LIFE CYCLE ASSESSMENT OF E-SCOOTERS

University of Calgary
ENER 503 – Life Cycle Assessment

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ABSTRACT

This life cycle assessment completed for e-scooters within the Calgary area serves to determine the environmental impact, specifically the global warming potential of e-scooters, and compare them to other modes of transportation available in the downtown core. By completing literature reviews and making assumptions and correlations between data, this study quantifies the impact of e-scooters on the global warming potential, measured in kg CO2e/passenger km in Calgary. This study was completed within a system boundary; which includes E-Scooter Components/Production, Delivery Transportation, Use of E-Scooters, Charging Methods, Collection of E-Scooter, and Recycling of the E-Scooter. The results of the impact assessment were then compared to literature values of other available modes of transportation. Based on the completed analysis, the e-scooters only outperform a full-sized gasoline car and are inferior to all other modes of transportation it was compared to. A sensitivity analysis is performed on multiple parameters of the e-scooter LCA; which determined that lifecycle and passenger distance travelled create almost exponential changes to the results. Two parameters that had little to no effect on the global warming potential were disposal emissions and transportation impact. It was determined that the e-scooters in Calgary performed much worse than in North Carolina; this is due to geographical differences and the ability for the scooters to run year-round. However, on a percentage basis, each parameter of the analysis contributed similar amounts to the overall impact in both the Calgary and North Carolina e-scooter life cycle analysis.

NOMENCLATURE

LCA…………………………………………………………………………………………………….. Life Cycle Assessment
LCI………………………………………………………………………………………………………. Life Cycle Inventory
Kg……… Kilogram
MJ…… Megajoule
U of C……………………………………………………………………………………………… University of Calgary
E-Scooter…………………………………………………………………………………… Dockless Electric Scooter
Km……… Kilometer
GHG……………………………………………………………………………………………………… Greenhouse Gas
PFD………………………………………………………………………………………………… Process Flow Diagram
I……………………………………………………………………………Life Cycle Impact (kg-eq/passenger-km)
M………………………………………………………………… Material/Manufacturing Impact (kg-eq/scooter)
T…………………………………………………………………………… Transportation Impact (kg-eq/scooter)
A…………………………………………………………………………………… Assembly Impact (kg-eq/scooter)
E………………………………………………………………………………… Disposal Emission (kg-eq/scooter)
MPS (Day)……………………….. …. Kilometers travel per day for collection and distribution (auto-km/scooter)
EF (Auto) ………………………………………. Emission Factor for distribution and collect vehicle (kg-eq/auto-km)
E (Grid) ………………………………………………………………………………… Electricity Use (MWh/scooter)
EF (Grid) ……………………………………………………………………… Emission factor for Grid (kg-eq/MWh)
D (d) …………………………………………………………………………… Passenger distance (passenger-kilometer)
d…………………………………………………………………………………………………… Functional lifetime (day)

INTRODUCTION

The City of Calgary has introduced many pilot programs to encourage residents to engage public platforms such as Calgary's recent introduction of electric bikes and scooters. The area of study of interest will be focused on is the City of Calgary's Environmental impact revolving around the life span of dockless electric scooters (E-Scooter). With the introduction of the electric scooter pilot program there has been many question circling around the topic of environmental impact within the City of Calgary's council. This brings forth the major research question of this LCA, "Which of the following transportation options in Calgary; dockless e-scooters, single passenger vehicles, public bussing, or bicycles have the lowest impact on the environment in terms of the global warming potential, measured in kg CO2e/passenger-kilometer? ".

With the introduction of shared public transportation such as E-Scooters, there has been wide variety of interest from common use to impact assessment studies. In early spring of 2019, Lime Scooters were introduced into Calgary's diverse ride sharing program, with public interest soaring there became quite a buzz around E-Scooter. With a large public interest revolving around the E-Scooter ever multiplying, Calgary's market was perceived as a valuable economic opportunity for E-Scooters transportation companies to invest in. Later in the spring Bird Scooters were also introduced to the streets of Calgary which has led to a more competitive market. With multiple companies introduced to Calgary's streets, a variety of impact assessments must be conducted to ensure sustainability. Many data reports have been generated but these reports mainly focus on general public safety while operating the E-Scooter and the safety of by-standards (pedestrians), therefore justification to why a Life Cycle Assessment would be vital in determining E-Scooters environmental impact.

With the popularity of E-Scooters growing there are many opportunities to conduct important studies to justify whether the pilot has greater environmental impacts than other ride sharing programs and local city public transit. The City of Calgary's E-Scooters shared mobility choices focus on sustainability, health and environment [1]. With the City's pilot in mind, a formal LCA should be conducted to show the proposed environmental impacts. Therefore, the purpose of this study is to help aid the City of Calgary with regards to comparisons between different modes of transportation and their environmental impacts. This process will be done by determining which methods are more environmentally intensive; the report will dive into details surrounding E-Scooters while using external research for other transportation services, these details will focus on greenhouse emission revolving around manufacturing and use, and recycling viability of the given comparisons. The comparison will be conduct based off the same functional unit, this way a fair and accurate conclusion may be obtained.

Goal and Scope

The goal of this study is to determine and justify if Electric Scooters are more greenhouse intensive than other forms of transportation. A carbon footprint for "cuddle-to-grave" will be analyzed then compared to other modes of transportation that include; different sizes of gas vehicles, electric vehicles, public busses, and bicycles. An appropriate functional unit of kg CO_2/passenger-kilometer will allow the study to compare each method of transportation fairly.

The scope of work is detailed in a system boundary flow diagram in Appendix A of this document. As shown in the flow diagram emission for creating individual components (Materials) of E-Scooters is not considered. An equal comparison is still achieved because of applied assumptions that there is one central manufacturing factory. The overview of the boundary aspect will allow for a detailed analysis of each critical component; the critical components are shown below.

- E-Scooter Components/Production
- Delivery Transportation
- Use of E-Scooters
- Charging Methods
- Collection of E-Scooter
- Recycling E-Scooter

These options will be compared using an analytical approach as well as a numerical method, this will narrow the topic into a functional group. This group will be comprised of methods that will allow us to simplify the results into one passenger per kilometer travelled comparison. From this functional group, an appropriate comparison of boundary conditions across the options will be analyzed and formulated into readable results.

Literature Review

Upon conducting preliminary research, there have been many studies into the environmental impacts of e-scooters [2], [3], [4]. We will use these to create a foundation to build our LCA of e-scooters; along with further research into the impacts of weather on their usability in Alberta winters [5]. We will also try to quantify the impact of shipping these products from China to North America using these references: [6], [7]. Using local studies done by the City of Calgary we can try to understand how often these products are used, the frequency of charging, and the impacts of collecting them to charge [1], [8]. Going forward we will continue to find literature that supports or denies our findings throughout this life cycle assessment of E-scooters. Below you can find short summaries of two pieces of literature that we used to complete our life cycle assessment.

Are E-scooters polluters? The environmental impacts of shared dockless electric scooters. [2]

This study was published last year in 2019, modelling the environmental impacts of stand-up electric scooters which are showing up in many large cities around the world. This study basis its analysis on a Monte Carlo simulation; therefore, any of the data we have pulled from this source has been adjusted or has assumptions made to better fit the local circumstances. It mainly focused on the global warming potential and concluded that much of the scooters environmental impacts came from the materials and manufacturing, as well as the daily collection for charging rather than the charging itself. The study also discussed issues with scooters average life cycles and collection emissions as both these parameters are subject to change for each scooter. Both these issues had large impacts on overall life cycle impact; and were reciprocal to our study, so assumptions were made to standardize these parameters.

