UBC Social Ecological Economic Development Studies (SEEDS) Student Report

Life Cycle Assessment of Georgia and Dunsmuir Viaduct

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CIVL 498E

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PROVISIO

This study has been completed by undergraduate students as part of their coursework at the University of British Columbia (UBC) and is also a contribution to a larger effort – the UBC LCA Project – which aims to support the development of the field of life cycle assessment (LCA).

The information and findings contained in this report have not been through a full critical review and should be considered preliminary.

If further information is required please contact the course instructor Rob Sianchuk.

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Abstract

This study sought to provide a baseline comparison point to the City of Vancouver for the construction of the Georgia and Dunsmuir viaducts, as well as an approximation of several of the end of life options that are possible. This is accomplished by doing a quantity takeoff of the viaducts using a combination of OnScreen Takeoff and Excel. The volumes developed from this were then modelled in Athena Impact Estimator in order to determine the net impact of the construction of the viaducts. In order to model the end of life options of the viaducts were considered; Greenway or Cut and Haul removal. Based on approximated models, Cut and Haul removal was found to have the lower environmental impact. The results should be considered preliminary due to the lack of information, LCA tools available and time constraints to complete a more detailed analysis. Further analysis is recommended to validate the material quantities and develop models of more detailed end of life scenarios.

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1.0 Introduction

The Georgia and Dunsmuir Viaducts originated as a single viaduct structure in 1915 to connect the eastern side of Vancouver to the downtown area. It crossed an industrialized area of False Creek. In the early 1960s Vancouver decided to replace this structure with two viaducts that would hopefully become a part of a larger inter-city freeway system. The proposed freeway system was cancelled in the late 1960s, but by this time construction on the current Georgia and Dunsmuir Viaducts was already approved and moving forward. The Georgia and Dunsmuir Viaducts were then finished construction in 1972.

Georgia and Dunsmuir Viaducts are now reaching a period in their life spans where the surrounding area is being considered for redevelopment by the City of Vancouver and developers. This has led the City of Vancouver to investigate and consider what should be done with the Viaducts. They are interested in evaluating the environmental impacts that the viaducts have had and the impacts of potential end-of-life options. The generic options that are being investigated are completed demolition, partial demolition, and greening of a viaduct. The consulting engineers on the viaduct project in 1972 were Phillips, Barratt, Hillier, Jones and Partners, and the as-built drawings were completed on February 22, 1973. The viaducts are in place to allow for vehicles, cyclists, and pedestrians to travel between Vancouver's downtown core, and the Eastside of Vancouver.

Overall, the viaduct structures include the structural components and accessories that are listed in Table 1.1.

Table 1.1: Structure Characteristics

Footings	Reinforced concrete boxes supporting reinforced concrete piers
Piers	Reinforced concrete columns supporting reinforced concrete cross-girders and stringers
Cross girder arms	Reinforced concrete support arms suspending the reinforced concrete stringers
Stingers	Reinforced concrete I-beams with post-tensioning steel suspended from the cross-girders and supporting concrete decking
Concrete deck	9 inch thick concrete slab suspended by the stringers
Asphalt topping	Road surface placed on top of concrete decking
Side rails	Reinforced concrete barriers with aluminum railings

2.0 Goal and Scope

The goal and scope of the study for the Georgia and Dunsmuir Viaducts allows for the definition of the analysis and interpretation that will be utilized throughout the study. The defined terms and clauses will also lead to appropriate recommendations. This section defines the goal and scope of this study in accordance with ISO 14044 Clause 4.2.2 and 4.2.3 (Canadian Standards Association, 2006).

- Intended application

  Describes the purpose of the study.

  > Examine life cycle impacts of creating the viaduct structures, and end of life scenarios in order to inform decision making around reducing the impacts of their end-of-life/next phase.

- Reason for carrying out the study

  Describes the motivation for carrying out the LCA study.

  > City of Vancouver wants a base line to examine future transportation infrastructure projects' environmental impacts.

- Intended audience , ie to whom the results of the study are intended to be communicated

  Describes those who the LCA study is intended to be interpreted by.

  > City of Vancouver officials and employees, as well as those keen to learn about life cycle assessment (LCA).

- Whether the results are intended to be used in comparative assertions intended to be disclosed to the public

  State whether the results of this LCA are to be compared with the results of other LCA studies.

  > Yes, the results of this LCA study will be available to the public and can be compared with the results of other LCA studies or similar infrastructure of functional equivalence. It is strongly recommended that the Goal & Scope be consulted to ensure a fair comparison.

- Product system to be studied

  Describes the collection of unit processes that will be included in the study

  > The product system includes those unit processes involved in the resource extraction and manufacturing of the construction and energy products used to create the viaduct, as well as those required in the two end of life scenarios.

- Functions of the product system or, in the case of comparative studies, the system
  Describes the functions served by the product focused on in the LCA study

  > The function of the viaducts is to provide a safe transportation surface between East Vancouver and the Downtown core.

