NOTE TO USERS

This reproduction is the best copy available.

UMI[®]

ESTIMATION OF DIRECT AND INDIRECT ENERGY REQUIREMENTS FOR BUS RAPID TRANSIT (BRT) AND LIGHT RAIL TRANSIT (LRT)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of
Master of Applied Science

by

A.K.M. Mushfiqur Rahman

M.A. in International Development, Nagoya University, Japan, 2005

B.Sc. Engineering (Civil), Bangladesh University of Engineering & Technology, 1993

Department of Civil and Environmental Engineering
Carleton University

Ottawa-Carleton Institute of Civil and Environmental Engineering

August, 2009

© Copyright 2009
A.K.M. Mushfiqur Rahman

**Library and Archives
Canada**

**Published Heritage
Branch**

**395 Wellington Street
Ottawa ON K1A 0N4
Canada**

**Bibliothèque et
Archives Canada**

**Direction du
Patrimoine de l'édition**

**395, rue Wellington
Ottawa ON K1A 0N4
Canada**

Your file Votre référence
ISBN: 978-0-494-60228-7
Our file Notre référence
ISBN: 978-0-494-60228-7

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

ABSTRACT

In recent years, Bus Rapid Transit (BRT) has emerged as a competitor of Light Rail Transit (LRT). There is a debate about which mode is more energy efficient. A few researchers have tried to compare BRT and LRT on the basis of direct energy consumption. To analyze energy consumption in its proper context, both direct and indirect energy need to be considered. This research was intended to fill this gap. The study first determined the energy intensities for different components of LRT and BRT. Then a life cycle energy assessment for a transit corridor in Ottawa was conducted. Several energy estimation models were developed to estimate vehicle and infrastructure energy consumption. It was found that BRT and LRT nearly consumed the same amount of energy, if a 2.5 km tunnel is considered. However, without the tunnel, LRT consumed approximately 12% more energy than BRT. The share of indirect energy was 66% of the total life cycle energy for both the systems.

ACKNOWLEDGEMENTS

I would like to express my profound gratitude and sincere appreciation to my supervisor Professor Ata M. Khan for his invaluable guidance, constant encouragement, regular feedback and immense support through out the course of this research and my academic pursuit at Carleton University. I am thankful to God to have been a student of Professor Khan. I have learnt a great deal from him as a student, an engineer and a person. He has been a true role model to me. His knowledge, critical thinking, sincerity and timeliness will guide me through out my life.

I am profoundly indebted to Ontario Government for providing me financial support through Ontario Graduate Scholarship Program (OGS). I am equally indebted to my supervisor for providing a research grant.

I would like to thank Dr. Mona Abouhenidy, Program Manager of Transportation Strategic Planning branch of the City of Ottawa, for her support in providing me the latest information and documents regarding City of Ottawa's updated transportation master plan and downtown tunnel project. I would also like to thank Mr. Salah Barj, Director, Planning and Development, Société de Transport de l'Outaouais (STO) for his suggestion and advice.

My deep appreciation goes to my classmates whom I studied with at Carleton University, shared ideas and views and spent time during my study period.

My heartfelt thanks to my beloved wife Dr. Naureen Mahbub Rahman for her love, endurance and constant support. I am also indebted to my daughter and son, whom I have not been able to give enough time and proper care during my studies. I owe to all of my family members whose continuous encouragement and support inspired me to carry out my studies. I am especially indebted to my mother-in-law for her valuable guidance and support.

The last, but surely most of all, I want to thank God, as without his blessing, this thesis would have never been completed.

TABLE OF CONTENTS

Abstract	i
Acknowledgements	ii
Table of Contents	iii
List of Tables	viii
List of Figures	xi
Glossary	xiv

Chapter 1: Introduction

1.1 Background	1
1.2 Problem statements	4
1.3 Research objective	6
1.4 Research framework	7
1.5 Thesis organization	9

Chapter 2: Energy Factors in Transportation System Analysis

2.1 Introduction	10
2.2 Sources of energy	10
2.3 Energy unit	12
2.4 Transportation fuel	12
2.5 Element of transportation and energy consumption	15
2.6 Framework of energy analysis	17
2.7 Energy analysis methodologies	19
2.7.1 The process based analysis	21
2.7.2 The input-output analysis	22
2.7.3 Combination approach	23

Chapter 3: Bus Rapid Transit and Its Energy Requirements

3.1 Introduction	24
3.2 What is Bus Rapid Transit (BRT)?	25
3.3 Features of BRT	26
3.4 Components of BRT	27
3.5 Energy analysis for BRT system	27
3.6 Life cycle assessment (LCA) of bus	27
3.7 Bus manufacturing energy	29
3.7.1 Combined approach	29
3.7.2 Input-output approach	31
3.7.2.1 Type of vehicle and propulsion technology	33
3.7.2.2 Unit vehicle costs	33
3.7.2.3 Production cost of vehicle	33
3.7.2.4 Useful life of transit buses	34

3.7.2.5 Estimation of vehicle manufacturing energy using EIOLCA	35
3.8 Bus maintenance energy	36
3.9 Bus operating energy consumption	37
3.10 Fuel production energy	40
3.11 Running way energy consumption	41
3.11.1 Running way construction	41
3.11.2 Type of pavements for running way and their construction process	42
3.11.3 Life cycle stages of ruining way	44
3.11.4 Estimation of running way construction energy	46
3.12 Running way maintenance	48
3.13 Winter maintenance	50
3.14 Running way lighting	51
3.15 Park-and-ride lot	51
3.16 Station energy consumption	52
3.16.1 Station cost	52
3.16.2 Energy requirement for a typical BRT station construction	53

Chapter 4: Light Rail Transit and Its Energy Requirements

4.1 Introduction	54
4.2 Overview of light rail transit system	54
4.3 Principal components of LRT	55
4.3.1 Trackways	56
4.3.2 Stations	56
4.3.3 Rolling stock	56
4.3.4 Electric power supply	57
4.3.5 Signals	58
4.3.6 Operation and maintenance center	58
4.3.7 Communications facilities	58
4.4 Capital cost of LRT	59
4.5 Factors affecting LRT energy consumption	60
4.5.1 The impact of station spacing on energy consumption	62
4.5.2 The impact of operating regime on energy consumption	63
4.6 Energy estimation for LRT vehicle	64
4.6.1 LRT vehicle life cycle energy consumption	64
4.6.1.1 Raw materials energy consumption	65
4.6.1.2 Manufacturing energy consumption	65
4.6.1.3 Energy consumption for delivery	66
4.6.1.4 Energy consumption for operation	66
4.6.1.5 Energy consumption for maintenance	66
4.6.1.6 Energy consumption for recycling	67
4.6.1.7 Total life cycle energy consumption	67
4.6.2 LRT vehicle manufacturing energy using EIOLCA	70
4.6.3 Energy consumption to generate electricity	71
4.7 Light rail transit infrastructure	72
4.8 Track construction energy	73

5.13. Light rail vehicle life cycle energy	127
5.13.1 LRV manufacturing energy	127
5.13.2 LRV maintenance	127
5.13.3 Light rail vehicle operating energy	127
5.13.4 Electricity generation energy	128
5.13.4.1 Electricity generation pathways	128
5.13.4.2 Electricity generation mix	130
5.13.4.3 Combustion technologies	130
5.13.4.4 Power plant conversion efficiencies	131
5.13.4.5 Electricity transmission and distribution efficiency	132
5.13.4.6 Summary of electricity generation energy analysis	132
5.14 LRT and BRT per km roadway construction energy	135
5.14.1 Busway construction energy	136
5.14.2 Design parameters	137
5.14.2.1 Bus way cross-section	137
5.14.2.2 Pavement structural layer	138
5.14.3 Construction energy for prime coat and tack coat	139
5.14.4 Construction energy for busway shoulder	140
5.14.5 Construction energy for curb and median block	140
5.14.6 Summary of busway construction energy	141
5.14.7 Other road infrastructure components	141
5.14.8 Bus way maintenance energy	143
5.14.9 Winter maintenance energy	144
5.15 LRT track construction energy	145
5.16 Tunnel construction energy	146
5.17 Stations construction energy	148
5.18 Station operation and maintenance	149
5.19 Maintenance facilities	151

Chapter 6: Results and Discussions

6.1 Introduction	152
6.2 Life cycle energy consumption for transit bus	153
6.2.1 Manufacturing energy	154
6.2.2 Maintenance energy	154
6.2.3 Operating energy	156
6.2.4 Fuel production energy	158
6.3 Life cycle energy consumption for light rail vehicle	160
6.3.1 Light rail vehicle manufacturing	160
6.3.2 Light rail vehicle maintenance energy	161
6.3.3 Light rail vehicle operating energy	162
6.3.4 Electricity generation energy	163
6.4 Infrastructure energy consumption	164
6.4.1 Busway construction energy	164
6.4.2 Maintenance energy	165
6.4.3 Trackway construction	166

6.4.4 Track maintenance energy	167
6.4.5 Tunnel construction energy	167
6.4.6 Stations construction energy	167
6.4.7 Station operation	168
6.4.8 Maintenance facilities	168
6.5 BRT/LRT total system life cycle energy	168
6.5.1 BRT 30-years life cycle energy	169
6.5.2 LRT 30-years life cycle energy	171
6.6 Energy intensity per unit output (Vehicle life cycle)	173
6.7 Energy intensity per unit output (Vehicle and Infrastructure)	175
6.8 BRT and LRT energy consumption (without Tunnel)	182
6.8.1 BRT infrastructure energy estimation	182
6.8.2 LRT infrastructure energy estimation	184
6.9 Energy intensity per unit output (Vehicle and Infrastructure)	185
 Chapter 7: Life Cycle Energy Estimation for an Automobile	
7.1 Introduction	187
7.2 Future automobile travel demand	187
7.3 Major travel flows	188
7.4 Selection of vehicle	188
7.5 Energy estimation	189
7.5.1 Automobile manufacturing energy	189
7.5.2 Automobile maintenance energy	192
7.5.3 Automobile operating energy	193
7.5.4 Gasoline production energy	194
7.5.5 Insurance	195
7.6 Infrastructure construction energy	195
7.6.1 Roadway construction	196
7.6.2 Road maintenance energy	200
7.6.3 Winter maintenance energy	201
7.6.4 Parking	202
7.7 Summary of direct and indirect energy consumption	205
7.8 Comparison of direct and indirect energy consumption of BRT, LRT and automobile	206
7.9 Comparison of energy intensity of BRT, LRT and automobile	207
 Chapter 8: Conclusions and Recommendations	210
 References	225
Appendixes	236