On the electrification of road transportation – A review of the environmental, economic, and social performance of electric two-wheelers [4]

This study, completed in 2015, discusses the economic, environmental, and social performance of two wheeled electric vehicles. As our analysis only focuses on environmental impact, we only used information from this source regarding that aspect of their study. The study compared different sizes of two wheeled electric modes of transportation to that of more standard modes of transportation; such as, bicycles, buses, gas passenger vehicles, electric rail, and battery powered cars. They measured global warming potential in kg CO2 e/100km as seen in figure 3 of the source; therefore, we had to make adjustment for the studies results to be comparative to our functional unit. It should also be noted that the figure shows error bars; which are due to assumptions in data used by the article.

METHODS AND DATA

In order to make a fair comparison between the environmental life cycle impacts of multiple types of passenger vehicles, public transit, passenger vehicles and E-scooters were compared. To properly do this we needed to find reliable public data for each transportation service. For public transit figures, we were able to retrieve credible data from the city of Calgary website for public transit by use of buses. For passenger vehicles and public transit by bus we used average numbers that we deemed to be reasonably accurate for the purposes of the project. Lastly, we were able to find data from a local research paper [3] along with very new data published by the City of Calgary showing logs of all e-scooter trips during the pilot program in 2019. This is very rare data to have, especially in the city of study which makes us believe that our data collection will prove to be very credible and accurate when we make our final comparisons.

For a functional unit we chose to use passenger-km for each mode of transportation. This functional unit was chosen because it is very hard to start incorporating any sort of weight measurement into the passenger portion of the calculations when looking at the data available for these modes of transportation. The data only shows trips made and does not specify the sex or the weight of the rider, making it nearly impossible to differentiate between riders. In this case it was best to use person • km as our functional unit.

As a group, we chose to make use of Microsoft Excel for our calculations pertaining to this report. The choice to use Microsoft Excel rather than OpenLCA was due to the unfamiliarity with OpenLCA, along with the fact that our data was not specific enough to warrant the use of a program such as OpenLCA. To fully understand the life cycle impacts of E-scooter production and use, a process flow diagram was created to help simplify the stages involved. Although this step seemed elementary, it proved to be very useful when going through the life cycle of the scooter, to eliminate confusion with which process certain things belonged to. This simple yet very helpful process diagram was used throughout the project and is shown in Appendix A.

Calculating the Results

Equation 1 describes the generalized calculation per passenger-km for an impact category, in this study it's the GWP; and was found in study [2]. However, a few modifications were added by adding the burdens associated with assembly, A, and disposal, E.

Equation 1-Impact

$$\boldsymbol{I = \frac{M+T+A+\sum_0^d (MPS_d * EF_{auto}) + \sum_0^d \sum_0^i \left(E_{grid,i,d} * EF_{grid,i,d}\right) + E}{\sum_0^d D_d}}$$

where,

- I : represents the life cycle impacts for the GWP of the e-scooter (kg-eq/passenger-km)
- M : represents the burdens associated with materials and manufacturing (kg-eq/scooter)
- T : the burdens associated with the transportation of the scooter from shipping and trucking (kg-eq/scooter)
- A : the burdens associated with the assembly (kg-eq/scooter)
- E : the disposal emissions (kg-eq/scooter)

- MPS_d : the auto-km traveled per day, d, for collection and distribution of scooters (auto-km/scooter)
- EF_{auto} : the emission factor for the vehicle used to collect and distribute scooters (kg-eq/auto-km)
- E_{grid} : the electricity used for charging (MWh/scooter)
- EF_{grid} : the emission factor associated with a specific grid region (kg-eq/MWh)
- d : represents functional lifetime of 1200 km (days)

To find the EF_{auto}, the emission factor of a vehicle type was calculated first using Equation 2 [9]. The vehicle type is assumed to be a Ford F-150, a Light Duty Diesel Truck type. The EF_{auto} was then calculated by multiplying the fuel economy of the F-150 to the $EF_{vehicle\ type}$.

Equation 2-Emission Factor

$$\boldsymbol{EF_{vehicle\ type} = \left(EF_{CO_2} + GWP_{CO_2}\right) + \left(EF_{CH_4} + GWP_{CH_4}\right) + \left(EF_{N_2O} + GWP_{N_2O}\right)}$$

where,

- $EF_{vehicle\ type}$: emission factor of a vehicle type (kg-eq/km)
- EF_i : emission factor of a gas, i, (kg/L-fuel)
- GWP_i : the global warming potential of a gas, i, (kg-eq/kg)

Study Assumptions

Due to the time constraint on the project and having to be completed from beginning to end within the course of a semester, multiple assumptions had to be made to complete our study and have tangible results to compare. For the purposes of this study, we used the term “juicer” to describe anyone who works for an e-scooter company and is responsible for picking up e-scooters and charging their batteries back to full for re-use.

The first major assumption made by our group was that the e-scooters’ usage and charging rates remained constant day to day. In other words, we modeled our study on the assumption that the e-scooter’s battery was drained all the way to zero daily. Additionally, upon the e-scooter running out of battery, it would then be picked up by a juicer and recharged back to full battery daily. This was an important assumption to make to simplify the study and be able to generate meaningful results. It is worthwhile to note that this assumption would most likely not model real world studies. The variability of daily battery usage for each e-scooter would not be the same and furthermore, each e-scooter battery would not be drained all the way to zero daily. This fact alone would reduce the life of the battery and produce less favorable results than our study results.

The second assumption made by the team was, juicers were readily available daily. This was a necessary assumption to make based on our first assumption previously explained. Due to our study assuming all e-scooters are recharged nightly, we had to then assume that for this to happen there were an adequate number of juicers available to perform the recharging service. If there were not enough people to provide this service reliably then our first assumption would fail.

The third assumption we made as a group was that every juicer would be subject to emissions attributed to driving a Ford F-150 pickup truck around the city to perform e-scooter pickups and deployments. This was an essential assumption to make based on our study because we had to standardize the emissions attributable to a single e-scooter charge and therefore we were required to standardize the emissions associated with pickup and re-deployment of the scooters. Moreover, given that these juicers would be subject to market forces, it would be much more worthwhile from a revenue standpoint for any juicer to drive a vehicle with equal or comparable cargo space to a Ford F-150 in order to squeeze more money out of each pickup and deployment trip. Aside from monetary forces, it would also be more logical for a juicer to use a larger vehicle from a time efficiency standpoint.

From the data we used on the manufacturing process for the e-scooters, the study data is based on average plausible scooter lifetimes. It was stated in the study that “In our analysis, we test a wide range of plausible scooter lifetimes (0.5-2 years), informed by battery lifetimes, the manufacturer warranty, and reports of damage under shared usage programs” [2]. The study was done in North Carolina and used 6 months on the low side and 18 months on the high side for e-scooter lifetime. Based on the more temperate climate in North Carolina when compared to Calgary, we assumed a more conservative lifetime of the e-scooter lifetime on the low side at 5 months. This assumption is reflective in Figure 4 in the appendix. Based on the lower expected lifetime of the same e-scooter in Calgary compared to North Carolina, on a passenger • km basis, the manufacturing and assembly emissions associated with each scooter would be lower per scooter in North Carolina than in Calgary when normalized over the e-scooter expected lifetime. We believe that this is a safe assumption to make given how hard Calgary’s climate is on vehicle wear.

The last assumption we made as a group is that the average values used to complete most of the calculations are reliable and do not skew the results of the study. In order to complete the study and generate tangible results to compare, we had to normalize and average certain data and use values from studies that had been averaged. Since the data on the subject matter is limited and the emissions associated with electricity production by region vary so much, we believe that using average values was a necessary and valid option to compute the data. To bring the main study results back to an Alberta figure, we used the electricity generation emissions on average based in the North Carolina region and converted this back to Alberta figures based on our local kg•CO_2e/kWh generated.

Study Limitations

Throughout the semester the team ran into many situations in which we were asked to define our limitations because of the time constraint associated with the term project. If there were more time available to conduct and refine the study, we would have been able to broaden our study and there would be fewer limitations.