- Functional unit
  A performance characteristic of the product system being studied that will be used as a reference unit to normalize the results of the study

  The functional unit is per m^2 area of elevated transportation surface (includes road and sidewalk).
- System boundary
  Details the extent of the product system to be studied in terms of product components, life cycle stages, and unit processes.

  The system boundary of this project includes the construction and deconstruction of the footings, piers, cross girders, stringers, concrete deck, asphalt topping, and side-rails for the Georgia and Dunsmuir Viaducts. It does include investigating the potential end-of-life options of deconstruction (Cut and Haul) and greening (Greenway) scenarios. The maintenance and use of the viaducts is not included in the system boundary.
- Allocation procedures
  Describes how the input and output flows of the studied product system (and unit processes within it) are distributed between it and other related product systems.

  No allocation was required in this study.
- LCIA methodology and types of impacts
  State the methodology used to characterize the LCI results and the impact categories that will address the environmental and other issues of concern.

  The primary impact assessment method used in the BE Building LCA study was the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), developed by the US Environmental Protection Agency (US EPA). An impact characterization method developed by the Athena Institute was also used to characterize weighted raw resource use and fossil fuel consumption.

  The impact categories selected and the units used to express them (i.e. category indicators) are listed below:

  - Global warming potential – kg CO_2 equivalents
  - Ozone depletion potential – kg CFC^{-11} equivalents
  - Acidification potential – H^+ mol equivalents
  - Eutrophication potential – kg N equivalents
  - Photochemical smog potential – kg NOx equivalents
  - Human health respiratory effects potential – kg $PM_{2.5}$ equivalents
  - Weighted raw resource use – kg
  - Fossil fuel consumption – MJ

- Interpretation to be used
  Statement of significant issues, model evaluation results, and concluding remarks.
  Assumptions and interpretations are discussed in the Results and Interpratation section of this report. Any concluding remarks are contained in the Conclusion section.
- Data requirements
  Explicit statement of all the data sources used to measure, calculate or estimate information from in order to complete the study of the product system.
  The data that was used in this study was collected from the as-built drawings that the City of Vancouver had on record and provided. Some questions were also asked of experts in the field of viaduct and bridge construction to gather what are typical types of materials and maintenance that can be expected on such structures.
- Assumptions
  Explicit statement of all assumptions used by the modeller to measure, calculate or estimate information in order to complete the study of the product system.
  As a part of this report an IE Assumptions document is enclosed as an appendix. This document lists all the assumptions that were made during this study.
- Value choices and optional elements
  Details of the application and use of normalization, grouping, weighting and further data quality analysis used to better understand the LCA study results.
  Due to the limitations of this study, and the time necessary, value choices and optional elements are not included. However, sufficient documentation is provided within this document to carry forth with further analysis.
- Limitations
  Describe the extents to which the results of the modelling carried out on the product system accurately estimate the impacts created by the product system defined by the system boundary of the study.
  It is important to consider the system boundaries, assumptions and data quality.
- Data quality requirements
  Qualitative and quantitative description of sourced data used in the LCA study, as well as the methods used to collect and integrate missing data.
  The data used in this study was collected from drawings provided by the City of Vancouver. These drawings were not a complete set, and the General Notes page was one of the missing sheets. Also one of the sheets with the Georgia Dunsmuir approaches meeting, G5 to G7 and GMS5 to G7, was also missing. This impacted the quality of data and required for many assumptions and estimation to be made.
- Type of critical review, if any
  A review of the methods, data, interpretations, transparency and consistency of the LCA study – to be included in the LCA report.
  Although this study is prebared to be compared with other end-of-life phases for the viaducts a critical review of the study is not included in this report. If one wishes to

utilize or include these results in future studies or reports it is advised they contact the authors of this report.

- Type and format of the report required for the study
  Statement of the type and format followed by the report.

  This report was drafted in accordance to the provided outline for CIVL 498E – Winter Session 2012. It also takes into consideration ISO 14040 and ISO 14044.

3.0 Model Development

This section outlines the methodology that was used to develop the material takeoff, associated assumptions, and the inputs for the impact estimator model.

3.1. Structure

3.1.1. Material Takeoff Development

The quantity takeoffs were done using a combination of methods. Because of the large repetition of shapes that had varied heights, strictly using OnScreen takeoff was not an option. Instead OnScreen takeoff was used to develop the cross sectional areas and linearly dependant volumes of basic structures that were measured. This data was then imported into Excel, and a range of formulae and spreadsheets were used to develop the volumes of material used.

Due to the age and scanning of the drawings there was a significant amount of optical distortion. This made accurate takeoffs difficult as some quantities, labels, and figures were difficult to interpret. There was also a number of missing pages from the drawings, which lead to an added difficulty when it came to certain volumes and assumptions.

3.1.2. Material Takeoff Assumptions

The pier foundations were done strictly in excel, using the conditions defined by the drawings. For instance, foundation type F-I was a rectangular type foundation with a depth of 6’ 0”, a width of B, and a height of A. By entering this formula into excel, in combination with the table of values presented by the drawings, a concrete volume estimation was established for foundations.