LIST OF TABLES

Table 3.1	: Costs of BRT vehicles by type	33
Table 3.2	: Contributors to manufacturers suggested retail price	34
Table 3.3	: Comparison of transit vehicle useful life	34
Table-3.4	: Bus manufacturing energy using EIOLCA method	35
Table 3.5	: Average fuel consumption by bus type	39
Table 3.6	: Examples of various types of BRT running ways	41
Table 3.7	: Busway construction costs (U.S. Dollars)	46
Table 3.8	: Busway construction costs by type (U.S. Dollars)	47
Table 3.9	: Typical busway costs (excluding right-of-way) and energy consumption	47
Table 3.10	: Running way maintenance energy, Toronto area	49
Table 3.11	: Roadway maintenance energy	50
Table 3.12	: Energy for salt and sand extraction	50
Table 3.13	: Construction energy for 500 car capacity park-and-ride lot	51
Table 3.14	: BRT station costs by type of running way	53
Table 4.1	: Capital cost comparison of light rail systems (costs in 2000 US dollars)	59
Table 4.2	: Raw materials and their energy consumption for LRV manufacturing	65
Table 4.3	: Recycling energy consumption	67
Table 4.4	: Vehicle manufacturing and maintenance energy intensity	68
Table 4.5	: Light rail vehicles direct energy consumption	68
Table 4.6	: Energy consumption for the manufacture of a rapid rail car	69
Table 4.7	: Total life cycle energy for two USA light rail systems	70
Table 4.8	: Average new light rail vehicle costs in 2008 (U.S.)	71
Table 4.9	: Track construction cost and energy requirement for selected LRT systems	74
Table 4.10	: Construction energy requirements for five types of rapid rail guideway	74
Table 4.11	: Rail track construction energy	75
Table 4.12	: Annual track maintenance energy	75
Table 4.13	: Costs and energy requirement by station type for LRT projects	76
Table 4.14	: Energy profile of systems analyzed	76
Table 4.15	: Energy for overhead electrical distribution system	77
Table 4.16	: LRV maintenance facility construction energy	78
Table 5.1	: Population and employment projection	88
Table 5.2	: City wide projected travel demand-all modes	90
Table 5.3	: Growth in travel by mode – Inner area cordon (a.m. peak hour)	92
Table 5.4	: Peak hour passenger load point forecasts for two alternative scenarios	94
Table 5.5	: Passenger capacity of BRT & LRT vehicles (No. of passenger/vehicle)	97
Table 5.6	: No of Transit Unit (TU) required in service to accommodate 2031 ridership	97

Table 5.7	: OC-transpo ridership variation over time	100
Table 5.8	: BRT Bus manufacturing energy using EIOLCA method	103
Table 5.9	: Definition of Vehicle Specific Power (VSP) modes	110
Table 5.10	: Energy efficiencies of petroleum-based fuel-cycle stages (%)	118
Table 5.11	: Shares of process fuels for each stage	118
Table 5.12	: Share of crude feedstock input to GREET model	119
Table 5.13	: Oil sands recovery and upgrading efficiency	119
Table 5.14	: Fuel specifications and refining efficiencies	124
Table 5.15	: Calculations of energy consumption of petroleum fuels by stage (Btu per MBtu of diesel fuel)	125
Table 5.16	: Feedstock energy (Btu/MBtu diesel fuel production)	126
Table 5.17	: Summary of energy consumption: Btu/MBtu of fuel throughput at each stage	126
Table 5.18	: Electricity generation mixes, combustion technology shares and power plant energy conversion efficiencies	131
Table 5.19	: Power plant energy use Btu per Mega Btu of electricity available at user sites (wall outlets)	134
Table 5.20	: Fuel-cycle and power plant energy use for electric generation: Btu per Mega Btu of electricity available at user sites (wall outlets)	134
Table 5.21	: Characteristics of pavement layers	139
Table 5.22	: Energy use to construct different layers of pavement	139
Table 5.23	: Construction energy for prime and tack coat	140
Table 5.24	: Construction energy for shoulder	140
Table 5.25	: Construction energy for one km busway (2-lane)	141
Table 5.26	: Description of characteristics item for all other infrastructure components	142
Table 5.27	: Annual unit winter maintenance costs (\$)	144
Table 5.28	: Summary of per km trackway construction energy (Double track)	146
Table 5.29	: The construction cost of the downtown tunnel	147
Table 5.30	: Construction cost and construction energy of stations	149
Table 5.31	: Annual operating energy consumption of stations	151
Table 6.1	: Summary of bus life cycle energy intensities	153
Table 6.2	: Summary of life cycle energy consumption for transit buses	159
Table 6.3	: Summary of life cycle energy consumption of a LRV	163
Table 6.4	: Summary of busway construction energy	165
Table 6.5	: Construction energy of different LRT trackways	166
Table 6.6	: Summary of trackway construction energy	166
Table 6.7	: BRT total system (vehicle and infrastructure) life cycle energy	170
Table 6.8	: LRT total system (vehicle and infrastructure) life cycle energy	172
Table 6.9	: Energy intensity per unit output	174
Table 6.10	: Energy intensity (vehicle and infrastructure) for standard hybrid bus	177
Table 6.11	: Energy intensity (vehicle and infrastructure) for light rail vehicle	178

Table 6.12	: Summary of energy intensity (vehicle and infrastructure)	179
Table 6.13	: Energy intensity (vehicle and infrastructure) at different load factor	181
Table 6.14	: BRT total system (vehicle and infrastructure) life cycle energy	183
Table 6.15	: LRT total system (vehicle and infrastructure) life cycle energy	184
Table 6.16	: Energy intensity (vehicle and infrastructure) for standard hybrid bus and articulated hybrid bus	186
Table 6.17	: Energy intensity (vehicle and infrastructure) for light rail vehicle	186
Table 7.1	: Projected transit and automobile travel demand (Morning peak hour)	187
Table 7.2	: The top 10 best-selling compact cars in Canada in 2007	189
Table 7.3	: Honda Civic specification	189
Table 7.4	: Summary of energy consumption: mmbtu per-vehicle lifetime	192
Table 7.5	: Automobile driving costs, 2005	193
Table 7.6	: Average fuel consumption of Honda Civic automobile	194
Table 7.7	: AASHTO specifications for roadway design	197
Table 7.8	: PaLATE roadway construction energy factors	197
Table 7.9	: Roadway usages by commuters (based on fastest route)	197
Table 7.10	: Construction cost of a 5 storied parking garage	204
Table 7.11	: Summary of automobile lifecycle energy consumption	205
Table 7.12	: Energy intensity (vehicle and infrastructure) for different types of vehicle	207
Table 7.13	: Energy intensity (KJ per passenger-km)	207
Table 7.14	: Energy intensity (KJ per seat-km)	208
Table 7.15	: Energy intensity per passenger-km at design capacity	209

LIST OF FIGURES

Figure 1.1	: Energy consumption by sector	2
Figure 1.2	: Energy use by the transport system	5
Figure 1.3	: The research frame work	8
Figure 2.1	: Sources of energy	11
Figure 2.2	: Transportation energy use by mode in Canada	13
Figure 2.3	: Frame work of energy analysis	18
Figure 3.1	: Major stages of bus life cycle	28
Figure 3.2	: Schematic representation of stages of bus life cycle	28
Figure 3.3	: Methods for estimating bus manufacturing energy	30
Figure 3.4	: Schematic representation of EIOLCA analysis	32
Figure 3.5	: The historical trend of average fuel efficiency of transit buses	38
Figure 3.6	: Total energy cycle for a vehicle	40
Figure 3.7	: The principal stages of asphalt road construction	43
Figure 3.8	: The principal stages of concrete road construction	43
Figure 3.9	: Asphalt pavement life cycle	44
Figure 3.10	: Reinforced concrete pavement life cycle	45
Figure 3.11	: Construction energy of different type of BRT running way	47
Figure 4.1	: Light rail power pick up system	58
Figure 4.2	: Chain of factors affecting energy efficiency of LRT	61
Figure 4.3	: Relationship between station spacing and energy consumption	62
Figure 4.4	: Different station-to-station travel regime affecting energy consumption of LRT	63
Figure 4.5	: The life cycle of light rail vehicle	64
Figure 4.6	: Light rail vehicle life cycle energy consumption	67
Figure 4.7	: The essential components of LRT infrastructure	73
Figure 5.1	: Ottawa's rapid transit network	81
Figure 5.2	: Primary rapid transit options for Ottawa	84
Figure 5.3	: Approved rapid transit network	85
Figure 5.4	: Ottawa downtown East-West transit corridor	85
Figure 5.5	: Schematic diagram of the case study framework	87
Figure 5.6	: Population and employment growth of city of Ottawa	88
Figure 5.7	: Major employment nodes and density in Ottawa Inner area: 2031	91
Figure 5.8	: Ottawa Inner area screenlines	92
Figure 5.9	: Transit trip assignments for the year 2031	93
Figure 5.10	: Two alternative scenario of transit demands in 2031 on the corridor	94
Figure 5.11	: Average retirement age distribution of transit buses	99
Figure 5.12	: Average daily ridership of OC Transpo	100
Figure 5.13	: Variation of ridership with time of day	100
Figure 5.14	: Percent of fleet in service during different period of day	101
Figure 5.15	: Average speed of OC Transpo service	102
Figure 5.16	: Annual maintenance cost of OC Transpo buses	104
Figure 5.17	: Direct energy estimation model	105
Figure 5.18	: Transit corridor in VISSIM model	108

Figure 5.19	: Simulation run in VISSIM	109
Figure 5.20	: Variation of bus fuel consumption with VSP mode	111
Figure 5.21	: Diesel production from crude oil distillation	112
Figure 5.22	: Flowchart of total energy-cycle analysis	113
Figure 5.23	: Closed -Loop calculation of upstream energy use	115
Figure 5.24	: Flow diagram of diesel production energy estimation	116
Figure 5.25	: Share of crude feedstock used in Canadian refineries	119
Figure 5.26	: Domestic supply of crude oil in Canada	120
Figure 5.27	: Calculation logic of energy use for feedstock and fuel transportation	121
Figure 5.28	: Crude transportation from oil fields to petroleum refineries	122
Figure 5.29	: Petroleum refinery fuel use in 2001	123
Figure 5.30	: Pathway of electricity generation	129
Figure 5.31	: Ontario's electricity generation mix	130
Figure 5.32	: Variation of power plant energy use with combustion technology	133
Figure 5.33	: Variation of fuel cycle and power plant energy use in electricity generation with different combustion technologies	135
Figure 5.34	: Bus way construction energy estimation process	136
Figure 5.35	: Typical cross section of busway at transitway and at station	137
Figure 5.36	: Typical cross-section of a rigid pavement	138
Figure 5.37	: Cross section of Curb and Median	141
Figure 5.38	: Typical cross section of LRT track	145
Figure 5.39	: 10.0 m diameter BRT tunnel	146
Figure 5.40	: 6.0 m diameter LRT tunnel	147
Figure 6.1	: Life cycle energy consumption of different transit buses	159
Figure 6.2	: Direct and indirect energy consumption of different transit buses	160
Figure 6.3	: (a) Life cycle energy consumption of light rail vehicle, (b) Direct and indirect energy consumption	163
Figure 6.4	: BRT system life cycle energy consumption	170
Figure 6.5	: (a) Share of BRT system components energy consumption, (b) Direct and indirect energy consumption	171
Figure 6.6	: LRT system life cycle energy consumption	172
Figure 6.7	: (a) Share of LRT system components energy consumption, (b) Direct and indirect energy consumption	173
Figure 6.8	: Energy intensity per vehicle-km traveled for BRT and LRT vehicles	174
Figure 6.9	: Energy intensity per passenger-km traveled for BRT and LRT vehicles	175
Figure 6.10	: Energy intensity per vehicle-km traveled for BRT and LRT vehicles considering both vehicle and infrastructure life cycle energy	179
Figure 6.11	: Energy intensity per passenger-km traveled for BRT and LRT vehicles considering both vehicle and infrastructure life cycle energy	180
Figure 6.12	: Variation of energy intensity of transit vehicles with different load factor	181