One of the limitations on the study was that our main study included a Monte Carlo simulation. Although this is a valid and widely accepted method, it would have been nice to find another comparable study that used a different method. However, because the study being described was by far the most comprehensive study we found, we decided this was acceptable and only needed to be noted that a Monte Carlo simulation was used. A second limitation on our study is based directly on our single semester time constraint and thus only allowed us to analyze our results against one impact category which was GHG equivalent emissions. In addition to GHG emissions, we would have liked to compare our results against toxicity and acidification. Our reasoning for wanting to expand the scope and compare against these other impact categories is that it would have provided us with a broader summary of results and further solidify our study. Our study boundary includes the disposal of the e-scooter lithium batteries which would directly play into these other secondary impact categories.

RESULTS

The e-scooter model used for this study is the Xiaomi m365 and the materials for manufacturing are consistent with the Hollingsworth study, [2]. The impacts for each component are normalized and will be based on the assumptions made in this study. As a result, the GWP for each component for manufacturing are found and is shown in the table below. Summing up the results, the total impact for the manufacturing is found to be 178.08 kg.CO2eq/scooter; this is M for Equation 1. The burdens associated with the assembly, A, is 5.43 kg.CO2eq/scooter and is consistent with another study [10].

Table 1-Material and Component Impacts

Scooter impacts for 1 Xiaomi m365 e-scooter	
Materials	**GWP (kg CO2-eq)**
Aluminum Frame (76/24: P/R)	7.4E+01
Aluminum (Other)	4.8E+00
Battery	4.5E+01
Battery Recycled Content	-9.2E-01
Motor	1.1E+01
Disposal	5.8E+00
Plastics	4.4E+00
Charger	4.8E+00
Circuit Board	9.3E+00
Steel	1.1E+00
Rubber	3.6E+00
Water	2.5E-04
Manufacturing	8.8E+00
Other	6.4E+00

The e-scooter is assembled in Shenzhen, China; then it is shipped to Vancouver and then trucked to Calgary. The burdens associated with transportation are found below and the total is T for Equation 1. The transportation route of the e-scooter is found in Appendix G.

Table 2-Transportation Impacts

Distance	***Values***	***Units***
Shenzhen, China to Vancouver	10571.76	km
Delivered to Calgary	971.04	km
Mass		
Total Mass of scooter with packaging	17.5	kg
Burden		
Trucking	70	ton-km
Shipping	207	ton-km
Emission Factors (CO2e)		
Shipping	4	gCO2e/tonne-km
Trucking	63.8	gCO2e/tonne-km

Emission per scooter				
Shipping	0.74	**TOTAL**	1.82	kg.CO2e/scooter
trucking	1.08			

For the collection to charge and distribution of the e-scooter, it is assumed that the lime juicers uses a Ford F-150 to do this task. By using Equation 2, the EF_{auto} is found to be 0.357 kg-CO2e/auto-km. To determine the MPS_d, a few assumptions were made, and the results are shown below.

Table 3-Auto-distance traveled per day for the collection and distribution of e-scooters.

VALUES	UNITS	ASSUMPTIONS
20	scooters	per night; assuming \$100 earnings a night, \$5/scooter
2	hours	average collection disctact range from 1-3.5 kilometers according to Hollingworth et al
25	km/h	average driving downtown speed, person lives around downtown
MPS_D	2.5	km/scooter

To determine the E_{grid} and EF_{grid}, it is based off on Alberta's electricity grid and is found to be 0.335 kWh/scooter and 800 kg-CO2eq/MWh, respectively [11]. Finally, the end of life flows table is found in the Appendix H and the disposal emissions, E, is 2.71 kg.CO2eq/scooter. As a result, the life cycle impact of the e-scooter, I, can be found using Equation 1 and the results are in Table 4.

Table 4 - Results for Equation 1

	Values	***CO2eq***
I	0.296	*(kg-eq/passenger-kilometer)*
M	178.08	(kg-eq/scooter)
T	1.82	(kg-eq/scooter)
A	5.43	(kg-eq/scooter)
E	2.71	(kg-eq/scooter)
MPS(d)	2.50	(auto-kilometer/scooter)
EF(auto)	0.357	(kg-eq/auto-kilometer)
E(grid)	0.00034	(MWh/scooter)
EF(grid)	800.00	(kg-eq/MWh)
D(d)	8.35	(passenger-kilometer)
d	143.74	(days)

The life cycle of the e-scooter is split into subcategories: Manufacturing, Assembly, Transportation, Charging, Collection, and End of Life. The values of these subcategories are based on the results of Table 4. For a visual on the e-scooter's life cycle, refer to Figure 2 in Appendix B.

Table 5 - E-scooter Lifetime Emissions

SUBCATEGORY	VALUES	UNITS
Manufacturing	0.1484	(kg CO2e/passenger-kilometer)
Transportation	0.0015	(kg CO2e/passenger-kilometer)

Assembly	0.0045	(kg CO2e/passenger-kilometer)
Collection	0.1069	(kg CO2e/passenger-kilometer)
Charging	0.0321	(kg CO2e/passenger-kilometer)
End of life	0.0023	(kg CO2e/passenger-kilometer)

INTERPRETATION OF RESULTS

By using Equation 1, the lifetime of Calgary's E-scooters has been split into subcategories: Manufacturing, Assembly, Transportation, Charging, Collection, and End of Life. A functional lifetime of 1200 km was used to determine these values. As a result, shown in Figure 2 of the Appendix, the bulk of the emissions comes from manufacturing and collection for charging which is approximately 50% and 35% of its lifetime; furthermore, the assembly, transportation and end of life are almost negligible.

As mentioned previously, the goal of this study is to determine whether Electric Scooters are more carbon intensive than other modes of transportation. Looking at the Lifetime Emissions graph in Figure 6 of the Appendix, Calgary's E-scooters is the second highest, following the Full-size Gasoline Car, which suggests that it is carbon intensive. The E-scooters in Calgary and North Carolina showed a substantial difference although the LCA was done on the same e-scooter make, the Xiaomi m365; this can be attributed to geographical differences and assumptions that were explained above. However, if the two results are scaled to the percent, the proportions appear to be relatively similar as shown in Figure 5 of the Appendix; the bulk of the emissions comes from manufacturing and collection for charging for both locations. A possible reason for this substantial difference is that these emission results are relative to its use. Calgary uses its scooters less due to its climate where it is unusable in the winter and North Carolina has a generally warmer climate therefore it can use its scooters more. The more the scooters are used, the more environmentally friendly they are.

SENSITIVITY ANALYSIS

The sensitivity results break down was spaced out in various subcategories, there are as follows; manufacturing, assembly, transportation, charging, collection, and end of life. By creating these subcategories, the LCA study can easily be compared to different transportation methods, which is highlighted in the sensitivity analysis and in Appendix F.

Lifetime:

The most sensitive parameters, by a large margin, is the lifetime of the scooter. The lifetime can be represented with battery cycles or total distance travelled. The distance travelled is the selected dimension utilized in the analysis. Reducing the lifetime by 40% drastically, almost exponentially, increases the lifecycle emissions of the e-scooter from 0.296 kg CO2e/km to 0.422 kg CO2e/km this comparison can be found in Appendix F. To contextualize a 40% reduction the e-scooter would go from being utilized for 1200km to 720km, or in the term of days, assuming the e-scooter is utilized to travel 8.3 km per day, goes from 145 days to 86 days. Thus, to reiterate, a lifetime reduction of 59 days increases the lifecycle emissions by 0.126 kg CO2e/km. It would be of the utmost priority to increase the lifetime of the e-scooter to reduce life cycle emissions. Hollingsworth's study [2] also demonstrates that the most sensitive parameter is the lifetime of the e-scooter.

