ridership has since recovered, nor when it will recover. When comparing the LCA of the high-speed rail project to its competitors, air and car travel, another complicating factor is that of the constant evolution of each mode. If hypothetically rail was found to have an overall smaller impact today, it could well be rendered inferior by improved auto technology. Likewise cleaner electricity sources could accelerate the rail project's carbon payback time. Based on the methods outlined in the paper, high speed rail at present conditions will reduce CO2 emissions but increase other pollutants making the decision less than cut-and-dry.

In terms of extracting raw data itself, the paper *Applying life cycle assessment to analyze the environmental sustainability of public transit modes for the City of Toronto* ([17] Taylor, 2016) could serve as a point of reference for this project. The paper harnesses the available data by analyzing LCAs of models similar to the trains used in Toronto's, from which it estimates energy consumption. It adopts a conservative estimate for energy consumption equal to the consumption of the train with the highest energy consumption (namely, the Norwegian Equivalent). Our project aims to be more accurate in its analysis. However, Toronto's LRT system is also under construction, finding ridership data also constitutes an issue. This paper adopts a range of values, from 0 to crush capacity, plotting a graph instead.

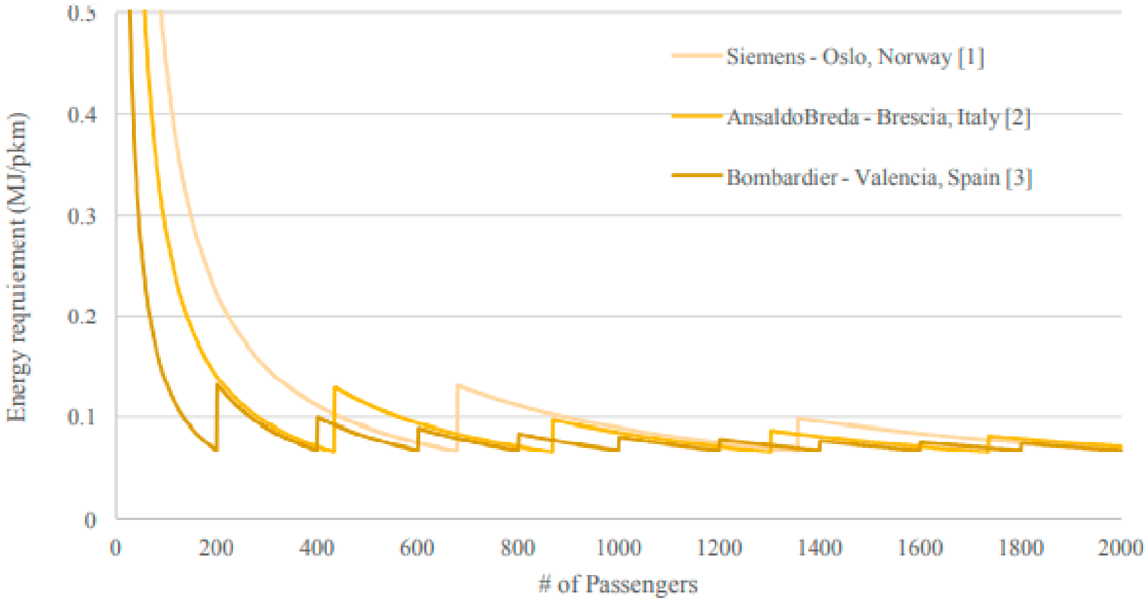
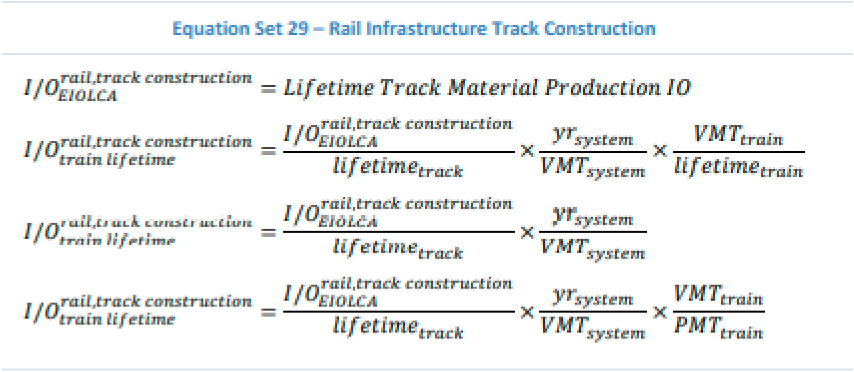


Figure 2: Energy requirement with increasing number of passengers in high speed rail [17]

Since the paper discusses other forms of transportation, it is worth noting that, where ridership data is available, inaccuracies remain. For example, there is an issue surrounding how to quantify distance travelled, largely due to the ticketing system.

Life cycle sustainability assessment of a light rail transit system: Integration of environmental, economic, and social impacts ([18] Gulcimen et al., 2021), conducts a Life Cycle Assessment without considering insurance or stations themselves, which could both be a significant source of environmental impacts. This was commonly observed within the literature covering LCAs for rail systems. On the other hand, the Chester and Horvath paper on passenger transportation in the United States does deal with this problem. In fact, the paper provides equations which help calculate the environmental impact of station construction, operation, maintenance and end of life. It also compares passenger transportation, from a LCI perspective, in New York, Chicago, Boston and San Francisco. The benefit of the comprehensive nature of this study is that some of these examples are very relevant for Ottawa. The heating demand in Boston and Chicago could be similar to that of Ottawa, for instance.



Equation Set 29 – Rail Infrastructure Track Construction

$$I/O_{EIOLCA}^{rail,track\ construction} = Lifetime\ Track\ Material\ Production\ IO$$

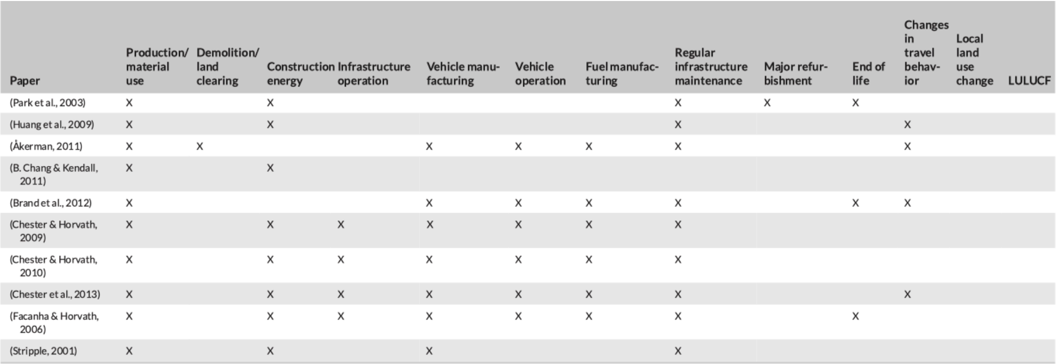
$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{lifetime_{train}}$$

$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}}$$

$$I/O_{train\ lifetime}^{rail,track\ construction} = \frac{I/O_{EIOLCA}^{rail,track\ construction}}{lifetime_{track}} \times \frac{yr_{system}}{VMT_{system}} \times \frac{VMT_{train}}{PMT_{train}}$$

Figure 3: Insurance emission calculation formula

Rethinking Environmental LCA Life Stages for Transport Infrastructure to Facilitate Holistic Assessment ([19] Saxe & Kasraian, 2020) proposes a new framework for Life Cycle Analysis of Transportation systems. The paper asserts that existing product-based LCA frameworks cannot fit larger more complex concepts such as transportation projects. Whereas the product-based assessments are item-centric and explore the subsequent impacts from production to disposal, LCA of a transportation project explores the indirect impacts. In particular, the paper discusses the need to incorporate feedback within its method, such as the transport-land use feedback cycle, where, for instance, land use changes drive transportation movements which increase demand for transport infrastructure. This could, for instance, influence ridership. Other non-linear criteria are posited as well including “major refurbishments,” land use change, and induced influences on travel behavior which Saxe and Kasrian argue should be treated as iterative processes instead of single, linear trends. The table below shows various related papers on LCAs and which topics are included in each.



Paper	Production/ material use	Demolition/ land clearing	Construction energy	Infrastructure operation	Vehicle manu- facturing	Vehicle operation	Fuel manufac- turing	Regular infrastructure maintenance	Major refur- bishment	End of life	Changes in travel behav- ior	Local land use change	LULUCF
(Park et al., 2003)	X		X					X	X	X			
(Huang et al., 2009)	X		X					X			X		
(Åkerman, 2011)	X	X			X	X	X	X			X		
(B. Chang & Kendall, 2011)	X		X										
(Brand et al., 2012)	X				X	X	X	X		X	X		
(Chester & Horvath, 2009)	X		X	X	X	X	X	X					
(Chester & Horvath, 2010)	X		X	X	X	X	X	X					
(Chester et al., 2013)	X		X	X	X	X	X	X			X		
(Facanha & Horvath, 2006)	X		X	X	X	X	X	X		X			
(Stripple, 2001)	X		X		X			X					

Table 1: Differences in Transportation LCAs [19]

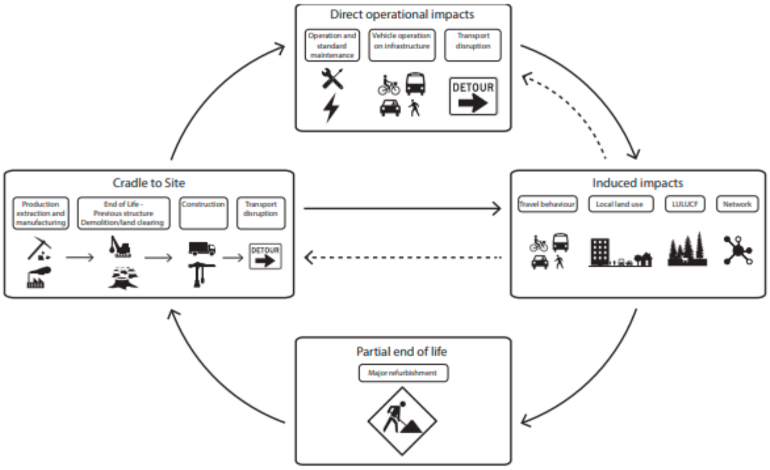


Figure 4: Feedback cycles in Transportation LCAs [19]

Environmental assessment of passenger transportation should include infrastructure and supply chains ([20] Chester & Horvath, 2009) provides a wealth of data on different stages of life relating to various transportation modes. This is an example of a study that highlights a specific metric, in this case various emissions per Passenger-Kilometer-Traveled (PKT) as well as energy usage. The paper draws direct comparisons between road transport including autos and buses, rail and air. They take an approach which largely inspired ours, by breaking each mode down into sectors in this case “vehicles,” “operation,” and “fuels”.

Figure 5 breaks down each mode by activity to illustrate in what ways each is superior/inferior in its overall impact. The paper argues that existing LCAs only consider one element of the transportation life-cycle and attempts to expand these strategies tracing back all the way to the source of different stages of life. Whereas Gulcimen advocates for an LCA approach diverging from linear product-based relations, this paper does an in depth analysis using a traditional LCA format beyond its previous shortcomings. Another important point made is the conditionality of each mode. As seen in the graphic below, the most intensive mode fuel-wise is a diesel bus off-peak. That same diesel bus is also the least intensive when on peak. In both cases, the energy required for operation is the largest contributor. Light rail does not distinguish between peak and off-peak but one can see that in both examples (SF MUNI and Boston Green), actual operation is a smaller fraction of the whole impact.