Figure 6.13	: (a) Share of BRT system components energy consumption, (b) Direct and indirect energy consumption	183
Figure 6.14	: (a) Share of LRT system components energy consumption, (b) Direct and indirect energy consumption	185
Figure 7.1	: Simulation logic for GREET vehicle-cycle analysis	190
Figure 7.2	: Highway 417 current and projected AADT	198
Figure 7.3	: Vehicle-km traveled per lane km in different major roads of municipalities of Ontario in 2005	199
Figure 7.4	: 2005 - Maintenance cost per lane-km in different municipalities of Ontario	201
Figure 7.5	: 2005-Winter maintenance cost per lane km in different municipalities of Ontario	202
Figure 7.6	: Life cycle energy consumption for an automobile	205
Figure 7.7	: Direct and indirect energy consumption of an automobile	206
Figure 7.8	: Direct and Indirect energy consumption of BRT, LRT and automobile	206
Figure 7.9	: Comparison of energy intensity of bus, LRV and automobile	208
Figure 7.10	: Comparison of energy intensity of vehicles per seat-km	208
Figure 7.11	: Comparison of energy intensity of bus, LRV and automobile at design capacity passenger load	209

GLOSSARY

ANL	:	Argonne National Laboratory
AREMA	:	American Railway Engineering and Maintenance-of-Way Association
BRT	:	Bus Rapid Transit
BTS	:	Bureau of Transportation Statistics
Caltrans	:	California Department of Transport
CBD	:	Central Business District
EIA	:	American Energy Information Administration
EIOLCA	:	Economic Input-Output Life Cycle Assessment
FTA	:	Federal Transit Administration
GREET	:	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GHG	:	Green House Gas
GJ	:	Giga Joule
HEV	:	Hybrid-Electric Vehicles
IEA	:	International Energy Agency
ISO	:	International Organization for Standardization
LCA	:	Life-Cycle Assessment
LRT	:	Light Rail Transit
LRV	:	Light Rail Vehicle
LSD	:	Low Sulfur Diesel
MJ	:	Mega Joule
MRC	:	Municipalité Régionale de Comté
MBtu	:	Mega British thermal unit
MALTESE	:	Management and Assessment of Light Rail Transit for Energy Saving and Efficiency
NCR	:	National Capital Region
NRCan	:	Natural Resource Canada
ROW	:	Right of Way
SETAC	:	US Society of Environmental Toxicology and Chemistry
TMP	:	Transportation Master Plan
TU	:	Transit Unit
TJ	:	Tera Joule
USDOE	:	U.S. Department of Energy
USEPA	:	US Environmental Protection Agency
WTW	:	Well to Wheel

Chapter 1

Introduction

1.1 Background

There has been a growing concern about environmental protection and energy conservation. The amount of energy sources on earth is limited. The world energy consumption is increasing day by day. Over the last 50 years, energy consumption has increased nearly three fold (BPS, 2008). In 1965, the world consumption of oil, gas, coal, nuclear and hydro energy were 1530.8, 597.6, 1482.0, 5.8 and 210.5 million tonnes (or tonne of oil equivalent), respectively, whereas in 2006, the consumption of the same was increased to 3952.8, 2637.7, 3177.5, 622.0, 709.2 million tonnes, respectively (BPS, 2008). Over the years there has been a changing trend in energy use. While oil and coal accounted for 40% and 38% of total energy consumption in 1965, this share dropped to 35.6% and 28.6% in 2006. The share of natural gas substantially increased (15.6% to 23.7%) from 1965 to 2006. Nuclear energy consumption experienced a high rise from 0.15% to 5.6% (BPS, 2008).

According to the American Energy Information Administration (EIA, 2005) and the International Energy Agency (IEA, 2009), the world-wide energy consumption will on average continue to increase by 2% per year. It is important to conserve energy sources for our future generations. Energy conservation is also important because energy consumption has impacts on the environment.

The transport sector is a major energy consumer and its consumption is increasing over time. In 1973, the transport sector consumed 42.3% of the total energy consumption,

whereas in 2007, the consumption became 57.7% (Fig. 1.1). The energy consumption by transportation is associated with significant negative environmental impacts. The greenhouse gas (GHG) emission from the transportation sector is one of the major environmental impacts, which eventually contributes to climate change (Litman et al, 2006). Environmental impact from transportation activity is not only limited to GHG emission. Environmental impacts of transportation also include air, water and noise pollution, and the use and alteration of land and other natural resources.

Fig. 1.1: Energy consumption by sector (Source: International Energy Agency, 2009)

Rising energy consumption, the uncertainty of future energy supply and the growing concern about environmental protection, all have a direct impact on the transportation sector (Pisarski, 2009). Due to rising negative environmental and social impacts, transportation has attracted attention as a logical starting point for achieving sustainability. The transportation sustainability is a relatively new concept and is still evolving (Nichols et al, 2009). Sustainable transportation systems aim to reduce emissions, fossil fuel consumption and the consumption of agricultural land, park land and wildlife habitat. The key to sustainability concept is the reduction of energy use. According to Fulton (2000), advances in technology and alternative energy sources have not substantially led to reductions in energy use, as they have been offset by increasing

population and higher rates of travel. Thus, in an era when the global supply of petroleum appears to be peaking, more attention should be placed on an energy efficient mode of transportation. Transportation policy makers are continuously making efforts to find strategies for more energy efficient transportation system. Since policy makers cannot make harsh policy decisions to restrict modes of transportation, they have been urging the government to provide financial incentives to public transit modes, making them more competitive, attractive and energy efficient. As a result, this puts an emphasis on reducing the role of the private automobile as the prime mode of transportation and shifting travel toward other sustainable modes such as public transit, cycling and walking.

There is now a consensus to encourage and provide for greater use of public transport. The public transport sector has already been recognized for its contribution to the improvement of energy efficiency and reduction of GHG emissions throughout the world. The high quality public transport offers a real alternative to the private car. Public transportation takes a variety of forms such as buses, subways, trolleys and light rail, commuter trains, monorails, van pool services, paratransit services, ferries, etc. The effectiveness and attractiveness of each mode of public transport depends on the size and population of the city, topography, climate, geographical condition, etc.

Transportation policy makers always find themselves confronted with the discussion about energy efficiency of modes. Existing literature related to the energy intensity of various transportation modes (automobiles, buses, trucks, rail, waterways, and airplanes) are mostly based on direct energy (i.e. operating energy) consumption. Energy intensity values were determined according to propulsion system, operating conditions, types of

fuel used, trip characteristics, load factors and types of commodities being shipped, etc. Indirect energy was rarely mentioned. Indirect energy is usually ignored for several reasons. It is often difficult to trace the indirect energy use in the various steps (raw material extraction to the final product) of transportation system. As well as it is thought that indirect energy may contribute little to the total energy intensity value. Moreover there is a scarcity of reliable methodology to analyze indirect energy.

Therefore this study conducted a comprehensive energy analysis by considering both direct and indirect energy to compare the total energy consumption (both direct and indirect energy) for Bus Rapid Transit (BRT) and Light rail Transit (LRT) systems. For reference purposes, a comparison of energy consumption was also made with automobile.

1.2 Problem statements

Transportation energy consumption can be categorized as direct and indirect. Direct energy is the energy required to propel the vehicle and run the accessories. Indirect energy includes all the energy required to construct, operate and maintain a transportation system, including vehicle manufacturing and maintenance, and infrastructure construction, maintenance and operation. The energy required to produce fuels/power is also a part of the indirect energy. Construction and maintenance of transportation infrastructure and vehicles represent a substantial energy investment. According to literature, for a typical transport system, while direct energy consumption accounts for 66% of the total energy consumption, the energy consumption for the provision of fuels/power, vehicles and infrastructures accounts for 34% (Fig.1.2), (Tolley et al, 1995). Therefore, both direct and indirect energy are important in the energy analysis. In the

past, urban transportation systems were analyzed on the basis of financial, economic, social and system performance criteria. Transportation energy consideration was not included in the urban planning processes. Now that energy has become an important issue, attempts are being made to include it in the transportation and urban planning process. To date, only direct transportation energy is considered in the transportation planning process. To analyze energy consumption in its proper context, both the direct and indirect energy consumption by the transportation systems need to be considered.

Fig. 1.2: Energy use by the transport system (Source: Tolley et al., 1995)

In recent years Bus Rapid Transit (BRT) has emerged as a competitor of Light rail Transit (LRT). Promoters of BRT claim that it can provide all the benefits of LRT and it is cheaper. On the other hand promoters of LRT claim that LRT is safer, energy efficient and environment friendly. However, which mode is really energy efficient is highly debated. Some comparative studies of BRT and LRT were carried out on the basis of direct energy consumption (Bradley, 2008; Puchalsky, 2005; Bruun, 2005; Stutsman,

2002). To analyze energy consumption properly, however, both direct and indirect energy needed to be considered. Therefore, a comprehensive and systematic study of the total life-cycle energy consumption of these two modes was conducted to fill this gap.

1.3 Research objective

The main focus of this research was to conduct a comprehensive life cycle energy analysis of BRT and LRT under identical conditions by considering both direct and indirect energy consumption. The research was also intended to make comparisons with the automobile lifecycle energy use for reference purposes. The specific objectives were:

- to investigate contemporary energy analysis techniques for transportation system
- to determine energy intensities for various elements of BRT and LRT and factors affecting energy consumption
- to conduct a comprehensive life-cycle assessment (LCA) for energy consumption (raw materials extraction, manufacturing, construction, operation, maintenance & end-of-life) for both vehicles (bus/rail) and infrastructures (transit way, rail track).
- to apply micro simulation technique in energy estimation
- to estimate fuel production and electricity generation energy using GREET model
- to compare total energy requirements (both direct and indirect energy) for Bus Rapid Transit and Light Rail Transit system in an identical situation
- to conduct a life-cycle assessment (LCA) for energy consumption for an automobile and compare the energy intensity with BRT and LRT
- to describe the methodological implication of energy analysis in transportation planning and policy decision making

1.4 Research framework

This research was mainly aimed at estimating both direct and indirect energy consumption for BRT and LRT systems. To do this, the contemporary energy analysis methods were reviewed first. Next, the various components of BRT and LRT systems were defined and energy intensity of each component was determined. This was accomplished by analyzing data obtained from literature sources. Then, a life cycle energy assessment for a transit corridor in Ottawa, i.e., from Baseline to Blair via downtown Ottawa was conducted. The work started with the travel demand and ridership forecasting. With this information and the characteristics of network elements, headway for different fleet composition was calculated. Then a micro simulation model was developed using VISSIM to estimate average fuel consumption. The GREET model was used to estimate energy consumption for diesel fuel and electricity production. Several other energy estimation models were also developed. These models are discussed in their respective sections. The overall research framework is shown in Fig 1.3.

Fig 1.3: The research framework

1.5 Thesis organization

Chapter-1 introduces the background of the study, delineates the research objectives and describes the framework of the research to attain the objectives.

Chapter-2 describes the sources of energy, energy units, elements of transportation energy consumption and the techniques for estimating the energy consumption of various elements of the transportation systems.

