Applying life cycle assessment to analyze the environmental sustainability of public transit modes for the City of Toronto

by

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Abstract

One challenge related to transit planning is selecting the appropriate mode: bus, light rail transit (LRT), regional express rail (RER), or subway. This project uses data from life cycle assessment to develop a tool to measure energy requirements for different modes of transit, on a per passenger-kilometer basis. For each of the four transit modes listed, a range of energy requirements associated with different vehicle models and manufacturers was developed. The tool demonstrated that there are distinct ranges where specific transit modes are the best choice. Diesel buses are the clear best choice from 7-51 passengers, LRTs make the most sense from 201-427 passengers, and subways are the best choice above 918 passengers. There are a number of other passenger loading ranges where more than one transit mode makes sense; in particular, LRT and RER represent very energy-efficient options for ridership ranging from 200 to 900 passengers. The tool developed in the thesis was used to analyze the Bloor-Danforth subway line in Toronto using estimated ridership for weekday morning peak hours. It was found that ridership across the line is for the most part actually insufficient to justify subways over LRTs or RER. This suggests that extensions to the existing Bloor-Danforth line should consider LRT options, which could service the passenger loads at the ends of the line with far greater energy efficiency. It was also clear that additional destinations along the entire transit line are necessary to increase the per passenger-kilometer energy efficiency, as the current pattern of commuting to downtown leaves much of the system underutilized. It is hoped that the tool developed in this thesis can be used as an additional resource in the transit mode decision-making process for many developing transportation systems, including the transit systems across the GTHA.
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<tbody>
<tr>
<td>AFV</td>
<td>Alternative Fuel Vehicle</td>
</tr>
<tr>
<td>BRT</td>
<td>Bus Rail Transit</td>
</tr>
<tr>
<td>CMA</td>
<td>Census Metropolitan Area</td>
</tr>
<tr>
<td>CNG</td>
<td>Compressed Natural Gas</td>
</tr>
<tr>
<td>CUTA</td>
<td>Canadian Urban Transit Association</td>
</tr>
<tr>
<td>DMU</td>
<td>Diesel Multiple Unit</td>
</tr>
<tr>
<td>EMU</td>
<td>Electric Multiple Unit</td>
</tr>
<tr>
<td>EPD</td>
<td>Environmental Product Declaration</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GTHA</td>
<td>Greater Toronto Hamilton Area</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>ISO</td>
<td>International Standards Organization</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>LRT</td>
<td>Light Rail Transit</td>
</tr>
<tr>
<td>LRV</td>
<td>Light Rail Vehicle</td>
</tr>
<tr>
<td>MJ</td>
<td>Megajoule</td>
</tr>
<tr>
<td>PKM</td>
<td>Passenger-kilometer</td>
</tr>
<tr>
<td>PKT</td>
<td>Passenger-kilometer travelled</td>
</tr>
<tr>
<td>RER</td>
<td>Regional Express Rail</td>
</tr>
<tr>
<td>ROW</td>
<td>Right-of-Way</td>
</tr>
<tr>
<td>RT</td>
<td>Rapid Transit</td>
</tr>
<tr>
<td>RTP</td>
<td>Regional Transportation Plan</td>
</tr>
<tr>
<td>TTC</td>
<td>Toronto Transit Commission</td>
</tr>
<tr>
<td>UTEC</td>
<td>Urban Transportation Emissions Calculator</td>
</tr>
<tr>
<td>VKM</td>
<td>Vehicle-kilometer</td>
</tr>
<tr>
<td>VKT</td>
<td>Vehicle-kilometer travelled</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-Wheel</td>
</tr>
<tr>
<td>WTP</td>
<td>Well-to-Pump</td>
</tr>
<tr>
<td>PTW</td>
<td>Pump-to-Wheel</td>
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</table>
1 Introduction

In 2013, transportation was the second highest contributing sector to Canada’s total greenhouse gas (GHG) emissions (Environment Canada 2014). Urban regions, which have high concentrations of light-duty vehicles - generally cars for personal use - contribute a significant share of the national transit-related GHG emissions. The Greater Toronto-Hamilton Area (GTHA), the Canadian region with the highest annual GHG emissions, is experiencing rapid population growth, which in turn is driving increased automobile use and corresponding increases in GHG emissions (Statistics Canada 2012). With the rise of environmental consciousness in urban design, many cities including Toronto have been proactive about installing and improving public transportation systems; the underlying hope is that by improving transit systems and thereby motivating people to opt for transit, these systems will assist in mitigating the overall environmental impact of urban regions.

In 2008, Metrolinx, Ontario’s provincial transit body, developed a plan called The Big Move - a multi-phase Regional Transportation Plan (RTP) designed to improve and integrate transportation in the GTHA region. The cornerstone of this plan is extensive additions and improvements to the region’s public transportation system intended to increase the mode share of public transit in the region (Metrolinx 2008). There have been many opposing opinions regarding the specific aspects of the plan, however, especially around the selection of specific public transportation vehicles (modes) for certain lines in the City of Toronto, leading to difficulties making final decisions and ultimately stalling development.

Though transportation planning is a process that is consistently evolving, cost and carrying-capacity of potential public transportation systems are often the dominant factors in decision
making. In Toronto, however, political will tends to trump even the quantitative evidentiary support for cost and ridership. This is especially problematic given the system’s promise of improving environmental sustainability, since it remains unclear whether, beyond mandatory environmental assessments, the broader environmental implications of the proposed system are being adequately assessed. This thesis sets out to identify a method to gauge environmental impact associated with different modes of public transit.

The quantity of literature that measures environmental impact of public transit is growing in number, but definitions are often unclear and measures vary. It also remains unclear whether these methods are utilized by public transit authorities and private consultants in the assessment of new transit lines. Tools that can compare different transit vehicles, and modes of transit, on the basis of energy consumption, would be an asset to planners.

1.1 Research Objectives

The goal of this thesis is to evaluate the energy requirements of different transit vehicles, across a variety of transit modes, on a basis that allows for comparison between these options. The objectives of the thesis are to:

(a) use existing life cycle assessment (LCA) studies to benchmark the relative energy requirements, on a per passenger-kilometer basis, of different transit vehicles under consideration in Toronto and across the GTHA;

(b) use the findings to examine an existing transit line in the GTHA to inform future transit options.
It is hoped that the analysis will be used as the basis for a series of recommendations that can inform future transit planning for Toronto.
2 Literature review

2.1 The City of Toronto & Toronto’s public transit system

2.1.1 Geography of Toronto and its current transit system

Toronto is the largest city in Canada in terms of population and geographic size (Statistics Canada 2013). As of 2011, the census metropolitan area was home to 2.6 million people (Statistics Canada 2013). In its modern form, the city is an amalgamation of six boroughs that existed separately until 1997: East York, North York, York, Etobicoke, Scarborough, and the original City of Toronto (Schwartz 2009). Toronto is now comprised of a large, population-dense downtown, the location of the pre-1997 Toronto, and the remainder of the boroughs, which are less dense urban and suburban pockets that surround the downtown.

Figure 2.1 Toronto with existing subway lines
Toronto’s urban form was influential in shaping the city’s public transit system. The city’s current subway network, which was constructed in the 1940s and expanded until the 1990s, consists of three lines. The Yonge-University-Spadina line currently runs from the west part of North York south to Toronto’s Union Train Station (in the core of the downtown), where it loops north again through the original City of Toronto and terminates in North York; the Bloor-Danforth line runs east-west along Bloor St. (northern part of downtown) from the edge of Etobicoke in the west to the edge of Scarborough in the east; the Sheppard line, built most recently, runs from the Yonge line through the northern part of North York to Scarborough through a low-density part of the east end of the city along Sheppard Avenue (Figure 2.1). The subway system is complemented by buses which service lower density areas of the city; various bus networks feed into lines along Toronto’s main streets, which are organized in a grid pattern, and thus into the subways themselves – a pattern of operation which was admired by other cities in the past (Mees 2010). Service has declined in recent years: the rapid rail system has not been updated since 1999 and bus transit is less thorough and frequent than it was before. As a result, Toronto transit has been under intense scrutiny for inadequate transit service, especially as demand has increased – not only has Toronto grown, but the region surrounding it has developed as well.

Multiple suburban townships surround the City of Toronto proper; the city and the townships, specifically the Census Metropolitan Areas (CMAs) of Toronto, Oshawa, and Hamilton are cumulatively referred to as the Greater Toronto-Hamilton Area or GTHA (Figure 2.2) (Bourne et al. 2011). The population of the GTHA region is greater than 6 million people (Metrolinx 2008). The majority of this region consists of sprawling residential neighbourhoods consisting mostly of single-family homes and occasional apartment complexes.
Figure 2.2 Greater Toronto-Hamilton Area (GTHA) region
Source: Metrolinx in Topolovic et al. 2012:331
2.1.2 Proposed updates to an aging system

The GTHA is an abstract region with no official political affiliation, as individual cities or regions elect their own governments. It is identified largely due to the transportation connection that exists through the daily commute of people within and between the City of Toronto and the surrounding townships (Bourne et al. 2011; Metrolinx 2008). The creation of Metrolinx, the provincial transit body assigned with the task of coordinating an improved transit system for the GTHA, in 2006 ratified the existence and unity of this region and the unifying transportation issues it faces (Metrolinx 2008). To address the GTHA’s transit needs, Metrolinx has developed The Big Move (see Figure 2.3).

The Big Move acts to connect the entire GTHA region using a variety of public transit options, with a great concentration of the routes in the City of Toronto. The plan is estimated to cost approximately $32 billion, most of which will be supplied by federal and provincial funding, with a variety of funding options having been discussed to supplement the government funds, including business parking taxes and toll lanes (Metrolinx 2008). The plan is broken up into two stages of projects.

Stage one includes:

- Mississauga Bus Rapid Transit: Along the 401 from Winston Churchill Boulevard to Renforth Drive
- Toronto York-Spadina Subway Extension: Extension from Downsview Station to Vaughn City Centre at Highway 7
- Union Pearson Express: Electrification of the Kitchener GO line so to accommodate a rail line that travels from Union Station to Pearson Airport
- York Region vivaNext BRT: One line running along Yonge Street from the top of the subway line to Davis Drive in Newmarket; A second line running along Highway 7 from Hellen Street to the Unionville Go station.
- Eglinton Crosstown LRT: On Eglinton from Pearson Airport to Kennedy station
- Sheppard East LRT: Sheppard East LRT extension to the Toronto Zoo
- Finch West LRT: On Finch from Humber College to Yonge Street
- Scarborough RT Extension (involves conversion to LRT): Extension from McCowan Station to the Big Move Sheppard East LRT line

Stage Two projects include:

- Brampton Queen Street RT: Runs along Queen Street (Brampton) from Albion Road to Hurontario Street
- Dundas Street BRT: Runs along Dundas Street from Brant Street (Burlington) to Kipling Station
- Downtown Relief line: Subway line that begins at Pape Station on the Bloor-Danforth line, runs down to Queens Street (Toronto) and connected at Queen and Osgoode Station, and back up to the Bloor-Danforth line at Keele Station
- Yonge North Subway Extension: Extension along Yonge from Finch Station to Highway 7
- Hurontario-Main LRT: Runs in Mississauga along Hurontario Street and Main Street (Mississauga) from Lakeshore Avenue
- Hamilton RT: Along King Street and Main Street (Hamilton), from McMaster University to Eastgate Square
- GO Lakeshore Rail Electrification: Electrification of current GO line from Oshawa Station to Hamilton Station
- Durham Scarborough RT: Along Ellesmere Road and Highway 2 from Scarborough Town Centre to the Oshawa GO Station (Metrolinx 2008).
Work on the Eglinton Crosstown LRT and the extension the Yonge-University-Spadina line to Vaughan have already begun. Issues with the implementation of other elements of the Big Move, specifically in regards to funding and consensus over routes and vehicle technology used on the routes, have raised concern that this plan may not be carried out completely.
2.1.3 Toronto’s public transit vehicle options

Public transit across the GTHA is currently available in a variety of modes. Four transit modes prevalent in The Big Move: conventional diesel buses, electric Light Rail Transit (LRT), electric subway trains, and electrified Regional Express Rail (RER) or SmartTrack. Toronto also has three additional transit modes – streetcars, commuter rail, and the Scarborough Rapid Transit (RT) – but there are no additions to these systems as part of the Big Move and therefore they will not be discussed in this project. The following section is an overview of the different modes, including a brief explanation of each mode, a review of advantages and disadvantages associated with the mode, and a note about its application in Toronto.

Transit modes are defined by a number of factors, as shown in Table 2.1. Due to the diversity of transit modes, individual modes can be categorized based on Right-of-Way, technology, and service (Vuchic 2005). Right-of-way (ROW) describes the physical location of where the vehicle operates: whether the vehicle is fully separated from the road and in its own track, either underground or on the surface and with the other roadways (classified as ROW A); partially separated from the road, usually divided from other traffic with a physical barrier (ROW B); or mixed in with other traffic, operating on existing roadways (ROW C). With each category of ROW from A to C the monetary investment and mode performance decreases, with ROW A as the highest cost to construct while being the highest performing mode (characterized by the ability to run large and fast vehicles at high frequencies) whereas ROW C requires the lowest investment and a less efficient mode performance when compared to the other ROW types (though there are tactics to mitigate this). The other elements listed (in Table 2.1) include the technology used in moving the vehicles on the system, including the method in which the vehicle
is guided, the style of guidance support, and the source of power used to move the vehicles (propulsion); and the service provision in the style and extent of the network (Vuchic 2005).

Table 2.1 Elements of transit modes, adapted from Vuchic 2005

<table>
<thead>
<tr>
<th>Element</th>
<th>Options</th>
</tr>
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<tbody>
<tr>
<td>1. Right of Way (ROW)</td>
<td>A – fully separated</td>
</tr>
<tr>
<td></td>
<td>B – partially separated</td>
</tr>
<tr>
<td></td>
<td>C – street with mixed traffic</td>
</tr>
<tr>
<td>2. Vehicle Guidance</td>
<td>Steered (highway vehicles)</td>
</tr>
<tr>
<td></td>
<td>Guided (mostly rail, some rubber tired)</td>
</tr>
<tr>
<td>3. Guided Support</td>
<td>Steel wheels on rails</td>
</tr>
<tr>
<td></td>
<td>Rubber tires on roadways or running beams</td>
</tr>
<tr>
<td>4. Propulsion</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td></td>
<td>- diesel, compressed natural gas (CNG), liquefied natural gas (LNG)</td>
</tr>
<tr>
<td></td>
<td>Electric engine</td>
</tr>
<tr>
<td></td>
<td>Linear induction motor</td>
</tr>
<tr>
<td>5. Driving and control</td>
<td>Driver-driven</td>
</tr>
<tr>
<td></td>
<td>Automated train operation</td>
</tr>
<tr>
<td>6. Network type</td>
<td>Multiple, overlapping lines</td>
</tr>
<tr>
<td></td>
<td>Rail trunk lines with feeder systems</td>
</tr>
<tr>
<td></td>
<td>Rail network with support buses</td>
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2.1.3.1 Diesel bus

Diesel buses are the most widely used public transit vehicle. Diesel buses are operated as individual units, by a driver. The passenger capacity of Toronto’s diesel buses is approximately 51 passengers per vehicle (TTC 2013). The Toronto bus fleet also consists of hybrid buses, which are a similar size to the conventional diesel bus but are powered with a hybrid diesel-electric engine, and articulated buses, which are approximately 20 feet longer than the average diesel bus and have a passenger capacity of 77 passengers per vehicle (TTC 2014). As the diesel bus is the most widely used vehicle in the city (accounting for approximately 759 of 952 vehicles), it is the only bus that will be included in this study (Bow 2016). Diesel buses involve the least direct infrastructure cost of all the public transit vehicle options, as they operate on city streets (ROW C). However, an update to diesel bus infrastructure is Bus Rapid Transit (BRT),
which uses the same diesel bus vehicles operating in an additional lane on the road that is
designated/accessible only to buses at all times or at certain points of the day, allowing buses to
avoid traffic and improve speed for public transit commuters (Vuchic 2005). This style of transit
is not prevalent in Toronto, but the upgrade to this ROW B transit, while expensive, can increase
the service performance significantly.