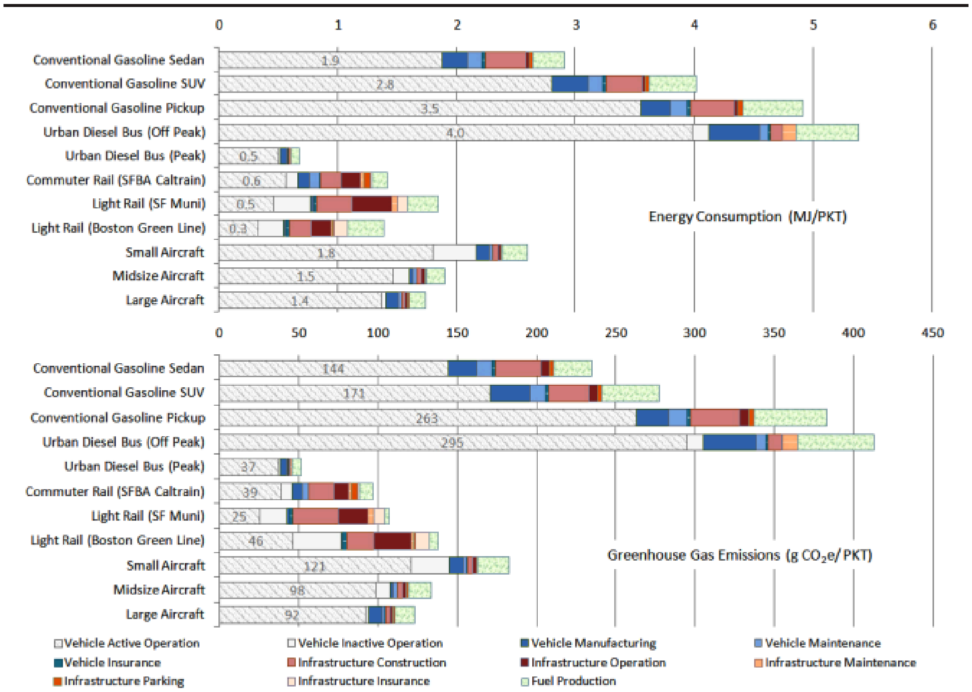


Figure 5: LCA emissions from different transportation sources [20]

Life cycle sustainability assessment of a light rail transit system: Integration of environmental, economic, and social impacts by Gulcimen and Aydogan evaluates a successful new light rail system in Kayseri, Turkey. This takes a straightforward LCA with cradle-to-grave assessment and expands upon it to assess the social impacts. Using SimaPro 8.4.1 PhD based on ISO 14040 and 14044, they were able to calculate an overall impact using the passenger-km metric. An environmental and economic cost was established and the study continued to include social and societal impacts which were found to be generally positive for workers and consumers. This is an important factor that will be of interest in Ottawa, as one large impact often overlooked by data is how it will alter social patterns and what effects those might have of their own.

Time-based life-cycle assessment for environmental policymaking: Greenhouse gas reduction goals and public transit ([21] Chester & Cano, 2016) highlights the need for time and project lifespan when assessing the overall impact of a new transportation project with regards to the standard CO2e/passenger-km. The case studies the new Expo line in LA, a notoriously car-centric city. All in all, the cost of new infrastructure for the rail line far outweighs that of auto manufacturing for carbon intensity. But an extended use of such infrastructure will normalize as more and more passengers ride trains diminishing the carbon cost over time. Moreover, an increase in rail passengers will have the direct effect of reducing road traffic as well which can be included in the overall CO2 difference between modes.

7. Modeling Approach and Data

Methodology

As described in the literature review, life cycle analyses of train lines have already been conducted and have improved our knowledge of the total impact of this mode of transportation compared to others. Here we build upon this foundation to study the specific case of the city of Ottawa, and analyze the life cycle greenhouse gas emissions of the confederation line. We will use the life cycle assessment (LCA) method to properly assess the project's environmental impact. This method has now become key for analyzing environmental impacts, as it considers all stages and their potential impacts including but not limited to:design, extraction of materials, process, manufacturing, transportation and distribution, use and maintenance, and end of life recycling. In this study we use the "process based" LCA method which identifies and quantifies the resource inputs and environmental outputs at each stage of the life cycle based upon unit process modeling and mass balance calculations. This method allows us to map each process to its associated energy and material inputs, and environmental outputs and wastes.

The implementation of the LCA method includes four main steps that we followed:

- Define the objective and scope of the study, as well as its assumptions
- Develop and analyze the product inventory
- Assessing the effects of this environmental impact (climate change, public health, etc.)
- Interpreting the results by reflecting the limitations of the calculation and the associated uncertainties.

The light rail system was divided into three main components for analysis: rails and track, stations and infrastructure, and train vehicles. A fourth component analyzed was the GWP and impact potentials of car transportation, for use as comparison to the LRT project. This division is the basis of organization for the following sections of this report. Each of our components required different degrees of lifecycle stages. Rolling stock for instance, requires everything from raw material extraction and manufacturing to end of life and disposal. For tracks and catenary, we excluded end of life calculations given their long lifespan. Infrastructure also excluded maintenance and end of life based on the assumptions that they outlive the functionality period of the line itself.

Environmental impacts included

The purpose of this study is to assess the extent to which the implementation of the Confederation Line is a means of reducing the impact of Ottawa's urban transportation on global warming. Therefore, this LCA focuses on quantifying energy consumption and greenhouse gas emissions as global warming potential (GWP), with units of kg CO_2e. However, the environmental impacts of such a project are not limited to atmospheric climate pollutants. Thus the criteria air pollutant emissions (particulate matter, carbon monoxide, sulfur dioxide, nitrogen oxides, volatile organic compounds) associated with the operational phase of vehicles and infrastructures are also considered. (Due to lack of data, we only consider them for the operation phase, but it makes sense because their impact is mainly on a local scale). Moreover, the impact of these pollutants is not only environmental but also causes serious health risks.

Data collection and Models

Each component of our study (vehicles, stations, track) was researched individually for data. Below we describe the data and methodology used for each component. A table summarizing the list of data used is also included in the Appendix.

In addition to the data collected, we also collected the data required to calculate the carbon intensity of Ottawa's electricity mix.

This was done using Hydro Ottawa's 2020 electricity mix, which provides the majority of the city's electricity.

Hydro Ottawa electricity mix 2020	
Coal	0%
Natural Gas	6.30%
Oil	0%
Nuclear	56.80%
Hydro	24.40%
Biomass	0.50%
Solar	2.40%
Wind	8.70%
Geothermal	0%
Total %	99.10%

Table 2: Electricity mix of Ottawa.

Of the company's electricity sources, 0.9% comes from non-contracted sources, representing a variety of fuel types that were not categorized due to a lack of information from local distribution companies. For this reason, we have removed them from our calculations and determined the carbon factor of Ottawa's electricity mix on the basis of 99.1% of its mix.

We then used the Life-cycle Emission Factors for Electricity Generation from Table 15 from Horvath, A., Stokes, J. (2011) to calculate the weighted average emission factors for Ottawa's electricity mix.

	gCO2(eq)/kWh	gNOx/kWh	g PM/kWh	g SOx/kWh	g VOC/kWh	g CO/kWh
Weighted mean of emission factors	72.09	0.20	0.03	0.15	0.01	0.06

Table 3: Ottawa mix emission factors

Stations and Infrastructure

This section investigates the emissions and impacts of the 13 confederation line stations (9 above and 4 below ground), as well as the 2.5km connecting the underground station. The Federal Highway Association (FHWA) infrastructure carbon estimator [22] served as the main source for the fuel and material consumption estimates of the stations and tunnels. For tunnels specifically, our life cycle assessment only accounts for manufacture itself. While this is a report completed in the U.S., we assumed that the sizing of infrastructure would be close to that of Ottawa. The following table reports the FHWA values.

Infrastructure	Concrete (MT/mi or station)	Steel (MT/mi or station)	Ballast (MT/mi or station)	Fuel (gallon of diesel/mi or station)	Energy (kWh/mi or station)
Underground Tunnel Through Hard Rock	9.04E+05	2.40E+03	n/a	3.15E+05	2.18E+06
At Grade Station	2.06E+04	6	1.32E+03	8.49E+02	n/a
Underground Station	2.94E+05	1.88E+02	n/a	6.06E+04	n/a

Table 4: FWHA Materials and Fuel Estimates for Light Rail Infrastructure [22]

The lifetime emissions factors for concrete, steel, ballast, and diesel were then abstracted from LCAs published by Ontarian companies [23]. The emission factor for the Ontario grid mix was applied for the energy used. These values are tabulated below.

Concrete ($kgCO_2e/MT$)	Steel ($kgCO_2e/MT$)	Ballast ($kgCO_2e/MT$)	Fuel ($kgCO_2e$/gallon of diesel)	Energy ($kgCO_2e/kWh$)
7.20E+01	1.89E+03	2.92E+00	1.20E+01	7.20E-02

Table 5: Emissions Factors for Materials and Fuel

The GWP attributed to the capital of stations and tunnel was then calculated using the following equation:

$$GWP_{Capital} = \sum^{j} n_j \sum^{i} M_{ij} E_{ij}$$

Where *j* represents the infrastructure type and *i* represents the material or fuel consumed. The variables n, M, and E represent the quantity of infrastructure type, the amount of material or fuel and the emission factor, respectively.

The GWP attributed to the operation of the stations was assumed to consist principally of the infrastructure lighting and HVAC systems, and water use. We first sized both of these systems to the confederation line project, then determined the emissions factors of each through previous LCAs. As there was no published data on the heating requirements of the OLRT line stations, we estimated this value using data from a similar system in Germany and scaled it to Ottawa's climate using reported Heating Degree Days (HDD). Rozycki et al. determined the operational heating requirement of a German Intercity Express train station to be 35.3 Wh/passenger. According to EU data, there are 3200 HDDs in Germany and 4335 HDDs in Canada [24][25]. Assuming that heating demand scales linearly with HDD, we therefore estimate the heating requirement to be 47.8 Wh/passenger in Ottawa. We should note that the baseline for heating degree days varies between both countries: in the European Union, the baseline is set at 15.5°C, whilst it is set at 18°C for Canada. This would effectively mean that there will be a slight underestimation in the heating calculation. Using the estimation of maximum ridership per year, our annual heating demand is approximately $152*10^3$ kWh per station.

Drinking water use was calculated using typical water consumption per person figures obtained from the Rozycki et al paper. These figures were then combined with the electricity consumption GHG intensity of water, which is based on a calculation of extraction, treatment and distribution of tap water for Ontario in 2015. Knowing the life cycle emissions factor for the Ontario Grid for 2015 (which is provided in the Environmental Commissioner of Ontario's 2016/2017 Energy Conservation Report [26]) allows us to back calculate an Energy intensity (in kWh/L), which we can combine with today's grid emissions factor for Ottawa to obtain a more modern value.

Tap Water usage (g/passenger)	1.96E+02
Number of passengers, over lifetime	1.24E+09
Total Lifetime Water use (L)	2.43E+08
Energy Intensity of Tap Water (kWh/L)	5.81E-03
Ottawa Grid Carbon Intensity (kgCO2e/kWh)	7.20E-02
Whole Life Emissions (kgCO2e)	1.02E+05

Table 6: Calculation of the lifetime carbon intensity of Ontario's water system, for a 30 year lifetime

The lighting and ventilation requirements were determined using monthly demand values as reported by Guan et al. for the North China Plain rail system [27]. Although this is not a study specific to Ottawa, we assume the values are representative of the confederation line as they were calculated for a similar, modern light rail system. The table below shows the energy demands of both lighting and ventilation in kWh for the four months studied in the report, as well as their average. This final value was assumed to be the annual average of energy consumption per station.

System	February	May	August	November	Average
Lighting (10^3 kWh)	4.12E+01	4.64E+01	4.69E+01	4.56E+01	4.94E+01
Ventilation (10^3 kWh)	2.65E+01	1.02E+02	1.45E+02	2.69E+01	6.62E+01

Table 7: Energy Demand of Lighting and Ventilation per Station, per month

For station lighting, heating and ventilation, we assume that only the underground stations will be concerned, as the overground stations will open air. For lighting specifically, we should note that there will be nighttime lighting for the overground stations, however this demand is negligible compared to the lighting required for the underground stations. Therefore the total operational energy consumption from each system over the 30 year lifetime are as follows:

Lighting Demand (10^3 kWh)	Heating Demand (10^3 kWh)	Ventilation Demand (10^3 kWh)
1.78E+03	1.19E+05	3.18E+03

Table 8: 30 Year Lifetime Operational Energy Demands of Infrastructure

These demands were then multiplied by the Ontario grid mix emissions factor determined earlier to determine the operational emissions.

Lighting Emissions ($kgCO_2e$)	Heating and Ventilation Emissions ($kgCO_2e$)	Water Emissions ($kgCO_2e$)
1.06E+07	3.06E+07	2.04E+05

Table 9: 30 Year Lifetime Operational Emissions of Infrastructure

Using this sizing of the lighting and HVAC systems (in kWh), we were then able to determine the emissions associated with their manufacturing processes. We based our calculations on the specifications of lights approved by Transport for London (TfL), a similar system. These bulbs have powers of 60W and 50,000 hr lifespans, and therefore lifetime energy consumptions of 3000kWh. To meet our lighting demand, we assume 10000 bulbs for the line, which must be replaced 5.3 times over the 30 year lifetime. The GWP of these 60W bulbs was determined by the U.S. Department of Energy to be 8.935 $kgCO_2e$/bulb ([28] Scholand and Dillon, 2012). The total emissions are represented in the table below.

Number of Lightbulbs over Lifetime	Manufacturing Emissions Factor ($kgCO_2e$/bulb)	Lightbulb Manufacturing Emissions ($kgCO_2e$)
5.30E+04	8.90E+00	4.77E+05

Table 10: Manufacturing Emissions of Lighting (30 year line lifespan)

The manufacturing GWP data for the HVAC system was derived from a manufacturer LCA ([29] Optimized Thermal Systems, Inc, 2020), which combined data from 5 sources of HVAC equipment, varying in sources, efficiencies, refrigerant for offices in both LA and Fresno. Since the weather in Fresno is similar to that of Ottawa, its HVAC data was applied to the Confederation Line's heating and ventilation demands. The emissions of each system was divided by its respective energy consumption and then averaged to determine a factor of kg CO_2e / kWh.