Manufacturing emissions:

Manufacturing emissions has the largest impact at baseline (178 kg CO2e/scooter) conditions and as evident from the graph, is quite sensitive to change. The baseline emissions are derived from the (Hollingsworth) study. The study used measured and proxy data from ecoinvent in [2], the proxy used for an electric bicycle production. A reduction of 40% manufacturing emissions to (107 kg CO2e/scooter) emissions reduces the life cycle emission from the e-scooter from 0.296 kg CO2e/km travelled to 0.236 kg CO2e/km. This puts it between a Full-Size BEV in Alberta (0.244 kg CO2e/km) and Full-Size BEV in USA (0.168 kg CO2e/km). This parameter is the second most sensitive revealed in the analysis. Any suggestions for impact reductions would include the adoption of a more environmentally friendly manufacturing process.

Transportation:

Transportation emissions, which may intuitively seem to contribute a large portion of the emissions and be a sensitive parameter has revealed to be completely insignificant. This is due to the relatively low emission per scooter (1.82 kg CO2e/scooter). A decrease of even 40% of emissions to 1.09 kg CO2e/scooter only produced a decrease of 0.001 kg CO2e/km compared to the baseline. Recommending any changes to this process will be futile.

End of Life:

Another just as insensitive parameter is disposal emission. It should be noted that e-scooter battery end of life emissions has not been considered and may prove to intensify other impact categories, if not GWP. End of life emissions are calculated using a secondary source which was based on the GREET model. A 40% reduction in end of life disposal emissions, from 2.7 kg CO2e/scooter to 1.62 kg CO2e/scooter provides insignificant reduction (0.002 kg CO2e/km) to lifecycle emissions.

Distance travelled per day:

The distance travelled per day of the e-scooter differs from the lifetime. The lifetime of the e-scooter remains at 1200km, but the daily utilization factor is increased. Currently according to The City of Calgary Transportation report of 2019, e-scooters where utilized to travel 8.34 km per scooter between the months of July and October. The sensitivity on this parameter reveals an interesting result. It behaves like the lifetime sensitivity but at a slightly lower intensity. A daily usage reduction of 40%, from 8.3 km per day per scooter to 5.01 km per scooter per day increases the lifecycle emissions to 0.388 kg CO2e/km from 0.296 kg CO2e/km. This revelation was not as intuitive. Upon further investigation, it was found to be explained by the fact that decreasing the daily utilization of the e-scooters means that it survives for a longer period of *time* (the lifetime distance remains at 1200km). When the number of days e-scooter survives increases, the number of nights they must be collected increases too. The collection emissions are a large component of the e-scooter lifecycle emissions. Lower daily utilization means that greater number of days the e-scooter must be collected for recharge which means greater tailpipe emissions produced from the collection vehicles.

An intelligent recommendation to reduce the lifecycle emissions would be to implement collection only when the battery level is below 40%. This would ensure the e-scooter is well utilized before collection and that, if it has not been utilized, the collection emissions would not be produced for an e-scooter with adequate charge remaining. If this strategy is implemented a more liner relationship will be observed with reducing the daily utilization increases the lifecycle emissions just as much as increasing it

Emission factor of the collection vehicle (EF(auto)) and the distance travelled per scooter per day by the collection vehicle (MSP(d)):

As illustrated by the dashed orange line (EF(auto)) and the blue line just underneath it, it is evident this parameter is quite sensitive. The emission factor of the collection vehicle is the tail pipe emissions produced in the collection process. This is significant in the lifecycle analysis; it is a point of contention and a deterrent as the lifecycle emission during the collection process ends up becoming the second largest portion of the GHG impact category. The baseline emission factor utilized is 0.36 kg CO2e/km travelled by the collection vehicle, which in this case is assumed to be a Ford F-150, to allow the storage of 20 e-scooters. When the tailpipe emissions are reduced by 40%, to 0.21 kg CO2e/km, (when for example using Ford New Mondeo [12]). the lifecycle emissions fall to 0.253 kg CO2e/km from the baseline 0.296 kg CO2e/km. Making it more efficient that a Mid-Size gasoline car. The fuel efficient of the collection vehicle should be emphasised in any recommendation intended to reduce the lifecycle emissions. An ideal scenario would be 0 kg CO2e/km tail pipe emissions as would be found in an electric vehicle. In that case the e-scooter lifecycle emissions would fall to 0.189 kg CO2e/km making it equivalent to a mid-size BEV in Alberta.

Nightly Collection distance of the e-scooter (MPS(d)):

Just as sensitive is the collection distance when collecting the e-scooter at night for a recharge. The collection distance is represented with a distance travelled to collect a scooter; the baseline is 2.5km/scooter. Collection distance is hard to estimate as it depends on a lot of factors, such as: population density of the urban area, utilization of the e-scooters, pathways accessible to the e-scooters, competition for e-scooter collection, distribution of the e-scooters, storage space on the collection vehicle, distance of starting and ending location of the collector, allowable radius for the e-scooters, number of e-scooters and nightly collection cap. It must be noted that this information is not available on the public domain and the respective companies are unwilling to share this information according to some reports [10], [2], use a collection ranges from 1-3.5 km per scooter. The graphic in Appendix E might give some insight to the distance travelled per scooter. Regardless, the sensitivity analysis might give some insight as to the impact of variation in the parameter. As noted, before, it is quite sensitive, just as sensitive as the collection vehicle emission factor. A reduction of 40% in the collection distance per day per scooter, i.e. from 2.5km/scooter to 1.25 km/scooter, reduces the lifecycle emission to 0.253 kg CO2e/km from the baseline. A suggestion to reduce the nightly collection distance would be by squeezing the allowable radius of the e-scooter use – though this may reduce ridership and distance travelled, producing a net negative result.

RECOMMENDATIONS AND IMPROVEMENTS FOR FUTURE STUDIES

Overall, the study was a success and as a group we believe that the results are meaningful and accurate. As with anything, there is always room for improvement and as we were working through some challenges there were a few areas that we noted could be improved upon. The major area of improvement is in the study assumptions category. Although we are very comfortable and confident with our study results, which are based upon our assumptions, we believe that if we were given more time, we could minimize error in the results. More specifically, we would have liked to search for detailed information on e-scooter life expectancy in a region more comparable to Calgary. Since North

Carolina is in a warmer climate, the life expectancies are much longer than the life expectancies in Calgary. Additionally, because the e-scooters are only available during a portion of the year in Calgary versus year-round in North Carolina, the e-scooters have a much harder run life in Calgary than North Carolina. Based on the pilot program information from the City of Calgary, people in Calgary tend to ride the e-scooters much more frequently and for longer periods of time. Longer and more frequent trips in a shorter amount of time will result in more wear and tear on the physical equipment as well as on the life of the battery. For this reason, we made an estimated guess on the Calgary e-scooter life expectancy to be 5 months. Although this is a good educated guess based on data, we would have liked to find a study completed in a more comparable region to Calgary that only offers the e-scooters for a portion of the year.

Another recommendation and possible area of improvement for the study would be to find a study that shows the most common type of vehicle used by juicers to pick up, deploy and transport the e-scooters. Our group made a very reasonable assumption that an average juicer vehicle would be an F-150, however we believe this assumption could also be refined. Because there was no data on juicer vehicles, we had to make a blind assumption using logic. If we were to find a study done on juicer vehicles, this would make our study results more accurate because the collection portion of the e-scooters' use is quite large at ~35% of lifecycle emissions. Due to the large portion of lifecycle emissions, it would be important to improve this parameter as much as possible to further enhance the results.

REFERENCES

[1] The City of Calgary, "Electric Scooter Share Pilot," January 2020. [Online]. Available: https://www.calgary.ca/_layouts/cocis/DirectDownload.aspx?target=http%3a%2f%2fwww.calgary.ca%2fTransportation%2fTP%2fDocuments%2fcycling%2fCycling-Strategy%2fWhat-We-Heard-Report-Shared-Mobility-Pilot-2019.pdf&noredirect=1&sf=1. [Accessed February 2020].