The pier pedestal volumes were calculated using the same technique used for foundations.

The piers themselves involved several steps. First of all, as there are 12 possible cross sections for piers, with 5 different elevations based rebar schedules. An area takeoff was done using OnScreen Takeoff of the 12 different possible concrete cross sections for the piers. Linear takeoffs were done at each of the 60 different cross sections to determine horizontal rebar volumes per unit height of a pier. Count takeoffs were used to calculate cross sectional area of rebar per unit height of a pier. This information was transferred into Excel, where a set of calculations were performed based on the information available from the drawings.

The Pier Cross girder’s used a similar method to the piers themselves, though more assumptions were made. Due to the complexity of the cross girder’s shape, and the difficulty in calculating their individual shapes because of variation it was necessary to idealize the shape as a simple chevron, and the volume was calculated for each chevron using excel. The exception to this were the cross girders for G6 North and South, and D6 North and South, for which the takeoffs were completed in OnScreen Takeoff.

The concrete surface spans were calculated entirely in OnScreen Takeoff using area measurements. Assumptions had to be made in the consistency of the concrete thickness across both viaducts.

The I-Bean spans were first measured in cross-sectional area from OnScreen Takeoff, as well as rebar areas per unit length. The length and number of spans were tabulated again using OnScreen Takeoff and the total volume of concrete and rebar was calculated inside Excel.

The guard railings were done using two area measurements and one linear measurement in OnScreen Takeoff. The area measurements were the cross section of the concrete curb, and the cross section of the metal rail. The linear measurement was the length of rail on each side of each viaduct. The total volume of the rail was calculated in excel by combining these values.

3.1.3. IE Inputs and IE Input Assumptions

This study utilized many sources of data and inputs. These inputs are outlined in the IE Input Document which is attached to this report as Appendix A. Appendix B outlines the assumptions that were made in relation to the inputs into our Impact Estimator.

4.0 Results and Interpretation

4.1. Inventory Analysis

4.1.1. Bill of Materials

By completing takeoffs for the viaduct structures a bill of materials was developed outlining all of the materials that were used in their construction. Table 4.1 outlines the metric quantities that make up the Dunsmuir Viaduct, while Table 4.2 outlines the bill of materials used in the Georgia Viaduct.

Table 4.1: Dunsmuir Viaduct Bill of Materials

Material	Quantity	Unit
Aluminum	9	Tonnes
Concrete 20 MPa (flyash av)	6458	m3
Concrete 30 MPa (flyash 25%)	1653	m3
Rebar, Rod, Light Sections	265	Tonnes
Welded Wire Mesh / Ladder Wire	16	Tonnes
Emulsified Asphalt Primer Coat	10	Tonnes
Superpave 9.5	1902	Tonnes

Table 4.2: Georgia Viaduct Bill of Materials

Material	Quantity	Unit
Aluminum	9	Tonnes
Concrete 20 MPa (flyash av)	7084	m3
Concrete 30 MPa (flyash 25%)	1408	m3
Rebar, Rod, Light Sections	240	Tonnes
Welded Wire Mesh / Ladder Wire	18	Tonnes
Emulsified Asphalt Primer Coat	10	Tonnes
Superpave 9.5	2088	Tonnes

The largest quantity, by far, was concrete, in total it accounted for 16,602 cubic meters, or approximately 40,000 tonnes. Compare this to the second most abundant material, Asphalt, which accounted for just under 4,000 tonnes. The third most present material is steel reinforcing rebar, which accounts for just over 500 tonnes.

It is important to reference the Assumptions Document in Appendix B to understand the assumptions that were required in calculating the volumes associated with concrete. In some cases, particularly for the cross girders where more assumptions were made regarding the shape and intersection space of the piers, a number of smaller models were summed together to form the total. In this case, any small mistakes may propagate throughout the whole system.

Because the exact specifications of the asphalt lift on the viaducts are unknown, an assumption had to be made there regarding both the material used as well as the lift thickness. Variations in both of these values could affect the entire mass by a significant amount over the total surface of the viaducts.

Rebar will not vary as much, as the takeoff was done on more linear measurements within OnScreen Takeoff. That said, there is room for some errors to propagate and create a slight variation off of the real values.

4.2. Impact Assessment

4.2.1. Impact Categories

In this section, the characterization of the LCA models are presented to provide some context to the estimated resources and energy consumed and air, water and land emissions resulting from the product system process activity. As mentioned in the Goal & Scope, the impact assessment method used is the US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), which includes impact categories of primary energy consumption, weighted resource use, global warming potential, acidification potential, human health (HH) respiratory effects potential, eutrophication potential, ozone depletion potential, and smog potential. The following tables are adapted from ISO 21931-1, and summarize the impacts with respect to each impact category for the manufacturing and construction of each of the viaduct components. The tables only include the manufacturing and construction phase of the viaduct life cycle as the use phase was not within the scope of this study. In addition, the end-of-life options will be examined within Section 4.2.3.