Energy Consumption (MWh)	6.56E+02	7.82E+02	3.24E+02	3.24E+02	3.76E+02	3.70E+02	4.72E+02
GHG Emissions ($kgCO_2e$)	1.20E+05	1.45E+05	6.00E+04	6.00E+04	7.00E+04	7.00E+04	8.75E+04
Emissions Factor ($kgCO_2e$/kWh)	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 11: HVAC Emissions Factors, for a 20-year HVAC Lifespan

This factor was then applied to the combined heating and ventilation demands calculated above. The emissions associated with the HVAC system are represented below.

HVAC Energy Demand (10^3 kWh)	Average HVAC Manufacturing Emissions Factor (kgCO$_2$e/kWh)	HVAC Manufacturing Emissions (kgCO$_2$e)
1.78E+05	2.00E-01	3.30E+07

Table 12: Manufacturing Emissions of Lighting (30 year line lifespan)

The emissions from construction of the stations and the lighting, HVAC and water systems were all summed to determine the final infrastructure GWP to be 3.52E+08 kgCO$_2$e over a 30 year lifetime. These calculations were then repeated for lifetimes of 60 and 90 years. The results of these calculations are reported in the Results section.

As it pertains to operational use, we have also calculated additional environmental impacts associated with the electricity consumption of the operational phase of the line's infrastructure.

Train Vehicles

The Confederation line operates 15 Alstom Citadis Light Rail Vehicles. Derived from the earlier Citadis Dualis tram-train used in Europe, they were manufactured in Alstom's plant in Hornell, New York, with final assembly taking place at Belfast Yard in Ottawa. [30] In order to evaluate the life cycle emissions associated with the vehicles used on the line, we take into account the different life cycle stages: extraction of materials, manufacturing, use and end of life.

To evaluate the environmental impact associated with the train vehicles we used data from an EPD provided by Alstom. The environmental product declaration assesses the environmental impacts of FlexityTM M33 trams for Gothenburg that have been characterized through the realization of an LCA in accordance with ISO 14040:2006 methodology, and the requirements of the Product Category Rules Rolling stock, UN CPC 495, 2009:05, version 3.04. The GaBi Software-System and Databases for Life Cycle Engineering were used to perform this life cycle impact assessment. The GaBi databases employed have reference years between 2017-2020 and are valid until 2023. The functional unit in the EPD is transport of 1 passenger over 1 km using a 3-car FlexityTM M33 Type B light-rail vehicle in service for 30 years operating on Line 6 between Kortedala and Länsmansgården in Gothenburg, with an average running distance of 100 000 km per year.

The following table reports the main design specifications of the Citadis and the Flexity models reported by the manufacturer.

Vehicles main characteristics	Citadis Spirit Alstom	Flexity Alstom

Length	48.5 m (159 ft)	33m
Weight	78 tons	49 tons
Passenger Capacity	300	220
Traction Motor	4 × Alstom 4LMA 1648 130 kW (170 hp)	6 Alstom motors (each 120 kW)
Energy	100% Electricity	100% Electricity
Lifetime	30 years	30 years

Table 13: Comparison of Citadis and Flexity vehicle design specifications

As Alstom has not reported an environmental product declaration (EPD) for the Citadis vehicles, we instead used the published data of Alstom's Flexity tramway vehicle for the calculation of impact potentials. Although this adds some uncertainty to our analysis, the Flexity is a good substitute for Citadis spirit as it is a similarly sized light rail train manufactured by the same company. Alstom divides the vehicle analysis into 3 phases: the upstream phase including the extraction and production of raw materials, the production of auxiliary materials, and the transportation of core systems to the assembly site, the core phase including vehicle assembly, energy, water and auxiliary material consumption, waste and emissions generation, and delivery to the operating site, and finally the downstream phase including energy consumption during operation, materials for operation, spare parts, and end of life.

In order to adapt this study to the Citadis vehicle, we used the Flexity data as is - except for the energy consumed during the use phase. Instead, we calculated the emissions associated with the energy consumed by taking into account the electricity mix of Ottawa. Calculations of GWP in units of kgCO_2e/passenger km for Citadis with considering Ottawa electricity mix:

$$GWP = GWP_{EPD} - Energy_{consumption} \cdot (EI_{EPD} - EI_{Ottawa})$$

Where EI_{EPD} is the emissions intensity from electricity generation in Vanttenfall with units of kgCO_2e/kWh and EI_{Ottawa} is the emissions intensity from electricity generation in Ottawa with units of kgCO_2e/kWh. To determine the total results of emissions per year we needed to know the distance covered by the rolling stock within a year. To do so, we first calculated the average train frequency on the line from the data provided by OC transpo, the operator of the trains (Appendix B). We therefore calculated the average number of simultaneous vehicles for a round trip. Considering that the duration of the round trip is 50 minutes according to OC transpo, this gave us an average of 8 trains operating simultaneously. We subsequently calculated the weekly distance covered by all rolling stock (excluding reported OC Transpo holidays)

$$Total\ km/week = 8\ trains \times 25km \times \left(\frac{hrs\ of\ operation}{round\ trip\ travel\ time}\right)$$

This gave us a total of 30,840 km for 50 weeks and 25,200 km for the 14 days of vacations. Thus we could calculate the life cycle emissions of vehicles in units per year, with the following formula :

$$GWP(kgCO_2/yr) = GWP\left(\frac{kgCO_2}{pass.km}\right) \times 600\ pass \times \frac{Total\ km}{yr}$$

We made the assumption that vehicles are fully loaded with 600 passengers in order to be consistent with Alstom's EPD. With these calculations and assumptions, we determined the GWP for each phase and summed them as totals reported in the table below. The calculations were then repeated for 60 and 90 year lifetimes, and reported in the results section.

Citadis	Unit	Upstream	Core	Downstream	Total
GWP Factor	kg CO2 eq / pass.km	2.4E-04	4.7E-05	1.7E-03	2.0E-03
GWP Annual Total	kg CO2 eq /yr	2.3E+05	4.5E+04	1.6E+06	1.9E+06
GWP Total	kg CO2 eq	6.9E+06	1.3E+06	4.8E+07	5.6E+07

Table 14: GWP of Rolling Stock for a 30 Year Lifetime

Emissions of criteria pollutants

As we are only considering the operation phase for the emissions of criteria pollutants, we calculated these emissions from the energy consumption. We used LCA emissions factors of criteria pollutants, associated with the electricity mix of ottawa. We then calculated total emissions per year with the same assumptions as previously: 1,592,400 km / yr for the rolling stock and 600 passengers per train, using the same method as for GWP.

Rail Tracks

Next, we estimate the life-cycle GHG emissions due to the rail tracks of the Confederation line. As the line has a length of 7.8 miles, 15.6 miles of tracks were constructed to operate in both directions of travel. The life-cycle inventory analysis of rail tracks is summarized in the following chart.

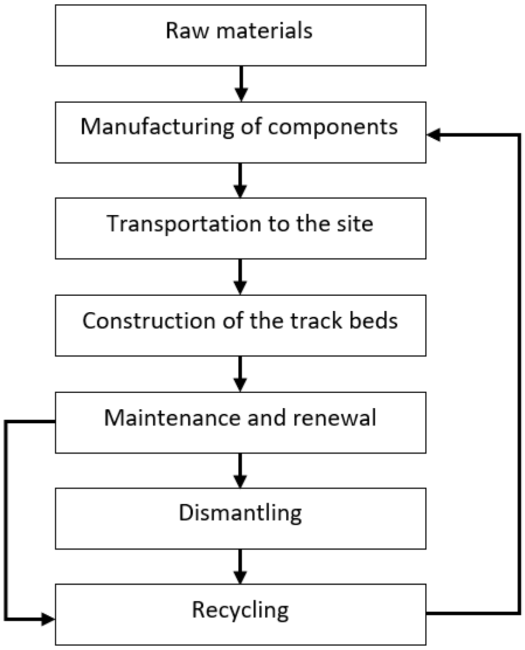


Figure 6: Life-cycle assessment inventory stages ([31] Kiani, Ceney, and Parry, 2008)

Our calculations take into account upstream and downstream emissions due to raw materials, manufacturing of the components, transportation to site, and construction of the track beds as well as maintenance. Emission factors for steps from extraction of the materials to the maintenance of the track beds were derived from the Federal Transit Administration [32]: though the data corresponds to practices in the US rather than Ottawa, the systems assessed are very similar. This means that the source is applicable to our assessment. Emission factors for dismantling and recycling were not accessed here. Some papers address those steps by making rough assumptions, as is the case for Kiani, Ceney, and Parry (2008) [31], which considers that fastenings, reinforcement bars and rails are recycled up to 85%. As we don't have any supporting data for Ottawa regarding recycling practices, we did not include the recycling within our review. Data from the FTA is aggregated into "construction" and "maintenance". The "construction" section includes extraction of raw materials, manufacturing of components, transportation to the site and construction of the track beds. For renewal, lifetime estimations are from Kiani, Ceney, and Parry (2008) [31]; it is assumed that tracks need to be renewed every 20 years. At each renewal, a new track is built in an upgraded mode.

As the tunneling construction was analyzed within the stations and infrastructure section, we assess the construction of the tracks as “at-grade”. The FTA emissions values associated with the “at-grade” rails are reported in the table below.

Phase	Units	Upstream	Downstream
Construction	$MTCO_2eq$ / mi	4.25E+02	1.38E+02
Maintenance	$MTCO_2eq$ / mi / year	n/a	4.42E+00
Upgrade	$MTCO_2eq$ / mi	2.69E+02	9.50E+01

Table 15: FTA Emissions Factors of At Grade Rail [32]

Noting the length of the tracks, $L = 15.6$ mi, the initial construction GWP emissions are:

$$E_{tracks,0}\ (MTCO_2) = L\,(mi) \times (GWP_{Upstream\ Construction}(MTCO_2/mi) + GWP_{Downstream\ Construction}(MTCO_2/mi))$$

Over the years, the GWP emissions due to maintenance of the tracks are calculated by incorporating lifetime in years as T.

$$E_{tracks,maint}\ (MTCO_2) = L\,(mi) \times GWP_{Downstream\ Maintenance}(MTCO_2/mi/year) \times T(year)$$

As well as GHG emissions due to renewal of the tracks every 20 years:

$$E_{tracks,renewal}\ (MTCO_2) = L\,(mi) \times (GWP_{Upstream\ Upgrade}(MTCO_2/mi) + GWP_{Downstream\ Upgrade}(MTCO_2/mi))$$

The results from these calculations for lifetimes of 30, 60, 90 years are all tabulated in the results sections. Further, as there is no operating activity associated with the rails, we neglect the environmental potential factors for this section.

Catenary

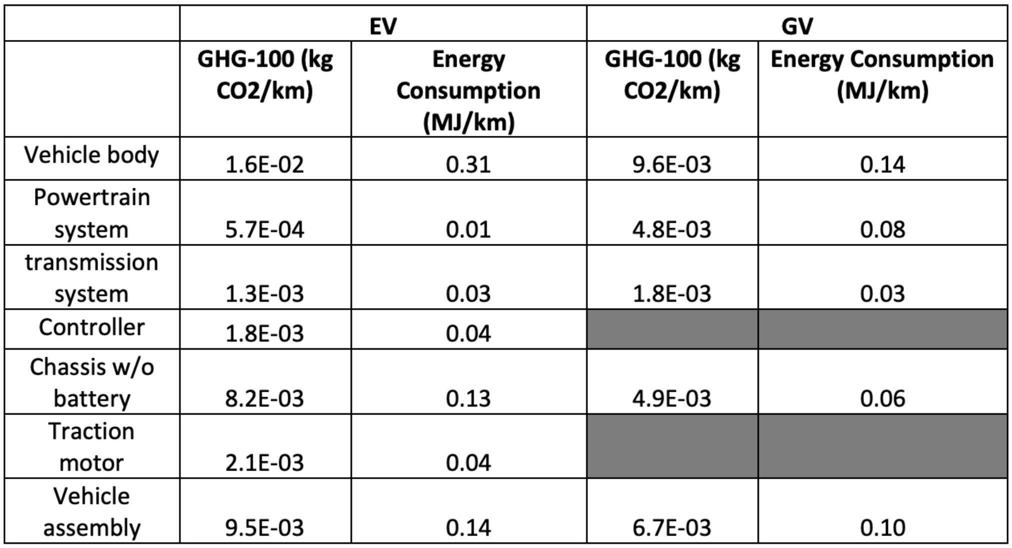
This section estimates the life-cycle GHG emissions due to the catenary of the Confederation line. The length needed for the catenary is 15.6 miles to cover the Confederation line in both directions. Our analysis includes extraction of materials, manufacturing of the components and maintenance of the catenary. Associated emission factors are obtained from the FTA [31] as with the rail data. Renewal of the catenary system is assumed to happen every 50 years, which is a minimum lifespan ([33] Nåvik, Rønnquist, and Stichel, 2016). At each renewal, GHG emissions associated with the initial construction of the catenary are produced. This emissions factor and total emissions for the catenary of a 30 year lifespan are reported below.