2.1.3.2 Light Rail Transit

Light Rail Transit is an electric rail transit technology that uses high-capacity vehicles, called
Light Rail Vehicles (LRVs), which operate on tracks either on the surface with an existing road
in a designated lane, or completely separated from the road and other traffic in an exclusive right
of way on the surface or underground (ROW B or ROW A, respectively) (Vuchic 2005). LRT
can take a variety of different forms. LRT systems can range in size from 5000-24,000 spaces
(sps)/hour (Vuchic 2005). The LRVs have maximum speeds of 70-100 km/hour, but often
operate at 20-35 km/hour (Vuchic 2005).

While the city has long been home to streetcars, LRT is new to Toronto. The lines planned for
the city include a mix of at grade and grade separated lines, such as the Eglinton Crosstown,
which consists of a 19-kilometer track, 9 kilometers of which will run above ground while the
other 10 kilometers will operate below the surface of Eglinton Avenue (TTC 2010). The vehicles
that have been purchased for Toronto’s future light rail system are Bombardier’s Flexity
Freedom model LRV. These vehicles can range in size depending on the demand the system
achieves, with passenger capacity of 130 or 251 passengers; when coupled into 2- or 3- trainset
vehicles, the Flexity Freedom offers a total passenger capacity ranging from 260 to 753
passengers/vehicle (TTC 2010).
Infrastructure costs for LRT systems are associated with track construction and line separation features (e.g., curbs) or tunneling for underground operation. Therefore, the cost is significantly higher than the implementation of a bus route or even a BRT. Investment costs for at grade systems range from $8-28 million/km, averaging at $15 million/km, while fully separated systems may incur costs of $21-38 million/km, averaging at $30 million/km; and vehicles may vary in cost depending on aspects of the vehicles and size of the order, but usually cost approximately $2-3 million (Vuchic 2005). For this cost, however, higher speeds and greater passenger capacity are achieved relative to bus technology. Additionally, the permanence of LRT systems can also have a beneficial mark on the city, not only encouraging greater ridership, but also impacting land use form in the city by encouraging large scale intensification in residential and mixed-use developments, which is often not the case with flexible bus routes (Vuchic 2005).

2.1.3.3 Subways

Also known as metro or rail rapid transit, subways are an electric, high-capacity, rail transit system featuring quick acceleration and breaking technologies. Subways operate in an exclusive right of way separate from existing road infrastructure and often underground (ROW A) (Vuchic 2005). Subway systems vary in terms of operational and physical elements, including line capacities ranging from 16 000 to 70 000 sps/h; operating speeds varying maximum speeds of up to 90 km/h and operational speeds that range from 30 to 80 km/h; vehicle sizes; and the spacing of stations (Vuchic 2005; CAF 2015b).

Toronto’s subway system is distinct from the city’s planned LRT system. The subway operates three lines, all in designated right of way away from other roadways, and mostly below ground. Subway vehicles used in Toronto are Bombardier’s “Toronto Rocket” model from the
Bombardier Movia family. These vehicles are 6-car trains, with a total capacity of 1100 passengers/train (TTC 2013).

The infrastructure cost associated with subways is very high (higher than LRT), and the construction of a subway line often results in a long period of disturbance associated with tunneling. However, these systems are long term investments that provide a very high passenger capacity that cannot be met by other urban rail systems. Subways are also associated with the greatest effect on encouraging ridership and intensification in urban development, among all of the modes (Vuchic 2005).

2.1.3.4 Regional Express Rail

Regional Express Rail (RER) is a high speed rail line that extends from the city centre into the outer suburbs. RER is distinct from commuter rail systems, which are primarily intended to move the workforce that lives in the suburbs to jobs in the city and back again. Commuter rail, such as the GO trains which currently operate in and around Toronto, are characterized by high frequency service during peak times and infrequent or termination of operation at all other times of the day. By comparison, RER is often a more frequent and consistent way of servicing the suburban population. Commonly with RER systems, there are more stops closer to the city center and along the line, sometimes even providing coverage between suburban centers, unlike radial commuter lines that service only directly from city centers to suburban centers. RER trains operate more frequently than commuter rail systems but significantly less frequently than subway systems, though their station styles are meant to operate similarly to a subway with high platforms allowing for frequent service. According to Vuchic (2005), RER can be considered a method of linking between commuter rail and subway services. RER lines can use diesel
locomotive trains, like already in use on the commuter rail corridors; electric locomotive trains, with an electric locomotive at the head of the trainset towing 10-12 passenger trains; Diesel Multiple Units (DMUs), which are self-propelled vehicles that operate using one or more diesel engines within the passenger cars; and Electrified Multiple Units (EMUs), which are also self-propelled vehicles that use one or more electric engines that are contained within the passenger cars (Metrolinx 2010). Capacity for a locomotive-pulled trainset is approximately 1944 seated passengers and 3720 at crush capacity, compared to bi-level DMUs or EMUs (1500 seated, 3480 at crush capacity) or single level DMUs or EMUs (1080 seated, 2940 at crush capacity) (Metrolinx 2010).

Currently, Metrolinx is in the process of converting some GO lines (e.g. Lakeshore, Kitchener) into Regional Express lines with more frequent service throughout the day. Over time, both Metrolinx and the City of Toronto plan to construct a system that is a mix of electric and diesel routes (Woo & Percy 2014). In his 2015 election platform, Toronto Mayor John Tory proposed the SmartTrack system along existing rail lines throughout the city; this system would operate EMU vehicles to provide frequent service to the suburbs. The city could use the current diesel locomotives on the diesel lines, convert the diesel trains to electric locomotives, or purchase new DMU and EMU vehicles.

While a significant aspect of the proposed RER plan for Toronto is the electrification of some of the line, Metrolinx does not provide any examples of any EMUs that carry a comparable number of passengers to their estimates. Metrolinx has compared their proposed system and the vehicles they plan to select to RER systems in Sweden (Woo & Percy 2014). The Coradia Lirex (X60) is used on the Stockholm Pendaltag, their Regional Express Rail system, and has a passenger...
capacity of 374 seated passengers and 918 total passengers (Alstom 2006). Additional EMU examples include the Bombardier Spacium operating on France’s regional system, with a crush capacity of approximately 1000 passengers (Bombardier 2011b), the CAF Civity EMU operating Italy’s commuter service, with a crush capacity of approximately 448 passengers (CAF 2015), and the Bombardier Regina and similar CRH1 model which operate on different intercity and commuter lines around the world including in Sweden and China respectively, and depending on the configuration have varying passenger capacities, 245 through 670 passengers (Bombardier 2012; Bombardier 2016c).

Railways are required infrastructure to operate RER. Metrolinx plans to continue integrating some of the current commuter rail lines into the RER system. However, high infrastructure costs will be associated with some track expansions, the required electrification of some of the rail tracks for the operation of the electric trains, and any additional stations required along the length of the line.

### 2.2 Sustainable transportation

#### 2.2.1 Defining environmentally sustainable transport

Within literature that defines and measures “sustainable transportation”, it is evident that there is growing focus solely on environmental sustainability of transit. Among the definitions in recent literature (2005 – present), most convey a broad understanding of sustainability, stressing the incorporation the three pillars of sustainability: environmental, economic, and social sustainability. There is some variation in how each definition accomplishes this, but generally the definitions identify transit that is equally accessible by all residents, is affordable to all residents, and has a minimal impact on the environment which is consistently identified as
actively trying to reduce potential GHG emissions and energy use (Black 2010; Schiller et al. 2010).

Aligned with these definitions and additional definitions that concentrate solely environmental sustainability, specific measures for environmental sustainability involves estimating GHG emissions, specifically \( \text{CO}_2 \) or \( \text{CO}_2 \) equivalents, and energy use (CUTA 2010). Based on this explanation, the emission of GHGs and fuel or energy consumption is a fair measure of the environmental sustainability of transit. However, there is inconsistency with respect to the way in which GHG emissions and energy are calculated within these programs. The most common measures are tailpipe emissions and energy consumption during the operation of a vehicle; in other words, the studies only consider operational emissions or energy use, rather than the full life cycle (i.e. well-to-wheel emissions or energy consumption). In the field overall there is at least an understanding of the benefit of LCA in comparison to tail pipe emissions; however, even within literature that acknowledges LCA, there are few who perform or utilize LCAs instead of opting for tail pipe emissions (Schiller et al. 2010; Strickland 2009).

2.2.2 Measuring environmental sustainability of transit

In seeking to improve the way environmental sustainability is considered in transit planning, this project has chosen to utilize energy consumption as the measure. The environmental concern associated with the production and use of energy is due to the resulting emission of greenhouse gases, and therefore total GHG emissions can be determined by using data of the total energy consumption. Energy consumption is measured in many LCA studies, even those where GHG emissions are not included. Additionally, in studies where GHG data is provided, it may be difficult to apply the GHG results to our study. The quantity of GHG emissions found in a given
study is dependent on the energy supply mix of the location where the vehicle under
consideration is operating. The energy supply mix identifies the different types of energy sources
for a given location and the percentage of energy that is produced using that source. In Ontario,
the current supply mix is 24% hydro, 28% gas, 37% nuclear, 9% wind, and 1% biofuel (IESO
2015). The production of energy from each source results in a different amount of GHG
emissions, so estimating the GHG emissions for a given location involves weighting each per
unit of energy. The amount of GHG emissions per unit of energy is then compared to the amount
of energy a vehicle uses to determine the GHG emissions, often per kilometer of vehicle travel.
Therefore, as energy supply mixes vary between locations, so will the amount of GHG emissions
per kilometer.

Support for using energy as a measure also comes from the fact that when discussing strategies
to reduce GHG emissions from vehicles, techniques often involve reducing energy consumption
or changing the type of energy consumed to something with a lower impact as it is less abstract.

The two prominent ways of measuring energy use discussed in the literature are input-output
analyses and life cycle assessment.

Simple input-output assessments of energy consumption are the more dominant method for
analyzing environmental impacts. Energy consumption is measured during the use of the vehicle
and GHG emissions associated with the energy consumption during the operation of the vehicle
are referred to as tail pipe emissions associated (measured solely as a factor of the operation of
the vehicle). It is the amount of energy (in whatever form) required to move the vehicle and the
emissions associated. Life cycle assessment (LCA), discussed in more detail in the next section,
involves the measurement of energy required from the entire life of the vehicle, from production

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to disposal, energy consumption during the use of the vehicle being just one component of the life cycle.

While energy efficiency numbers are easy to obtain in comparison to LCA, Chester and Horvath (2009) argue that these numbers are not a complete representation of the energy required to - and therefore the impact associated with – passenger transportation systems.

This project has chosen to explore the possibility of utilizing LCA in hopes of developing a more complete picture of the environmental cost of transit for comparison of alternatives than is currently established utilizing energy consumption during operation only.

2.3 Life cycle assessment

2.3.1 Description of life cycle assessment

LCA is a method of measuring the environmental impact of products and processes, accounting for inputs and outputs, specifically the energy and material flows through stages of resource extraction, production, use, and disposal (ISO 2006). Chester and Horvath (2009) argue that LCA energy use and emissions are the most comprehensive method for ensuring that the number attributed to the environmental impact of a given transportation vehicle is as accurate as possible.

LCAs are conducted in accordance with a methodology set out by the International Organization for Standards (ISO). Commonly, this method outlines three phases: goal and scope definition, inventory analysis, and impact assessment. Defining the goal and scope of a project involves setting the goal for the study as well as the functional unit that will be used. The goal of the project guides the LCA approach that is carried out: transit LCA can be conducted in a retrospective or prospective approach. A retrospective approach considers the impact of a transit system to consist of all of inputs (ancillary, direct, and supply chain) for the entire life of a
system. A prospective approach seeks to understand how the impact (resulting from the direct and ancillary inputs) changes with the implementation of a new system. Chester et al. (2014) explains the difference using two questions: for the retrospective approach, the way they phrase the goal in an example question is “What is the greenhouse gas footprint of automobile travel versus bus travel in a city?”, whereas for the prospective approach, the goal would be in line with the question “How does a new BRT line on an existing arterial help a city meet its greenhouse gas reduction goals?” (p. 5). Most LCA studies, and the studies required for this project are retrospective so as to be aligned with the goal of this project to assess the overall environmental impact differences among transit systems; however, prospective studies create a different opportunity for cities and transit agencies to assess the way in which the installation of a system could improve their environmental performance.

The approach selected influences the system boundaries and has an impact on the second phase of the study, the inventory analysis. Inventory analysis is the data collection and calculation phase, where all of the material and energy flows outlined in the scope are considered to provide quantitative results. Common system boundaries of LCAs are raw material acquisition, manufacturing, operation, and end-of-life, in line with the life cycle of an average vehicle. The exact features of these phases may vary, but generally, the raw material extraction is a phase of obtaining raw material that composes the end product to processing the material. The manufacturing phase consists of the material and energy required in the production of the vehicle and the transport of the vehicle to the buyer. The operation phase is the energy consumption during the driving of the vehicle and the maintenance of the vehicle. The end-of-life phase is the disposal of the vehicle, which can include waste or recycling through pretreatment, dismantling and shredding of the vehicle (Siemens 2014). These phases can be divided amongst direct
processes, the fuel use; and ancillary processes, the processes that need to occur first for the direct processes to occur, such as vehicle manufacture and the supply chain for providing materials (Chester et al. 2014). These phases can be labelled differently, further separated into additional phases (ie. a transportation phase or maintenance phase), or excluded, depending on the system boundaries set in line with the goal and scope of the project.

If the goal of the study is to complete a Life Cycle Inventory (LCI) only, the study may conclude at this point. If the aim is to further explore the implications of the results in the inventory, the third phase is the impact assessment, which involves evaluates the potential environmental impacts using the quantitative results from the inventory analysis. Here, different results are associated with “impact categories”, such as CO₂ emissions calculated in the inventory are used to identify the impact category of global warming potential (GWP). A final phase carried out throughout the study is Life Cycle Interpretation, where the findings from each section are used together to form conclusions in line with the goal and scope of the study (ISO 2006).