Chapter-3 discusses about the components of BRT system and their energy requirements. The energy intensities of various components of BRT are also established through literature review and own analysis.

Chapter-4 reviews the basic elements of light rail transit system and their direct and indirect energy consumption. The various factors that affect energy consumption of LRT are also discussed and the energy intensities of various components of LRT are established.

In Chapter-5, a life cycle energy assessment (both direct and indirect energy) is described for both BRT and LRT for the Ottawa east-west transit corridor.

In Chapter-6, the life cycle energy consumption for both BRT and LRT vehicles is discussed first. Then the total transit system (vehicle and infrastructure) energy requirement for both LRT and BRT is evaluated. Finally the energy intensities per vehicle-km and passenger-km for BRT and LRT are presented, considering both direct and indirect energy.

In Chapter-7, the life cycle energy requirement for an automobile commuting to Ottawa downtown is presented for reference purposes.

Chapter-8 presents the conclusions and recommendations.

Chapter 2

Energy Factors in Transportation System Analysis

2.1 Introduction

Energy is a critical aspect of modern life. Energy is the capacity of a physical system to perform work or change the state of the system. It allows us to predict how much work the system could be made to do, or how much heat it can exchange. The consumption of energy can be divided into various broad sectors i.e., residential, commercial, industrial and transportation sectors. The transportation sector, which moves passengers as well as freight, is a major energy consumer. The energy consumption in transportation is diverse. Construction, maintenance, and operation of transportation infrastructure and vehicles consume substantial amount of energy. This chapter describes the factors, process and techniques to estimate the energy consumption of various elements of transportation sector.

2.2 Sources of energy

Energy occurs in two primary states, potential and kinetic. Potential energy is stored energy. Kinetic energy is the release of the potential energy to create motion, ultimately to do work. Energy, whether in the potential or kinetic state, occurs in different forms. These forms can be transformed from one to another to generate energy necessary to do work. The principal forms of energy are electrical energy, thermal energy, chemical energy, radiant energy, mechanical energy and nuclear energy (Rodrigue et al, 2008).

Energy is derived from both renewable and non-renewable sources. Renewable sources of energy are those which can be replenished, such as solar energy, wind energy, tidal

energy, hydraulic or water energy, geothermal energy and biomass energy. Non-renewable sources of energy can be used up or depleted. They include coal, petroleum, natural gas and nuclear energy. Fig. 2.1 depicts various sources of energy.

Fig. 2.1: Sources of energy

Oil, natural gas, and coal are called fossil fuels because they are derived from the remains (or "fossils") of dead plants and animals that were under exposure to heat and pressure in the earth's crust over hundreds of millions of years. Nuclear energy is produced from uranium through the process of nuclear fission. Nuclear energy is basically used to produce electricity. Wind, geothermal, and hydro energy are also used mainly to generate electricity. Solar energy can be directly converted to thermal (or heat) energy or electric energy by solar thermal collectors or photovoltaic cells. Biomass can be converted to heat or other usable forms of energy like methane gas or transportation fuels like ethanol and bio-diesel (Natural Resource Canada, 2008).

2.3 Energy unit

As energy is defined via work, the SI unit for energy is the same as the unit of work – the joule (J). The joule is the work done by a force of one Newton traveling through a distance of one meter. In English system, energy unit is expressed in British thermal Unit. A Btu is defined as the amount of energy required to increase the temperature of 1 pound of water by 1 degree Fahrenheit, at normal atmospheric pressure. Energy takes much form such as potential, kinetic, chemical, nuclear and thermal. But the most important form related to transportation is the thermal energy value or calorific value. Historically the calorie was defined in terms of the heating of water. Thus, in a traditional definition, one calorie is the amount of heat required to raise the temperature of 1 gram of water by 1°C. The equivalence between the calorie and joule is known as the mechanical equivalent of heat. The energy unit used for electricity is the kilowatt-hour (Kwh). Energy in kilowatt hours is the product of power in kilowatts multiplied by time in hours. The joule (J), equal to one watt second (one watt is equal to one joule per second); one kilowatt hour is 3.6 mega joules. The units for all forms of energy are convertible to each other.

2.4 Transportation fuel

There are various types of transportation fuels available today. While few of them are predominantly used, others are in experimental stage or have limited use due to economy of scale of production. Fuels derived from petroleum include conventional gasoline, reformulated gasoline, conventional diesel, reformulated diesel and liquefied petroleum gas. These are the most widely used transportation fuel. Fuels are also derived from

natural gas. These include compressed natural gas, liquefied natural gas, liquefied petroleum gas, methanol, Fischer-Tropsch diesel, dimethyl ether, hydrogen. The transportation sector also uses electricity as fuel. Electricity can be generated from residual oil, gas, coal, uranium, hydropower, solar, wind and geothermal. Other fuels include biomass, ethanol, biodiesel, and methanol (Wang, 1999).

Although the transportation sector uses a variety of substances as fuel, gasoline and diesel make up 86% of all the energy used in transportation (Natural Resources Canada, 2008). Gasoline is used mainly by cars, motorcycles, and light trucks. Diesel is used mainly by heavier trucks, buses, and trains. Fig. 2.2 shows transportation energy use by mode in Canada from 1990-2006.

Fig. 2.2: Transportation energy use by mode in Canada (based on data of Natural Resources Canada, 2008)

In 2006, cars and trucks consumed 46% and 31.5% of the total transportation energy in Canada, respectively. The share of urban transit was 1.8% only. Air accounted for 18% of total transportation energy. The biggest share of transportation energy was consumed by

the small and large cars. However, the trend of energy consumption by car is declining. In 1990, the energy consumption by cars (large and small) was 61.9% of the total energy, where as, in 2006, it was 46%. This may be due to the invention of more energy efficient vehicles as well as transit oriented development.

There is currently a push to develop vehicles that run on fuels other than petroleum products, or on blended fuels. There are some vehicles that run on electricity, natural gas, propane, and ethanol. Hybrid-electric vehicles (HEVs) combine the benefits of internal combustion engines and electric motors, reducing the amount of fuel required for propulsion. HEVs may be the best alternative vehicle for the near future. HEVs have the potential to be two to three times more fuel-efficient than conventional vehicles (Sreedhar, 2006). There are several hybrid buses in the market today. The majority of hybrid transit buses are currently being manufactured by three companies; General Motors (GM) Allison transmission, British Aerospace Engineering Systems, and ISE corporation. These buses employ similar technology that used in hybrid cars and trucks, including regenerative braking, electric motors, and battery storage.

Natural gas can be used as transportation fuel when compressed or liquefied. Propane, often called liquefied petroleum gas (LPG), is the most widely used and most accessible alternative fuel. Taxicab companies, government agencies, and school districts often use propane instead of gasoline to fuel their fleets. Ethanol is also considered as an alternative fuel. Ethanol is made by fermenting the sugars found in grains, such as corn, wheat, as well as potato wastes and urban wastes. There are about three million vehicles on the road today using ethanol blends. Bio-diesel, a fuel made by chemically reacting

alcohol with vegetable oils, fats, or greases, can be used in unmodified diesel engines with the existing fueling infrastructure. It is the fastest growing alternative transportation fuel in the U.S (Murugesan et al., 2009). Dedicated electric vehicles (EVs) have a great potential to replace gasoline-powered vehicle. However, dedicated electric vehicles require batteries that need to be discharged and recharged repeatedly. The weight of batteries and the cost associated with the replacement is the biggest drawback. In the future, hydrogen may provide a significant contribution to the alternative fuel mix (Ogden et al., 1999). Fuel cells use hydrogen and oxygen to produce electricity without harmful emissions. The vehicle design is simpler. However it requires developing a more complex refueling infrastructure (Berry et al., 1996).

2.5 Element of transportation and energy consumption

Transportation is essential to the life of a community for the movement of people and goods. This movement is performed by various modes, such as air, rail, road, water, cable, and pipeline. Each mode requires some basic components to move people and goods. This component can be divided broadly into infrastructure, vehicles, and operations.

Infrastructure consists of a network of fixed installations such as roads, railways, airways, waterways, airports, terminals and stations, etc. Vehicles traveling on these networks include vehicles of appropriate types such as automobiles, buses, trains, trucks, aircraft, etc. Operations deal with the way the vehicles are operated, and the procedures set for this purpose including financing, legalities and policies and administration.

The energy consumption of each mode of transport differs based on their infrastructure requirements, vehicle performance and way of operation. The energy requirements for the basic elements that are necessary for the provision of transport facilities are:

- **Vehicle manufacture, operation, maintenance and disposal:** The vehicle energy consumption includes vehicle operation (direct energy) and vehicle manufacturing, maintenance and disposal energy (indirect energy). The energy consumption of each of the lifecycle stages depends on vehicle type, size, complexity, material used and service life (Rodrigue, et al., 2009).
- **Infrastructure construction maintenance and operation:** The construction and maintenance of roads, railways, bridges, tunnels, terminals, ports, airports, etc., require substantial amount of energy. The operation of this infrastructure such as the provision of lighting and signaling equipment etc. also consumes significant amount of energy (Rodrigue, et al., 2009).
- **Administration of transport business:** The energy consumption involved in planning, developing and operating transport infrastructures is also a part of the total energy consumption by the transport sector.
- **Energy production and trade:** The production of fuels and generation of electricity involves various stages from crude extraction to final use at vehicle. The various production stages consume substantial amount of energy.

The energy consumption in transportation sector has strong modal variations. Road transportation alone consumes on average 85% of the total transportation sector energy in developed countries. Rail transport accounts for 6% of global transport energy demand

(Bonnafeous and Raux, 2003). Water transport is a highly energy efficient method of moving large quantities goods. This mode uses 9% of global transport energy demand (Davis and Diegel, 2008). Air transport provides the transportation network essential for global business and tourism. The energy intensity of air transport is very high. The aviation industry accounts for 8% of the energy consumed by transportation.

2.6 Framework of energy analysis

The total energy consumption of a transportation system can be divided into two parts; direct energy consumption and indirect energy consumption. Direct energy consumption includes the fuel required to propel the vehicle and run the accessories (air-conditioning, lighting etc.). Indirect-energy is all the remaining energy needed to construct, operate, and maintain the infrastructure and manufacture and maintain the vehicles. Indirect energy also includes the energy consumption for producing or generating direct energy (fuel, electricity). Figure 2.3 shows the framework of energy analysis.

Direct energy consumption substantially varies with characteristics of each vehicle. Variables that affect fuel consumption can be classified into two groups; vehicle related and facility related. Vehicle related items include such as engine size, fuel type, weight, speed and cold or hot starts. Other factors that have lesser impacts on fuel consumption are driver behavior, engine tune, tire type and pressure and aerodynamics.

Facility related variables affecting energy consumption are such as grade, traffic congestion (slowdowns or stop and go) and substandard pavements. Other factors that have lesser impacts are roadway curvature, altitude and weather conditions.

Fig. 2.3: Framework of energy analysis

In order to calculate indirect energy to construct, operate and maintain the facility and to manufacture and maintain the vehicles, various factors are required to consider. Vehicle manufacturing energy requires the information regarding energy requirement to extract and produce each material that form the component parts and assemble the vehicle. In a like manner, the energy required to construct transportation facilities need to be estimated. Maintenance energy factors for the vehicles and facilities can be developed by studies performed in a manner similar to the manufacturing and construction energy. Energy required producing direct energy needs information regarding energy spent in

every step of fuel refining or power generation process. The details will be discussed in the respective section.