[2] J. Hollingsworth, B. Copeland and J. Johnson, "Are e-scooters polluters? The environmental impacts of shared dockless electric scooters.," 2 August 2019. [Online]. Available: https://iopscience.iop.org/article/10.1088/1748-9326/ab2da8.

[3] R. Nocerino, A. Colorni, F. Lia and A. Lue, "E-bikes and E-scooters for Smart Logistics: Environmental and Economic Sustainability in Pro-E-bike Italian Pilots," *Transportation Research Procedia,* vol. 14, pp. 2362-2371, 2016.

[4] M. Weiss, P. Dekker, A. Moro, H. Scholz and M. K. Patel, "On the electrification of road transportation – A review of the environmental, economic, and social performance of electric two-wheelers," *Transportation Research Part D: Transport and Environment,* vol. 41, pp. 348-366, 2015.

[5] J. Mathew, M. Liu and D. Bullock, "Impact of Weather on Shared Electric Scooter Utilization," in *IEEE Intelligent Transportation Systems Conference (ITSC)*, Auckland, New Zealand, 2019.

[6] B. Shui and R. Harriss, "The role of CO2 embodiement in US-CHINA trade," *Energy Policy,* vol. 34, no. 18, pp. 4063-4068, 2006.

[7] O. Andersen, S. Gossling, M. Simonsen, H. J. Walnum, P. Peeters and C. Neiberger, "CO2 emissions from the transport of China's exported goods," *Energy Policy,* vol. 38, no. 10, pp. 5790-5798, 8 June 2010.

[8] J.-M. Mendoza, A. Josa, J. Rieradevall and X. Gabarrell, "Environmental Impact of Public Charging Facilities for Electric Two-Wheelers," *Journal of Industrial Ecology,* vol. 20, no. 1, pp. 54-66, 2015.

[9] University of Calgary, "2014-2015 Greenhouse Gas Inventory," Calgary, 2015.

[10] M. Chester, "It's a Bird…It's a Lime…It's Dockless Scooters! But Can These Electric-Powered Mobility Options Be Considered Sustainable Using Life-Cycle Analysis?," 28 January 2019. [Online]. Available: https://chesterenergyandpolicy.com/2019/01/28/its-a-bird-its-a-lime-its-dockless-scooters-but-can-these-electric-powered-mobility-options-be-considered-sustainable-using-life-cycle-analysis/. [Accessed January 2020].

[11] Environment and Climate Change Canada, "2019 National Inventory Report 1990-2017: Part 3," 2019.

[12] car-emissions.com, "Car Emissions-Car MPG, CO2 and Emissions data," [Online]. Available: https://www.car-emissions.com/cars/view/1793). [Accessed March 2020].

[13] Google, "ford f150 fuel econmomy," [Online]. [Accessed 2020 March].

[14] Government of Canada, "Canada's Official greenhouse Gas Inventory," 21 November 2018. [Online]. Available: http://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/Emission_Factors.pdf. [Accessed March 2020].

[15] L. Micromobility, "www.li.me/en-us/home," [Online]. [Accessed February 2020].

[16] bullfrogpower, "Green Electricity Emissions Calculator," 2019. [Online]. Available: https://www.bullfrogpower.com/wp-content/uploads/2015/09/2015_bullfrog_power_electricity_emission_calculator.pdf. [Accessed 10 March 2020].

[17] Government of Canada, "Global Warming Potentials," 18 February 2019. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/quantification-guidance/global-warming-potentials.html. [Accessed March 2020].

[18] The City of Calgary, "Shared Mobility Pilot Trips," 16 December 2019. [Online]. Available: https://data.calgary.ca/Transportation-Transit/Shared-Mobility-Pilot-Trips/jicz-mxiz. [Accessed March 2020].

[19] Environment and Climate Change Canada, "National Inventory Report 1990–2017: Part 2," 2019.

[20] City of Calgary, *SPC ON TRANSPORTATION AND TRANSIT,* Calgary, 2019.

[21] N. Rachael, R. David and A. Don, "Cleaner Cars from Cradle to Grave," Union of Concerned Scientists, 2015.

[22] W. Martin, D. Peter , M. Alberto, S. Harald and P. Martin , "On the electrification of road transportation – A review of the environmental, economic, and social performance of electric two-wheelers," *Transportation Research Part D: Transport and Environment,* vol. 41, pp. 348-366, 2015.

[23] L. Ellingsen, G. Majeau-Bettez, B. Singh, A. Srivastava, L. Valoen and A. Stromman, "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack," *Journal of Industrial Ecology,* 2013.

[24] Xiaomi United States, "Mi Electric Scooter," [Online]. Available: https://www.mi.com/us/mi-electric-scooter/specs. [Accessed February 2020].

[25] DP WORLD, "SEA RATES," 2020. [Online]. Available: https://www.searates.com/services/distances-time/.

[26] CN, "Carbon Calculator Emission Factors," [Online]. Available: https://www.cn.ca/repository/popups/ghg/Carbon-Calculator-Emission-Factors. [Accessed January 2020].