For vehicle LCAs, a common method is the well-to-wheel model (WTW), which groups sub-stages into two phases, a production phase and an operation phase, usually to identify the impact in energy use and greenhouse gas emissions cycle for individual sub-stages and combined for the entire lifecycle. Well-to-wheel method is commonly employed for evaluating transit vehicles. The well-to-wheel method divides the LCA process into two subsections along the lines of production and operation of the product. The first is well-to-pump (WTP), which covers all stages of the production of the vehicle’s energy source spanning from the abstraction of the raw material to the market distribution of the product. The second section of the well-to-wheel model
is pump-to-wheel (PTW). Pump-to-wheel evaluates the impact of the use of the fuel in the movement of the vehicle (Kliucininkas et al. 2012).

It is an accepted practice among LCA practitioners that LCAs are difficult to compare due to the inherent and infinite differences in LCA studies (ISO 2006). In addition to the studies, differences in findings are also the result of inherent differences between vehicles. Many public transit vehicles are made for a specific city and therefore the exact same vehicle may not be used anywhere else in the world. Because LCAs integrate every attribute of the vehicle, data obtained for a unique vehicle may not be applicable to any other vehicle in the world, depending on the attributes of any other vehicle in question. Manufacturers may have different families of vehicles, in which each city receives a different model; Bombardier’s family of Movia metro trains serves as a good example of this, in which many models have been distributed worldwide, to cities such as Toronto, London, England, and Munich, Germany (Bombardier 2016). We can assume that there are many similarities between the trains used in different cities, meaning that LCA data would be more easily applied between each other, if an LCA were completed on one; however, there are often variances in appearance (especially in size) that suggest that there may be various less apparent, but more influential technical differences. Additionally, even between the exact same model, there are differences between each vehicle that can impact the performance of the vehicle, this includes age, maintenance, and use. Therefore, even the exact same vehicle at different times of its life can incur different energy costs. For this reason, we accept that LCAs work as a snapshot in time of the impact, and acknowledge that the number is an approximation. The differences between the vehicles, but also between the parameters of the LCA studies influence the results.
As existing LCA studies serve as the sources for the data used in this study, the following is an in-depth description of some of the literature surveyed. This section also highlights the varied nature of LCA so to demonstrate that it is difficult to compare the results of LCA studies, especially in an attempt to choose one result as an estimate for the same product.

2.3.2 LCA literature

Literature on life cycle assessments for passenger transportation is not only numerous, but also diverse. Based on the goal of the projects, vehicle LCAs can be grouped into multiple categories, meaning that though there is a plethora of articles on similar topics, identifying applicable literature can be challenging.

Literature tabulating the amount of energy required for the entire life of a public transit vehicle dates back to the 1970s (Lenzen 1999). These original studies were not completed as life cycle assessments but as a form of calculating all the requirements in a similar way based on an economic method referred to as input-output analysis. This still remains an alternative to the life cycle assessment today.

Of the literature that attempts to identify the energy and GHG emissions of vehicles, most studies conducted on transit vehicles have analyzed the impact of buses: comparing diesel buses to alternative fuel buses, such as those which operate on biogas and biodiesel, compressed natural gas (CNG), or hydrogen fuel cells. There are two ways these alternative fuel studies have been completed: analyzing the entire life cycle of the vehicles in question or analyzing the life cycle of the fuels only that are used in the different vehicles.

Sanchez et al. (2012) compared the impact of diesel, natural gas, and biodiesel buses for Madrid’s transit system in the period of 2009-2010. The goal outlined for this project was to
identify the environmental impact of the diesel, B20 (20% biofuel), B100 (100% biofuel), and CNG vehicles, with a concentration on the impact of exhaust after-treatment technology in relation to the given impact categories. The LCA was conducted in accordance with ISO14404 standards, which outlines stages for completing an LCA. For vehicle LCAs, most studies measure the impact in energy use and greenhouse gas emissions. Many studies also, as in this study, extended the scope to include additional impact categories. The impact categories analyzed in this study included direct land-use change and abiotic depletion of fossil fuels. As for the system boundaries of this project, both the automotive cycle and the fuel cycle were included in the analysis, and in general, the fuel extraction, production, and distribution phases were accounted for, as well as the automobile construction, operation and maintenance, and recycling were included. Data on these energy flows - the amount CO\textsubscript{2} equivalents and energy requirements, and the proportion for the fuel type - was largely attained from LCA database software that detail energy flows and the proportion associated with the given product, GaBi 4 and GEMIS. As is outlined in the goal, there is also special consideration for the exhaust after-treatment technology, a system within the vehicle that treats post-combustion exhaust gases before tailpipe emission. These stages are reflected in the functional units of the different stages, the functional unit of the well-to-pump stage is megajoule of fuel supplied, as the desired results are the amount of energy (or pollutants) resulting with each megajoule of fuel produced, whereas the functional unit of the PTW stage is kilometers driven for the bus, as the desired result is the amount of energy (or pollutants) resulting from each kilometer driven. The functional units of the entire WTW system is energy per kilometer driven, reflecting both stages. Based on the numerous outputs, there is not one bus that performs unanimously “the best”, but it is dependent
on the variables included, for example, if 0% land use change is assumed compared to 50% or
100%.

Ally and Pryor (2007) completed an analysis that, similarly, included the automotive cycle and
the fuel cycle but for hydrogen fuel cell, compressed natural gas, and diesel powered buses in
Perth, Australia in 2007. The goal of this project is to evaluate environmental impact and energy
demand of hydrogen fuel cell bus, compare results to diesel and natural gas bus transportation
system, and perform scenario analysis identifying potential technologies and impacts based on
supposed future advancements. The LCA was carried out in accordance with the ISO 14040-
14043 methodology. The system boundaries include raw material extraction, material
processing, manufacturing, operation and disposal, though the exact pathways varied with the
type of fuel. The material flows associated with each phase is identified using GaBi 4 software.
The impact categories include energy demand and GHG emissions by way of global warming
potential, as well as acidification potential, eutrophication potential, and photochemical ozone
creation. The different vehicles perform differently for each impact: at present, CNG buses have
the highest GWP, diesel buses have the highest acidification and eutrophication potential and
hydrogen fuel cell buses have the highest photochemical ozone creation potential. The hydrogen
fuel cell vehicle currently in use also has the highest energy requirement per kilometer; however,
the authors present evidence that there is more potential for the fuel cell to be the best option,
especially based on energy efficiency with further research, as “future” fuel cell buses are
estimated to consume half the energy of diesel buses and one-third the energy consumed by
CNG buses per kilometer (MJ/km) (p.410).
Kliucininkas et al. (2012) examined solely the impacts associated with the fuel pathway, comparing diesel buses, heavy fuel oil trolley buses, natural gas trolley buses, CNG buses, and compressed biogas buses in Kaunas, Lithuania in 2012. The goal of this study is to compare buses and trolleybuses through the different possible fuel chains listed above, using LCA methods to quantify the energy requirements associated with the fuel chains and demonstrate how the total requirement can be attributed to the different life cycle stages included: fuel extraction, transportation, production, distribution, and use. The ReCiPe method was used for Life Cycle Impact Assessment and SimaPro 7.1 for the LCI database. Beyond the analysis of energy requirements, the authors also included human health, ecosystems, and resources as impact categories. While the compressed biogas bus required the most fuel per kilometer, it and the electricity pathway for the natural gas trolley buses were considered the best option from an environmental perspective, as they had the least life cycle impact as relayed in an overview of all of the impact categories.

Ou et al. (2010) completed a study on the life cycle of the fuel chains of diesel, liquefied petroleum, gasoline, CNG, hydrogen fuel cell, coal derived methanol, coal derived dimethyl ester, and electric buses in Beijing. The aim of this study is to use life cycle methodologies to determine the energy consumption and GHG emissions associated with the alternative fuel bus (AFV), compare the other vehicles utilized in China, identify possible areas of improvement, and suggest potential future policy options and methods of implementation. The system boundaries of this study are raw resource extraction, feedstock transportation, fuel production, fuel transportation, storage, and distribution, and downstream fuel combustion in the vehicle engine. This study focused on fuel use and GHG emissions, including a breakdown of the different stages of fuel production. This study required a great deal of data, due to the number of vehicle
fuel pathways under consideration. Data was obtained from a variety of sources, all directly applicable to China, and used in the extensive calculations within LCA. A model directly applicable to China was utilized for the energy supply and demand balance calculations. The electric bus required the least energy and emitted the least GHG emissions, while the coal derived dimethyl ester required the most energy and resulted in the highest GHG emission.

While there is a plethora of articles detailing life cycle assessments of buses, other public transit vehicles have not been analyzed in the same way. There are only two life cycle assessments of metro vehicles available.

Del Pero et al (2015) performed a full cradle-to-grave analysis of a heavy metro train that is proposed to operate in Rome. This analysis was of a single metro, not a comparison of variations of metro vehicles; therefore, the focus was on comparing the impact associated with different parts of the life cycle. The purpose of these single vehicle LCAs is to determine the stages of the metro train’s life cycle that have the largest impact and identify stages where improvements could be made that would reduce the overall impact of future iterations of the vehicle, in a way that may be compared against similar vehicles. The system boundaries included the car body, interior including windows and doors, bogies and running gears, propulsion and electric equipment, and comfort systems within the usual four stages of material acquisition, manufacturing, use, and end of life. Data was obtained from the same model that provides the method of analyzing the supply chains, GaBi 6.106. As the vehicle is the focus of this study, not the fuel, the functional unit for the entire study is vehicle-km travelled (VKT). Eleven impact categories were included in the analysis beyond electricity consumption, including abiotic depletion potential elements and fossil, fresh water aquatic eco-toxicity potential, human toxicity
potential, marine aquatic eco-toxicity potential, ozone layer depletion potential, and terrestrial eco-toxicity potential. This study, like many of the other studies, uncovers that the use stage accounts for the highest impact of the entire life cycle. This is particularly troubling for a train in Rome due to the amount of fossil fuel used to produce electricity (energy mix which contains a significant amount of fossil fuel).

Struckl and Wimmer (2007) completed a similar cradle-to-grave study of a light rail vehicle in Oslo conducted in 2005 through 2006. This study accounted for three types of systems boundaries: 1) system environment, which is the boundaries seen in the other reports (raw material, manufacturing, distribution, use, maintenance, and end of life); 2) location and time, such as the change in location from the manufacturing site in Vienna to the purchaser in Oslo and 3) technology, including the advanced components that mitigate energy use or recycling of the products. Excluded was the manufacturing process and transportation from suppliers and any energy recovery in end of life. The data was attained from Siemens Transportation Systems, the manufacturer of the vehicle. The functional unit is a fully occupied vehicle that operated for 30 years, at an average of 120 000 km per annum. This report also includes a significant number of impact categories: GWP, ozone depletion, acidification, eutrophication, photochemical smog, human toxicity, ecotoxicity, bulk waste, slags and ashes, hazardous waste, and radioactive waste. The Use stage was found to have the greatest environmental impact, and similar to the Del Pero et al. (2015) article, the largest impact was associated with the traction in moving the vehicle and both suggested using lighter materials to reduce the impact.

Chester and Horvath (2009) discussed that most LCA research (up until 2009) concentrated on one mode of transportation within each study rather than comparing different modes. This
remains the case: most LCA studies focus on demonstrating the feasibility of a certain mode of transit, mostly alternative fuel public buses (as an alternative to conventional diesel public buses). Despite Chester and Horvath’s (2009) acknowledgement of the lack of literature comparing different types of vehicles, Chester completed one of the only comparisons of different vehicle types for his dissertation in 2008. Within the dissertation and following papers including Chester et al (2010), Chester compares personal vehicles, large trucks, public transit buses, light rail trains, metros, commuter trains, and air crafts across three American cities with the goal to build an inventory that would convey the environmental performance of transit in each region (p.1072). They found that in regards to energy consumption and GHG emissions, commuter and light rail systems performed best. Chester has since expanded his work in LCAs, performing environmental analysis on additional passenger transit (Chester & Horvath 2012; Chester et al. 2013), and American High Speed Rail trains (Chester & Horvath 2010). He is an advocate for the fact that an understanding of the true environmental cost of transportation includes accounting for the entire life cycle, despite the consistent admission that the use stage of the vehicles life – the actual operation of a vehicle – is responsible for the largest impact of all of the stages (Chester & Horvath 2009; Chester et al. 2010; Chester & Horvath 2012). However, the method of comparison Chester uses does not lend itself to use in other areas as the comparison is system based, not based on the individual vehicle (Chester & Horvath 2009).

Some companies have begun conducting LCA studies to document the environmental impact in their product reports. These documents are referred to as Environmental Product Declarations (EPD), which are regulated documents that outline the life cycle environmental impact of the vehicles. Bombardier (2012), Alstom (2006), and Siemens (2014) are some of the examples of the EPDs utilized in this project, analyzing EMUs as they become more popular for those
seeking sustainable transport. They analyze the full life cycle of the vehicle, highlighting key features of the train. There is less transparency in EPDs than LCAs conducted by independent researchers. Though all are presented differently, most EPDs are conducted in a similar style. EPDs follow ISO 14040 and divide assessment amongst the four phases of life cycle phases of material acquisition, manufacturing, use and maintenance and end of life, often completed with the functional unit of vkm or pkm. The results included can vary, like in other studies, but EPDs often explore impacts including energy consumption and GHG emissions, as well as acidification potential, eutrophication potential, ozone depletion potential, photochemical ozone creation potential, often highlighting potential for recycling potential. As these documents are essentially advertising, and technical details on the LCA can be omitted where other features of the vehicles irrelevant to LCAs may be emphasized; however, EPDs provides data where there currently remains a gap in academic literature.

2.3.3 **LCA and geography**

LCA, while a more complete picture of the amount of energy and emissions that are associated with a given vehicle (as opposed to tailpipe emissions that only quantify the vehicle use in operation), is not a perfect measure. As previously noted, LCA is a modeled estimate and cannot be considered reality, as each study has different parameters, and differing results, thereby demonstrating potential inaccuracy. The act of completing an LCA is a difficult task, requiring a great deal of work and knowledge about the procedure and applicable tools, including software. In the same vain, LCAs can be difficult to understand and therefore may remain unused despite their potential uses, such as informing policy. Unfortunately, even if an LCA is completed and utilized, it is not widely applicable as they are geographically dependent. As a result, LCAs are difficult to accurately apply to multiple locations, so new studies need to be carried out all the
time. What is included in the life of a product can vary with geography, due to differences associated with location, such as climate, and as a result of differences in building practices in different locations. Using subways as an example, tracks must be able to withstand extreme climate conditions associated with colder countries, whereas that is not a concern in warmer countries. Furthermore, a significant part of accounting for the greenhouse gas emissions associated with the life of a vehicle (or any other product) is the energy mix of the location in which the product is constructed and operated. The energy mix identifies the sources used to produce energy for that region, such as coal, oil, natural gas, and renewable sources, including bioenergy, solar power, or hydro. Each source incurs a different amount (and composition) of emissions, therefore, the amount of emissions associated with the development and operation of a product is dependent on the source that a location uses, or the mix of multiple sources – hence, energy mix. Unlike the measurement of operational energy consumption only, LCA requires a great deal of resources and is not easily accessible making it difficult to apply without experts.