Emissions Factor ($MT\ CO_2e$ / mi)	Length of Track (mi)	Total Emissions ($MT\ CO_2e$)
3.16E+03	1.56E+01	1.6E+06

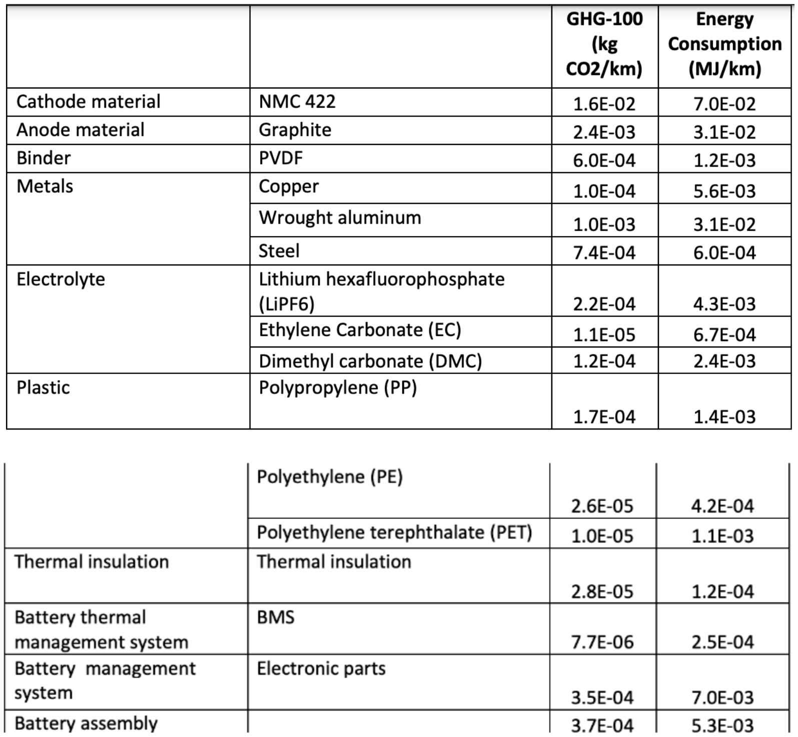
Table 16: Emissions of Catenary for 30 Year Lifetime

Automobile

The intent of this study is to compare the new technology of electric rail to existing transportation methods, namely cars. As such, the lifecycle impact of automobiles was calculated to help determine a breakeven point. Thanks to the readily available automobile LCA data, Canada-specific information was widely available, eliminating the need to use approximations as was the case with other elements of the analysis. Much of the data pertaining to the comparison of GVs and EVs was sourced from Poovanna, Davis and Argue [34]. The report factors everything from individual component manufacturing and battery production (Figure 7), to specific recycling methods (Figure 8).



	EV		GV	
	GHG-100 (kg CO2/km)	Energy Consumption (MJ/km)	GHG-100 (kg CO2/km)	Energy Consumption (MJ/km)
Vehicle body	1.6E-02	0.31	9.6E-03	0.14
Powertrain system	5.7E-04	0.01	4.8E-03	0.08
transmission system	1.3E-03	0.03	1.8E-03	0.03
Controller	1.8E-03	0.04		
Chassis w/o battery	8.2E-03	0.13	4.9E-03	0.06
Traction motor	2.1E-03	0.04		
Vehicle assembly	9.5E-03	0.14	6.7E-03	0.10



		GHG-100 (kg CO2/km)	Energy Consumption (MJ/km)
Cathode material	NMC 422	1.6E-02	7.0E-02
Anode material	Graphite	2.4E-03	3.1E-02
Binder	PVDF	6.0E-04	1.2E-03
Metals	Copper	1.0E-04	5.6E-03
	Wrought aluminum	1.0E-03	3.1E-02
	Steel	7.4E-04	6.0E-04
Electrolyte	Lithium hexafluorophosphate (LiPF6)	2.2E-04	4.3E-03
	Ethylene Carbonate (EC)	1.1E-05	6.7E-04
	Dimethyl carbonate (DMC)	1.2E-04	2.4E-03
Plastic	Polypropylene (PP)	1.7E-04	1.4E-03
	Polyethylene (PE)	2.6E-05	4.2E-04
	Polyethylene terephthalate (PET)	1.0E-05	1.1E-03
Thermal insulation	Thermal insulation	2.8E-05	1.2E-04
Battery thermal management system	BMS	7.7E-06	2.5E-04
Battery management system	Electronic parts	3.5E-04	7.0E-03
Battery assembly		3.7E-04	5.3E-03

Figure 7: Production energy use and emissions for GV vs EV (top) and battery manufacturing (bottom)

Total energy consumption	0.3 MJ/lbs. of batteries processed
Total CO_2 emission	0.008 kg/lbs. of batteries processed

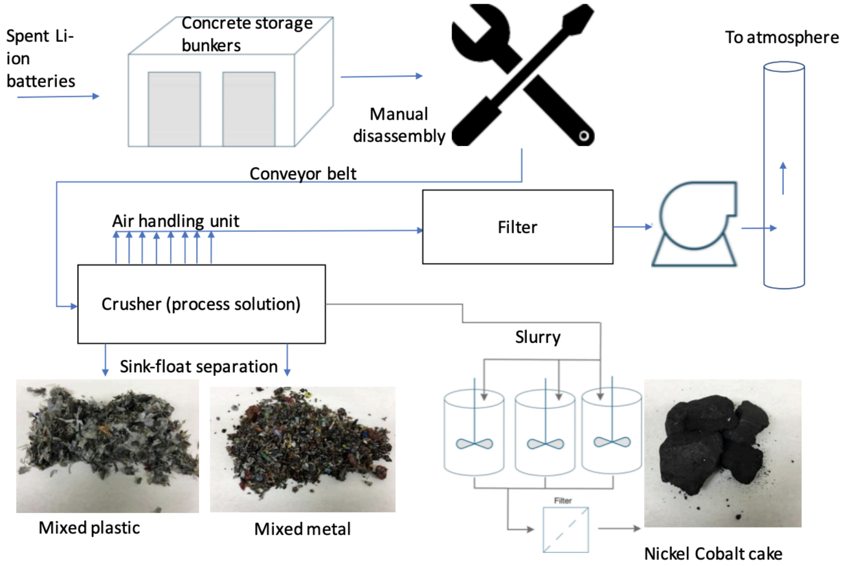


Figure 8: Battery recycling methods using Retriev Technology

The complicating factor boils down to the energy use required to manufacture and disassemble batteries. Retriev Technologies collects the various components of automobile batteries and converts them into a form that can be stored or reused. The process itself requires energy to break down the raw materials - which adds to the overall EOL emissions. As both GVs and EVs require similar energy use to recycle and break down metal for scrap, the main difference is in the battery processing for EVs.

The report gave CO2 values as adjusted to three specific grids: Alberta, British Columbia, and Canada average. Given our specific case study in Ottawa, the energy use was adjusted to Ontario's specific energy grid composition. Given the high percentage of nuclear and hydro, use phase emissions for EVs were expected to be substantially lower than GVs. All emissions values were calculated on a per km basis, which meant for the fixed values of manufacturing and EOL, a vehicle lifespan of 150,000 km was used [34] to establish a per km unit. While newer cars generally get around 200,000 to 300,000 km, we used a conservative estimate to factor in older cars still in use as well as maintenance emissions, tire usage, oil changes and other factors that would overall add to the use phase emissions. While EV use phase emissions were calculated directly from the grid, GVs were calculated using Ottawa's specific gasoline specifications [35]. As of 2020, Ontario gasoline was required to contain 10% ethanol and have 45% lower lifecycle greenhouse gas emissions. To calculate total emissions, ethanol data was collected [36] and aggregated with standard gas emissions. All auxiliary emissions associated with cars such as roadwork and maintenance were excluded.

To account for both EVs and GVs, different usage scenarios were used. As a baseline, we used data from Statistics Canada to establish a starting value of 1.14% EVs as percentage as a total [37]. This is based on new car registrations and gives an optimistic estimate as this value has only been increasing from year to year. Using the same 30, 60 and 90-year timelines, 25%, 50%, and 100% EV scenarios were considered as well. To distinguish between a per-passenger and a per-vehicle unit, 1.2 riders were assumed per vehicle [38] and the commute was scaled to the average rail commute length of 7.8 km one-way to assess the direct impact of the rail line.

Break Even Point

To link our GWP calculations for cars and the OLRT system, we then determine the number of passengers required to achieve an environmental profit "break-even" point; We calculate how many car commuters would need to switch to commuting via the light rail transit system in order for the GWP costs of the project to equal the GWP savings of reducing car use. This is done using the following equation:

$$Passengers\ per\ year\ =\ GWP_{LRT}/(GWP_{Car,\ per\ passenger}\times T)$$

Here, GWP_{LRT} is the total lifetime global warming potential of the train system in $kgCO_2e$, $GWP_{Car,\ per\ passenger}$ is the global warming potential of car commuting per passenger, and T is the lifetime of the system in years. The final values output from this equation are presented in the results section.

8. Results and Findings

Global Warming Potential Results

The final Global Warming Potential values of the LRT system determined as detailed in the methods section are tabulated below for 30, 60 and 90 year lifetimes.

System Component	Annual GWP (kgCO2e/year)	Lifetime GWP (kgCO2e)
Station HVAC	5.10E+05	1.53E+07
Station Construction	3.39E+06	1.02E+08
Station Lighting	1.76E+05	5.28E+06
Station Water Use	3.39E+03	1.02E+05
Storage Facility	1.03E+04	3.08E+05
Tunneling	7.66E+06	2.30E+08
Rolling Stock	1.87E+06	5.60E+07
Tracks	5.51E+05	1.65E+07
Catenary	1.64E+06	4.93E+07
Total	**1.58E+07**	**4.75E+08**

Table 17: GWP of LRT System Components Over 30 Year Lifetime

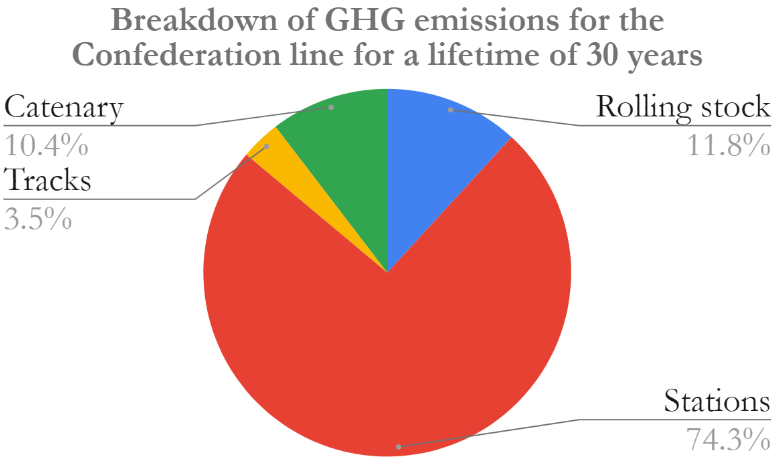
System Component	Annual GWP (kgCO2e/year)	Lifetime GWP (kgCO2e)
Station HVAC	5.10E+05	3.06E+07
Station Construction	1.70E+06	1.02E+08
Station Lighting	1.76E+05	1.06E+07
Station Water Use	3.39E+03	2.04E+05
Storage Facility	1.03E+04	6.15E+05
Tunneling	3.83E+06	2.30E+08
Rolling Stock	1.87E+06	1.12E+08
Tracks	4.99E+05	3.00E+07
Catenary	1.64E+06	9.86E+07
Total	**1.02E+07**	**6.15E+08**

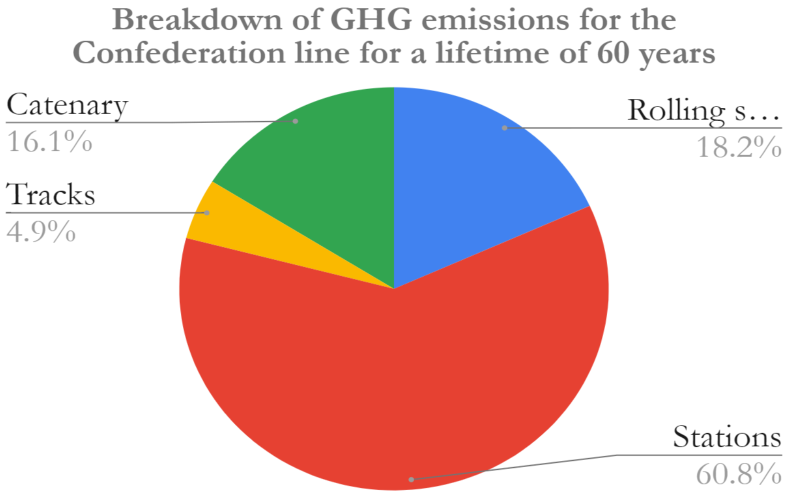
Table 18: GWP of LRT System Components Over 60 Year Lifetime

System Component	Annual GWP (kgCO2e/year)	Lifetime GWP (kgCO2e)
Station HVAC	5.10E+05	4.59E+07
Station Construction	1.13E+06	1.02E+08
Station Lighting	1.76E+05	1.58E+07
Station Water Use	3.39E+03	3.05E+05
Storage Facility	1.03E+04	9.23E+05
Tunneling	2.55E+06	2.30E+08
Rolling Stock	1.87E+06	1.68E+08
Tracks	4.19E+05	3.77E+07
Catenary	1.10E+06	9.86E+07
Total	**7.76E+06**	**6.99E+08**

Table 19: GWP of LRT System Components Over 90 Year Lifetime

From the station data, we should note that the tunnels and station infrastructure is not replaced within the lifetime of the line in any of the scenarios. On the other hand, during the lifetime of the line, the proportion of emissions represented by the trains themselves increase over time, due to the fact that the lifetime of a train is only 30 years. According to our assumptions, the catenary system needs to be rebuilt every 50 years, making its GHG emissions increase periodically. This explains why GHG emissions per year for the scenario of 90 years is smaller than those for 30 and 60 years as the scenario ends before a new catenary system needs to be installed.