APPENDIX

A: System Boundary

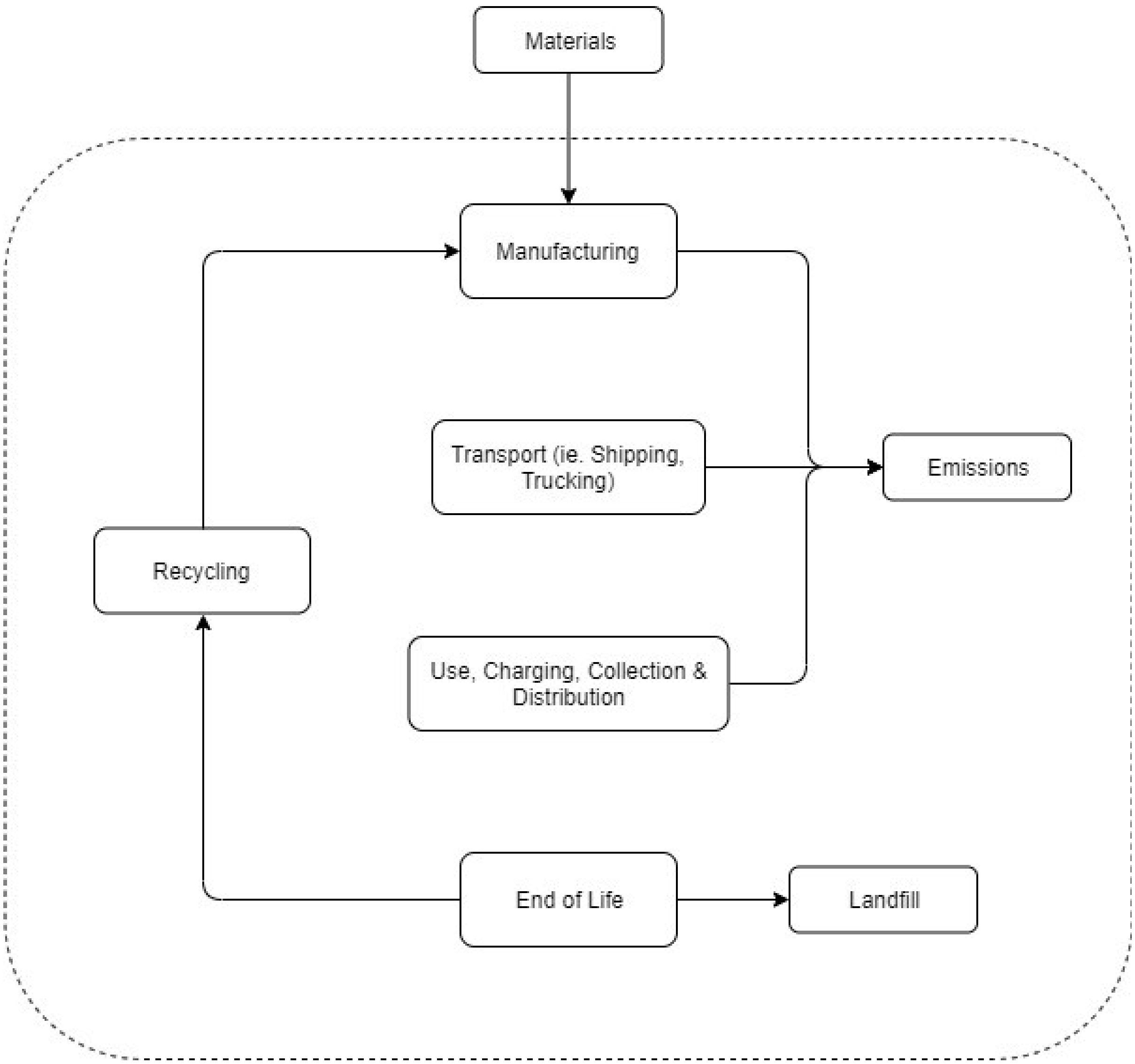

Figure 1-System Boundary

B: E-Scooter Emissions

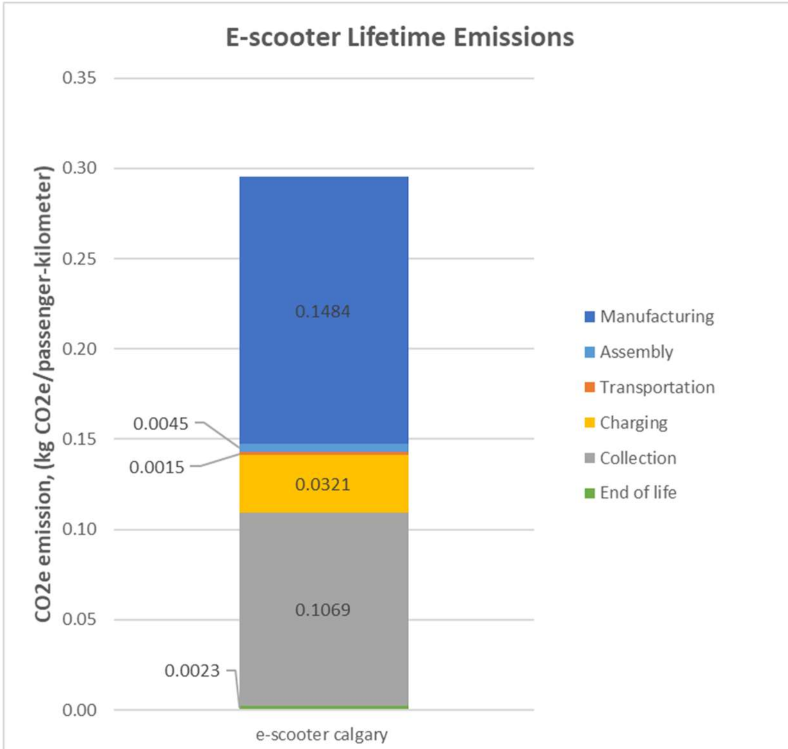

Figure 2-E-Scooter Lifetime Emissions

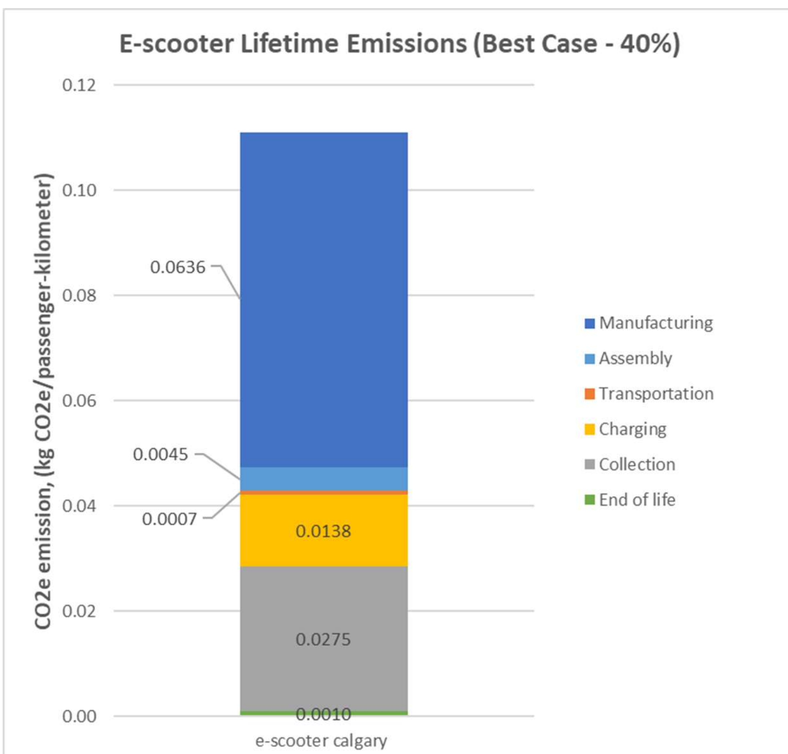

Figure 3-E-Scooter Emissions (Best Case)

C: E-Scooter Comparison

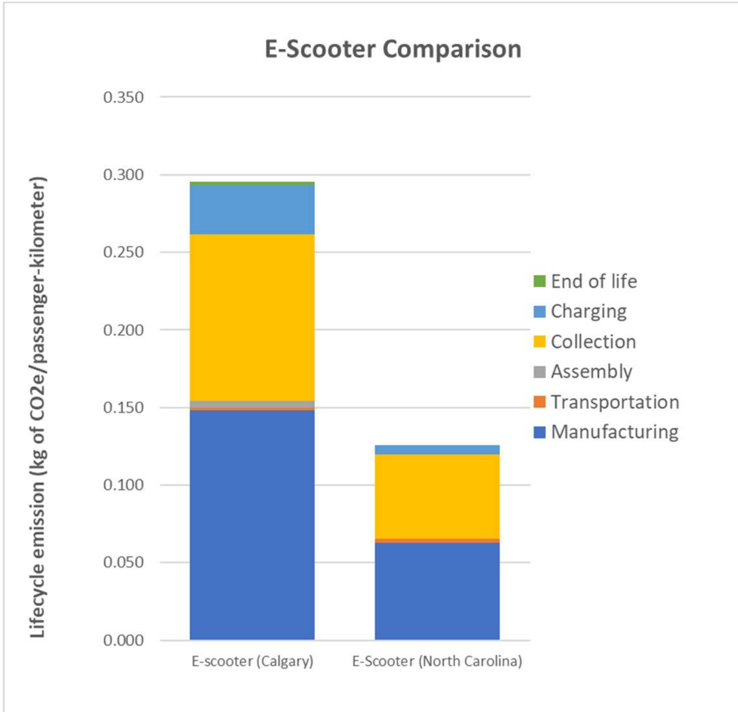

Figure 4-Calgary vs. North Carolina Emissions

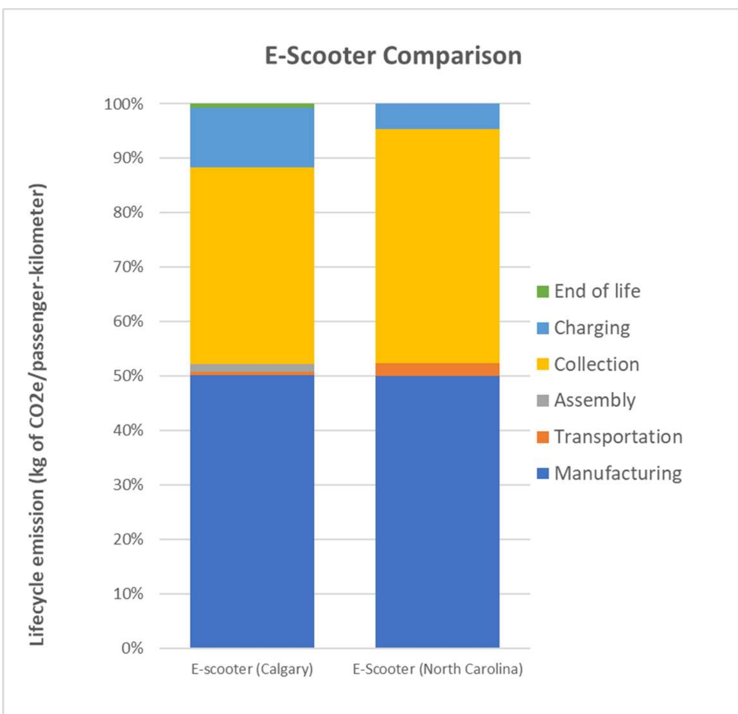

Figure 5-Calgary vs. North Carolina Emissions (Percentage)