2.4 Planning environmentally sustainable transit

To understand the potential application of LCA in the tool developed in this project, it is necessary to understand the general process of transit planning (though it is malleable), specifically in terms of how the measurement of environmental sustainability is factored into the process. There are many aspects of transit service that require planning consideration beyond the selection of modes, including the selection of networks or routes, vehicle model selection, frequency, and vehicle and crew scheduling (Ceder 2007). Vuchic (2005) outlines a general methodology that can be applied to each aspect of transit operation and is flexible based on different types of transit planning projects.
The planning process in general includes (1) identifying the goals for the transit system; (2) obtaining data about the city and the current or potential transit system; (3) developing a method for analyzing and comparing the alternatives based on the goals; (4) the creation and evaluation of alternatives; and finally, (5) the selection of the ideal option. This process, as Vuchic (2005) outlines it, is general enough that it can be applied to almost all of the different aspects of transit planning. However, in terms of the initial planning of transportation systems, the key aspects to transit taking shape are as this process applies to the selection of networks and, most pertinent to this project, modes.

To assess alternative modes for a potential line, there are additional steps within the general planning process. In creating alternatives, the right mode may be chosen is by first, outlining the “conditions” required for choosing a model, second, designing a preliminary plan of each alternative, and finally, comparing and selecting the mode based on the evaluation criteria.

The conditions are factors or requirements set by 1) passengers, 2) transit agencies, 3) greater community or city including government. The requirements set out by passengers would include attributes that would attract them to the system, including a certain level of availability in many geographical areas and at many times of the day; high frequency; punctuality and reliability; competitive speed and travel time to other modes; a level of comfort on the vehicle and in stations; convenience over other travel options; security and safety; and cost to ride. The requirements for transit agency surround the cost of the system and the ability to operate an efficient system, these include the area that can be serviced by the proposed mode; reliability of the mode in terms of likelihood of malfunctioning; speed and capacity of the mode; flexibility, which can be considered an advantage for service or a disadvantage to encouraging land use
development, depending on the goal set out in the first stages of the planning; security and safety of the mode; capital investment cost and operating costs; the ability for the proposed mode to attract passengers; vehicle occupancy; regime of travel; and additional factors, which can include impacts on the physical and atmospheric environment, including vibration, noise, and air pollution. Finally, the community requirements are associated with the greater impacts of the transit system on the success of the city, including the quality of service and availability to residents, especially those who do not have access to automobiles or other modes of transit; the cost of the system as often the public carries the burden of operational costs or investments from federal, provincial, or municipal governments; reliability at all times especially states of emergency; impacts on the natural environment; and long term impacts on the community, especially in the form of shaping the physical landscape of the city and improving economic activity (Vuchic 2005).

Depending on the goals and objectives outlined in selecting a mode, the decision-making body may select which of these factors are applicable and assign weight to them, in combination with the preliminary designs, make their selection. This can include consulting other models that have been developed to provide quantitative evidence in transit planning, including transit demand and ridership forecasting models. Vuchic (2005) discusses that this can be a very difficult process as many of the conditions are qualitative rather than quantitative descriptors and may not have a numerical measure, never mind a monetary value, that would allow for them to be easily compared; therefore, in these decisions the goals of the proposed line and the definitions of these factors play a crucial role in comparing the alternatives. An overview of the overall decision making process can be seen in Figure 2.4, which combines the overall transit planning methodology with the specifics of selecting alternative modes.
Figure 2.4 The mode selection planning process, from Vuchic 2005
The key point from this decision making process is that there are many factors that contribute to choosing a transit vehicle for a given line and in the establishment of the proposed line. Vuchic does discuss the inclusion of environmental impact in the process, specifically the consideration of air pollutants during the use of the transit vehicle, as a condition that may be required by both the agencies and the greater community. Vuchic (2005) also mentions energy consumption, but states that due to many factors, energy consumption is often overlooked and is “likely that the trend is toward increasing in importance of energy efficiency in the future” (p. 543). Ceder (2007) also describes the increasing importance of the environmental impact of transit in decision making, but emphasizes further work on this topic is required for it to be utilized in decision making.

The lack of consideration of the environmental impact (or a quantitative methodology to do so) is evident in documents outlining transit decisions, including more recent literature. For Toronto, there is evidence that the Toronto Transit Commission (TTC) and Metrolinx are conscious of the environmental impact associated with their organizations and that there are differences between the impact of different vehicles. The best example of this is the Urban Transportation Emissions Calculator (UTEC) developed by Transport Canada explicitly for the purpose of providing GHG emission from operation and upstream cycle of fuel production, and providing the amount of electricity a transit vehicle or system would use (Government of Canada 2006). This calculator shared some characteristics with the LCA approach, but was not completely comparable as boundaries of the emissions calculator did not extend to vehicle manufacture or system infrastructure in the case of liquid fuel or electric vehicles. This calculator is mentioned in some literature and was used at least in one transit benefits case assessing a potential line in the GTHA around the time it was developed (PB Americas 2013; Metrolinx 2009). However, there is no
evidence that this tool is used in planning new lines and overall, is not a popular too. As of 2015, UTEC is not accessible from the web as all links are broken. Further, though the city’s transit organizations have avidly set many goals surrounding the greening of the city’s transit fleet, there is very little explanation informing the public if and how the agencies are measuring environmental cost. In 2008, the TTC implemented a Green Procurement Policy, which sought to instill environmental consciousness in the corporate culture and ensure that products purchased by the TTC were environmentally sound, as they acknowledged the impact the TTC had on the city’s natural environment (TTC 2008). This policy defines Life Cycle Assessment (LCA), but does not mention how it will be utilized by the TTC; and while a 2010 report does mention that LCA was being tested for use by the TTC, no further documents, such as the follow up reports for the Green Procurement Policy, mention the use of LCA by the agency. Either way, even if the TTC is using LCA to quantify the environmental sustainability of individual vehicles, there is no evidence to suggest that they are using the information to decide between vehicles on new lines.

Outside of Toronto-specific agencies, the majority of sources, which were not academic, describe indicator systems that include economic, social, and environmental sustainability and list indicators under each of these subtopics of sustainability. CUTA (2010), the Canadian Urban Transportation Association, developed a list of indicators that could be used to evaluate transit modes, including GHG emissions as an environmental indicator, though this did not include an inherent method of comparing vehicles. Additionally, the American Federal Transit Administration has mandated “alternative analysis studies” for transit agencies seeking federal funding. These reports involve the evaluation of different transit modes based on a number of criteria to determine the best vehicle for a given line. There is a noticeable lack of environmental
consideration even in the most recent versions of these documents, and where included the common indicators include CO\textsubscript{2} emissions, other GHG emissions (FTA 2016; Vuchic 2005; City of Minneapolis 2014; City of Seattle Department of Transportation 2013; TransLink 2012).

Leader in transit LCA, Dr. Mikhail Chester of Arizona State University, and his colleagues have developed one indication that the transit field is moving toward employing environmental consideration in decisions. In 2014, Chester et al. released a brief introductory text outlining the way in which LCA could be implemented in transit decisions. The document discusses the state of environmental consideration in the transit field as lacking and discusses LCA as a solution. In the few documents available from American transit planners and agencies in the since this document was published, there is no evidence their suggestions have been implemented; however, it has not been long since the document was released and in the coming years the impact may become more apparent. The document could further explore the way that LCA can be applied in alternative analyses, such as the way in which LCA is employed in this project.

Further concern for the state of transit planning in Toronto arises from the way in which transit decisions appear to be made in the city, largely due to the constant uncertainty and reversals in decisions where the city council votes differently each time seemingly at will and with little reference to data justifying their decisions. This phenomenon supports not only the improvement of quantitative environmental sustainability measures but also the further integration of quantitative evidence in all aspects of transit planning in Toronto.

2.5 Chapter Summary

Based on literature documenting and describing environmentally sustainable transit, a common measure of environmental impact is energy. Many have tried to quantify it using energy
consumption/efficiency methods, while LCA is advantageous as it creates a more complete understanding of the impact, but because it is only recently developing not a lot of data is available in general or for Toronto specifically. The data is also limited: because most of the studies are not consistent in their approach and parameters, it is not possible to use entire life cycles as the results are not consistent. The operational energy consumption is the only part of the life cycle that is reported relatively consistently. Additionally, none of the applicable data accounts for infrastructure impacts, despite the fact that infrastructure can result in an immense contribution to the overall environmental impact, especially with transit modes that require large infrastructure undertakings. While this demonstrates potential for future research, it means that data for this project must be derived from sources depicting vehicles in other places. There has also been no attempt to compare modes based on energy consumption with the objective of choosing the best option. This creates an opportunity to explore these aspects of this field in this work. The current application of models in transportation planning, factoring in the limited consideration for environmental effect, emphasizes the potential application of the tool developed in this project in the transportation planning process.
3 Methods

This project involves developing a tool that can be used to identify the public transit mode that requires the least energy to service the expected ridership on a given transit line. To establish the energy efficiency of each transit vehicle for comparison, the Life Cycle energy consumption associated with each vehicle was determined from existing literature. In this way energy consumption was considered an indicator of environmental sustainability, with the intention of creating a quantitative way of integrating environmental impact of transit vehicles into transit planning decision making.

LCA operational energy consumption (measured in energy per vehicle-kilometer) of transit vehicles was considered. The operational phase of the life cycle is isolated for this project because it is the only phase for which data is consistently available among LCA sources. The operational phase provides a fair indication of the LCA energy requirements as it accounts for a significant majority of the energy from the entire lifecycle of the vehicles discussed (as identified in most of the literature including Chester & Horvath 2009). As further discussed in Chapter 2, this phase of the LCA can – depending on the parameters of the study – include aspects of the operation in addition to the direct energy consumed in moving a vehicle, such as lights, door controls, or sound systems. All of these aspects contribute to what can be a significant difference between the energy consumption and LCA differences, but also between different LCA studies. For this reason, LCA data is considered estimates, not a precise representation of reality. Therefore, multiple sources are utilized to develop a range in an attempt to provide the most accurate depiction of the reality of the transport vehicles. [See Chapter 2 for more information about the LCA operational phase.]
3.1 Benchmarking energy consumption for transit modes

3.1.1 Collecting life cycle data on transit vehicles

To ensure appropriate data on the transit vehicles was obtained, the composition of Toronto’s current transit fleet was identified. Table 3.1 details the vehicles and specific models that operate in Toronto, although a few points of clarification are important. First, Toronto has had a number of public transit vehicles throughout the city’s history; therefore, we limited the count to vehicles from the 1990s, except for the Scarborough RT for which vehicles were only purchased in the 1980s. Second, while Toronto does not currently have any LRT lines in operation, the city has chosen the Bombardier Flexity Freedom LRV for the LRT line under development, the Eglinton Crosstown (TTC 2010). It is assumed that other proposed LRT lines in Toronto will also use this vehicle. Lastly, the city also does not currently have a Regional Express Rail/SmartTrack system; but, unlike the LRT system, a vehicle has not yet been selected for this system. In an initial report, Metrolinx compared the vehicles they plan to use on the proposed system to vehicles used on similar systems in Paris and Stockholm (Percy & Woo 2014). The vehicles used on these lines are also built by Bombardier (Alonso-Breda who work with Bombardier), a Canadian company that provides most vehicles to Toronto’s different transit lines and could be the provider of the vehicles for Toronto’s line. Therefore, where required, the Alstom-Bombardier Cordia Lirex X60 from Stockholm and the Bombardier Regina Intercity X55 used elsewhere in Sweden may serve as representations of the vehicles that may be chosen for Toronto for the purpose of this project.
Table 3.1 Toronto's current public transit fleet

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Date</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Number</th>
<th>Fuel</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td>2006</td>
<td>Orion Bus Industries</td>
<td>Orion VII</td>
<td>150</td>
<td>Hybrid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007-09</td>
<td>Daimler Buses NA</td>
<td>Orion VII Next Gen</td>
<td>541</td>
<td>Hybrid</td>
<td>Bow 2016</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>Nova Bus</td>
<td>RTS</td>
<td>19</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1998-99</td>
<td>New Flyer Industries</td>
<td>D40LF</td>
<td>50</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002-06</td>
<td>Orion Bus Industries</td>
<td>Orion VII</td>
<td>562</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>Daimler-Chrysler CBNA</td>
<td>Orion VII</td>
<td>100</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>Daimler-Chrysler CBNA</td>
<td>Orion VII Next Gen</td>
<td>120</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2011-12</td>
<td>Daimler-Chrysler CBNA</td>
<td>Orion VII</td>
<td>97</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2015-16</td>
<td>Nova Bus</td>
<td>Nova LFS</td>
<td>4/105</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2013-14</td>
<td>Nova Bus</td>
<td>LFS Artic</td>
<td>153</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>LRT</td>
<td>1982-86</td>
<td>UTDC</td>
<td>ICTS</td>
<td>27</td>
<td>Electric</td>
<td>Bow 2015</td>
</tr>
<tr>
<td></td>
<td>n/a</td>
<td>Bombardier</td>
<td>Flexity Freedom</td>
<td>n/a</td>
<td>Electric</td>
<td>TTC 2010</td>
</tr>
<tr>
<td>Subway</td>
<td>1995-01</td>
<td>Bombardier</td>
<td>T1</td>
<td>371</td>
<td>Electric</td>
<td>Bow 2015</td>
</tr>
<tr>
<td></td>
<td>2010-15</td>
<td>Bombardier</td>
<td>Toronto Rocket</td>
<td>795</td>
<td>Electric</td>
<td></td>
</tr>
<tr>
<td>Rail</td>
<td>Locomotives</td>
<td>GMDD</td>
<td>F59PH</td>
<td>8</td>
<td>Diesel</td>
<td>Bow 2014</td>
</tr>
<tr>
<td></td>
<td>1990-94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2007-10</td>
<td>MPI</td>
<td>MP40PH-3C</td>
<td>57</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>Passenger Coaches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002-14</td>
<td>Bombardier</td>
<td>Bi-level Coach I-VI</td>
<td>338</td>
<td>n/a</td>
<td>Bow 2016b</td>
</tr>
</tbody>
</table>

Next, life cycle data was collected on a range of transit vehicles that approximated the Toronto fleet. LCA literature was selected through a database search, using synonyms for life cycle assessment (including “LCA”, “life-cycle analysis”, and “life cycle assessment”), energy consumption (including “energy efficiency” and “energy use”), and public transportation (including “public transit”, “passenger transit”, and “passenger transportation”) including individual vehicle types (specifically “light rail transit”, “LRT”, “subway”, “metro”, and “bus”). A total of 150 studies were found. The most applicable studies were selected from these based on the following criteria:

1. **LCA data**: There are many studies that seek to quantify the environmental impact of vehicles; however, not all studies contain numerical data values for the energy consumption related to LCA operation. Any studies that did not identify LCA or energy consumption data specifically were eliminated. [See Chapter 2 for more information on LCA].