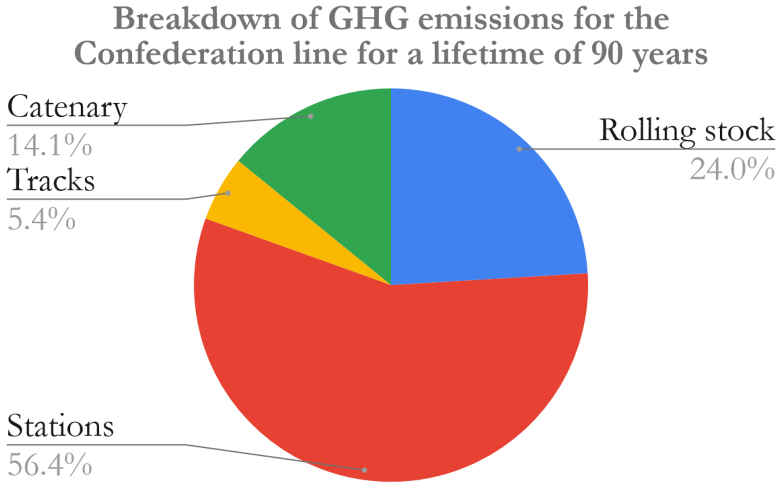


Figure 9: Breakdown of GHG emissions for the Confederation line for lifetimes of 30, 60 and 90 years

Passengers Break-event point

The table below displays the break even point for the 3 possible lifetimes of the line. The number of passengers for a break even point to be reached corresponds to the number of people who would need to switch from cars to trains as part of their daily commute in order for the environmental impact of the confederation line to be mitigated. As the lifetime increases, the more each individual car passenger accounts for a higher amount of emissions, and therefore the fewer passengers are required for a break even point to be reached in that particular lifetime.

To obtain a sense of how realistic this quantity of passengers truly is, we have compared the number of passengers required for a break even point to the number of car commuters located within 5 kilometers of Ottawa's city center, as this corresponds to a radius similar to that of the Confederation Line stage 1 itself.

Time (years)	30	60	90
Number of passengers for break even point - current EV (people/year)	601	194	98
Number of passengers for break even point - current EV (people)	18024	11667	8851
Percentage of Ottawa's inner city car commuting population	41%	27%	20%

Table 20: Break even point for the 3 examined lifetimes of the Confederation Line Stage 1

Distance to Centre (km)	Less than 5	5 to 14.9	15 to 24.9	25 or more
Percentage of car commuters (%) [39]	24.9	57.2	68.7	80.5
Number of car commuters [40]	43920	135319	70414	64759

Table 21: Ottawa-Gatineau car commuter data, 2016 Census

Criteria Pollutants Results

For the other criteria pollutants, the tables below report the results for the operational phase due to the energy consumption, first for vehicles and for station infrastructures. We then calculate the total emissions of criteria pollutants.

Rolling Stock				
Criteria pollutants	Time	30	60	90
PM emission	kg PM	1.84E+04	3.68E+04	5.52E+04
NOx emissions	kg NOx	1.25E+05	2.49E+05	3.74E+05
SOx emissions	kg SOx	9.42E+04	1.88E+05	2.83E+05
VOC emissions	kgVOC	7.53E+03	1.51E+04	2.26E+04
CO emissions	kgCO	3.98E+04	7.95E+04	1.19E+05

Table 22: Criteria pollutants emissions of Vehicles Over 30, 60 and 90 years Lifetime

Station				
Criteria pollutants	Time	30	60	90
PM emission	kg PM	2.70E+03	5.40E+03	8.10E+03
NOx emissions	kg NOx	1.83E+04	3.65E+04	5.48E+04
SOx emissions	kg SOx	1.38E+04	2.77E+04	4.15E+04
VOC emissions	kgVOC	1.10E+03	2.21E+03	3.31E+03
CO emissions	kgCO	5.84E+03	1.17E+04	1.75E+04

Table 23: Criteria pollutants emissions of Stations Over 30, 60 and 90 years Lifetime

Criteria pollutant emissions from Confederation Line				
Criteria pollutants	Lifetime	30	60	90
PM emission	kg PM	2.11E+04	4.22E+04	6.33E+04
NOx emissions	kg NOx	1.43E+05	2.86E+05	4.28E+05
SOx emissions	kg SOx	1.08E+05	2.16E+05	3.24E+05
VOC emissions	kgVOC	8.63E+03	1.73E+04	2.59E+04
CO emissions	kgCO	4.56E+04	9.12E+04	1.37E+05

Table 24: Total Criteria pollutants emissions for the operation phase

In the case of the calculation for cars, we take into account the use and end-of-life phases, as recycling takes place in the Ottawa area and contributes to local emissions of criteria pollutants.

Cars				
Criteria pollutants	Time	30	60	90
PM emission	kg PM /pass	4.46E+03	8.92E+03	1.34E+04
NOx emissions	kg NOx /pass	4.22E+04	8.45E+04	1.15E+05
SOx emissions	kg SOx/pass	1.63E+04	3.25E+04	4.88E+04
VOC emissions	kgVOC/pass	2.21E+04	4.42E+04	6.63E+04
CO emissions	kgCO/pass	3.77E+05	7.55E+05	1.13E+06

Table 25: Total Criteria pollutants for cars per passenger for operation and end-of-life phases

In order to compare the emissions of the criteria pollutants between the use of the cars or the line, here are the emission results for the cars for a number of passengers corresponding to the break-even point calculated for the GHG emissions

Cars' criteria pollutants emissions at the GHG breakeven point			
Time (years)	30	60	90
Number of passengers for break even point - current EV (people)	1.80E+04	1.17E+04	8.85E+03
PM emission kgPM	8.04E+07	1.04E+08	1.18E+08
NOx emissions kgNOx	7.61E+08	9.85E+08	1.02E+09
SOx emissions kgSOx	2.93E+08	3.79E+08	4.32E+08
VOC emissions kgVOC	3.98E+08	5.16E+08	5.87E+08
CO emissions kg CO	6.80E+09	8.80E+09	1.00E+10

Table 26: Cars' criteria pollutants emissions at the GHG breakeven point

According to our findings, the use of cars is much more polluting than the confederation line, so it is environmentally preferable in terms of criteria pollutants emissions.

9. Sensitivity Analysis

The two quantitative variables of greatest significance are the lifetime of the project, and the fraction of electric vehicles used for commuting.

Sensitivity with the lifetime of the project

Our results above report the GWP of the train system and the passenger breakeven point over three lifetimes: 30, 60 and 90 years. As a sense check, we can evaluate these values with a lifespan of 1 year in order to better visualize the influence of time. With this 1 year lifetime, the number of passengers required for the break-even point is over 540,000 people. A scatter plot of these values over all timelines is below.

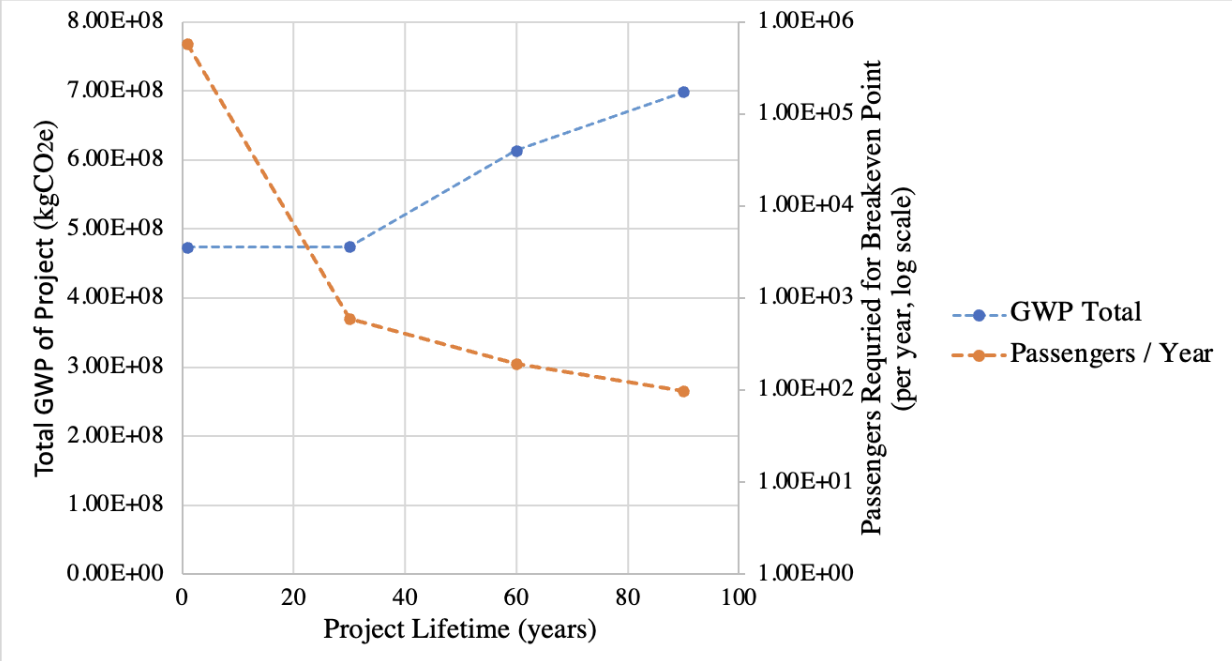


Figure 10: Sensitivity of Results to Project Lifetime

As shown above, increases in project lifetime increases the total GWP associated. However, these increases are offset by the fact that the longer a passenger uses a car before switching to trains, the more emissions per passenger they will represent. Therefore the required number of passengers per year for the breakeven point decreases with increasing lifetime.

Sensitivity with the share of EV vehicles

Next we investigate the sensitivity of our results to the mix of electric vehicles to internal combustion engines in Ottawa. Our primary scenario assumes that the split between electric and gasoline vehicles is 1:99. This is subject to a decrease over time, which is likely to make car use more environmentally competitive with train use. To assess the impact of this factor we calculated the GWP per car passenger and the passenger break-even points over a series of EV percentages - 25%, 50%, 100% - for each LRT lifespan.