Table 4.3: Global Warming Potential, kg CO2 eq

Life Cycle Stage	Process	Global Warming	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	kg CO2 eq	1095063.67	1554077.03	209826.81	972151.84	3336597.54	133419.33	406988.67	7708124.89
	Transportation	kg CO2 eq	36858.85	52308.82	7062.58	32721.75	112306.83	4490.77	13698.87	259448.46
	Total	kg CO2 eq	1131922.52	1606385.85	216889.38	1004873.58	3448904.38	137910.11	420687.54	7967573.36
Construction	Material	kg CO2 eq	239288.15	339589.58	45850.36	212430.03	729097.56	29154.16	88933.24	1684343.10
	Transportation	kg CO2 eq	63475.14	90081.75	12162.57	56350.58	193405.18	7733.62	23591.01	446799.86
	Total	kg CO2 eq	302763.29	429671.34	58012.93	268780.61	922502.74	36887.79	112524.26	2131142.95

Table 4.4: Ozone Depletion Potential kg CFC-11 eq

Life Cycle Stage	Process	Ozone Depletion Potential	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	kg CFC-11 eq	2.549E-03	3.617E-03	4.884E-04	2.263E-03	7.767E-03	3.106E-04	9.474E-04	1.794E-02
	Transportation	kg CFC-11 eq	1.526E-06	2.166E-06	2.925E-07	1.355E-06	4.651E-06	1.860E-07	5.673E-07	1.074E-05
	Total	kg CFC-11 eq	2.551E-03	3.620E-03	4.887E-04	2.264E-03	7.771E-03	3.108E-04	9.479E-04	1.795E-02
Construction	Material	kg CFC-11 eq	8.370E-06	1.188E-05	1.604E-06	7.430E-06	2.550E-05	1.020E-06	3.111E-06	5.892E-05
	Transportation	kg CFC-11 eq	2.592E-06	3.679E-06	4.967E-07	2.301E-06	7.899E-06	3.159E-07	9.635E-07	1.825E-05
	Total	kg CFC-11 eq	1.096E-05	1.556E-05	2.101E-06	9.732E-06	3.340E-05	1.336E-06	4.074E-06	7.716E-05

Table 4.5: Acidification Potential, Moles H+ eq

Life Cycle Stage	Process	Acidification	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	Moles H+ eq	353843.21	502162.22	67800.43	314127.24	1078140.40	43111.22	131508.50	2490693.21
	Transportation	Moles H+ eq	13510.60	19173.78	2588.79	11994.15	41166.04	1646.09	5021.32	95100.76
	Total	Moles H+ eq	367353.81	521336.00	70389.22	326121.38	1119306.44	44757.31	136529.81	2585793.98
Construction	Material	Moles H+ eq	78690.51	111674.89	15078.01	69858.15	239765.57	9587.42	29245.92	553900.47
	Transportation	Moles H+ eq	20002.16	28386.38	3832.64	17757.08	60945.46	2437.00	7433.95	140794.68
	Total	Moles H+ eq	98692.67	140061.27	18910.65	87615.23	300711.03	12024.42	36679.87	694695.15

Table 4.6: Eutrophication Potential, kg N eq

Life Cycle Stage	Process	Eutrophocation	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	Kg N eq	377.61	535.90	72.36	335.23	1150.57	46.01	140.34	2658.01
	Transportation	Kg N eq	14.13	20.05	2.71	12.54	43.04	1.72	5.25	99.44
	Total	Kg N eq	391.74	555.94	75.06	347.77	1193.61	47.73	145.59	2757.45
Construction	Material	Kg N eq	77.41	109.86	14.83	68.72	235.88	9.43	28.77	544.91
	Transportation	Kg N eq	20.72	29.41	3.97	18.40	63.14	2.52	7.70	145.87
	Total	Kg N eq	98.14	139.27	18.80	87.12	299.02	11.96	36.47	690.78

Table 4.7: Smog Potential, kg NOx eq

Life Cycle Stage	Process	Smog Potential	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	kg Nox eq	3698.27	5248.47	708.63	3283.17	11268.44	450.59	1374.49	26032.06
	Transportation	kg Nox eq	307.25	436.04	58.87	272.77	936.18	37.43	114.19	2162.74
	Total	kg Nox eq	4005.53	5684.51	767.50	3555.94	12204.61	488.02	1488.68	28194.80
Construction	Material	kg Nox eq	1700.43	2413.19	325.82	1509.57	5181.10	207.17	631.98	11969.26
	Transportation	kg Nox eq	446.55	633.73	85.56	396.43	1360.63	54.41	165.97	3143.29
	Total	kg Nox eq	2146.98	3046.92	411.39	1906.00	6541.73	261.58	797.94	15112.54