2. **Applicable to Toronto’s system**: The vehicles featured in the literature needed to be comparable to the vehicles used or proposed for use in Toronto to create an accurate depiction of the energy requirements of Toronto’s system.
The most applicable studies are shown in Table 3.2 below.

### Table 3.2 LCA operational energy use requirements for study vehicles

Inclues original source units and conversion to MJ/km

<table>
<thead>
<tr>
<th>Vehicle/Location</th>
<th>Energy Use</th>
<th>Units</th>
<th>Energy Use (MJ/km)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bus (diesel)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perth, Australia</td>
<td>17.0</td>
<td>MJ/km</td>
<td>17.0</td>
<td>Ally &amp; Pryor 2007</td>
</tr>
<tr>
<td>Beijing, China</td>
<td>16.1</td>
<td>MJ/km</td>
<td>16.1</td>
<td>Ou et al. 2010</td>
</tr>
<tr>
<td>China</td>
<td>1470.0</td>
<td>MJ/100 km</td>
<td>14.7</td>
<td>Yang et al. 2012</td>
</tr>
<tr>
<td>Kaunas, Lithuania</td>
<td>319.6</td>
<td>grams of fuel/km</td>
<td>14.7</td>
<td>Kliucinininkas et al. 2012</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>11.2</td>
<td>MJ/km</td>
<td>11.2</td>
<td>Sanchez et al. 2012</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>11.9</td>
<td>MJ/km</td>
<td>11.9</td>
<td>Sanchez et al. 2012</td>
</tr>
<tr>
<td><strong>LRT (electric)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oslo, Norway</td>
<td>12.4</td>
<td>kWh/km</td>
<td>44.5</td>
<td>Struckl &amp; Wimmer 2007</td>
</tr>
<tr>
<td>Brescia, Italy</td>
<td>7.8</td>
<td>kWh/km</td>
<td>28.1</td>
<td>AnsaldoBreda 2010</td>
</tr>
<tr>
<td>Valencia, Spain</td>
<td>3.7</td>
<td>kWh/km</td>
<td>13.3</td>
<td>Bombardier 2012b</td>
</tr>
<tr>
<td><strong>Subway (electric)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Montreal, Canada</td>
<td>26.0</td>
<td>kWh/km</td>
<td>93.6</td>
<td>Bombardier-Alstom 2015</td>
</tr>
<tr>
<td>Rome, Italy</td>
<td>16.7</td>
<td>kWh/km</td>
<td>60.1</td>
<td>Del Pero et al. 2015</td>
</tr>
<tr>
<td>Not yet deployed</td>
<td>9.6</td>
<td>Wh/pkm</td>
<td>50.2</td>
<td>Siemens 2014b</td>
</tr>
<tr>
<td>Helsinki, Finland</td>
<td>11.8</td>
<td>kWh/km</td>
<td>42.6</td>
<td>CAF 2015b</td>
</tr>
<tr>
<td><strong>Rail (electric)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>24.6</td>
<td>kWh/km</td>
<td>88.6</td>
<td>Bombardier 2011b</td>
</tr>
<tr>
<td>France</td>
<td>13.2</td>
<td>kWh/km</td>
<td>47.5</td>
<td>Bombardier 2014</td>
</tr>
<tr>
<td>Italy</td>
<td>0.02</td>
<td>kWh/pkm</td>
<td>38.7</td>
<td>CAF 2015</td>
</tr>
<tr>
<td>Sweden</td>
<td>0.1</td>
<td>p-kWh/km</td>
<td>33.7</td>
<td>Alstom 2006</td>
</tr>
<tr>
<td>Sweden</td>
<td>8.0</td>
<td>kWh/km</td>
<td>29.0</td>
<td>Bombardier 2012</td>
</tr>
<tr>
<td>Germany</td>
<td>6.4</td>
<td>kWh/km</td>
<td>22.9</td>
<td>Bombardier 2010</td>
</tr>
<tr>
<td>France</td>
<td>0.02</td>
<td>kWh/pkm</td>
<td>13.6</td>
<td>Alstom 2015</td>
</tr>
</tbody>
</table>

For the diesel buses, the capacity was consistent at 51 passengers, and it was assumed that diesel fuel would have the same energy content despite the location of the study. Data describing the vehicle specifications, including manufacturer, was collected for LRT, subway, and rail options as shown in Table 3.3.
Table 3.3 Specifications of various transit vehicles
Italics indicate Toronto vehicle specifications

<table>
<thead>
<tr>
<th>Vehicle [source]</th>
<th>Location</th>
<th># of cars</th>
<th>Trainsets</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Total passengers</th>
<th>Seated passengers</th>
<th>Standees (m³)</th>
<th>Operating speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Light Rail Transit (LRT)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siemens Oslo Metro(^{[1,2]})</td>
<td>Oslo, Norway</td>
<td>3</td>
<td>1</td>
<td>54.3</td>
<td>3.2</td>
<td>678</td>
<td>124</td>
<td>+14</td>
<td>6</td>
</tr>
<tr>
<td>AnsaldoBreda MLA Metrobus Brescia(^{[3]})</td>
<td>Brescia, Italy</td>
<td>3</td>
<td>1</td>
<td>39</td>
<td>2.7</td>
<td>434</td>
<td>74</td>
<td>+2</td>
<td>6</td>
</tr>
<tr>
<td>Bombardier Flexity Outlook(^{[4]})</td>
<td>Valencia, Spain</td>
<td>5</td>
<td>1</td>
<td>32.4</td>
<td>2.4</td>
<td>200</td>
<td>50</td>
<td>3</td>
<td>71</td>
</tr>
<tr>
<td><strong>Toronto Bombardier Flexity Freedom(^{[5,6]})</strong></td>
<td>Toronto, Canada</td>
<td>3, 5</td>
<td>2, 3</td>
<td>20, 30.5</td>
<td>2.7</td>
<td>130, 251</td>
<td>38, 64</td>
<td>6</td>
<td>80</td>
</tr>
<tr>
<td><strong>Subway</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bombardier Azur(^{[7]})</td>
<td>Montreal, Canada</td>
<td>9</td>
<td>1</td>
<td>152.4</td>
<td>2.5</td>
<td>1539</td>
<td>272</td>
<td>4</td>
<td>72.4</td>
</tr>
<tr>
<td>AnsaldoBreda &amp; Ansaldo STS Driverless Metro(^{[8,9]})</td>
<td>Rome, Italy</td>
<td>6</td>
<td>1</td>
<td>109.8</td>
<td>2.9</td>
<td>1204</td>
<td>194</td>
<td>6</td>
<td>90</td>
</tr>
<tr>
<td>Siemens Inspiro(^{[10]})</td>
<td>n/a</td>
<td>6</td>
<td>1</td>
<td>117.8</td>
<td>2.8</td>
<td>1450</td>
<td>256</td>
<td>7</td>
<td>80</td>
</tr>
<tr>
<td>CAF Metro units M300(^{[11]})</td>
<td>Helsinki, Finland</td>
<td>4</td>
<td>1</td>
<td>88.2</td>
<td>1.4</td>
<td>1028</td>
<td>238</td>
<td>n/a</td>
<td>90</td>
</tr>
<tr>
<td><strong>Bombardier Toronto Rocket(^{[12,13]})</strong></td>
<td>Toronto, Canada</td>
<td>6</td>
<td>1</td>
<td>137.8</td>
<td>3.1</td>
<td>1100</td>
<td>384</td>
<td>6</td>
<td>88</td>
</tr>
<tr>
<td><strong>Regional Express Rail (RER)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bombardier Spacium(^{[14]})</td>
<td>France</td>
<td>8</td>
<td>1</td>
<td>112.5</td>
<td>3.1</td>
<td>1000</td>
<td>500</td>
<td>4</td>
<td>140</td>
</tr>
<tr>
<td>Bombardier Omneo(^{[15]})</td>
<td>France</td>
<td>6</td>
<td>1</td>
<td>80.9</td>
<td>3.1</td>
<td>684</td>
<td>380</td>
<td>4</td>
<td>160</td>
</tr>
<tr>
<td>CAF Civity EMU regional electric train(^{[16]})</td>
<td>Venezia Giulia, Italy</td>
<td>5</td>
<td>1</td>
<td>91.6</td>
<td>2.9</td>
<td>448</td>
<td>282</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Alstom Coradia X(^{[17]})</td>
<td>Sweden</td>
<td>6</td>
<td>1</td>
<td>68.5</td>
<td>4.5</td>
<td>918</td>
<td>541</td>
<td>5</td>
<td>160</td>
</tr>
<tr>
<td>Bombardier Regina(^{[18]})</td>
<td>Sweden</td>
<td>4</td>
<td>1</td>
<td>215.6</td>
<td>3.5</td>
<td>245</td>
<td>245</td>
<td>n/a</td>
<td>200</td>
</tr>
<tr>
<td>Bombardier Talent 2(^{[19]})</td>
<td>Germany</td>
<td>4</td>
<td>1</td>
<td>40-104</td>
<td>2.9</td>
<td>221</td>
<td>221</td>
<td>n/a</td>
<td>160</td>
</tr>
<tr>
<td>Alstom Coradia Polyvalent(^{[20]})</td>
<td>France</td>
<td>4</td>
<td>1, 2, or 3</td>
<td>72</td>
<td>2.9</td>
<td>220</td>
<td>220</td>
<td>n/a</td>
<td>160</td>
</tr>
</tbody>
</table>

3.1.1.1 *Diesel bus*

There is more LCA data available for diesel buses than any other public transit vehicle. Nearly all LCA studies conducted on buses (specifically alternative fuel buses) include diesel buses as a baseline comparison. Therefore, there was enough data from academic sources to confidently develop a potential range of energy consumption for diesel buses. Because of the nature of diesel bus LCAs, some articles do not list a bus model used in the study, therefore, as a result of the fact that many public buses are similar in size, it was assumed that the vehicles had the same passenger capacity as the Toronto vehicles. In practice, some vehicles may be slightly larger or smaller.

3.1.1.2 *Light Rail Transit*

As shown in Table 3.2, LCA data on three LRT options have been collected for analysis. No studies describe the LRT under consideration in Toronto (Bombardier’s Flexity Freedom train). Specification for these 3- or 5-module trains are shown in Table 3.3 (Bombardier 2011). In order to meet the expected ridership demand, Metrolinx plans to operate these modular trains in a 2- or 3-train set, meaning that they would connecting multiple modules into a longer train between 40 and 90 metres in length, increasing the total capacity to between 260 and 753 at crush capacity (Bombardier 2011; TTC 2010). Bombardier has conducted an EPD to identify the LCA of another model in the Flexity family of vehicles, the Flexity Outlook in operation in Valencia and Alicante, Spain. The version of the Flexity Outlook that operates in Valencia and Alicante is a 5 module train with capacity of approximately 200 people, as shown in Table 3.3 (Bombardier 2012b). The Flexity Outlook EPD may be a fairly close approximation of Flexity Freedom vehicles, although the Outlook values may be slightly conservative, due to the larger size and passenger capacity of the Spanish vehicles. An estimate of Toronto’s vehicles would also have to
include an adjustment for the incorporation of the 2- or 3- train sets, although the energy requirements could be different between these two models.

3.1.1.3 Subway

Toronto uses Bombardier’s “Toronto Rocket” subway vehicles, a version of subway train from Bombardier’s popular Movia line of vehicles (Bombardier 2016). Specifications for this vehicle are shown in Table 3.3. While this model operates in over 15 cities around the world, there are presently no LCA studies available for a Movia vehicle, possibly due to the age of the trains or the variation in the design of the models within the Movia line (Bombardier 2016). Therefore, to obtain an estimate of the LCA energy consumption in the operational phase of a subway, similar trains to the model in Toronto are described in Table 3.2, including the Bombardier Azur which operates in Montreal.

3.1.1.4 Regional Express Rail

As the RER is still in development stages and Metrolinx has not chosen the vehicles that will be used on the proposed lines, estimates on the potential LCA operational phase energy consumption of the mode have been obtained from comparable vehicles operating in other cities. The vehicles that were chosen to represent the vehicles that will operate in Toronto in the future were based on a comparison made by Metrolinx between the Toronto system and Regional Express Rail systems in Stockholm (Woo & Percy 2014).

As can be deduced from mention on the state of metro LCAs by Del Pero et al. (2015), there are no academic studies to date that quantify RER vehicles. Therefore, two EPDs from different manufacturers of Stockholm vehicles are used in combination with five EPDs for vehicles from other locations. See Table 3.3 for specifications of RER vehicles included in the study.
3.1.1.5 Converting and standardizing data

The data described above was obtained in different units. Thus, to utilize the data within this project, the data was converted to megajoules (MJ) and reported per vehicle-km, a common measurement of energy that can be used to compare different types of energy such as liquid fuel and electricity. For multi-car vehicles such as subways, LRTs, or other EMUs, for the data to be comparable to other multi-car vehicles and single car vehicles (such as buses), the data had to be attributable to the entire train not just a single car, as EMUs and DMUs can have multiple engine cars. However, a number of the studies do not identify whether the data value is applicable to a train or car, or use “vehicle” indiscriminately without defining if “vehicle” refers to a train or car or. For example, Kennedy (2002) states that to move a subway vehicle in Toronto with a capacity of 75 passengers requires approximately 9.75 MJ/km (when converted from kWh/km). As subway vehicles in Toronto carry approximately 180 passengers per car and 1100 passengers per train, it appears, based on the passenger capacity that Kennedy cited, that he is describing a subway car and not an entire train, because 75 is a very low average passenger capacity for an entire train but a fair estimate for a single car. Accordingly, the 9.75 MJ/km value would be applicable to 1 car in a 6-car train, and therefore have to be multiplied by 6 (the number of (engine) cars on the train) to provide the energy value for a train, as is required for this project. It is concerning that the value provided Kennedy (9.75 MJ/km) is similar to values obtained from other sources but unlike Kennedy these authors do not specify whether the value applied to a “car” or “train” or identify passenger capacity estimates as Kennedy has, making it feasible to estimate. Therefore, where required, this project uses the best estimate regarding whether the value represents the train or car requirement based on the energy value supplied by the literature. The conversion factors used for this project can be found in Table 3.4.
Table 3.4 Conversion factors to megajoules (MJ), from Hofstrand 2008

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Conversion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kilowatt-hour (kWh)</td>
<td>= 3.6 MJ</td>
</tr>
<tr>
<td>1 litre (l) diesel fuel</td>
<td>= 35.9 MJ</td>
</tr>
<tr>
<td>1 gallon diesel fuel</td>
<td>= 135.8 MJ</td>
</tr>
</tbody>
</table>

3.1.2 Estimating energy requirements on a per passenger basis

An objective of this thesis is to assess transit options in terms of the energy required to move passengers. The most energy efficient transit mode can be identified by comparing different vehicles according to the amount of energy required per passenger-kilometer. Where vehicle-kilometer (vkm) is the measure of one vehicle travelling one kilometer, passenger-kilometer (pkm) is the measure of moving one passenger one kilometer, and is a way of standardizing between passenger vehicles that have different passenger carrying capacities. To calculate the energy required per passenger-kilometer, the tool uses the inputs of energy consumption per vehicle-kilometer (the format in which the data was obtained, MJ/km) and the passenger capacity of the vehicle (see equation below). The total energy per passenger-kilometer varies with the number of passengers in the vehicle; as the ridership increases, the amount of energy required per passenger-kilometer decreases. Assuming that different modes require different amounts of energy to operate and have different passenger carrying capacities, when the vehicles are compared based on the energy consumption per passenger-kilometer, one will be able to identify the passenger capacity required to make each vehicle the most efficient when compared amongst all vehicles.

\[
E_{\text{pkm}} = \frac{E_{\text{vkm}}}{P}
\]

where

\( E_{\text{pkm}} \) = Energy (MJ) per passenger-kilometer
\( E_{\text{vkm}} \) = Energy (MJ) per vehicle-kilometer
\( P \) = Number of passengers
To identify the specific ridership at which one transit mode becomes more efficient than others, the vehicles need to be compared using a range of passenger loads, ranging from zero (moving an empty vehicle) to higher loads (thousands of passengers).