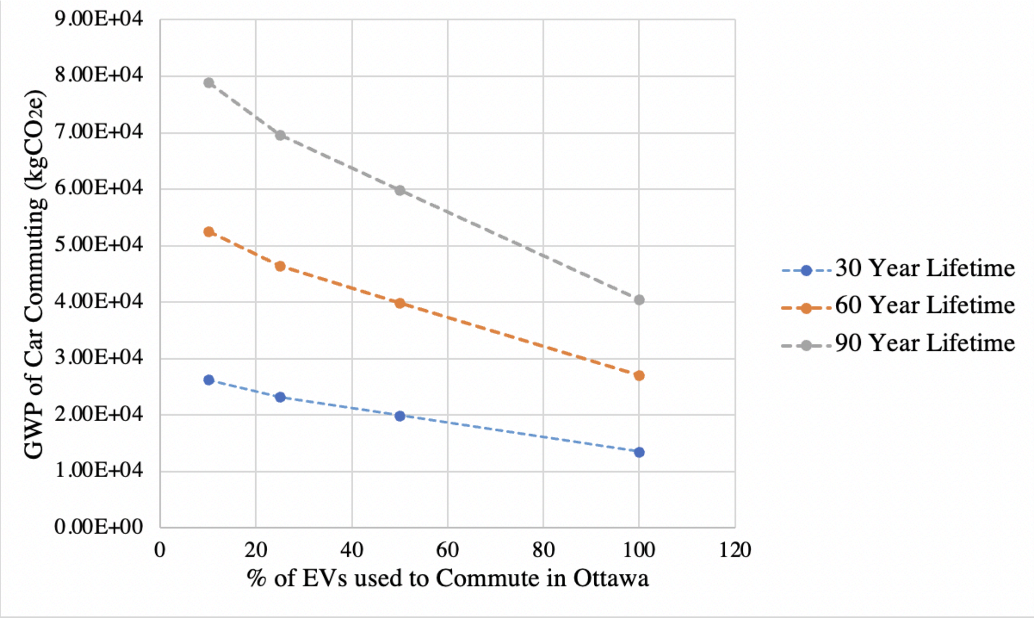


Figure 11: Sensitivity of GWP Results to EV Use

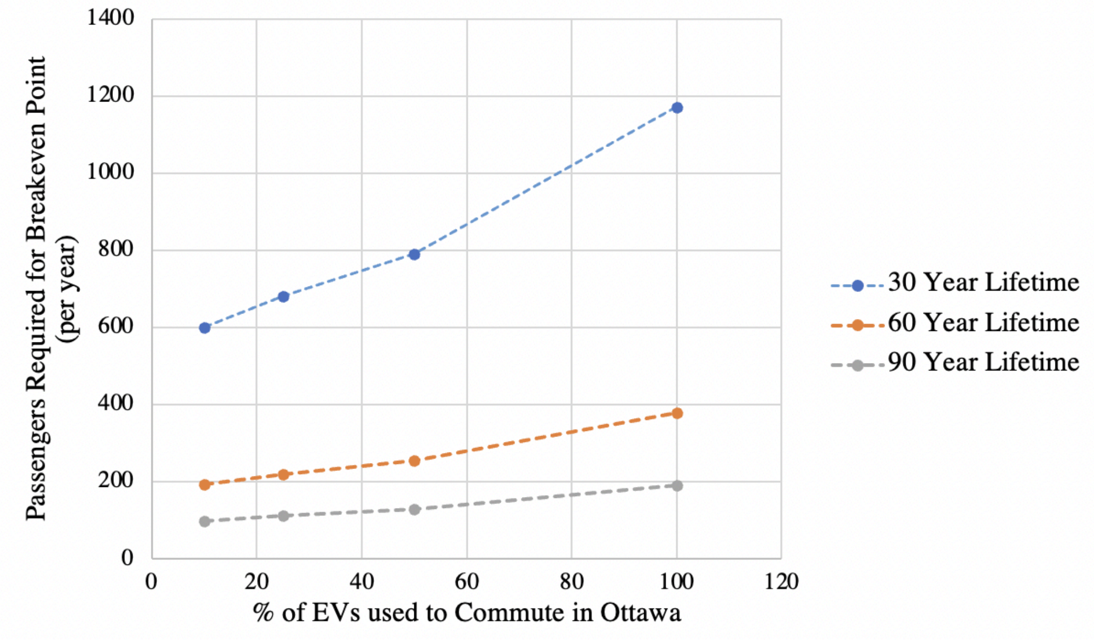


Figure 12: Sensitivity of Ridership Breakeven Point Results to EV Use

The future transition to electric vehicles is shown to decrease the GWP associated with single passenger vehicle travel as per the figure above. Therefore, this method of transit becomes more environmentally competitive with the OLRT system. This is reflected in the increase of passengers required for the breakeven point with increasing EV use.

Time (years)	30	60	90
Number of passengers for break even point - 25% EV (people/year)	681	220	112
Number of passengers for break even point - 25% EV (people)	20436	13228	10035
Percentage of Ottawa's inner city car commuting population	47%	30%	23%

Table 27: Break even point, 25% EV scenario

Time (years)	30	60	90
Number of passengers for break even point - 50% EV (people/year)	791	256	130
Number of passengers for break even point - 50 % EV (people)	23745	15370	11660
Percentage of Ottawa's inner city car commuting population	54%	35%	27%

Table 28: Break Even Point, 50% EV scenario

Time (years)	30	60	90
Number of passengers for break even point - 100% EV (people/year)	1171	379	192
Number of passengers for break even point - 100% EV (people)	35120	22732	17246
Percentage of Ottawa's inner city car commuting population	80%	52%	39%

Table 29: Break Even Point, 100% EV scenario

As the break even point increases, it edges closer to the maximum number, namely the total number of car commuters within Ottawa's inner city. This is particularly acute for the 30 year lifespan at 30 years, where the number increases to 80%. Not all the scenarios above are plausible, however: a 1% EV scenario within 90 years is quite unlikely, and a 100% EV scenario within 30 years is less likely than a 100% EV scenario within 90 years.

Feedback loops that could affect the results

The current capacity of Stage 1 of the line is 21,700 passengers per hour in both directions, covered by 15 trains. Current plans for the Confederation Line are to increase capacity to 36,000 passengers per hour in both directions by 2031 through the purchase of 25 additional LRVs, which corresponds to approximately 12 new trains on top of the 15 trains already in operation [41]. The feedback loop this constitutes is on where an increase in passenger numbers corresponds to an increase in trains being manufactured. However, this is a feedback which cannot be easily calculated, as it would require knowing how close to capacity the line truly is, the maximum frequency of trains (asking if it would be possible to increase frequency from one every 5 minutes to one every 2 minutes, for instance), in order to calculate a limit of trains on the line within one hour. We therefore opted not to take on this calculation.

Another feedback loop created by increases in the number of passengers is the increase in heating demand, as the latter is linked to passenger numbers. This number is negligible in comparison to the daily ridership of the line, as an increase of 600 rush hour passengers per year would amount to an increase in daily ridership of 1200, which corresponds to 0.75%, which increases the overall heating emissions for a 10% EV scenario, by the following percentages:

Lifetime	Initial Heating Demand (kWh)	Number of passengers added	New Heating Demand (kWh)	Percentage Change (%)
30	59306945	18024	59307807	1.45E-03
60	118613891	11667	118614449	4.70E-04
90	177920836	8851	177921259	2.38E-04

Table 30: Impact of the increase of passengers on heating demand

10. Uncertainty Assessment and Management

Stations and Infrastructure

The biggest source of uncertainty in the station data pertains to the use of concrete. This material, as opposed to steel, displays considerable variability in its whole life carbon data. The table below highlights its variability, for phases A1-A3.

Figure 2.4: Example of possible variation in embodied carbon for concrete mixes. The concrete strength class reported is highest end in given ranges for those mixes

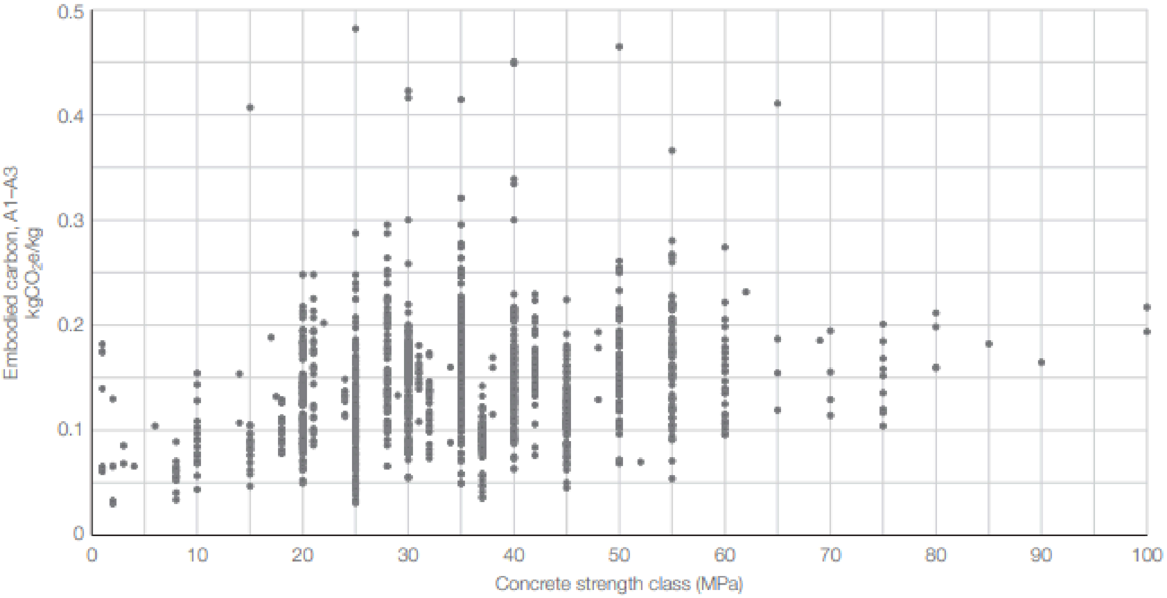


Table 31: Variability in A1-A3 Emissions of Concrete [42]

In all scenarios, infrastructure amounts to close to 70% of emissions. A significant proportion of these emissions can be attributed to concrete. By increasing the emissions factor for concrete from 72 kgCO2e/t to 100 kgCO2e/t, the results are the following:

Lifetime (years)	30	60	90
Infrastructure Emissions (72 kgCO2e/kg) (kgCO2e)	3.52E+08	3.73E+08	3.94E+08
Infrastructure Emissions (100 kgCO2e/kg) (kgCO2e)	4.70E+08	4.91E+08	5.12E+08
Increase in Emissions (kgCO2e)	1.17E+08	117599811	1.18E+08

Percentage increase (%)	25%	19%	17%

Table 32: Impact of increase in concrete emissions factor on the whole life emissions of the Confederation Line

Another source of uncertainty pertains to heating. As the amount of heating required is dependent upon ridership, fluctuations in passenger numbers would lead to changes in the overall HVAC demand. As the confederation line is recovering from the COVID-19 pandemic, it becomes difficult to predict the actual demand for heating, and how this demand will change over time. Furthermore, a conversion from the German heating degree days to the Canadian heating degree days is unconservative, purely because the Canadian Baseline is higher than the German baseline. Furthermore, the data for Germany applies for High Speed Rail, not Light Rail, which is predominantly overground, and could therefore result in heating levels being higher than usual due to higher heat loss through glazing and entrances. Values for lighting and ventilation comes from a typical underground train station in Northern China, where lighting requirements could vary based upon building regulations, and ridership influences ventilation requirements.

Train Vehicles

The data we used to estimate Train Vehicles life cycle emission have several sources of uncertainties.
First, there are indirect sources of uncertainties that comes from the Alstom's EPD :

- The end-of-life phase of the life cycle is modeled according to technology available today applying the UNIFE methodology.
- Uncertainties from measurements of materials bills by Alstom.
- Uncertainties from Energy consumption: data is based on a simulated run on a Line with 45 intermediate stops and a total length of 24.8 km. The assumption is that the vehicle is fully loaded with 220 passengers, and all auxiliary and passenger comfort systems operating at normal conditions. Regenerative braking is included with up to 2.22% depending on the environmental conditions.
- Uncertainties from the GaBi dataBase used.

Then the rest of the uncertainties come from our model: from the way we used the EPD data :

- From the calculation of the total traveled km of the rolling stock from the frequency data and the average result of 8 trains simultaneously for a duration of 50 minutes.
- From the normalization used in the functional unit in the EPD, the assumption on the number of passengers.

In addition to the above uncertainties, there are variabilities. These arise firstly from the differences between the Flexity vehicle and the Citadis tramway in terms of material bills, manufacturing, energy consumption and recycling. These variabilities are not expected to be significant, as both vehicles have similar uses and are built by the same company.

The other major source of variability is the geographical variation of the parameters, as the Flexity study is made taking into account the parameters of the different phase locations, Germany and Sweden. This has an impact on the emissions of the construction and transport phase, as well as on the recycling.

Rail Tracks

The FTA Carbon Infrastructure Estimator [43] bases its data on different sources.

Materials emissions factors are based on several EPDs when available from both the United States and Canada. Fuel emission factor is assumed to be the one of diesel and is estimated with GREET. Fuel usage factors are from National Cooperative Highway Research Program (NHCRP). Electricity emission factors are from Emissions & Generation Resource Integrated Database (eGRID). Quantities of materials needed for the construction of at-grade tracks are from Life-Cycle Environmental Inventory of Passenger Transportation in the United States ([44] Chester, Mikhail, 2008). The data is not specific to Ottawa but is representative of practices in the United States.

Catenary

The data for the catenary is based on the FTA Carbon Infrastructure Estimator and reflects practices in the US. The tool does not include energy use factors for catenary system construction due to a lack of available data.