2.7 Energy analysis methodologies

An analysis of energy involves conducting a life cycle assessment of products, processes or services. Life-cycle assessments (LCAs) involve cradle-to-grave analysis and provide comprehensive evaluations of all upstream and downstream energy inputs. LCAs can be very complex, costly and time-consuming. It requires careful energy and materials balance for all the stages of the life cycle of a product i.e. from raw materials acquisition through production, use and disposal (ISO 1997). US Environmental Protection Agency (USEPA, 2009) defines LCA as,

“a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases; evaluating the potential environmental impacts associated with identified inputs and releases; and interpreting the results to help you make a more informed decision.”

The key to LCA is the preparation of a life cycle inventory (LCI). LCI is a process of quantifying energy and raw material requirements, atmospheric emissions and other environmental burden for the entire life cycle of a product, process, or activity (SAIC, 2006). Data collection and data organization during life cycle inventory phase is the most important task of an LCA. The level of accuracy and detail of the data collected is reflected throughout the remainder of the LCA process.

The method of LCA analysis requires detailed input-output information for every stage of a particular product's life cycle. Numerous agencies throughout the world have developed the process model for LCA for their product. While some of them are replicable to other products, others are product-specific. The US Society of Environmental Toxicology and Chemistry (SETAC) and Environmental Protection Agency (EPA) have played the leading role in standardizing LCA (Hendrickson et al, 2006). European LCA hub also developed LCA tools, services and data.

Numerous commercial software products are now available for LCA. A few of them are The Environmental Impact Estimator, BEES 3.0, Eco-Indicator 99, The Ecoinvent Centre, ECO-it 1.3, Economic Input-Output Life Cycle Assessment (EIO-LCA), GHGenius, GaBi 4 Software System and Databases, GEMIS (Global Emission Model for Integrated Systems), GREET Model, IDEMAT 2005, IVAM LCA Data 4.0, KCL-ECO 4.0, LCAPIX, Life-Cycle Inventory Database etc. (USEAP, 2009).

In this study two of them, namely, Economic Input-Output Life Cycle Assessment (EIO-LCA), developed by Green Design Initiative of Carnegie Mellon University and GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, developed by the U.S. Department of Energy, were used.

EIO-LCA tool allows researcher to estimate the overall environmental impacts including energy consumption from producing a certain dollar amount of any of 500 commodities or services in the United States. Transportation system consists of diverse range of elements. There is hardly any software that can cover energy analysis for all the elements

of a transportation system. The EIO-LCA tool covers the entire economy. Therefore, this tool was selected for this study.

The GREET Model allows researchers to evaluate energy and environmental burden of various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis (Wang, 1999). The GHGenius model, developed for Natural Resources of Canada, and GREET model both are similar Excel based lifecycle models but there are significant detailed differences between them in terms of the system boundaries, the fuel pathways modeled, and the default data stored in the models. The GHGenius model focuses on estimating life cycle emissions of greenhouse gases and the criteria pollutants from combustion sources (NRCan, 2009d). Fuel cycle energy estimation is combined within the emission estimation. GREET estimates fuel-cycle energy use in three subcategories: feedstock, fuel, and vehicle operations. The feedstock and fuel stages together are called WTP stages and the vehicle operation stage is called PTW stages. As the focus of this study was to estimate WTP energy consumption, the GREET model was selected for this.

Basically any LCA analysis can be conducted by two fundamental methods or a combination of them. These are:

- The process based analysis; and
- The input/output analysis

2.7.1 The Process based analysis: The process based analysis typically consists of preparing a detailed inventory of resources input in the actual physical process used in producing a good or a service and examining the energy inputs into each step of the process. It is usually described as tracing the energy requirements of each step of the

production process. In order to be complete, a process analysis should trace all the steps back to the original production of primary materials. Doing a complete life cycle energy analysis of a complex product is practically impossible. An automobile has roughly 30,000 components. Tens of thousands of processes are involved in mining the ores, transporting the materials, refining the materials, making the components, and assembling the vehicle. Compiling and updating all the materials and energy balances is all but impossible. Furthermore, each of the processes directly involved in producing the component requires input from other process (IBI Group, 1978).

There are several other problems with using process based analysis. Two main issues are defining the boundary of the analysis and circularity effects. An initial step of a process-based analysis is defining what will be included in the analysis, and what will be excluded and ignored. Defining this boundary of the analysis is a difficult task. In the production process, many plants produce several different products at the same time and a lot of the same product is used to make other products. For example, to make the paper cup requires steel machinery. But to make the steel machinery requires other machinery and tools made out of steel, which create circularity effect. The advantage of the process based analysis is that it can answer as detailed a question as desired concerning the materials and energy balances of each facility studied (IBI Group, 1978).

2.7.2 The Input-output analysis: The Economic input-output (EIO) analysis represents the monetary transactions between industry sectors in mathematical form. The EIO models indicate what goods or services are consumed by other industries. The input-output analysis divides an entire economy into distinct sectors and presents them as a set

of $n \times n$ matrix. This matrix maps the economic flows between sectors in an economy. Each sector of the economy is represented by one row and one column. This matrix represents total sales from one sector to others, purchase from one sector or the amount of purchase from one sector to produce a dollar of output for the sector. When this matrix is combined with environmental data for each industry sector, an Environmental Input-Output matrix is produced. The results express the environmental load per unit value of a sector (Hendrickson et al, 2006).

A basic problem with using the input-output tables is that it provides an aggregate view of a sector. The energy requirements of a particular process within an industry cannot be obtained. The advantage of the input-output analysis is that it does not need to draw any boundary and so covers the entire economy, including all the material and energy inputs. The second major advantage is that it is quick and cheap. However, the use of input-output analysis without discrimination or judgment could lead to large errors or anomalies in the estimation of total energy (IBI Group, 1978).

2.7.3 Combination approach: In such an approach, the direct energy consumption in producing a good or service would be traced back one or two steps. From this point the various input materials and services would be identified and these would be used to enter the input-output tables to determine the remaining energy inputs to the entire process. This approach, however, requires a fairly detailed analysis of at least several stages in the process analysis tree (IBI Group, 1978).

In this research, a combination of both the process based approach and “Economic Input-output approach were used.

Chapter 3

Bus Rapid Transit and Its Energy Requirements

3.1 Introduction

Buses are the most widely used transit technology in nearly all major cities in the world. At the global scale, there are probably 8000 to 10,000 communities and cities that provide organized bus transit (Grava, 2003). Bus is the principal mode of public transport in medium and small cities. They offer virtually all types of services, from short-haul to regional, from local to express, from all day service to peak period service only. They also provide special transit service for the elderly and handicapped and supplement and feed rail transit lines in the very large cities (Levinson, 2001).

Despite the inherent advantages of bus service in terms of flexibility and low capital cost, passengers frequently find that the quality of conventional bus services provided in urban centers is deficient. Bus operations are often sluggish and slow on congested streets, resulting in disruptive scheduled operation. The delay is associated not only with congestion and traffic signals, but also with frequent and time-consuming stops for boarding and alighting passengers. Too often, service is perceived as slow and unreliable. The image is poor and concerns are expressed over safety and security. The image of conventional bus services is therefore usually not very distinctive and it is often mostly oriented to regular, predominantly captive users (FTA, 2009).

Bus service is indeed important. It provides mobility for all, since many people do not have access to cars. It increases person-capacity in heavily traveled corridors and preserves urban land for more productive use. In addition, it is more energy efficient than

driving a car. Therefore, maintaining and improving bus services is essential to keep urban areas vital and vibrant.

In response to the increasing need for higher performance and more attractive transit services that can compete with autos and reduce street congestion, numerous improvements of bus services have been introduced in recent decades. Now, there is a broad range of physical and operational characteristics of bus systems, which culminated in the introduction of the bus rapid transit (BRT) concept (Vuchic, 2007). The purpose of this chapter is to discuss about the components of BRT system and their energy requirements.

3.2 What is Bus Rapid Transit (BRT)?

Bus Rapid Transit (BRT) is a high-quality bus-based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations, and excellent marketing and customer service (Wright, 2007). TCRP Report 90 expands this definition to

“A rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and ITS elements into an integrated system with a strong image and identity” (TCRP Report 118, 2007).

In brief, BRT is an integrated system of facilities, services, and amenities that improves the speed, reliability, and identity of bus transit. The term “BRT” has emerged in North America and Europe. However, the same concept is also conveyed around the world through different names such as Metro bus, Express bus systems, etc (Wright, 2007).

3.3 Features of BRT

The BRT has some distinctive features that make it different from conventional bus system. The following is a list of features that are required for successful BRT systems (Wright, 2007):

- Segregated busways and existence of an integrated road network;
- Provision of convenient, comfortable, secure, and weather-protected stations;
- Frequent and rapid service between major origins and destinations;
- Rapid boarding and alighting through pre-board fare collection and fare verification;
- Low-emission and low-noise vehicle technologies;
- Automatic fare collection and fare verification technology;
- System management through centralized control centre and applications of Intelligent Transportation Systems (ITS);
- Signal priority or grade separation at intersections;
- Distinctive marketing identity for system such as OC Transpo;
- Integrated access system between other urban mobility options such as walking, bicycles, taxis, paratransit, private motorized vehicles, etc.;
- Special provisions for physically disadvantaged groups; and
- Clear route maps, signage, and/or real-time information displays.

The above factors are the essential requirements for a full BRT system. However, only few systems have achieved status as a complete BRT system based on above criteria. As of March 2007, there existed only two truly “full BRT” systems in the world: Bogotá (Colombia) and Curitiba (Brazil) (Wright, 2007). The BRT systems are continuously evolving all around the world (Appendix A-1 provides lists of cities that are currently possessing, constructing or planning BRT systems).

3.4 Components of BRT

Levinson et al., (2003), put forward seven principal components of BRT. These are running ways, stations, vehicles, services, route structure, fare collection and intelligent transportation systems (each of these components is briefly discussed in Appendix A-2).

3.5 Energy Analysis for BRT system

Energy analysis of BRT system can be divided into two parts, i.e., Vehicle energy and Infrastructure energy. Vehicle energy consumption includes vehicle operation (direct energy) and vehicle manufacturing and maintenance energy (indirect energy). Vehicle indirect energy consumption also includes fuel production energy. Infrastructure energy comprises of infrastructure construction and maintenance energy. Infrastructure consists of not only the busway but also a range of other components. These include stations, terminals, depots, control centre, traffic control signals, feeder infrastructure, commercial space, public utilities (e.g., electricity, gas, water, sewage, telephone, etc.), landscape, park and ride facilities. In this study, only the major infrastructure components were incorporated namely, busway, stations, depots and park & ride. The following section describes the energy requirements of each of the components in details.

3.6 Life Cycle assessment (LCA) of bus

The formulation of LCA is a complex task with many possible pathways to reach the desired objectives. A bus can be studied in the LCA context by separating the life cycle into processes of raw materials extraction, materials processing, bus manufacturing, operation and disposal, as shown in Figure 3.1. In addition, the study also accounts for the flow of resources and wastes through each life cycle process, resulting in a comprehensive balance of material and energy flows.