The tool was then used to conduct the following comparisons:

1. Buses and LRT vehicles, to compare the vehicle options used with lower ridership within the city;
2. LRT and subway vehicles, to determine the ridership where a larger rail vehicle becomes more efficient within the city; and
3. Subways and RER vehicles, to demonstrate the difference in ridership required for higher capacity rapid rail vehicles and highlight the interurban option.

The comparison establishes where there is a discernable difference in per passenger-km energy consumption between transit modes. In this project, a range is compared for each mode, where in application, a planner could perform a more precise comparison by using data for the exact vehicles they were considering.

3.2 Implications of energy requirements on transit planning

Exploring the implications of the benchmarking exercise consists of comparing the different modes of transit based on per-passenger energy requirement, and opting for the vehicle that requires the least energy per passenger. Using the tool, the per passenger-kilometer energy requirement at different passenger capacities is identified. In order to apply the tool to a specific location or line, accurate ridership data for the location in question is compared to the range of ridership in the tool to identify the energy consumption per passenger at that capacity. Accurate ridership data reflects the number of passengers on a vehicle at any given time, therefore boarding and alighting data—where passengers get on and off of the system— is best because it provides an understanding of the number of passengers on the system and the flow of traffic.
3.2.1  *Toronto case study – Bloor-Danforth line*

Toronto is used as a case study to demonstrate the ways in which the tool can be applied. In order to apply the tool, accurate ridership data for the line or system under consideration is required. However, the ridership numbers for all Toronto’s public transit systems are poorly reported. For the subway and bus routes, in addition to the occasional supplementary report, only consistent annual ridership information publicly available includes daily averages, often divided by line for bus routes or by station usage for subways.

The tool can still be utilized for Toronto with the little data that is currently available, but the results must be recognized as an imprecise estimate that could not be used to make decisions without more comprehensive ridership data.

Due to the lack of reliable data for Toronto, the Bloor-Danforth line was chosen as a case study simply to demonstrate the potential applications of the tool. (See Figure 3.1 and Section 2.1.1 for a description of the exact location).
Figure 3.1 Toronto's subway network, highlighting the Bloor-Danforth line

3.2.2 *Train frequency on the Bloor-Danforth line*

Per-train ridership is achieved using the maximum hourly ridership data from the Bloor-Danforth line, based on the calculations above, using the orientation of the trains toward Bay Station the total ridership was divided by the number of trains operating per hour obtained from frequency estimates to determine an estimate of total number of passengers per train.

Subway frequencies were determined using Toronto Transit Commission schedules, as shown in Table 3.5. For the vehicles that are not in operation yet, frequency was determined through information on potential RER scheduling from the Metrolinx for the RER system, and using the current frequency of Toronto’s comparable streetcar vehicles and the speed of the LRT vehicles
for the LRT system and the potential frequencies outlined by the planning documents (TTC 2010b; Metrolinx 2012).

Table 3.5 Expected daily frequencies and vehicle numbers by transit mode, Toronto
Sources: Metrolinx 2012; TTC 2010b; TTC 2016

<table>
<thead>
<tr>
<th></th>
<th>Rail</th>
<th>RER</th>
<th>Subway</th>
<th>LRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating times</td>
<td>5 AM to 5 PM</td>
<td>6 AM to 5 PM</td>
<td>1:30 AM 2 PM</td>
<td>6 AM to 2 PM</td>
</tr>
<tr>
<td>AM Peak time</td>
<td>6 to 9 AM</td>
<td>6 to 9 AM</td>
<td>6:30 to 10 PM</td>
<td>6:30 to 10 PM</td>
</tr>
<tr>
<td>PM Peak time</td>
<td>4 to 7 PM</td>
<td>4 to 7 PM</td>
<td>3:30 to 7 PM</td>
<td>3:30 to 7 PM</td>
</tr>
<tr>
<td>Peak time frequency</td>
<td>15 minutes</td>
<td>15 minutes</td>
<td>2 minutes</td>
<td>4 minutes</td>
</tr>
<tr>
<td>Vehicles per hour</td>
<td>4</td>
<td>4</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Total number of vehicles (Peak)</td>
<td>12</td>
<td>12</td>
<td>210</td>
<td>105</td>
</tr>
<tr>
<td>Off-peak time frequency</td>
<td>30 minutes</td>
<td>15 minutes</td>
<td>4 minutes</td>
<td>7 minutes</td>
</tr>
<tr>
<td>Vehicles per hour</td>
<td>2</td>
<td>4</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Total number of vehicles (Off-Peak)</td>
<td>24</td>
<td>48</td>
<td>188</td>
<td>108</td>
</tr>
<tr>
<td>Weekday Total</td>
<td>36</td>
<td>60</td>
<td>398</td>
<td>213</td>
</tr>
<tr>
<td>Saturday Operation</td>
<td>7 AM to 7 PM</td>
<td>6 AM to 1:30 PM</td>
<td>6 AM to 1:30 PM</td>
<td></td>
</tr>
<tr>
<td>Saturday Total</td>
<td>32</td>
<td>64</td>
<td>293</td>
<td>168</td>
</tr>
<tr>
<td>Sunday Operation</td>
<td>7 AM to 11 PM</td>
<td>8 AM to 1:30 PM</td>
<td>8 AM to 1:30 PM</td>
<td></td>
</tr>
<tr>
<td>Sunday Total</td>
<td>32</td>
<td>64</td>
<td>263</td>
<td>150</td>
</tr>
</tbody>
</table>

Frequency of transit vehicles is not always consistent. Often, frequency varies with “peak” and “off-peak” travel times, as shown in Table 3.5. Peak time coincides with the busiest travel times in the day; in Toronto this is specifically identified as rush hour periods in the morning between 7 AM and 10 AM and in the evening between 4 PM and 7 PM. Off-peak time is all operating time outside of peak time. Peak time corresponds with an increase in demand on the system; while passenger capacity may not be steady during off-peak time, the system needs to be able to meet what can be a significant increase in passengers during peak time. Therefore, the Toronto
system, like most transit systems, operates at high frequencies during peak time to meet demand and lower frequencies during off-peak time to conserve resources. Higher frequency service requires more vehicles.

For this project, the highest frequency for each vehicle type was used in calculations to demonstrate the highest potential energy requirement: for RER 15 minutes, for subway 2 minutes, and for LRTs 4 minutes. Using these frequencies (e.g. a subway train every 2 minutes), the number of trains that visit each station, in each direction, on an hourly basis can be estimated (by dividing the 60 minutes in an hour by 2).

3.2.3 Ridership data for the Bloor-Danforth line

Data made available by the TTC (2012 Subway Platform Usage document) tallied the maximum hourly usage for each station in the peak direction (TTC 2013b). Unlike the more general daily ridership of the average report, this data could be used to estimate ridership patterns required for the tool. A search was conducted to identify whether this or similar data was publicly available and easily accessible, but nothing similar was located.

The data obtained from the Subway Platform Usage report includes an estimate of the maximum hourly station usage for both the morning and afternoon for the peak (or dominant) direction at that time of day (Table 3.6). For example, Kipling Station is utilized by most passengers as an origin in the morning, so the ridership number that is recorded as the morning estimate reflects the maximum number of passengers in one hour entering the subway system from that station (designated in Table 3.6 as “ENTER”). Whereas in the afternoon most passengers use Kipling Station as a destination, so the maximum number of passengers in one hour exiting the system from that station is recorded (designated in Table 3.6 as “EXIT”). Not all ridership data is
recorded in these tallies, because at a given time of day some stations are popular origins whereas others are popular destinations. For this project, the peak AM data – slightly higher than the PM data – was utilized to get a sense of maximum ridership along the line.

Table 3.6 Subway platform usage in 2012 (passengers/hr, peak direction), from TTC 2013b

<table>
<thead>
<tr>
<th>Station</th>
<th>AM Maximum</th>
<th>Direction</th>
<th>PM Maximum</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kipling</td>
<td>4364</td>
<td>ENTER</td>
<td>3820</td>
<td>EXIT</td>
</tr>
<tr>
<td>Islington</td>
<td>2740</td>
<td>ENTER</td>
<td>3233</td>
<td>EXIT</td>
</tr>
<tr>
<td>Royal York</td>
<td>1679</td>
<td>ENTER</td>
<td>1318</td>
<td>EXIT</td>
</tr>
<tr>
<td>Old Mill</td>
<td>610</td>
<td>ENTER</td>
<td>432</td>
<td>EXIT</td>
</tr>
<tr>
<td>Jane</td>
<td>1548</td>
<td>ENTER</td>
<td>1284</td>
<td>EXIT</td>
</tr>
<tr>
<td>Runnymede</td>
<td>1319</td>
<td>ENTER</td>
<td>1329</td>
<td>EXIT</td>
</tr>
<tr>
<td>High Park</td>
<td>1634</td>
<td>ENTER</td>
<td>1160</td>
<td>EXIT</td>
</tr>
<tr>
<td>Keele</td>
<td>1321</td>
<td>ENTER</td>
<td>902</td>
<td>EXIT</td>
</tr>
<tr>
<td>Dundas West</td>
<td>2204</td>
<td>ENTER</td>
<td>1740</td>
<td>EXIT</td>
</tr>
<tr>
<td>Lansdowne</td>
<td>1307</td>
<td>ENTER</td>
<td>922</td>
<td>EXIT</td>
</tr>
<tr>
<td>Dufferin</td>
<td>1426</td>
<td>ENTER</td>
<td>1661</td>
<td>EXIT</td>
</tr>
<tr>
<td>Ossington</td>
<td>1684</td>
<td>ENTER</td>
<td>1588</td>
<td>EXIT</td>
</tr>
<tr>
<td>Christie</td>
<td>656</td>
<td>ENTER</td>
<td>794</td>
<td>EXIT</td>
</tr>
<tr>
<td>Bathurst</td>
<td>2008</td>
<td>EXIT</td>
<td>2012</td>
<td>ENTER</td>
</tr>
<tr>
<td>Spadina</td>
<td>2698</td>
<td>EXIT</td>
<td>2504</td>
<td>ENTER</td>
</tr>
<tr>
<td>St. George</td>
<td>12116</td>
<td>EXIT</td>
<td>12139</td>
<td>ENTER</td>
</tr>
<tr>
<td>Bay</td>
<td>4528</td>
<td>EXIT</td>
<td>3284</td>
<td>ENTER</td>
</tr>
<tr>
<td>Bloor Yonge</td>
<td>14525</td>
<td>EXIT</td>
<td>14402</td>
<td>ENTER</td>
</tr>
<tr>
<td>Sherbourne</td>
<td>1684</td>
<td>EXIT</td>
<td>1649</td>
<td>ENTER</td>
</tr>
<tr>
<td>Castle Frank</td>
<td>880</td>
<td>EXIT</td>
<td>693</td>
<td>ENTER</td>
</tr>
<tr>
<td>Broadview</td>
<td>1815</td>
<td>ENTER</td>
<td>1692</td>
<td>EXIT</td>
</tr>
<tr>
<td>Chester</td>
<td>302</td>
<td>ENTER</td>
<td>512</td>
<td>EXIT</td>
</tr>
<tr>
<td>Pape</td>
<td>1634</td>
<td>ENTER</td>
<td>1652</td>
<td>EXIT</td>
</tr>
<tr>
<td>Donlands</td>
<td>747</td>
<td>ENTER</td>
<td>606</td>
<td>EXIT</td>
</tr>
<tr>
<td>Greenwood</td>
<td>937</td>
<td>ENTER</td>
<td>755</td>
<td>ENTER</td>
</tr>
<tr>
<td>Coxwell</td>
<td>1066</td>
<td>ENTER</td>
<td>974</td>
<td>EXIT</td>
</tr>
<tr>
<td>Woodbine</td>
<td>1378</td>
<td>ENTER</td>
<td>1071</td>
<td>EXIT</td>
</tr>
<tr>
<td>Main Street</td>
<td>2013</td>
<td>ENTER</td>
<td>1918</td>
<td>EXIT</td>
</tr>
<tr>
<td>Victoria Park</td>
<td>2413</td>
<td>ENTER</td>
<td>1701</td>
<td>EXIT</td>
</tr>
<tr>
<td>Warden</td>
<td>2114</td>
<td>ENTER</td>
<td>1990</td>
<td>EXIT</td>
</tr>
<tr>
<td>Kennedy</td>
<td>6565</td>
<td>ENTER</td>
<td>6072</td>
<td>EXIT</td>
</tr>
</tbody>
</table>

3.2.4 Limitations on ridership data

The platform counts reflect the highest ridership per train possible (in 2012). This data is limited, however, as it is impossible to know how many people board and alight the train at each
stop. Toronto has had issues with accuracy around ridership estimates, as evident in the case of the Scarborough RT replacement where six separate demand forecasts have been prepared, all of which varied significantly in expected ridership results; recently it was divulged from City of Toronto staff that some of the reports and methods related to this line were erroneous (Pagliaro 2016). Electronic fare payment systems foster hope that ridership counts will provide more accurate data, as systems like Presto (being implemented in Toronto in 2016) require passengers to scan an electronic fare card when they enter and exit the system.

It should also be clear that ridership at other times of the day would be lower on average, but it is also possible that ridership would be higher on individual trains during peak times in the morning and evening.
4 Results and discussion

4.1 Benchmarking transit mode performance

The data collected on transit vehicle performance, as described in Chapter 3, established a range of energy requirements for each mode of transit. This range provides a more accurate depiction of the possible energy requirements of each mode than one estimate from a single vehicle within that mode, and allows a comparison of energy use between modes transit modes (i.e. LRT vs. subway). The data also allows similar vehicles to be compared within a single mode (i.e. two subway options). Figure 4.1 shows an example of how data will be described.

Figure 4.1 Example of expected results from the energy requirement analyses

The chart identifies where there is a transition between the most sustainable transit solutions (black arrows). See Figure 4.2 for diesel bus results, Figure 4.3 for LRT results, Figure 4.4 for subway results, and Figure 4.5 for RER results.

A series of graphs were produced that display the energy requirement per passenger-kilometer at varying passenger loads for each vehicle. By comparing the plots from each vehicle, a range of
per passenger-kilometer energy requirement for that mode can be established as shown in Figure 4.1. The variation in the amount of energy required to is largely the result of the fact that different vehicles have different capacities, sizes, ages, and maintenance. The variable nature of LCA studies also contributes to the variation in the results.