Table 4.8: Human Health Respiratory Potential, kg PM2.5 eq

Life Cycle Stage	Process	Respiratory Impacts	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	kg PM2.5 eq	2524.68	3582.93	483.76	2241.30	7692.55	307.60	938.31	17771.13
	Transportation	kg PM2.5 eq	16.33	23.18	3.13	14.50	49.77	1.99	6.07	114.97
	Total	kg PM2.5 eq	2541.01	3606.12	486.89	2255.80	7742.32	309.59	944.39	17886.11
Construction	Material	kg PM2.5 eq	104.30	148.01	19.98	92.59	317.79	12.71	38.76	734.14
	Transportation	kg PM2.5 eq	24.04	34.12	4.61	21.34	73.25	2.93	8.93	169.22
	Total	kg PM2.5 eq	128.34	182.13	24.59	113.93	391.03	15.64	47.70	903.36

Table 4.9: Weighted Resource Use, kg

Life Cycle Stage	Process	Weighted Resource	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	kg	13300409.75	18875488.13	2548511.62	11807548.81	40525601.96	1620482.77	4943197.57	93621240.61
	Transportation	kg	13500.53	19159.49	2586.86	11985.21	41135.36	1644.86	5017.57	95029.88
	Total	kg	13313910.28	18894647.62	2551098.47	11819534.02	40566737.31	1622127.64	4948215.14	93716270.48
Construction	Material	kg	73372.23	104127.37	14058.96	65136.81	223561.07	8939.46	27269.34	516465.24
	Transportation	kg	19969.50	28340.04	3826.39	17728.09	60845.95	2433.03	7421.82	140564.81
	Total	kg	93341.73	132467.41	17885.35	82864.90	284407.02	11372.48	34691.16	657030.05

Table 4.10: Fossil Fuel Use, MJ

Life Cycle Stage	Process	Fossil Fuel	Assembly Group							
			Piers	Footings	Girders	Stringers	Decking	Side Rails	Paving	Total
Manufacturing	Material	MJ	16374906.27	23238708.80	3137620.54	14536958.55	49893420.31	1995070.38	6085857.39	115262542.24
	Transportation	MJ	574790.16	815722.60	110136.41	510274.72	1751353.35	70030.74	213625.10	4045933.09
	Total	MJ	16949696.43	24054431.40	3247756.96	15047233.27	51644773.66	2065101.12	6299482.48	119308475.32
Construction	Material	MJ	3121407.78	4429795.53	598097.66	2771055.59	9510754.32	380303.14	1160094.74	21971508.76
	Transportation	MJ	847551.27	1202815.87	162400.58	752420.66	2582441.15	103263.15	314998.82	5965891.51
	Total	MJ	3968959.06	5632611.40	760498.24	3523476.25	12093195.47	483566.29	1475093.56	27937400.27

4.2.2. Uncertainty

The project presents a rather large amount of uncertainty stemming primarily from a deficit of information and the lack of an LCA tool to handle viaduct analysis.

The takeoff method used required a large number of calculations outside of OnScreen Takeoff. The Takeoff method could only be relied on for area measurements, when the various heights and different cross sections were taken into account, an external compiling software was required. A large number of Excel formulas worked to achieve this. Unfortunately, due to a combination of rounding changes, and potential errors in the formulas, a source of error is introduced with this intermediate step.

As mentioned earlier, the age of the drawings also contributes to the uncertainty. Many drawings were signed off in 1969, and the scanned versions of these are missing sections of text, blurred out text due to low resolution, mis-scanned text, or blacked out text. This makes it difficult to perform the proper takeoff in OnScreen Takeoff and errors can be introduced. This was particularly problematic in the transferring of large volumes of values from tables in the drawings into Excel, when some numbers could be misinterpreted. In some cases a 6 or an 8 could be confused, leading to 2 foot differences in measurements.

Another significant area of uncertainty was the information deficit. Due to the age of the project, as well as the change in construction technology, many of the production methods are unknown. For instance, the specific composition of concrete used in the viaducts is unknown, due to a missing general notes page. As a result the impact associated with concrete may vary as the specific mixture varies. The same is true for asphalt, as well as the specific construction methods used in assembling the viaducts. Machinery impacts are difficult to account for because, while it is possible to predict what equipment was used in the assembly, it is hard to know what their working hours were and how that will affect the impact.

The final source of uncertainty was the lack of specialized life cycle assessment software. Athena Impact Estimator for Buildings and Athena Impact Estimator for Highways, while strong software for building estimation and highway estimate respectively, are not designed for conducting LCAs on bridges and viaducts. Unfortunately, there are no other available LCA tools for use in this study, so these tools were used to develop results in using the material takeoffs. The anticipated results are some material additions, changes in rebar ratio, or smaller values.

4.2.3. End of Life Assessment

Two end-of-life options for the viaducts were analysed; converting them into a greenway, like High Line Park in New York, or using a Cut and Haul method of removal. By comparing their potential impacts, it should be possible to draw some conclusions regarding which option is better, or if there is an optimal combination of the two.

The first method, greenway construction, would add a lift of rubberized asphalt in order to seal the viaduct surface. A layer of drainage rock would be added above that in order to drain away excess water during rain or water and prevent standing puddles. On top would be a lift of loam that would be populated with grass and plant life. This method is viewed as low impact, while improving green space in the region.