D: Transportation Comparison

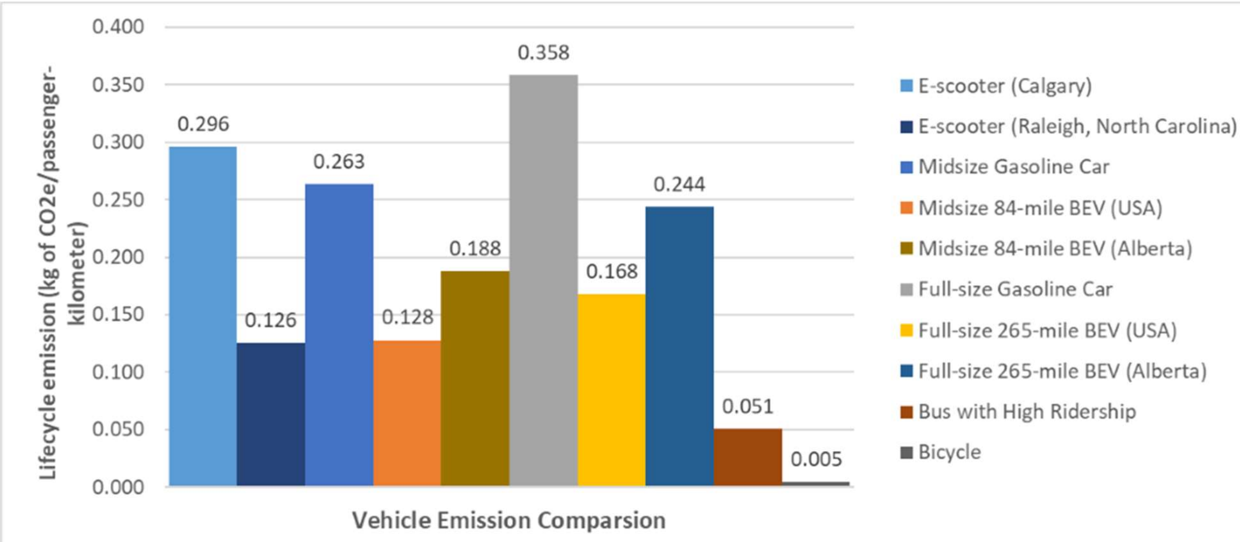

Figure 6-Transportation Comparison

E: E-Scooter Travel Distance

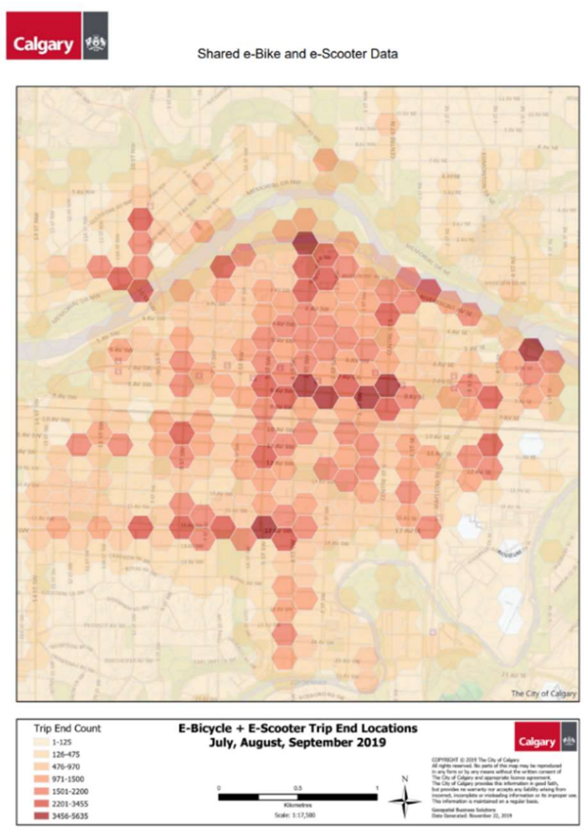

Figure 7-Calgary E-Scooter travel distance

F: Sensitivity Analysis

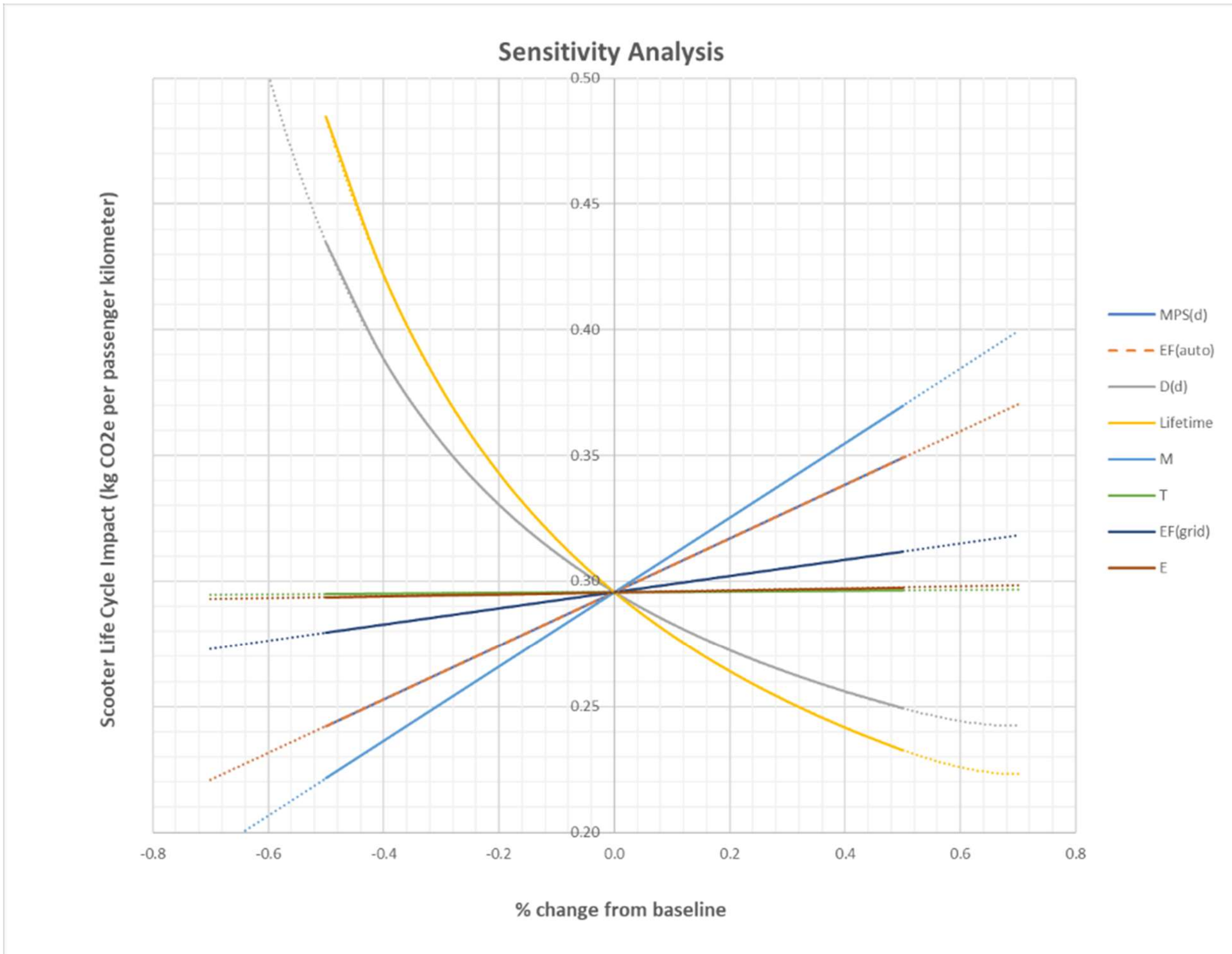

Figure 8 - Sensitivity Analysis

G: Transportation for the E-scooter

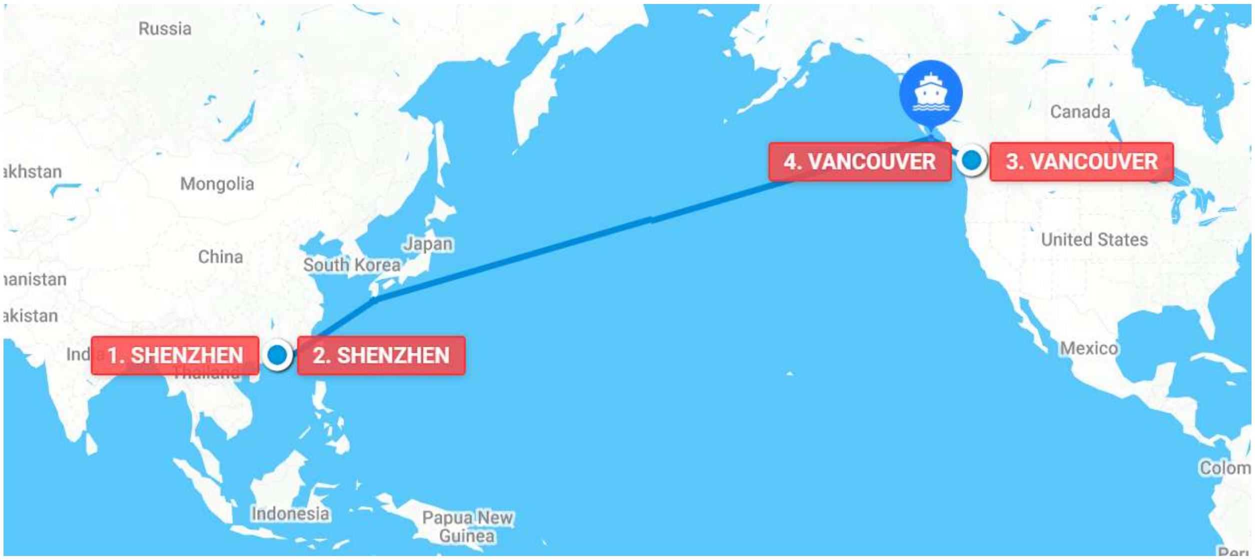

Figure 9-Shipping Freight Transportation

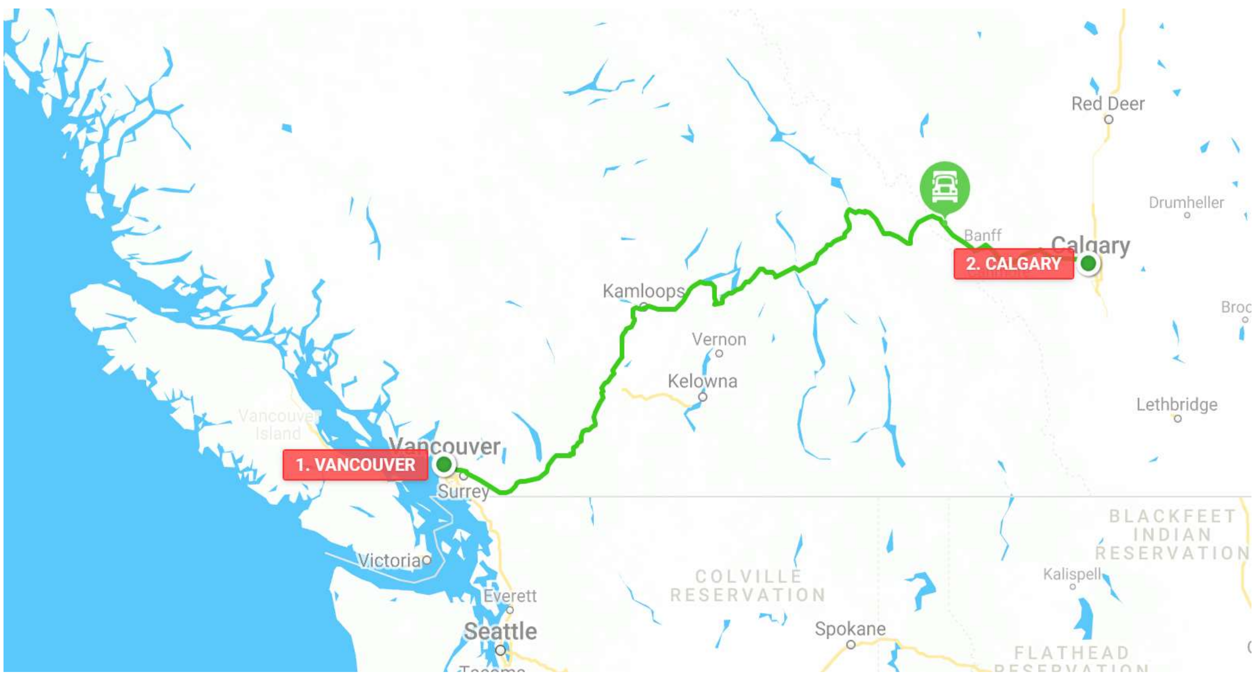

Figure 10-Shipping Trucking Transportation

H: End of Life Flows

***End of Life Flows** [2]*

Flows	Flow Property	Unit	Amount	Description	Measured/Proxy, Data Source
Electric scooter - produced	Number of items	Item(s)	1		
Municipal solid waste	Mass	kg	4.5	Disposal requirements	Proxy1, ecoinvent [2]
Wastewater, average	Volume	m3	0.0007	Disposal requirements	Proxy1, ecoinvent [2]
Water	Mass	kg	0.0001	Disposal requirements	Proxy1, ecoinvent [2]
Used Li-ion battery	Mass	kg	0.8487	Disposal requirements	Ecoinvent [2]

Disposal GHG emissions per ton of vehicle [10]	221.442	kg.CO2e/ton
Disposal GHG emissions per scooter [10]	2.702	kg.CO2e/scooter

Figure 11-End of Life Flow

I: Assumptions

Table 6-Assumptions

Assumption	Description	Value	Unit	Notes	Source
1	Scooter collection for charging.	20	Scooters per night		[2]
2	Duration of scooter collection in an average distance of 1-3.5 kilometers.	2	Hours		[2]
3	Average driving speed in Calgary downtown	25	Km/hour	1 person living downtown	
4	Neglecting maintenance during scooter's lifetime.				
5	Fuel economy for a Ford F-150 truck.	13	L_{fuel}/100km	Used for scooter collection.	[13]
6	Emission factors for light duty diesel trucks.	2.681kg/L_{fuel} 0.000068kg/L_{fuel} 0.00021kg/L_{fuel}			[14]