As shown in Figure 4.1, the range of energy requirements on a per passenger-kilometer basis for a given vehicle model is established as described in Chapter 3. Starting at zero passengers, the energy requirement per passenger-kilometer declines until the vehicle’s crush capacity is reached (point marked A). At this point, a second vehicle must be added to handle additional passengers, and it is assumed that passenger loads are evenly spread between the vehicles. As additional vehicles are added, the energy requirement on a per passenger-kilometer basis rises. On occasion, the most efficient vehicle (i.e. with the lowest line on the graph) will change because of these factors (point marked B).

The full range for each transit mode is the gap between the highest and lowest energy requirements on a per passenger-kilometer basis. The overall trend depicted in the graphs is decreasing energy requirement per-passenger kilometer as passenger loads increase, with periodic jumps in energy consumption signifying the addition of another vehicle to meet the ridership needs.

4.1.1 Establishing energy consumption ranges

4.1.1.1 Diesel bus

The range of energy requirements for diesel buses was established from six different sources. The highest footprint for a diesel vehicle included in this project is from a bus operating in Perth, Australia (Ally & Pryor 2007), which requires about 17 MJ to move one kilometer. The overall
energy required to move this diesel bus one kilometer is approximately 17 MJ; at a crush capacity of 51 people, the energy requirement per passenger-km is approximately 0.33 MJ/pkm (Ally & Pryor 2007). The lowest energy requirement for diesel buses is taken from a study carried out in Madrid; at crush capacity, the energy requirement is approximately 0.22 MJ/pkm (Sanchez et al. 2012). Data for all six vehicles is shown in Figure 4.2, with ridership ranging from 0 to 1000 passengers.

![Figure 4.2 Diesel bus energy requirement by passenger load (MJ/pkm)](image)

**Figure 4.2 Diesel bus energy requirement by passenger load (MJ/pkm)**


Two important takeaways can be taken from this figure. First, the overall energy requirement for passengers is highly variable at low passenger numbers (<250, or 5 busloads). Beyond this level, the energy requirements on a pkm basis begins to stabilize. Second, the values for diesel vehicles have quite a consistently large range. At low passenger numbers, estimated energy requirements range between 0.24 and 0.65 MJ/pkm. Even at higher passenger numbers, when
the full range of energy requirements for this transit mode have stabilized, there is still a 50% difference between the most and least energy efficient vehicles.

The implications of this exercise suggest that minimal energy requirements can only be met if service frequency closely matches demand, particularly at low ridership numbers. For example, if a transit service needed to service 100 passengers per hour, doing so with 2 buses running on a 30 minute schedule would likely minimize the energy footprint associated with each bus; upping the service to every 15 minutes would effectively double the energy requirement on a pkm basis. At higher ridership numbers, the implication is much less dramatic; above 300 passengers per hour, the implications of adding another bus to the route are minimal. When assessing a proposed diesel bus route from a sustainability perspective, the goal is to ensure that demand is consistently high enough to sustainably operate the vehicles, ensuring that they are reaching low value of energy consumption per passenger-kilometer.

The figure also suggests that in areas where demand is not consistently high, characterized by few passengers on the line as a whole or few passengers at the ends of the line where there is greater demand in the middle of the line, the average amount of per passenger-km energy required to operate the vehicle can be high enough to make the vehicle unsustainable considered against other transit or private automobile options. Thus extended bus lines where the end of the line is characterized by low ridership should be avoided. Beyond trying to increase ridership along the line, the best approach to improving sustainability in transit operation is to reduce the amount of travel by modes that require higher amount of energy than alternatives in fringe areas where there are not enough passengers to make them competitive to other modes. There will be other justification for operating these low points, such as coverage, and factors that complicate
selection, but in planning with sustainability in mind, reducing these low points with multi-modal systems and ensure that on average the vehicle operating in a given area has enough passengers to make it sustainable will ensure a more sustainable system overall.

The best way to establish an estimate of a minimum level of ridership required for diesel vehicles to operate sustainably is to compare it to a private automobile based on per passenger-km energy requirement. Using an average occupancy rate for cars from the most recent Canadian Vehicle Survey (2009) of approximately 1.58 passengers/vehicle (Natural Resources Canada 2009) and the estimate of 7.68 MJ/km to move a conventional car, the average energy requirement for cars is approximately 3.04 MJ/pkm (Aguirre et al. 2012). This rate could be easily reached by any of the diesel vehicles included in this study, as the energy requirement per passenger decreases below 3 MJ/pkm at a ridership of 4-6 passengers. This suggests that below 4 passengers, a car is always a better choice from an energy perspective; between 4 and 6 passengers, either a car or a bus might be a good choice, and above 6 passengers, diesel buses are a significantly better choice.

Additionally, one may argue that energy requirements on some points of the line may reach such a low point that they offset other points on the line where higher energy requirements are the result of less ridership; however, this would go against encouraging a multi-modal system and goes against the stance of this project that argues that it is best to transfer between vehicles that are constantly the most sustainable option possible than to operate a vehicle just to operate a vehicle. But there are other factors such as accessibility and convenience that could make this type of evaluation useful.
4.1.1.2 Light Rail Transit (LRT)

To evaluate the sustainability of LRT vehicles, three LRT vehicle models were included in establishing a range of energy requirement for the mode. Of the vehicles considered, the vehicle with the highest vehicle-km energy consumption was the largest vehicle included, the Siemens Metro used in Oslo Norway (Struckl & Wimmer 2007). At a crush capacity of 678 passengers, this vehicle reaches the second lowest per passenger-km energy requirement of the LRT vehicles considered at 0.07 MJ/pkm (compared to the lowest requirement, 0.067 MJ/pkm, that characterizes the Ansaldo Breda MLA Metrobus in Brescia Italy).

![Figure 4.3 LRT energy requirement by passenger load (MJ/pkm)](image)

Figure 4.3 LRT energy requirement by passenger load (MJ/pkm)
The LRT results highlight an important aspect of vehicle comparison based on sustainability. First, the energy requirements on a per-passenger basis at crush capacity for each vehicle are very similar, but to achieve these similar values requires significantly different ridership. These results communicate that one can use sustainability to even select an optimal vehicle amongst vehicles of the same mode. Even though at crush capacity the vehicles are comparable, this comparison emphasizes that there is an optimal choice at different levels of ridership, and that each vehicle becomes the most efficient of the vehicles compared if the ridership approaches its maximum capacity. This result emphasizes the need for accurate ridership information so that the right vehicle can be chosen to reduce excess energy use.

Similar to with the caveats of sustainability when considering implementing a diesel bus route, even though these vehicles only require approximately 0.065-0.066 MJ/pkm at crush capacity, this is only the case if you are filling the vehicle completely. When only partially filled, smaller vehicles or even diesel buses become more sustainable to operate on the route.

4.1.1.3 Subway
There are five models of subway vehicles considered in this project to establish the energy requirement range. There is significant variation within the energy requirement for these vehicles. The Bombardier-Alstom Azur is the largest subway included in this study; operational in Montreal, it is a 9-car vehicle that can carry 1539 passengers requiring approximately 93.6 MJ/vkm. The smallest vehicle, the CAF Metro M300, operates in Helsinki, Finland with a capacity of 208 passengers/vehicle and requires only 42.6 MJ/vkm.
Figure 4.4 Subway energy requirement by passenger load (MJ/pkm)

It is interesting to note that two of the subway choices were comparably inefficient. The AnsaldoBreda line in Rome falls behind the anticipated performance of the Siemens Inspiro; similarly, the Bombardier Azur is less efficient than the CAF line in Helsinki. Beyond simply difference with energy requirement of the vehicle, this could be due to a variety of factors such as different conditions of the vehicles in the studies (age, maintenance, etc), or the stated issues with comparing LCAs.

This demonstrates that by considering the amount of energy required by transit vehicles, one can reduce the amount of energy consumed by a transit system by selecting the vehicle model that requires the least amount of energy without any impact on mode choice. There are examples in which the change in vehicle model would also require a change in frequency so to meet the ridership, for the CAF vehicle, a system would need to operate the vehicles twice as fast. Though
the feasibility of this is not a component of this project, this would be an additional factor to consider, as the frequency can become too high to be feasible from an operational and an economic perspective. This is also relevant when comparing the different transit modes.

These results also convey the fact that comparing vehicles of the same modes (and different modes) in this way may further motivate manufacturers to reduce the passenger-km energy requirements and ensure they are building and maintaining the most efficient vehicles so to remain competitive amongst the other model options.

4.1.1.4 Regional Express Rail

There are seven RER vehicles considered in this project to establish the energy requirement range for this mode. The vehicles vary significantly in size and energy requirement, ranging from carrying capacities of 220 through 1000 passengers. Some systems, like the two Alstom vehicles (in France and Sweden), outperform Bombardier and CAF vehicles, while the Bombardier Talent 2 has better performance than the Bombardier Spacium.
Figure 4.5 RER energy requirement by passenger load (MJ/pkm)

The RER results, similar to the results for the other modes, demonstrate that issues of accurate ridership and choosing the most sustainable vehicle, not just mode but model, based on expected ridership is a consistent issue amongst all vehicle types.
4.1.2  Comparing energy requirements by transit mode

It is often the case that transit authorities consider different modes for the same line to ensure that the best mode is chosen for an area. Some vehicles are more commonly compared as a result of similar passenger capacities and attributes of the areas for which the vehicles are being considered. For example, it would be unlikely that a public bus and a subway would be considered for the same route because they imply drastically different ridership requirements; or it would be unlikely that RER and buses would be compared because they imply different passenger expectations: a bus is for local stops, whereas RER expects further distance to travel on the line and between stops. For the purpose of this project, the scenarios run in the tool were determined based on this idea, but could be altered to compare any vehicles. Therefore, scenarios are: bus and LRT, LRT and subway, and subway and RER.

The way the comparison of modes is conducted, using ranges of energy use for each mode, may not accurately capture the way that this tool would be applied for an actual decision-making situation because a given agency would know the exact models of vehicles they were choosing between and could compare the exact vehicle it was considering, if an LCA was available. However, data for the vehicles considered for Toronto is not available, so the ranges are to establish estimates for the purpose of this project alone. The optimal situation in the future may be if there was a time where a database of LCA data for transit vehicles available for comparison.

4.1.2.1  Diesel bus and Light Rail Transit

Figure 4.6 displays the diesel bus and LRT comparison.
Figure 4.6 Comparing diesel bus (green) and LRT (yellow) energy requirements


The point where one mode is more sustainable than the mode it is being compared to is where the range of energy requirement per passenger kilometer of one vehicle is lower than the range of the other vehicle. This approaches the issue as attempting to determine the ridership value at which the larger system (the system that requires more energy and investment) becomes more efficient, therefore when making the comparison the ridership required to make a vehicle efficient is considered on using the larger vehicle as the unit.

For the comparison between the diesel buses (represented in green) and LRTs (represented in yellow), there is a clear point below 51 passengers where the majority of the LRT range is higher
than the bus range, reflecting that a capacity of 51 passengers the LRT requires more energy than the diesel buses. However, at the addition of the second diesel bus, especially in the top end of the diesel range (the first peak visible on the green graph), the overlap of the diesel and LRT vehicle becomes more prevalent and the overlap continues until just before the addition of the third vehicle (the second peak of the green graph). At the lower end of the bus plot, the vehicle remains more efficient than the majority of the LRT range until the addition of the third vehicle (the second peak in the low end of the green graph) representing approximately 103 passengers. The overlap continues until the addition of the fourth vehicle, at 154 passengers, where the higher end of the LRT range is just slightly less than the lower end of the bus range until 200 passengers, where the entirety of the LRT range is lower than the bus range consistently.

The most apparent conclusion from this graph is that, from a sustainability perspective, below an average of 51 passengers per LRT vehicle, the bus requires less energy per passenger-km, and is considered the more environmentally sustainable option, but above an average of 200 passengers per vehicle, the LRT is more sustainable than the diesel bus and the associated need of continually adding more buses to meet the ridership. Between 51 and 200 riders, the overlapping in the range depicts that the vehicles are similar in terms of energy use, therefore in choosing the optimal vehicle when a line was expected to have ridership at these levels – without eliminating the range and using two specific vehicles for the comparison – agencies could rely on the other factors considered in choosing between alternatives to distinguish the optimal alternative, as sustainability would not be drastically different.
4.1.2.2  Light Rail Transit and Subway

**Figure 4.7 Comparing LRT (yellow) and subway (blue) energy requirements**

Between 0 and 600 passengers LRT range remains below the subway range until 600 passengers (at 3 vehicles for the vehicle that composes the low end of the range).

The overlap for the LRT and subway vehicles is significant, existing the entirety of the graph. If the graph continued beyond 2000 riders, the LRT range would clear the subway range as the number of LRTs increased. However, we can obtain a point where the subway becomes more sustainable by assessing where the majority of the LRT range becomes greater than the majority of the subway range. This is at approximately 869 passengers, at the addition of the third Ansaldo Breda vehicle. There is further overlap as additional subway vehicles are added; however, the energy requirements for ridership as it approaches crush capacity of the subway...
vehicles will always be lower energy requirement per passenger-kilometer than the LRT vehicles.

The extensive overlap of the point wherein LRT and subway systems are similarly sustainable, between 400 passengers through 600 or 869 passengers and beyond depending on the standards, is the point where other factors would be more heavily weighted in the decision making process considering the similarity in the sustainability measure at this point in ridership.

Comparing the urban transit vehicles - buses, LRTs and subways- the graduation in optimal vehicle of the three vehicles from a sustainability standpoint from buses at the lowest ridership capacity through to subway at the highest ridership, is expected considering the size of the systems and cost of the systems also progress in that order.

4.1.2.3 Regional Express Rail and Subway

The RER is compared with a subway as a similar rapid-high performance transit mode (Vuchic 2007), based on the assumption that an agency may assess these two alternatives for extending a subway further toward a suburb or beginning to implement a regional service with a connection to a subway line. These two are compared also because of the implementation of the RER vehicles in Toronto, which is proposed to enhance service on the current commuter rail system in the Greater Toronto Hamilton Area. The RER system is always discussed in tandem with the commuter rail system and this application in Toronto has made it appear as though the RER is comparable to commuter rail. From existing energy consumption (not LCA) on Toronto’s commuter rail system, the comparison of commuter rail and RER implied that RER systems may require a significant amount of energy in operation compared to subway systems, which reinforced that this would be two vehicles most likely compared for the same line.
Figure 4.8 Comparing LRT (yellow) and RER (red) energy requirements

It can be seen from Figure 4.8 that energy requirements for LRT and RER options overlap completely. This is due to the similarity between the technologies; many of the vehicles are made by the same manufacturers and have similar capacities. The primary difference between these modes is the speed at which they operate and the distances which tend to be covered. There is a larger range in energy required to move passengers associated with RER options.