The second option is Cut and Haul. This requires large section of the viaduct to be saw cut and then, using a crane or excavator, placed in haul vessels. The option for haul that was analysed was barging from the viaducts to the North Vancouver concrete recycling facility. A trip of approximately 18km. This was determined to be one of the most effective methods of removal.

Table 4.11 Greenway Impact

Impact category		Manufacturing			Construction			Overall
		Material	Transport	Total	Material	Transport	Total	Total
Fossil Fuel Consumption	MJ eq.	31830795.70	208683.59	32039479.30	11661285.41	1202067.37	12863352.78	89805664.14
Weighted Resource Use	kg	25580220.94	4917.07	25585138.01	274558.47	28323.50	302881.98	51776039.98
Global Warming Potential	CO2 eq.	237765.78	16019.21	253784.99	906173.41	92274.46	998447.88	2504465.74
Acidification Potential	H+ moles eq.	146078.50	4926.95	151005.45	279212.16	28380.41	307592.57	917196.04
HH respirator effects	PM2.5 eq.	1013.38	5.92	1019.30	381.20	34.11	415.31	2869.22
Eutrophocation Potential	N eq.	107.03	5.10	112.14	275.37	29.40	304.77	833.82
Ozone Depletion Potential	CFC-11 eq.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Smog Potential	Nox eq.	991.63	110.02	1101.65	5914.69	633.73	6548.42	15300.14

Table 4.12 Cut and Haul Impacts

Impact category		Deconstruction	Recycling Transport	Total
Global warming	CO2 eq.	18784.63	41983.92	60768.55
Acidification	H+ moles eq.	6271.73	49265.89	55537.63
Respiratory effects	PM2.5 eq.	8.29	55.88	64.17
Eutrophication	N eq.	5.99	46.39	52.38
Smog	NOx eq.	127.94	1050.77	1178.71
Total energy	MJ eq	259886.20	573061.80	832948.00
Fossil energy	MJ eq	257320.48	567404.25	824724.72
Non-renewable, nuclear	MJ eq	2189.03	4826.93	7015.96
Renewable energy	MJ eq	376.69	830.63	1207.32

All model uncertainties considered, it would appear that Cut and Haul has a drastically lower impact than a greenway. It should be considered that the delivered services from these scenarios are not perfect functional equivalents, as the Cut and Haul does not include the development of the greenspace provided by the greenway, and the greenway does not provide the street level development space of the Cut and Haul. Further analysis of these scenarios should address this in the LCA model development.

Taking the above results at face value, however, would indicate that removing the viaducts completely is the correct course of action based solely on this impact estimation.

4.2.4. Chain of Custody Inquiry

This study included investigating the chain of custody for concrete. Lehigh Concrete Group is a group of local concrete manufacturers that manage all links in the supply chain, from resource extraction to ready-mix delivery. They were contacted as they were likely the concrete suppliers for the viaduct structures during their construction. Their chain of custody, with regards to their aggregate suppliers, cement suppliers, etc., is the shared amongst the Ocean Concrete Group and Allied Ready Mix.

Lehigh Concrete Group gets its extracted aggregate from Sechelt Island and then the aggregate is barged to the mix facilities. The Cement is manufactured at their plant in Delta, BC and is then shipped via barge or truck to the mix facilities. The fly ash that is used in their mixes is sourced from Edmonton, AB and typically shipped to the mixing facilities in Vancouver via rail or truck. There are three Lehigh Concrete mixing facilities in the Lower Mainland. These mix facilities are located on Mitchell Island in Richmond, Granville Island in Vancouver, and in North Vancouver. The ready mix concrete is then loaded into a concrete truck and transported to site.

Lafarge is the other current major supplier of concrete within the Lower Mainland. Their facilities are a further distance from the viaducts and not likely to be the supplier of the concrete to this structure. Their chain of custody information was not available upon request.

4.2.5. Functions and Impacts

The following section outlines the function that the Georgia and Dunsmuir Viaducts provide, and the functional unit that is used to measure the impacts of the viaducts.

4.2.5.1. Structure Functions

The Georgia and Dunsmuir Viaducts serve as a part of the transportation infrastructure within the Lower Mainland. Its one function is to provide a means for vehicles, cyclists and pedestrians to travel between Vancouver's downtown core and East Vancouver. One hundred percent of the surface of the viaducts contributes to this function.

4.2.5.2. Functional Units

In a LCA study, a functional unit is a performance characteristic of the product system that will be utilized to express LCA results relative to its delivered performance. In this study, the functional unit relatively measures the performance of the viaduct structures. As previously mentioned, the viaducts provide a transportation solution for vehicles, cyclists and pedestrians. This study is designed to determine the effect of the viaducts have, and the effects of alternative solutions for the end-of-life of the viaducts. Considering the function that the viaducts serve the functional unit is:

- Per m2 area of elevated transportation surface (includes road and sidewalk)

In order to equate results using functional units, the total impacts of the viaducts need to be divided by their total area of road and sidewalk.