Figure 3.1: Major stages of bus life cycle (source: Ally, et al., 2007)

Figure 3.2: Schematic representation of stages of bus life cycle (Whitaker, 2007)

Figure 3.2 outlines the basic activities in major stages of the bus life cycle. It can be noted that fuel is required not only to propel the bus, but also required in every stages of bus life cycle.

3.7 Bus manufacturing energy

Bus manufacturing energy can be estimated using process based approach or input-output approach or a combination of both of them. To conduct a process-based approach is very difficult. It requires tracing energy consumption in all the steps back to the original production of materials. A vehicle consists of thousands of components. Tracing energy and materials balance for each component is practically impossible. Moreover, there is no system in place to trace all these energy consumptions. So, a combined approach or input-output analysis is usually adopted. In this study, both the combined approach and input-output analysis were considered.

3.7.1 Combined approach

In this approach the energy requirements to manufacture a bus is separated into two basic parts, the energy required to produce the raw materials and the energy consumed in the transformation of these materials into finished vehicles. In order to calculate material energy requirement, an inventory of all the basic materials for bus manufacturing is prepared. Then the energy intensity for each material production is determined using the input-output values relating to the particular industry producing the product. Having established the energy intensity of each material, the quantity of materials is multiplied by the intensity to get the total material production energy for a particular material. By summing up the individual material production energy yields the total material energy for bus manufacturing.

The transformation of the basic materials into finished vehicles involves several activities such as fabrication of parts, manufacturing of electrical parts, batteries production, suspension production, tire production, bus body assembly, etc. The determination of energy requirements for each individual process is very complex. Therefore, an indirect approach is adopted here. First the producer price is determined for a bus. Then the vehicle parts manufacturing and assembly cost is determined by deducting producer price from total material cost. This is the value added to the input materials in manufacturing the vehicle. Then the manufacturing energy intensity per dollar value is determined from the economic input-output analysis. Multiplying value added price with this energy intensity provides the energy required for vehicle assembly. Finally vehicle assembly energy is added to the total material energy to get the vehicle manufacturing energy (IBI Group, 1978). Figure 3.3 schematically shows the approach for estimating bus manufacturing energy.

Figure 3.3: Methods for estimating bus manufacturing energy

A report prepared by the IBI Group (1978) for the strategic studies branch of Transport Canada estimated manufacturing energy requirement for a typical “Orion” small bus. The study reported 1.07 Giga Btu of energy consumption to manufacture an “Orion” small bus (Appendix A-3). The manufacturing energy for a standard 40’ bus was also calculated based on the weight ratio of a standard 40’ bus and “Orion” small bus. The manufacturing energy for a standard bus was reported as 1.40 Giga Btu.

Herbert et al. (1984), reported the manufacturing energy for the various types of transit vehicle operating in Toronto metropolitan area. The manufacturing energy of a diesel bus was found to be 1099.0 Giga Joules or 1.04 Giga Btu (Appendix A-4).

The Transportation Laboratory of California Department of Transport (Caltrans) published a report entitled “Energy and Transportation Systems” (ETS) in 1978. It was extensively used as a primary reference for transportation energy studies. Later on in 1983, this report was updated to augment the old publication. In this report, the manufacturing energy intensity for a standard bus was reported as 1.04 Giga Btu.

Fels (1975) conducted an analysis to estimate energy consumption for manufacturing of automobile, bus, rapid rail and personal rapid transit. The energy consumption for manufacturing of a bus was reported as 1.023 Giga Btu (Appendix A-5). The bus manufacturing energy reported in all these studies came up with reasonably close values.

3.7.2 Input-output approach

In order to estimate bus manufacturing energy using input-output approach, the EIOLCA tool, developed by researchers at Carnegie Mellon University, USA, was used. To use the EIOLCA model, the first step is to determine which life cycle stage is under consideration and how best to determine the dollar value of the product, process or

service output of that life cycle stage. Here the product output is the bus and the product output value is the bus production cost. The next step is to convert this dollar value to EIO LCA model base price dollar value (1997\$). Then this dollar value is entered in to the appropriate sector of the EIO LCA model. The EIO LCA model divides an economy into distinct sectors. Once this value is specified into the appropriate sector in the EIO LCA model, the model estimates all the supply chain requirements, from extracting raw materials to produce the final product. The model simultaneously computes the environmental discharges and energy input associated with each economic activity of the supply chain in producing the desired output. Finally the model sums up the environmental burden and energy input of each activity in the economy in producing the desired output (Whitaker, 2007). The process is schematically shown in Fig.3.4.

EIO LCA Analysis:

Fig.3.4: Schematic representation of EIO LCA analysis

In order to conduct the EIO LCA analysis for the BRT bus manufacturing energy, a few important factors need to be considered, such as the type of vehicle and propulsion technology, unit price of vehicle, production cost of vehicle and useful life of vehicle.

3.7.2.1 Type of vehicle and propulsion technology

In general, vehicle manufacturing energy consumption depends on the type of vehicle and propulsion technology. A bus can be classified by size or by propulsion technology. There are different sizes of buses operating on the road such as a minibus, standard bus, articulated bus, double articulated bus, and double decker bus. The manufacturing energy significantly varies with the size of bus. The buses also come with various propulsion technologies such as diesel, electric, hybrid, ethanol, bio-diesel and liquefied petroleum gas (LPG), and compressed natural gas (CNG). The manufacturing of some of these buses is more energy intensive than others.

3.7.2.2 Unit vehicle costs

Table 3.1 shows approximate prices (in 2005 dollars) for BRT vehicles based on size and styling options. The cost of a hybrid bus is about \$150,000 more per vehicle.

Table 3.1: Costs of BRT vehicles by type

Bus Type	Bus Length	Typical Price Range
Conventional Standard	40-45 ft	\$300,000 to \$350,000
Stylized Standard	40-45 ft	\$300,000 to \$400,000
Conventional Articulated	60 ft	\$500,000 to \$600,000
Stylized Articulated	60 ft	\$600,000 to \$950,000
Specialized BRT	60-80 ft	\$950,000 to \$1,600,000

(Source: TCRP Report 118)

3.7.2.3 Production cost of vehicle

In the process of manufacturing and selling vehicles, the price is determined by the costs that incurred directly as a part of manufacturing operations and those incurred indirectly in the processes of manufacturing and selling. The Argonne National Laboratory (ANL) breaks down the retail price of a vehicle as shown in Table 3.2. The production price of a vehicle is determined by deducting price discounts, dealer markup and profit (25%) from the retail price.

Table 3.2: Contributors to manufacturers suggested retail price

Cost Category	Cost Contributor	Share of MSRP (%)
Vehicle Manufacturing	Cost of manufacture	50.0
Production Overhead	Warranty	5.0
	R&D/Engineering	6.5
	Depreciation and amortization	5.5
Corporate Overhead	Corporate overhead	7.0
Selling	Distribution, marketing, dealer discount	23.5
Profit		2.5
Total		100.0

*MSRP - Manufacturer Suggested Retail Price (Source: Vyas, et al., 2000)

3.7.2.4 Useful life of transit buses

Useful life is typically defined as the age (i.e., number of years) after which a bus is no longer fit for use, i.e., not fully operational, unreliable, and cannot provide service of acceptable quality. The Federal Transit Administration's (FTA's) service-life policy establishes 12 years or 500,000 miles (whichever comes first) as the minimum service life for transit buses (Richard et al., 2007), (details in Appendix A-6). Calgary transit planning division reviewed different transit vehicles in North America and reported the useful life of different transit vehicles as shown in Table 3.3.

Table 3.3: Comparison of transit vehicles useful life

Type	Passenger Capacity	Service Life (years)
Standard Bus	60 ~80	15+
Trolley Bus	60 ~80	20+
Articulated Bus	110 ~120	15+
Articulated Trolley bus	110 ~ 120	20+
Double Decker Bus	110 ~120	15+
Electric Street Car	100 ~150	25+
Tram	150 ~200	30+
Light Rail Vehicle	180 ~ 220	30+

(Source: Calgary transit, 2002)

3.7.2.5 Estimation of bus manufacturing energy using EIOLCA

To determine the manufacturing energy for different types of buses using EIOLCA tool, the average prices reported in Table 3.1 were used. The prices are in U.S. 2005\$. These prices were converted to EIOLCA tool base year price (1997\$). The prices are the selling price to the buyer. The production price of a bus was determined by deducting price discounts, dealer markup and profit (25%) from the base price. This price is then inputted to EIOLCA analysis tool to get the energy consumption for vehicle production. In EIOLCA tool, there is no sector for bus manufacturing. But there are “Automobile and Light Truck Manufacturing” (Sector # 336110) and “Heavy Duty Truck Manufacturing” (Sector # 336120) sectors. Bus manufacturing is more energy intensive than automobile and light truck manufacturing but less energy intensive than heavy duty truck manufacturing. So bus manufacturing energy was estimated by averaging the energy requirements for these two sectors. The detail of this estimate is shown in Table 3.4.

Table 3.4: Bus manufacturing energy using EIOLCA method

Bus Type	Average price	Average price	Production Price (25% less for discounts, dealer markup & profit,)	Automobile and light truck manufacturing energy	Heavy duty truck manufacturing energy	Bus Manufacturing energy Col.(5+6)/2
	(US\$ 2005)	(US\$ 1997)	(US\$ 1997)	(TJ)	(TJ)	(TJ)
Conventional Standard	325,000.0	274420.9	205815.7	1.74	1.56	1.65
Stylized Standard	350,000.0	295530.2	221647.7	1.88	1.68	1.78
Conventional Articulated	400,000.0	337748.8	253311.6	2.14	1.92	2.03
Stylized Articulated	775,000.0	654388.3	490791.2	4.15	3.71	3.93
Specialized BRT	1275,000.0	1076574	807430.7	6.83	6.11	6.47

It can be seen from the above table that the energy required to manufacture a conventional standard bus is 1.65TJ, i.e., 1.56 Giga BTU, which is reasonably close to other studies.

3.8 Bus maintenance energy

Bus maintenance is the most important activity that spans throughout the service life. The reliability, safety and life of transit buses depend on the maintenance. Maintenance cost is the second highest expense category after vehicle operations (Bladikas et al., 1986). They account for approximately 21% of the total operating expenses in a typical transit system (Purdy et al., 1987).

Bus maintenance energy estimation is very complex, because maintenance includes diverse ranges of activities from simple parts replacement to major overhaul. It also includes the supply of labor, tools, power, heating, lighting and transport and storage of parts. So, the process based analysis is practically not a reasonable option for calculating maintenance energy. The maintenance energy can easily be estimated by EIOLCA analysis. The first step in this approach is to determine the life cycle maintenance cost. Then this cost can be used as an input to the appropriate sector of EIOLCA tool to obtain the life cycle maintenance energy.