It is clear that at the lower end of the passenger load, LRT makes more sense than RER; they offer more energy efficient options for moving passengers (on average). With passenger loadings greater than 428, however, RER begins to compete effectively with LRTs.
Figure 4.9 Comparing subway (blue) and RER (red) energy requirements

Similar results are obtained when comparing RER with subway options. RER and subways compete effectively in terms of energy efficiency at low- to mid-range passenger loadings. With loads of 870 people or greater, RER and subways begin to compete more effectively. The majority of subway options perform better than RER after 918 passengers. These findings suggest that subway vehicles are only more efficient than RER vehicles at high average ridership.

The fact that RER vehicles are more sustainable than subway options is unsurprising; typical RER systems are intended for fewer riders than subways, as subways typically act as trunk lines fed by other forms of transit, while RER tends to connect population centres across larger regions. These findings raise some interesting questions for the Toronto case, however, as the
DMUs that operate on commuter rail lines are much larger (in terms of capacity) than the City’s subways; if these systems are converted to RER, they would represent a very large system, which would be less energy efficient and less competitive with the subway option. This demonstrates the need for continued analysis of the suitability of RER in Toronto and the GTHA.

4.1.3  Identifying best transit option by passenger load

From the previous section, it is possible to identify the best transit option across various ranges of passenger loading, as shown in Figure 4.10. It can be seen that diesel buses are only competitive in a range from 4 people (where they compete with passenger cars) to about 200 passengers. LRTs have a wide range where they are an energy efficient choice, ranging from 52 passengers to as many as 869 passengers. Regional express rail begins to compete with LRTs at a loading of about 428 people, while subways are not competitive with LRTs until loading passes 600 people. Above a load of 900 passengers, subways are a clear best choice for passengers.

Figure 4.10 Best transit options by passenger load

What is interesting about these findings is that there are wide ‘grey areas’ where more than one transit option makes sense. Thus planners have access to options when designing transit systems; buses are clearly the best choice for areas which are likely to remain low density, but...
LRTs are surprisingly energy efficient and easily compete with buses, RER, and subways. Subways are really only energy efficient at high passenger loading. The emerging transit modes of LRT and RER fill an important gap in terms of offering an energy-efficient option for moving passenger loads between 52 and 918.

4.2 Implications for the Toronto case study

For many years, Toronto has debated the future development of the city’s transit system; much of the discussion concentrated on selecting the “right” mode for different lines.

As described in Chapter 3, limited ridership data hinders the potential to create a tool to assess best transit options. Using existing data from Toronto’s Bloor-Danforth line (Table 3.6), a simulation of peak rush-hour passenger loads on that line were assembled.

4.2.1 Estimates of ridership during AM peak, Bloor-Danforth line

The total number of passengers on the system per hour, during morning peak times, was estimated by following a number of assumptions. First, it was assumed that all passengers entering the system at stations west of Bathurst, or east of Castle Frank, were staying on the system until they reached one of the seven destination stops. Second, it was assumed that the passengers exiting the system at each of the seven destination stops were equally divided between eastbound and westbound trains. Third, it was assumed that any remaining passengers moving east or west would exit the system over the entire remaining length of the line. A fourth assumption was that approximately half of the remaining passengers might travel through to very end of the line. Finally, a fifth assumption was that the passenger load would be evenly spread out over the 30 trains offered during peak AM travel times. The estimated passenger load for
two trains travelling through the system at peak AM travel – one eastbound from Kipling (in blue), one westbound from Kennedy (in red) – is shown in Figure 4.11.

Figure 4.11 Estimated passenger loads on a single train during peak AM travel

As discussed in Section 4.1, subways begin to compete with LRTs in terms of energy efficiency at a loading of approximately 600 passengers. Figure 4.11 suggests that this loading is obtained or exceeded on 6 out of 30 segments for eastbound trains, and 5 out of 30 segments on westbound trains. Average loading on eastbound trains is 318 passengers; average loading westbound is 276 passengers. Thus, on first examination the ridership on the existing Bloor-Danforth line is not really sufficient to merit the choice of subway over other options, except in a concentrated stretch close to the downtown.
Closer examination of the figure reveals a couple of other interesting trends. First, both eastbound and westbound trains run at very low capacity for half of the line, as they roll out to the terminal stations before turning around and returning. Second, the unique configuration of Toronto’s geography means that there is only a single ‘destination’ region along the line – a band of seven stops in the downtown core – and the rest of the line essentially acts as a collector to move passengers to this destination. Similar patterns appear in the evening peak, but in reverse, as commuters return to the suburbs.

4.2.2 Energy requirements (MJ/pkm) during AM peak, Bloor-Danforth line

Figure 4.12 shows the amount of energy required per passenger-kilometer at each stop of the Bloor-Danforth line based on the estimated ridership values developed in the previous section. This data was developed using one of the five subway vehicles included to establish the energy requirement range for this project, specifically the Siemens Inspiro as the median and average vehicle included in this study.

Figure 4.12 Energy requirements per passenger during peak AM travel
It is evident from the figure that on a per-passenger basis at the ends of the line more energy is required and in the center of the line less energy is required. This reflects the fact that there are less riders on the fringes of the line and more in the center, where most destinations are. At the western terminus (Kipling), 4364 passengers board per (peak) hour, which works out to 145 passengers per vehicle; the amount of energy per passenger is approximately 0.35 MJ/pkm. Similarly, trains at the eastern terminus (Kennedy) are loaded with 219 passengers per vehicle during the morning peak, resulting in an energy requirement 0.23 MJ/pkm. As passengers embark at each station in the system, the eastbound and westbound trains improve in terms of energy efficiency; eastbound trains reach a minimal energy requirement of 0.067 MJ/pkm, and westbound trains reach a minimum of 0.071 MJ/pkm. In the downtown destination region, the bulk of passengers disembark and the energy required rises on a per-passenger basis.

As identified in the previous section, the real problem comes as nearly empty trains proceed east- or westbound towards the terminal stations. Without good ridership numbers, it is impossible to make accurate estimates, but using the estimated passenger loadings it can be seen that energy requirements rise sharply – reaching maximums of 0.88 MJ/pkm for eastbound trains, and 1.87 MJ/pkm for westbound trains.

All of the calculations of ridership on the Bloor-Danforth line are rudimentary, resulting from the ridership data that was available. The relevance of the results is also impacted by the fact that the data is from 2012, and ridership has more than likely increased since then.

As discussed in the previous section, ridership for the subway is relatively low for much of the system, even during peak times. Eastbound trains west of Lansdowne and east of Bay are
underutilized; eastbound trains that are east of Pape or west of Bay are also characterized by low ridership. Figure 4.11 and 4.12 each illustrate the same, important point: the Bloor-Danforth line is very long, and the length of the line is undercutting the overall energy efficiency of this service.

4.2.3 Implications for future transit planning

The analysis in the previous section suggests that long transit lines serving a single destination zone face challenges in terms of energy efficiency. One solution – and one that is heavily debated in Toronto – is opting to install LRT lines to extend the reach of transit routes, rather than simply extending existing subway lines. This can greatly reduce energy requirements associated with transit options in these parts of the city. The tool developed in this thesis suggests that LRTs, operating on a frequency of 4 minutes (rather than the subway frequency of 2 minutes), could carry peak traffic eastbound from Kipling to Old Mill (3 line segments) or westbound from Kennedy to Warden (1 line segment). This result suggests that essentially these parts of the line are overbuilt; a single LRT can more efficiently service the same passenger load.

There are two critical takeaways from this discussion. First, the process of planning new lines or extensions to existing lines should be informed by the benchmarking tool developed in this thesis. If planned ridership is low, significant energy savings – and thus reduced environmental impact – can be achieved by selecting the appropriate technology. This input can be taken into consideration with other aspects of decision-making – cost, future development plans, local geography, etc. - to aid in the selection of the most optimal mode.

Including an analysis of energy requirements can help improve the environmental sustainability of transit systems. The reality is that extending a single line at infinitum into the far ends of a
city so that all riders may leave at the same single stop is not as sustainable as combining
different transit modes as appropriate. Using this sort of tool could lead to the implementation of
more multi-modal systems, where different technologies are used to optimize energy use across
different ridership requirements.

A second critical takeaway is the role that this tool has in informing urban land use planning. The
findings support the idea that the establishing destinations in multiple places along a line
improves sustainability and encourages other land use patterns that support the use of transit,
including mixed use development. Toronto has recognized the importance of coordinating
public transit and land use planning through the implementation of a mobility hub policy in
2008, and further policy that incentivizes development of attractions in all major transit station
areas (Metrolinx 2008). As mobility hubs and major transit zones assist in making transfers from
different transportation modes seamless, this tool discussed in this project supports these policies
and the development of similar policies elsewhere.

A critical goal in planning any transit mode is a more equal distribution of boarding and
alightings. Long lines that pick up commuters in the morning, and return them in the evening,
are not likely to be particularly energy efficient. Thus, it is not just increasing development
along a line; it is creating a balance of residential and commercial development in order to fill up
capacity, particularly as transit lines become extended across a wide geography. Following this
sort of development pattern would increase sustainability all along the transit line.
5 Conclusions

This thesis has provided an in-depth evaluation of the energy required to move passengers, on a per passenger-kilometer basis, with various transit vehicles. While the transportation planning process involves a variety of stages, the consideration of environmental impacts associated with transit – which can be estimated by energy consumption - remains limited. Additionally, as evident in Toronto, planning around transit continues to be compromised by political goals. The tool developed in this thesis can provide quantitative measures to support evidence-based decision making around selecting appropriate modes of transit.

5.1 Benchmarking energy requirements by transit mode

The first objective of the thesis was to benchmark relative energy requirements associated with different vehicles. A methodology was proposed and applied across four transit modes: diesel buses, light rail transit (LRT), regional express rail (RER), and subways. The method drew from a range of existing life cycle assessments to draw information describing the operational energy requirements associated with each vehicle, on a MJ/vehicle-kilometer travelled basis. Using the limited LCA data available on transit modes provided a more holistic approach to evaluating the environmental impact of transit than the more-widely used measure of GHG emissions. Specifications on each vehicle, including carrying capacity, was also collected. This data was used to determine the energy required to move increasing numbers of passengers through the system. Ranges of energy requirements at different passenger loadings were developed for each mode. The ranges of LCA energy use demonstrate that there is patterns in energy use for each mode; depending on the passenger capacity, certain vehicles are shown to be more efficient than
others. Using the ranges developed using this tool, different transit modes could then be compared on an energy requirement basis.

It was found that three of the four transit modes under consideration were the clear best choice at certain ridership levels. Diesel buses are the clear best choice from 7-51 passengers, LRTs make the most sense from 200-427 passengers, and subways are the best choice above 918 passengers. Regional express rail was never selected as a single ‘best choice’, but is a viable alternative from 428 to 918 passengers. There are a number of other passenger loading ranges where more than one transit mode makes sense. A critical takeaway is that both LRT and RER represent relatively new modes of transit for Toronto and the GTHA, and that these modes can service a wide range of potential passenger loads.

5.2 Applying the tool to examine existing and future transit options

A second objective of the thesis was to use the tool under development to examine existing transit line in the GTHA, in order to inform future transit options. Toronto’s Bloor-Danforth subway line was examined through the lens of energy requirements in order to demonstrate the way in which LCA data can be utilized to determine which vehicles are sustainable at the number of passengers on the line.

The analysis of the Bloor-Danforth line provides some critical insights. First, the line is very long, and is characterized by long ‘collection’ zones in the east and west serving a small number of destination stations in the center. In practice, this means that the energy requirements on a per passenger-kilometer basis are very high for the majority of the line, for both eastbound and westbound trains. The number of stations where ridership and thus per passenger energy
requirements are sufficient to justify subways over LRTs or RER are actually quite low; 6 and 5 of 30 line segments (station-to-station) meet this threshold for eastbound and westbound trains, respectively.

Two critical takeaways were identified. First, extensions to the existing Bloor-Danforth line should be informed by energy requirements, as well as other aspects of decision-making. The results suggest that LRT options could service the passenger loads at the ends of the line with far greater energy efficiency. A second takeaway was that urban planning should seek to develop destinations along the entire transit line; it is not enough to greenlight development of residential density to drive peak passenger loads, as the current commuter-to-downtown pattern leaves trains running virtually empty when returning to terminal stations from the downtown.

It is hoped that the tool developed in this thesis can be used as an additional resource in the transit mode decision-making process for many developing transportation systems, including the transit systems across the GTHA.

5.3 Future Work

One of the most problematic issues with this project was the lack of applicable LCA data to Toronto. Developing life cycle data geared to transit is a developing field, with a growing collection of literature on diesel buses but very little data on other transit modes. Currently, no LCA studies are available on transit within Toronto itself, a significant gap in the literature.

Not only is more transit LCA literature required, but the LCA studies that are conducted need to be more transparent and communicated clearly so that researchers, policy makers, and other decision makers can utilize this tool to incorporate environmental consideration into making
informed decisions. Where literature does not identify the exact details of the system it is analyzing, the parameters of the study, or the units used, it limits the way in which that study can be applied accurately.

Further, if LCA practitioners are interested in lending their work to these broader informative uses, than the field needs to confront issues of standardization amongst LCA studies. The ISO 14404 standard on LCA specifies important considerations when comparing two studies; most studies vary significantly, however, and thus are difficult to compare. In this study, the issue was avoided by focusing on energy consumption, which can be compared relatively easily. Looking at a wide range of environmental impacts, however, requires more comparable LCA studies. This includes standardizing measurements and terms throughout the field, such as the term “vehicle” (which should refer to operational units, not single cars in a train), to support use of the results in other applications. Future work in the LCA field should seek to improve the usability of LCA data.

This project also highlighted the issues with ridership data, specifically that available for Toronto’s current and proposed systems. In order to make decisions regarding transit modes, as well as for general accounting of the service the system provides, projected or current ridership data is needed by transit agencies for various reasons. The ridership data for Toronto’s current transit system that the TTC makes public is very generalized, and details on passenger boarding and alighting at each station are not provided. This project could not conduct independent studies of ridership due to lack of available data, funds to purchase the forecast software, and expertise. Presto, the electronic fare system that Toronto is currently installing, may serve as a more accurate method of obtaining actual ridership numbers.
Another issue is related to future ridership projections is that existing travel forecasting models can be misleading as they provide only estimates and results can be manipulated to convey desired results. Transparency with regard to data from the TTC and City of Toronto would improve accessibility to data. Further work into improving ridership data quality and sharing would improve the way in which the tool developed in this thesis could be applied.

There were a few topics that this project lends itself to that were not explored here. One topic that is important to the discussion of sustainable transit is the application of alternative fuels, especially liquid biofuels and renewable electricity. There is potential that employing renewable energy sources to transit vehicles may drastically improve sustainability of transit, therefore future research into geographic availability, policies encouraging or discouraging use, and implication of renewable energy in the transit field could assist in the furthering of reducing the environmental impacts of transportation. Additionally, this project excluded many urban transit modes, as well as private transportation options, that could be explored in future research. One area that was not covered included vehicles that are used as different modes on different parts of the line, such as the vehicles on green line in Boston, Massachusetts that operate as a streetcar or and LRT on different parts of the line. While this project focused on the modes relevant to Toronto’s system, future research should explore the impacts of modes not discussed here.
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