5.0 Conclusions

This LCA study applied LCA methods to create models of the Georgia and Dunsmuir viaducts from drawings. These models made it possible to provide a preliminary estimate of the impact of construction and end of life for the two viaducts which can be used as a benchmark for further development in the area of urban highways, and even as a comparison point for all road construction projects in the City of Vancouver. This information will allow urban planners to make more informed decisions when it comes to determining transportation infrastructure in the City.

The study found that the optimal end of life option for the viaducts is the removal by a Cut and Haul scenario. This should be taken with a grain of salt, however, since there was lack of information and LCA tools to complete a more detailed analysis to be done with confidence. Time constraints also caused issues with researching end of life modelling.

It is recommended that future work on estimating the impacts of removing the viaducts begin by validating the material quantities estimated for the viaducts. Then, research and develop end of life models using more sophisticated LCA modelling techniques and more complete datasets on machinery type and their useage.

Appendix A: IE Input Document

IE Inputs Document				
Assembly Group	Assembly Name	Input Fields	Input Values	
			Known/Measured	IE Inputs
1 Piers	1.1 Georgia Viaduct Cast-in-place Piers	Number of Piers	28	29
		Elevations (ft)	varied	varied
		Volume of concrete (tonnes)	9678.2415	9678.2415
		Concrete (psi)	unknown	4000
		Concrete flyash %	unknown	2500%
		Volume of rebar (tonnes)	2.013801814	2.013801814
	1.2 Dunsmuir Viaduct Cast-in-place Piers	Number of Piers	24	24
		Elevations (ft)	varied	varied
		Volume of concrete (tonnes)	8226.16441	8226.16441
		Concrete (psi)	unknown	4000
		Concrete flyash %	unknown	2500%
		Volume of rebar (tonnes)	1.705662184	1.705662184
2 Footings	2.1 Georgia Viaduct Concrete pile cap/foundations	Number of foundations	28	1
		Volume of concrete (tonnes)	13780.73719	13780.73719
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		Volume of rebar (tonnes)	7.014395229	7.014395229
	2.1 Dunmuir Viaduct Concrete pile cap/foundations	Number of foundations	24	1
		Volume of concrete (tonnes)	11620.93444	11620.93444
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		Volume of rebar (tonnes)	5.91505563	5.91505563
3 Cross Girders	3.1 Georgia Viaduct Cross girders	Number of cross girders	28	28
		Volume of concrete (tonnes)	1667.393756	1667.393756
		Concrete (psi)	unknown	4000

		Concrete flyash %	unknown	2500%
		Volume of rebar (tonnes)	176.192396	176.192396
	3.2 Dunsmuir Viaduct Cross girders	Number of cross girders	24	24
		Volume of concrete (tonnes)	1437.740942	1437.740942
		Concrete (psi)	unknown	4000
		Concrete flyash %	unknown	2500%
		Volume of rebar (tonnes)	150.07588	150.07588
4 Stringers	4.1 Georgia Viaduct Precast I-beam stringers	Number of I-beams per span	varies per span	varies per span
		Span length (ft)	varies per span	varies per span
		Total number of i-beams	142	142
		Total length of i-beams	2635.128	2635.128
		Total volume of concrete (tonnes)	8115.986	8115.986
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		Total volume of rebar (tonnes)	348.2291895	348.2291895
	4.2 Dunsmuir Viaduct Precast I-beam stringers	Number of I-beams per span	varies per span	varies per span
		Span length (ft)	varies per span	varies per span
		Total number of i-beams	170	170
		Total length of i-beams	2918.25	2918.25
		Total volume of concrete (tonnes)	7124.00158	7124.00158
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		Total volume of rebar (tonnes)	309.869721	309.869721
5 Decking	5.1 Georgia Viaduct 9" concrete slab	Total surface area (sq ft)	186554	186554
		total volume (tonnes)	28559.1735	28559.1735
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
	5.2 Dunsmuir Viaduct 9" concrete slab	Total surface area (sq ft)	169876	169876
		total volume (tonnes)	26005.8794	26005.8794
		Concrete (psi)	unknown	3000

		Concrete flyash %	unknown	average
6 Side rails	6.1 Georgia viaduct	concrete (tonnes)	1059.98208	1059.98208
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		rebar (tonnes)	29.653	29.653
		railing (tonnes)	8.553597252	8.553597252
	6.2 Dunsmuir viaduct	concrete (tonnes)	1050.71112	1050.71112
		Concrete (psi)	unknown	3000
		Concrete flyash %	unknown	average
		rebar (tonnes)	24.4947	24.4947
		railing (tonnes) - aluminum	8.478784448	8.478784448
7 Paving	7.1 Georgia Viaduct topping	primer	17.33587	17.33587
		ashpalt	3620.487754	3620.487754
		Asphalt Type	unknown	SuperPave 9.5
	7.2 Dunsmuir Viaduct topping	primer	15.78604	15.78604
		ashpalt	3002.080164	3002.080164
		Asphalt Type	unknwon	SuperPave 9.5