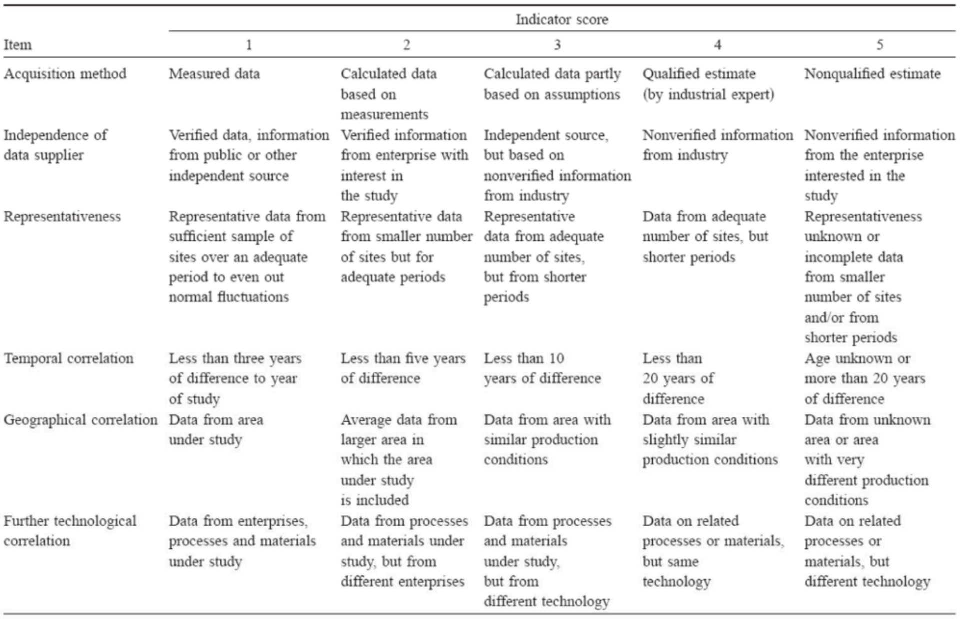
Automobile

In calculating the emissions associated with automobiles, multiple assumptions and approximations were required. The data from Poovana, Davis and Argue via PluginBC segmented lifecycle emissions into manufacturing, use, and end-of-life phases. While use phase emissions could be calculated directly using Ontario-specific information, manufacturing and end-of-life required use of their assumptions. While negligible for GVs, manufacturing, especially relating to the battery, is a significant percentage of EV emissions. For our purposes, a global average of 475 gCO2e/kWh was used [46][47] to account for the various countries that manufacture automobiles. Regarding EVs, this has the potential to be the greatest single area of variability. Furthermore, a large gray area is encountered when talking about HEV or PZEVs. While still gasoline-dependent, the use phase is the largest contributor for GVs and has the potential for the most variability. For this study, the average fuel economy was used across all Canadian cars [48] to establish a gCO2e/km value. EOL values for GVs are orders of magnitude smaller than use phase and thus can be considered negligible but for EV's they are also a significant factor. Fortunately PluginBC accounted for Retriev Technologies' actual emissions.

Ridership and driving patterns were also a large source of approximation and uncertainty. To calculate emissions on a per year basis, trip length was scaled to match the maximum length of the train line to determine the exact emissions being compared. To establish a per passenger-km basis, ridership was estimated to be 1.2 people per car [38]. Potential changes in ridership patterns and/or socio-geographic layouts of urban areas could potentially have drastic impacts on the viability of cars as opposed to mass transit but for this study, we have assumed current conditions to remain for our study periods of 30, 60 and 90 years. One significant element to note regarding the scope of the automobile section is that road maintenance and construction has been excluded. We are comparing a new technology which includes the trains and infrastructure combined against the current use of cars and are assuming roads have been in existence for a long enough time to exclude them from our study.

Parameter Uncertainty and Data Quality

In order to investigate the degree of variability in the model parameters, we performed an assessment of data quality in conjunction with a sensitivity analysis to determine the critical parameters on the final results. This method is based on the use of a pedigree matrix that specifies qualitative criteria to evaluate a score that can then be used to calculate a ranking of the components. The final ranking is determined by comparing the averages of each component analyzed.



Item	Indicator score				
	1	2	3	4	5
Acquisition method	Measured data	Calculated data based on measurements	Calculated data partly based on assumptions	Qualified estimate (by industrial expert)	Nonqualified estimate
Independence of data supplier	Verified data, information from public or other independent source	Verified information from enterprise with interest in the study	Independent source, but based on nonverified information from industry	Nonverified information from industry	Nonverified information from the enterprise interested in the study
Representativeness	Representative data from sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from smaller number of sites but for adequate periods	Representative data from adequate number of sites, but from shorter periods	Data from adequate number of sites, but shorter periods	Representativeness unknown or incomplete data from smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study, but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials, but same technology	Data on related processes or materials, but different technology

	Acquisition method	**Independence of data supplier**	**Representativeness**	**Temporal correlation**	**Geographical correlation**	**Technological correlation**
Vehicles data (Alstom' EPD)	**2**	**2**	**1**	**1**	**3**	**1**
Rail tracks (FTA)	**3**	**2**	**2**	**4**	**4**	**4**
Catenary (FTA)	**3**	**2**	**2**	**4**	**4**	**4**
Stations and Tunnel Construction (FHWA)	**2**	**3**	**2**	**4**	**2**	**2**
Stations Lighting, Ventilation (Guan et al)	**2**	**1**	**2**	**1**	**3**	**1**
Station Heating, Water, use (Rozycki)	**1**	**1**	**2**	**3**	**3**	**1**
Cars (Poovanna, Davis, Argue)	**1**	**2**	**3**	**2**	**3**	**1**
Average	**2**	**1.86**	**2**	**2.71**	**3.14**	**2**

Table 33: Data Quality Table for the Confederation Line Life Cycle Assessment

The total average in terms of data quality is 2.29. Our principal source of uncertainty across all data sources was the lack of regional specificity. When data specific to Ottawa, Canada was not available, we sourced information from similar projects and adjusted the scope to our project. For example, this was discussed to adjust for the heating demand published in a German report in Section 7: Stations and Infrastructure. Further, the Alstom train data was reported for use in Gothenburg, and was adjusted to our scenario using the Ontario grid mix to determine operational emissions.

11. Interpretation and Discussion of Results

Using these numerical results, we can now return to the questions posed in section 5:

- What are the different parameters that could have an impact on the break-even point?
- What is the potential impact of these parameters?
- What should be the period of use of the line?
- Should the system be resized?
- How many passengers are needed to make the Confederation line more environmentally beneficial than private cars?

As a sense check for the data, it is currently estimated that, by 2031, the emissions savings created by the line would be equivalent to taking 7300 cars off the streets [49] . It is unclear if this figure corresponds to Life Cycle Assessment data, however we know that 7300 cars in 13 years of use corresponds to just over 560 per year, which is in line, in terms of passengers switching per year, with our results for a 30 year scenario.

The break even point itself is primarily dependent on the lifetime of the project and the percentage of EVs within Ottawa's car makeup. In this sense, certain scenarios are more feasible than others. For example, the 1% EV scenario is the most unlikely scenario to materialize, as is the 30 year lifetime for the line - as it is rare for rail lines to last anything less than 100 years.

As major cities generally have carbon targets which aim at 2050 rather than longer term, we could assume that the 25% and 50% EV scenarios within 30 years are the ones which should be taken on by readers of this work. In both scenarios, roughly half of Ottawa's inner city car driving population would have to switch from cars to the LRT as part of their daily commute.

This proportion is significant, and should therefore translate into ambitious targets for reducing car use. Should this target be deemed unachievable, ways to reduce the pressure on the system should include lowering the carbon impact of the concrete used within the scheme. System resizing is only a possibility if size is a barrier to ridership increases - if the system is at capacity, something which is currently difficult to establish since the line's ridership is slowly recovering from the COVID-19 pandemic.

However, there are questions as to whether or not light rail will displace cars primarily, or also buses, walking or cycling. This LCA is not consequential, meaning that it does not measure the impact of the

Confederation Lines on other forms of transport, but simply compares light rail to car driving. Although this study focuses, for the sake of comparison, between inner city car commuting and light rail transit, it is difficult to predict how car drivers will respond to the line's construction if there are no benefits or incentives beyond environmental concerns. To pedestrians, and bus drivers however, the line presents the advantage of faster commutes, whilst for cyclists, the line provides for a more comfortable commute. The benefits are less clear for car drivers, which means that incentives would have to be created by the city to encourage this switch.

12. Conclusions and Recommendations

Currently, in our case study location of Ottawa, cars are very much the dominant form of transit. In an area with such extreme temperature variation and relatively nascent public transportation, it is the obvious choice for most. Establishing an adequate transportation system that can compete with established methods is an enormous undertaking and the cost of construction, maintenance and operation are non-negligible and cannot be ignored. The effectiveness of such a system hinges on sustained ridership; it must provide people with function and comfort. This means trains that run often and fast, stations that are well-maintained, facilities that are sturdy and large and in Ottawa, temperature-controlled.

With enough ridership, rail transit overall does have a lower environmental impact than the current norm of auto-centric transportation, even if important amounts of car drivers would have to switch to rail for the line to break even. Social patterns and policy decisions are beyond the scope of this project, but given the success of transit systems such as London, New York and Paris, the idea of a highly-utilized transit system is feasible. In December 2022, the Confederation Line will be free to use for the whole month, which is an attempt to boost ridership. Ensuring that taking the LRT is economically beneficial compared to car use is a way of boosting ridership, and yielding environmental benefits as soon as possible. Other policies worth exploring could be more restrictive, including, for instance, low traffic neighborhoods in city centers, or congestion charges for cars, to reduce the quantity of cars within the city center. To reduce carbon payback times even further, it would be important to reduce the carbon footprint of the concrete used in the infrastructure, as well as focusing on electric arc furnace manufacture for steel.

One potentially complicating factor however is the proliferation of EVs. As gas prices increase and environmental awareness and policies assert themselves, companies are rapidly switching to EV manufacturing. While this could potentially be seen as a pitfall rendering rail transit less environmentally superior, we would argue it is actually a benefit and a positive feedback loop in achieving the overall goal of emissions reduction in the transportation sector. The decarbonisation of the grid itself is not discussed within this project, but would help further reduce the emissions from this sector.

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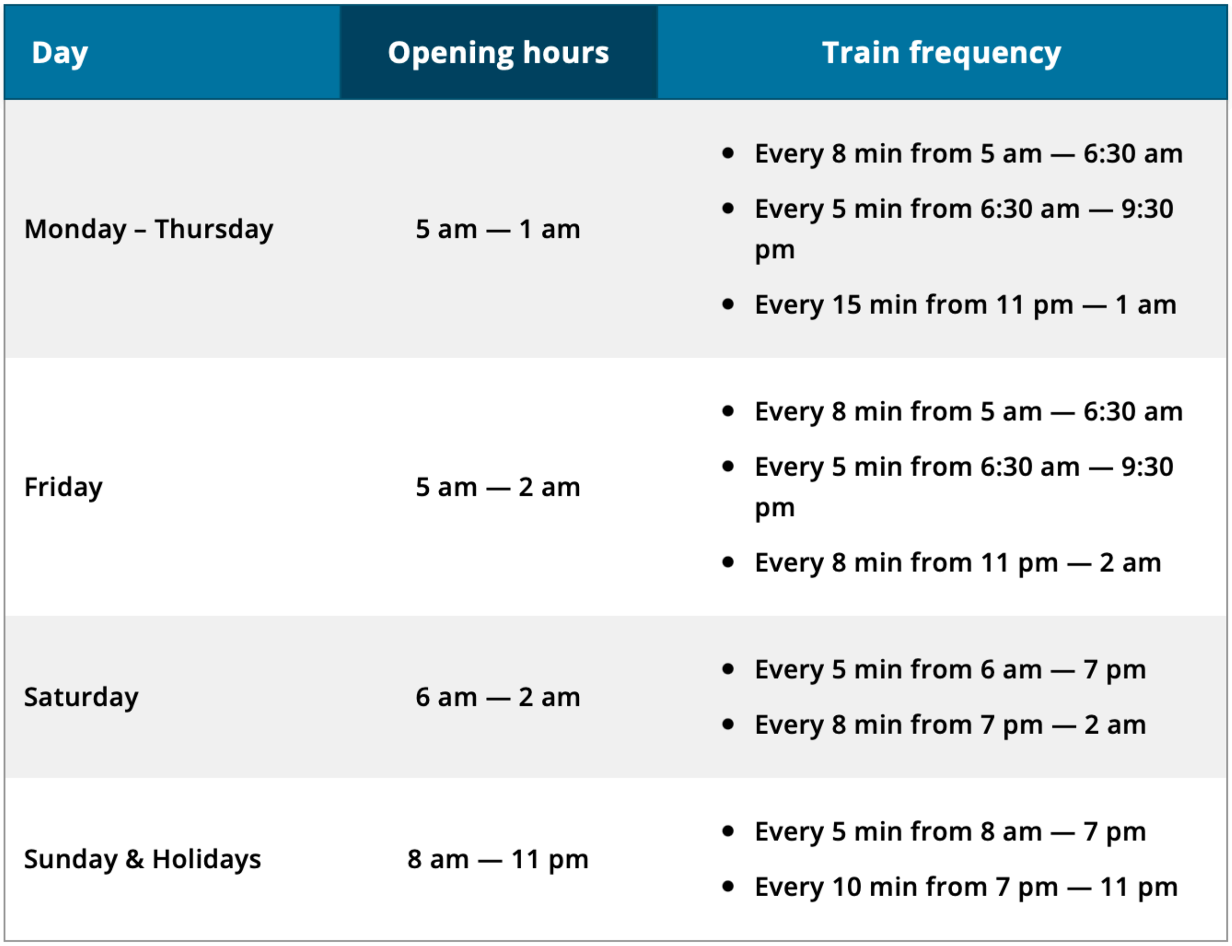
Appendix A: Data Sources for each component