In a recent Federal Transit Administration (FTA)-sponsored research, the life-cycle cost for a transit bus is reported using data supplied by the local transit operators and vehicle manufacturers (Richard, et al. 2007). This cost includes the expected cost and timing (in years) for replacement of all major vehicle components. The cost estimation is shown in Appendix A-7. The bus maintenance energy consumption was calculated on the basis of this cost. There is no bus maintenance sector in the EIOLCA tool. So, automotive repair and maintenance sector (Sector #8111A0) was used in this analysis. The result is shown below:

<i>Total life cycle maintenance cost (\$2007)</i>	<i>: \$ 0.14 million</i>
<i>Total life cycle maintenance cost (\$1997)</i>	<i>: \$0.11 million</i>
<i>Total life cycle maintenance energy (TJ)</i>	<i>: 1.03</i>
<i>Total life cycle maintenance energy (Mega Btu)</i>	<i>: 976.45</i>
<i>Life cycle vehicle mile travelled (VMT)</i>	<i>: 500000</i>
<i>Maintenance Energy Btu/VMT</i>	<i>: 1,952.98</i>
<i>Maintenance cost/VMT (2007\$)</i>	<i>: 0.28</i>
<i>Maintenance cost/VMT (1966\$)</i>	<i>: .05</i>

It can be seen from the above analysis that the maintenance energy required for a standard bus is 1,952.98 Btu/VMT. The Transportation Laboratory of California Department of Transport's (Caltrans) publication "Energy and Transportation Systems" reported 13,142 Btu/mile of maintenance energy intensity for a standard bus (Caltrans, 1983). A report prepared by the IBI group for the strategic studies branch of Transport Canada estimated the bus maintenance energy intensity to be 3,360 Btu/VMT (IBI Group, 1978). The IBI report was produced in the late 1970's. The maintenance cost during that time was estimated as 9.8cent/VMT (1966\$). The maintenance cost today is equivalent to 5cent/VMT in 1966\$. There has been a lot of technological advancement since that time. Today's vehicles need less maintenance than before. Moreover, maintenance operation has become less cumbersome. This might be the reason for this variation.

3.9 Bus operating energy consumption

Vehicle fuel consumption varies with several factors such as average speed, acceleration, traffic density, road topography, traffic management and controls, weather, visibility,

driving behavior, etc. (a brief discussion of such factors is provided in Appendix A-8). The individual impact of all these factors on fuel consumption is very difficult to determine. For life cycle fuel consumption assessment, several assumptions are required. It is convenient to use the actual historical data on fuel consumption to conduct the LCA analysis.

The Bureau of Transportation Statistics (BTS), USA, is an important source of historical data. It provides various statistics on the transportation systems. The historical data on average fuel consumption of transit buses was collected from this document. It was found that the fuel efficiency of transit bus has been increasing over time (Fig 3.5). In 1960, while the average fuel consumption of transit bus was 1.84 km/liter, it was 2.44 km/liter in 2002.

Figure 3.5: The historical trend of average fuel efficiency of transit buses

California Department of Transportation conducted a study to determine the fuel consumption rate of a number of makes and models of buses under three load factors: empty, 20 passengers, and full. The fuel consumption rates were further refined into three route types: Central business district, Arterial streets, and Commuter. The study findings are shown in Table 3.5.

Table 3.5: Average fuel consumption by bus types

Passenger load	Type	Average Capacity	Km/liters					
			Non-Air Conditioned			Air Conditioned		
			CBD*	ART*	COM*	CBD	ART	COM
No passengers	ADB	47	1.50	1.73	2.34	1.27	1.50	2.23
	New Look	51	1.65	1.76	2.32	1.28	1.42	2.05
	Articulated	66	1.19	1.37	1.95	0.98	1.18	1.71
20 Passengers	ADB	47	1.41	1.60	2.21	1.21	1.39	2.10
	New Look	51	1.54	1.59	2.24	1.20	1.28	1.98
	Articulated	66	1.15	1.29	1.86	0.94	1.11	1.63
Full load	ADB	47	1.32	1.45	1.99	1.14	1.26	1.77
	New Look	51	1.39	1.38	2.13	1.11	1.14	1.89
	Articulated	66	1.06	1.12	1.65	0.87	0.97	1.45

*CBD: Central Business District; ART: Arterial; COM: Commuter; ADB: Advanced Design Bus

CBD Route: 7 acceleration/stops per mile between zero and 20 mph; average speed = 12.9 mph.

ART Route: 2 acceleration/stops per mile between zero and 40 mph; average speed = 26.7 mph.

Com Route: 1 acceleration/stop per 4 miles between zero and 55 mph; average speed = 46.5 mph.

Although this study was conducted in the 1980's, the study had some very important findings. The variation of fuel consumption with type of routes (CBD, ART, and COM), type of buses (ADB, New Look, articulated), passenger load and the availability of air condition, can easily be understood. During the literature review, no such type of extensive and comprehensive study was found. This study's findings were used elsewhere in this study in the absence of any authentic data.

A recent study conducted by Barnitt & Battelle (2006), evaluated the fuel economy of buses with three type of propulsion system; CNG, Hybrid and Diesel. The buses were operated on New York City Transit (NYCT) routes. The study focused on a 12-month evaluation period for the selected transit buses. The study collected and analyzed the data from the actual field operation of ten CNG, ten hybrids and two groups of diesel buses. The average fuel economy for CNG buses was found to be 1.70 miles per equivalent gallon of diesel. The average fuel economy of two groups of diesel buses was 2.28 and 2.38 mpg. The average fuel economy of the hybrid buses was 3.19 mpg, which was 34% higher than the diesel buses.

3.10 Fuel production energy

In order to determine the energy consumption of fuel production, a life cycle assessment (LCA) for fuel production is required. The Well-to-Wheel concept takes into account the whole lifecycle of a fuel. The Well-to-Wheel analysis can be divided into two parts; Well-to-Pump (WTP) and Pump-to-Wheels (PTW). The WTP energy consumption can be calculated by tracking the energy inputs to a fuel production process from steps including: feedstock extraction, feedstock processing, feedstock transport and storage, feedstock refining to product fuel, product fuel transport, product fuel storage, local delivery, retail storage and dispensing. Figure 3.6 shows the Well-to-Pump (WTP) & Pump-to-Wheels (PTW) stages of fuel cycle analysis.

Figure 3.6: Total energy cycle for a vehicle (Source: Wang, 1999).

To do an accurate life cycle energy assessment for fuel production, the GREET model,

developed by Argonne National Laboratory, can be used. This model was used to estimate diesel fuel production and electricity generation energy consumption, which is reported in a later part of this thesis. The details about the model are also reported there.

The life-cycle energy consumption for gasoline and diesel fuel production can also be calculated using EIOLCA. The “Petroleum Refineries” (Sector #324110) sector is an accurate representation of the petroleum refining process in EIOLCA tool.

3.11 Running way energy consumption

3.11.1 Running way construction: The construction of the running way typically represents approximately 50% of the total infrastructure costs (Wright, 2007). Running way can be classified according to degree of access control. Each classification has an important bearing on BRT system performance, costs and energy. Examples of various types of BRT running ways are shown in Table 3.6.

Table 3.6: Examples of various types of BRT running ways

Facility Type	Access Class*	Examples
Busways:		
Bus tunnel	I	Boston, Seattle
Grade-separated busway	I	Ottawa, Pittsburgh
At-grade busway	II	Miami, Hartford, Los Angeles (Orange Line)
Freeway lanes:		
Concurrent flow lanes	I	Ottawa, Phoenix
Contraflow lanes	I	New Jersey approach to Lincoln Tunnel
Bus-only or bus priority ramps	I	Los Angeles
Arterial streets:		
Arterial median busway	III	Curitiba (Brazil), Vancouver (BC), Cleveland
Curb bus lane	IV	Rouen (France), Vancouver, Las Vegas
Dual curb lanes	IV	New York City (Madison Ave)
Interior bus lanes	IV	Boston
Median bus lane	IV	Cleveland
Contraflow bus lane	IV	Los Angeles, Pittsburgh
Queue jump/bypass lane	V	Leeds (UK), Vancouver
Transit Signal Priority (TSP)	V	Los Angeles, Oakland

(Source: TCRP Report 118)

*Access Class Definition: I : full control of access; II : Partial control of access; III : Physically separated lanes within street; IV : Exclusive/semi-exclusive lanes V : Mixed traffic operations

The construction cost and construction energy of running way substantially varies with degree of separation. Running way with high degree of separation (tunnel, grade separated bus way) cost more and require much more energy for construction than the mixed traffic lane. The choice of running way type depends on market potential, route-specific opportunities and constraints (TCRP, 118). The running way construction energy also varies with type of pavements as well.

3.11.2 Type of pavements for running way and their construction process

Running ways generally consist of two types of pavements; flexible pavement and rigid pavements. The flexible pavements are constructed with bituminous (or asphalt) materials and sometimes referred as asphalt pavements. Rigid pavements are constructed with Portland Cement Concrete (PCC) and also referred as concrete pavement. The pavement construction processes up to the sub-grade are very similar for both asphalt and concrete pavements. They differ in the construction of sub-base, base and surface materials only. Figure 3.7 and Figure 3.8 outline the construction processes for asphalt and concrete pavement respectively. It can be seen from the figures that construction of pavements involves a large number of activities. By estimating energy consumption in each step and summing up the energy consumption in all steps will provide total energy for construction.

Figure 3.7: The principal stages of asphalt road construction

Figure 3.8: The principal stages of concrete road construction

3.11.3 Life cycle stages of running way

The life cycle of a pavement can be divided into five basic stages: i) Extraction of raw materials, ii) Manufacturing raw materials, iii) Placement of pavement materials iv) Maintenance of pavement and v) Removal, recycling and disposal of pavement.

Within each stage there are significant activities and processes necessary for the construction and subsequent operation of asphalt and concrete pavements. These stages and activities are shown in Figures 3.9 and 3.10.

Fig-3.9: Asphalt pavement life cycle

Figure 3.10: Reinforced concrete pavement life cycle

The total energy consumption during the service life of a pavement can be calculated as the sum of the consumption of energy of the individual processes within each stage. The energy intensity of different activities and processes can be established based on the studies of energy consumption in cement, asphalt, and aggregate industries as well as on literature on life cycle analyses. Zapata and Gambatese (2005) conducted an extensive literature review in establishing energy intensities of different stages of asphalt and concrete pavement (shown in Appendix A-9).

3.11.4 Estimation of running way construction energy

The running way construction energy can be estimated using both process based approach and EIOLCA approach. Since, the process based approach is complex and requires detailed information regarding materials input and energy balance in every step of the construction processes, EIOLCA method can be used to get quick estimates. To use the EIOLCA model, the first step is to determine the construction cost of running way. The costs of running ways vary with location, type, design features and the type of terrain. Table 3.7 shows various types of busway construction cost. Costs for grade separated busway range from \$5 million to \$44 million per mile. Costs of Ottawa's Transitway in the 1980's were \$13 million per mile. Table 3.8 shows the range of different busway construction cost. The costs are expressed as per lane-mile.