Appendix B: IE Input Assumptions Document

IE Input Assumptions Document		
Assembly Group	**Assembly Name**	**Specific Assumptions**
1 Piers	Because there is no assembly in the IE that would mimic the construction of the piers, given the higher rebar content and highly varied shapes, it was necessary to enter these into the IE as extra basic materials: both concrete are rebar quantities were determined externally and separately and the input into IE. Concrete was entered as a raw volume (yards cubed), and rebar as a weight (tons).	
	1.1 Georgia Viaduct Cast-in-place Piers	The concrete type was unknown, so it had to be entered based on assumed structural requirements. In this case we consulted with two external sources who claimed that a 28 day strength of 4000psi at 25% flyash would be the likely concrete for construction. The rebar was assumed to have a standard density of steel, and the volume was calculated used excel tables.
	1.2 Dunsmuir Viaduct Cast-in-place Piers	The concrete type was unknown, so it had to be entered based on assumed structural requirements. In this case we consulted with two external sources who claimed that a 28 day strength of 4000psi at 25% flyash would be the likely concrete for construction. The rebar was assumed to have a standard density of steel, and the volume was calculated used excel tables.
2 Footings	The footings were assumed to be constructed using a similar method as defined by Concrete Footing Foundations in the IE. Unfortunately, because of the shear volume of footings involved, the volume of concrete used for all footings in one viaduct was used. The thickness was assumed to be 1 foot, the width 25 feet, and the length determined from that. The concrete was assumed to be 3000psi with #5 rebar. The equation used to L = Volume/(width*height)	
	2.1 Georgia Viaduct Concrete pile cap/foundations	The formula: Length = Volume/25 was used to calculate the length, which was input into the document as the length of the concrete slab assuming a depth of 1 foot and a width of 25 feet.
	2.1 Dunsmuir Viaduct Concrete pile cap/foundations	The formula: Length = Volume/25 was used to calculate the length, which was input into the document as the length of the concrete slab assuming a depth of 1 foot and a width of 25 feet.
3 Cross Girders	The cross girders were also entered as extra basic materials. Unfortunately, because of their complex geometry, it was difficult to get an exact volume of concrete and rebar used in their construction. As a result the shape was idealized in excel as a chevron with a flat base, and the individual dimensions were pulled from the drawings. This did represent a source of error as some of the numbers on the drawings were illegible.	

	3.1 Georgia Viaduct Cross girders	The width was assumed to be 5 feet based on the drawings for cross girders. The width was assumed to be twice the value of g found in the design drawings. The slope was assumed to be approximately 2% for the super elevation of the cross girder. An exception to this was G6 North and South, which, due to unique and more complex geometry, was calculated in OnScreen Takeoff with an assumed thickness of 5 feet.
	3.2 Dunsmuir Viaduct Cross girders	The width was assumed to be 5 feet based on the drawings for cross girders. The width was assumed to be twice the value of g found in the design drawings. The slope was assumed to be approximately 2% for the super elevation of the cross girder. An exception to this was D6 North and South, which, due to unique and more complex geometry, was calculated in OnScreen Takeoff with an assumed thickness of 5 feet.
4 Stringers	The stringers were entered into the IE as extra basic material. The volume calculation was done based on the cross sectional area of the stringer, the number of stringers per span, and the total length of each span. The rebar weight was calculated in a similar way, based on the cross sectional area of rebar per linear meter.	
	4.1 Georgia Viaduct Precast I-beam stringers	
	4.2 Dunsmuir Viaduct Precast I-beam stringers	
5 Decking	The decking entered into the IE as concrete slab on grade. Since the depth of concrete slab is limited to 4 or 8", the thickness was assumed to be 8" and the width assumed to be 25feet in order to ease calculations.	
	5.1 Georgia Viaduct 9" concrete slab	The width of the span was assumed to be 25 feet, and the formula L = volume/(0.6667 feet*25 feet) in order to generate the appropriate values. The volume was found by using the actual concrete thickness of 10" multiplied by the actual surface area of the road. Superelevation was ignored.
	5.2 Dunsmuir Viaduct 9" concrete slab	The width of the span was assumed to be 25 feet, and the formula L = volume/(0.6667 feet*25 feet) in order to generate the appropriate values. The volume was found by using the actual concrete thickness of 10" multiplied by the actual surface area of the road. Superelevation was ignored.
6 Side rails	The side rails were done as a linear measurement in TakeOff, as well as a cross section. By multiplying the two, an approximation of concrete and rebar use was obtained. Unfortunately, the guard rail has a more complicated shape, and	

	so some of the variation in concrete shape was neglected. The aluminium railing was calculated based on its cross sectional area multiplied by its length.	
	6.1 Georgia viaduct	A single railing cross section was developed with concrete and rebar areas per unit length. This was multiplied by the total length of railing in the structure.
	6.2 Dunsmuir viaduct	A single railing cross section was developed with concrete and rebar areas per unit length. This was multiplied by the total length of railing in the structure.
7 Paving	The paving was assumed to be a standard 50mm lift of SuperPave 9.5. The IE for Highways was used with an assumed width of 10m, and a length calculated based on the surface area of the street divided by that width.	
	7.1 Georgia Viaduct topping	
	7.2 Dunsmuir Viaduct topping	