Components	**Data Sources**
Vehicles	
Manufacturing	Alstom Environmental product declaration (EPD) for flexity tram; EIA; [50]
Operation	Alstom Environmental product declaration (EPD) for flexity tram; EIA;
Maintenance	Alstom Environmental product declaration (EPD) for flexity tram, EIA;
End of life - Recycling	Alstom Environmental product declaration (EPD) for flexity tram, EIA;
Infrastructure:	
Construction and Maintenance	
Station construction	Ecology Profile of the German High-speed Rail Passenger Transport System [51]
Rail construction and maintenance	Environmental Life-Cycle Assessment of Railway Track Beds [31] Transit Greenhouse Gas Emissions Estimator v3.0: User Guide - April 2022 [32]
Operation	
Station heating	Ecology Profile of the German High-speed Rail Passenger Transport System, [51]
Station electricity	Ecology Profile of the German High-speed Rail Passenger Transport System [51]
Station water usage	Ecology Profile of the German High-speed Rail Passenger Transport System [51]
Electricity	
Ontario electricity carbon intensity	Canada Energy Regulator,Provincial and Territorial Energy Profiles – Ontario [52]
New York electricity carbon intensity	EIA

Appendix B: Frequency during hours of operation



Day	Opening hours	Train frequency
Monday – Thursday	5 am — 1 am	• Every 8 min from 5 am — 6:30 am • Every 5 min from 6:30 am — 9:30 pm • Every 15 min from 11 pm — 1 am
Friday	5 am — 2 am	• Every 8 min from 5 am — 6:30 am • Every 5 min from 6:30 am — 9:30 pm • Every 8 min from 11 pm — 2 am
Saturday	6 am — 2 am	• Every 5 min from 6 am — 7 pm • Every 8 min from 7 pm — 2 am
Sunday & Holidays	8 am — 11 pm	• Every 5 min from 8 am — 7 pm • Every 10 min from 7 pm — 11 pm

Appendix C: GWP breakdowns by section

Rail Tracks

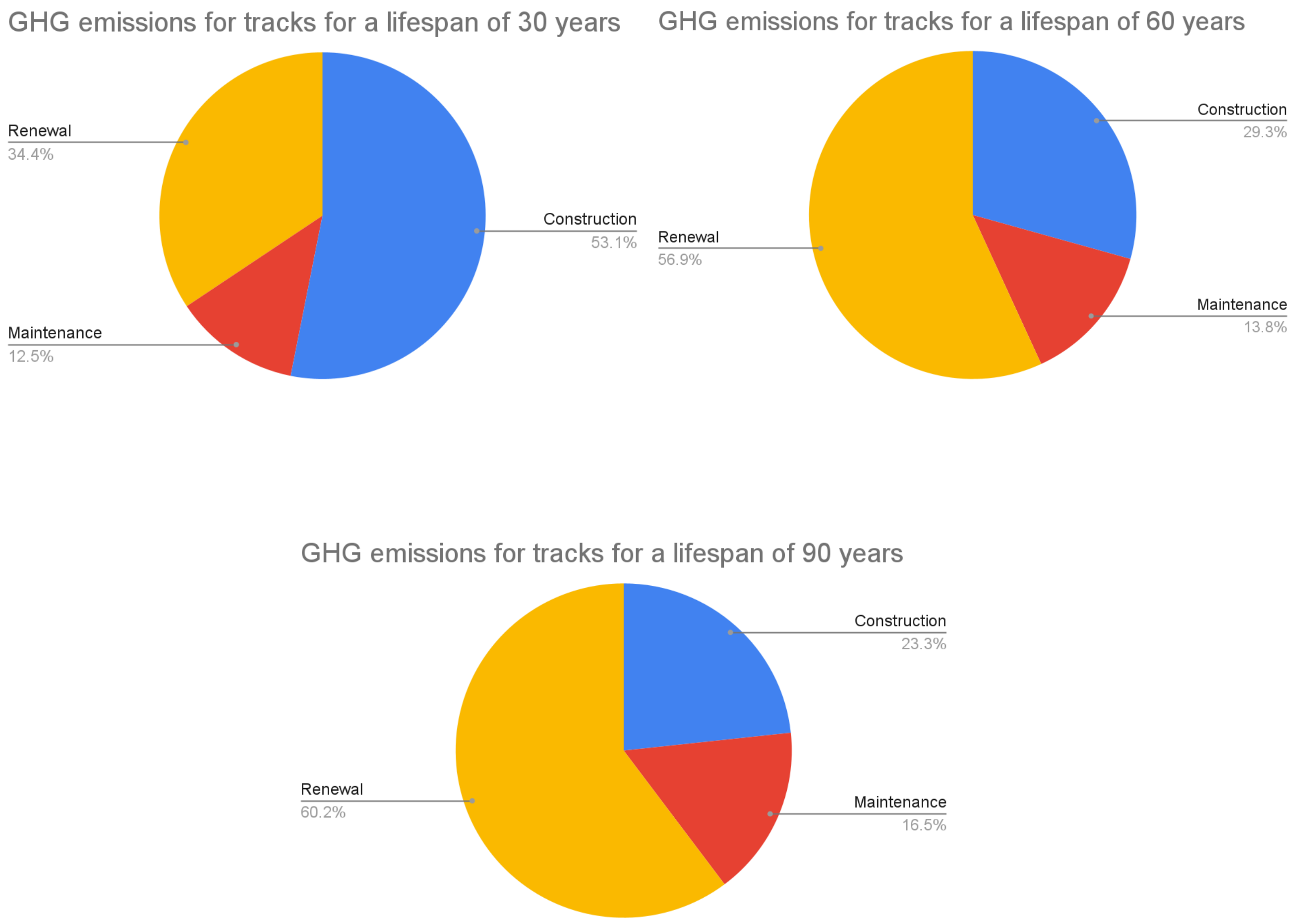


Figure 13: Repartition of GHG emissions for tracks for different lifespans (30, 60 and 90 years).. “Construction” includes extraction of raw materials, manufacturing of the components, transportation to the site and construction of the track beds for the initial installation of the track beds. “Renewal” includes extraction of raw materials, manufacturing of components, transportation to the site and construction of the upgraded tracks for each renewal (occuring every 30 years). “Maintenance” includes maintenance.

Stations

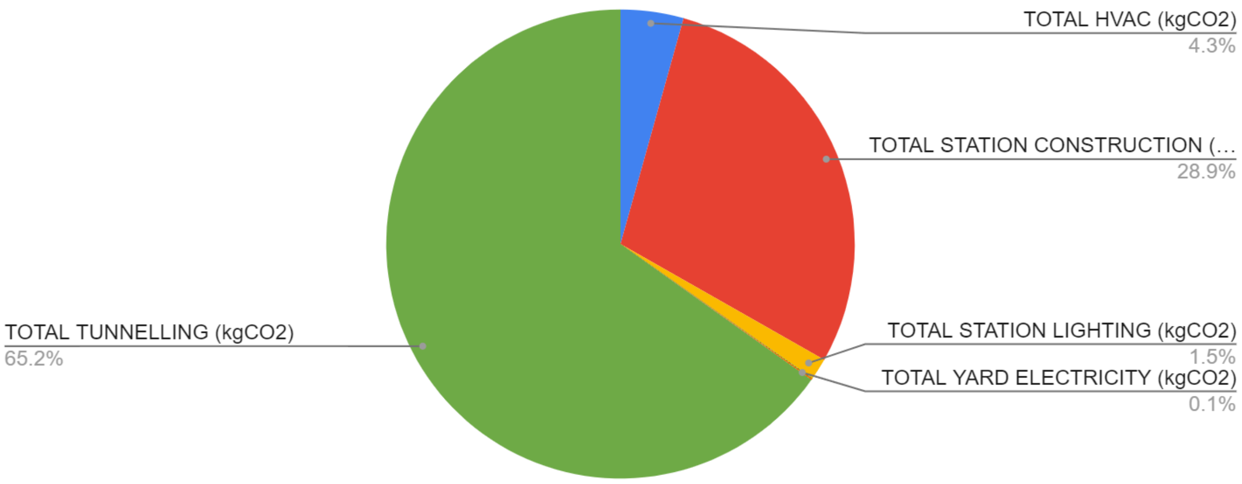


Figure 14: Breakdown of station infrastructure emissions, 30 year lifespan

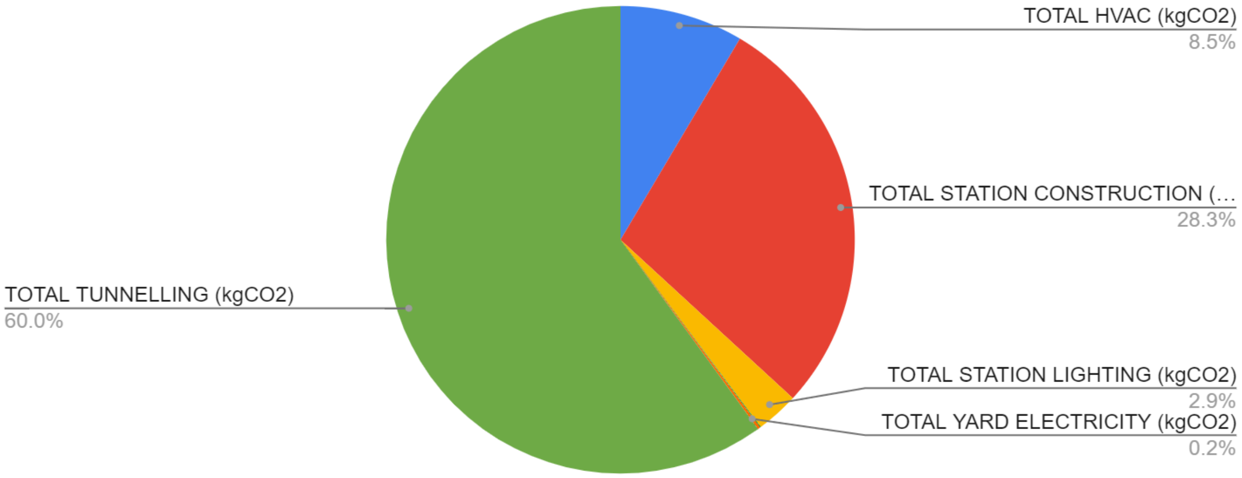


Figure 15: Breakdown of station infrastructure emissions, 60 year lifespan

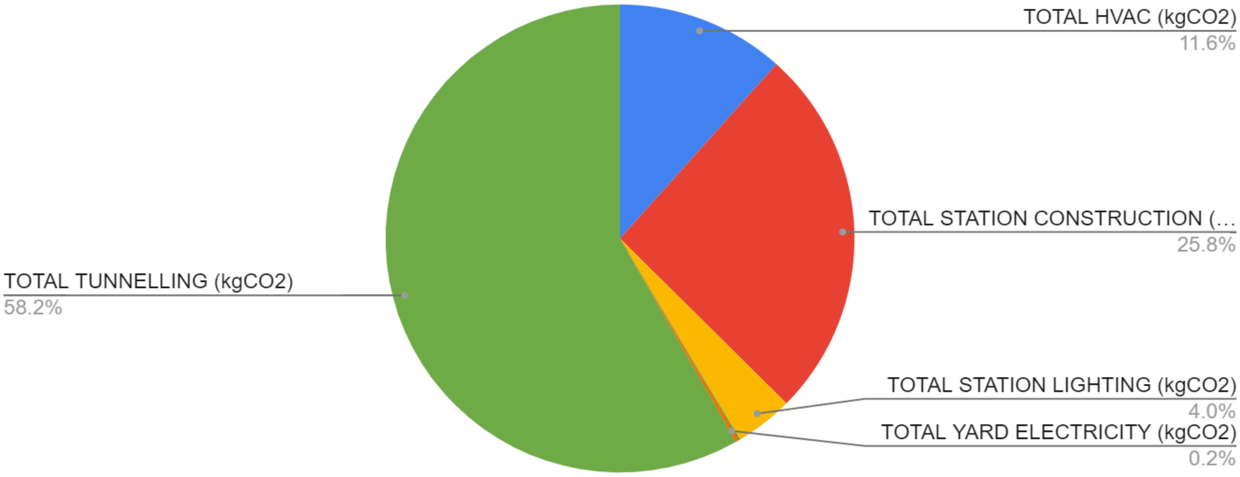


Figure 16: Breakdown of station infrastructure emissions,90 year lifespan