Table 3.7: Busway construction costs (U.S. Dollars)

Busway Type and System	Year Opened	Miles	Cost (millions)	Cost (millions)/Mile
Bus Tunnels:				
Boston: Silver Line	2005	4.1	\$1,350.0	\$329.3
Seattle	1989	2.1	\$450.0	\$214.3
Grade-Separated Busways:				
Adelaide, Australia (guided bus)	1989	7.5	\$37.0	\$4.9
Brisbane, Australia: South East Busway	2001	10.3	\$262.8	\$25.5
Ottawa: Transitway	1983	16.0	\$212.6	\$13.3
Pittsburgh: South Busway	1977	4.3	\$27.0	\$6.3
Pittsburgh: East Busway	1983	6.8	\$113.0	\$16.6
Pittsburgh: East Busway Extension	2003	2.3	\$30.1	\$13.1
Pittsburgh: West Busway	2000	5.0	\$220.9	\$44.2
At-Grade Busways (Off-Street):				
Hartford: New Britain (proposed)	2007	9.6	\$53.8	\$5.6
South Miami-Dade	1996	8.2	\$57.0	\$7.0
South Miami-Dade Extension	2007	11.5	\$9.5	\$0.8
At-Grade Busways (On-Street):				
Bogotá	2000	23.6	\$184.0	\$7.8
Cleveland: Euclid Avenue2	2008	10.7	\$44.3	\$4.2

(Source: TCRP Report 118)

Table 3.8: Busway construction costs by type (U.S. Dollars)

Busway Type	Cost/Lane-mile (millions)
At Grade	\$6.5 to \$10.2
Aerial	\$12 to \$30
Below Grade	\$60 to \$105
Additional Lanes	\$2.5 to \$3.0 (within existing roadway profile)
	\$6.5 to \$10.2 (outside existing roadway profile)

(Source: TCRP Report 118)

In the EIOLCA model, there is “Highway, Street, Bridge, and Tunnel Construction Sector” (Sector #230230). This sector was used to calculate the construction energy requirements for busway. The average busway construction cost (US \$2004) reported in Table 3.8 were used for energy estimation. These costs were converted to U.S. \$1997 and inputted to EIOLCA model. The result of busway construction energy is shown in Table 3.9.

Table 3.9: Typical busway costs (excluding right-of-way) and energy consumption

Running Way Type	Cost (Millions)/ lane-mile	Average cost Million(\$2004)	Average cost Million (\$1997)	Energy (TJ)/ lane-mile
Grade-separated busway				
Below grade (tunnel)	\$60 to \$105	82.5	71.91	1280
Aerial	\$12 to \$30	21	18.30	325
At-grade busway				
Separate ROW or median	\$6.5 to \$10.2	8.35	7.28	129
Arterial lanes	\$2.5 to \$3.0	2.7	2.35	41.7
Mixed flow lanes	\$0.1 to \$0.29	0.2	0.17	3.02

Figure 3.11: Construction energy of different type of BRT running way

A report prepared by the IBI Group (1978) estimated the busway construction energy as 119 Giga Btu/lane-mile i.e., 125.5 TJ/lane-mile. If the construction energy for at grade (Separate ROW) busway shown in Table 3.23 is compared with the IBI report, it can be stated that busway construction energy calculated by EIOLCA model is in well agreement with IBI report.

Several researchers calculated energy consumption for both concrete and asphalt pavement. Zapata & Gambatese (2005) conducted an energy assessment for construction of a continuously reinforced concrete pavement and an asphalt pavement. The road selected for the assessment was a 1 km section of a typical two-lane (7.2m wide) highway with a high volume of traffic in the United States. The analysis showed that while the energy required to construct a typical two-lane asphalt pavement is 3.78×10^6 MJ/km, the energy required for continuously reinforced concrete pavement is 4.58×10^6 MJ/km. The construction of concrete pavement consumes approximately 20% more energy than asphalt pavement.

Levinson et al. (1984) estimated the construction energy for a freeway. The freeway construction energy estimation was based on a 4-lane express way in Ontario (Highway 404) The estimated construction energy for freeway was 12,132 GJ/lane-km.

3.12 Running way maintenance

The operation and maintenance of running way use energy in different forms and in different ways. The operation and maintenance of running way has three major energy using components. These are routine and periodic maintenance, winter maintenance and

lighting. Routine running way maintenance includes both temporary and permanent patching, crack sealing and surface coatings. Routine maintenance is generally performed on a scheduled basis to prolong the serviceability of the pavement. Periodic maintenance includes overlays which are intended to augment the structural capacity of the existing pavement. Herbert et al. (1984) in a study summarized the energy consumption of different routine maintenance activities for roads in Toronto areas (Table 3.10).

Table 3.10: Running way maintenance energy, Toronto area

	Freeway-4 Lane	Rural Road-2 Lane	Urban Arterial-2 Lane
	GJ/km	GJ/km	GJ/km
Total	75.6	82.3	162.0
Per lane-km	19.1	41.1	81.0

(Source: Levinson et al., 1984)

It can be seen from the above table that a 4-lane freeway required 19 GJ/lane-km annual maintenance energy, as compare with 41 GJ/lane-km for a rural 2-lane road and 81 GJ/lane-km for 2-lane arterial road.

IBI Group (1978) estimated the road maintenance energy by calculating the annual cost (\$1966) of maintenance and multiplying this cost by an energy intensity of 40,000 BTU's per dollar. The study reported 1.5 Giga Btu annual maintenance energy per lane-mile for busway.

California department of transport reported the following road maintenance energy shown in Table 3.11.

Table 3.11: Roadway maintenance energy

Pavement type	Annual energy consumption Btu/Lane-mile	
	Urban	Rural
Portland cement concrete	1.634×10^8	6.61×10^7
Asphalt concrete	1.776×10^8	8.03×10^7

(Source: Caltrans, 1983)

3.13 Winter maintenance

Winter maintenance includes snow plowing, snow removal, and salting or sand spreading. About 80% of the total winter maintenance energy is attributable to the salting operation including the energy required to produce the salt, the energy required to transport the salt, and the energy involved in spreading (IBI Group, 1978). Snow clearance can be done using different types of vehicles such as tractors, wheel loaders, etc. The most common vehicle for snow clearance of the public road network is a tractor with an attached snow clearance unit. Spreading of sand or salt during winter maintenance is mostly done using a truck. The activity can be divided into two components, namely driving of the truck and production of sand or salt. Sand can either be from a natural origin or from crushed material. Extraction of salt for winter road maintenance is mainly done through the working for salt in mines. The energy for the extraction can be based on coal or natural gas. Generally, 120g/m^2 of sand or $15\text{-}20\text{g/m}^2$ of salt are spread over road surface during winter maintenance (Strippel, 2001). By calculating the hour of tractor operation and amount salt or sand spread, the total energy consumption for winter maintenance can be calculated. Table 3.12 shows energy for salt and sand extraction.

Table 3.12: Energy for salt and sand extraction

Extraction of	MJ/ton	Source
Salt	2220	(Strippel, 2001)
Sand	15.82	(NCHRP, 85)

3.14 Running way lighting

The estimation of running way lighting energy is straight forward. By assuming the wattage of a light and multiplying by the required number of light posts per km and annual hour of operation, the total annual energy consumption can easily be calculated.

3.15 Park-and-ride lot

The provision of park-and-ride lot is an expanded option to commuters. The establishment of park-and-ride lots served by the transit operation is considered as an effective way of conserving energy as well as reducing air pollution and traffic congestion. Cooper (1982) conducted an extensive study to estimate indirect energy consumption for constructing a park-and-ride lot with 500 car capacity. The study estimated 2.07 Giga Btu energy consumptions for constructing a 500 car capacity park-and-ride lot (Table 3.13).

Table 3.13: Construction energy for 500 car capacity park-and-ride lot

Component	Material type	Amount	Energy consumption (Mega Btu)			
			Production	Hauling	Construction	Total
Loading Zone	Portland Cement	262	1983	20	343	2345
	Aggregate	130	9	10	23	42
	Lime	16	96	1	8	105
Total			2088	31	374	2492
Car parking area	Asphalt	1716	837	170	11119	12126
	Aggregate	4688	328	352	825	1505
	Lime	703	4218	53	366	4637
Total			5383	575	12310	18268
Grand Total			7471	606	12684	20761

(Source: Cooper, 1982)

3.16 Station energy consumption

BRT Stations may range from various kinds of bus stops to bus station, interline transit terminals, and station complexes integrated in varying degrees with other developments and functions. Station functional design and sizing largely is a function of the projected number of passengers boarding and alighting at any particular station and the frequency of buses that need to be accommodated at that station. Beyond the size of a station, BRT station may also vary with type of running way (busway, arterial bus lane, etc.) or type of construction (at-grade, elevated, or under ground). BRT stations could be simple road side stop or be permanent, weather-protected facilities that are convenient, comfortable, safe, and fully accessible. They could also provide a full range of passenger amenities, including shelters, passenger information, telephones, lighting, and security provisions. Thus the energy consumption for constructing stations largely depends on the type of station under consideration.

3.16.1 Station cost

BRT stations cost range from about \$150,000 (Miami) to more than \$3 million (Ottawa) (TCRP, 118). A major cost item is the provision of a station building. Costs for stations on arterial streets range from about \$60,000 to \$100,000 (Los Angeles and Vancouver) to \$250,000 (Las Vegas). Costs for bus shelters are moderate. The costs are slightly increased if benches, telephones, trash receptacles, special painting, and bicycle racks are provided. Station costs are substantially increased when ticket vending machines are added. Typical BRT station components costs are shown in Appendix A-10. By knowing the functional components of a specific station and using the unit cost shown in

Appendix-10, total station construction cost for a station can be estimated. Once the cost of station construction is determined, then with the help of EIOLCA model, station construction energy can be estimated. Table 3.14 shows several BRT station costs by type of running way.

Table 3.14: BRT station costs by type of running way

Type of Running Way	System	Cost/Station (millions)
Busway	Adelaide, Australia	\$1.50
	Brisbane, Australia	\$1.90
	Hartford (proposed)	\$2.40
	Miami (extension)	\$0.15
	Pittsburgh: West Busway	\$0.45
	Pittsburgh: East Busway (extension)	\$0.50
	Ottawa	\$3.30
Freeway shoulder lanes	Ottawa	\$4.40
Median arterial bus lanes	Cleveland	\$0.30
Mixed traffic or bus lanes	Boston	\$0.23
	Las Vegas	\$0.25
	Los Angeles	\$0.06 to \$0.10
	Ottawa	\$0.10
	Vancouver, BC	\$0.07

(Source: TCRP Report 118)

3.16.2 Energy requirement for a typical BRT station construction

Using EIOLCA tool, the construction energy consumption for a busway station was estimated. The average construction cost of a station on busway can be considered as \$1.46 million (\$ 2004) (Table 3.14). Converting this cost in to EIOLCA base year cost, and entering this cost into “Commercial and Institutional Buildings (Sector #230220) sector in EIOLCA tool, provided 9.5 TJ/ Station construction energy consumption.

Chapter 4

Light Rail Transit and Its Energy Requirements

4.1 Introduction

Light rail transit (LRT) is a concept that fits between the bus and the heavy metro or conventional railway. In comparison with bus systems, it is more expensive to construct, but may be cheaper to operate for a given capacity, may have lower whole-life costs, offer a higher operating speed, reduce pollution, and be more successful in attracting motorists to public transport. In comparison with a metro or urban railway, LRT is cheaper to build and operate, but operates at a lower operating speed. However it offers better penetration of urban areas, enjoys better security, and generates less noise. Light rail demonstrates its flexibility by its ability to operate in a wide range of built environments. LRT can run on streets, freeway medians, railroad rights-of-way, underground or aerial structures (Boorse, 2000). Light rail can be economically feasible with a passenger volume between 2000 and 20,000 passengers/hour (Taplin, 1998). The focus of this chapter is to review the basic elements of Light rail transit system and its direct and indirect energy consumption.

4.2 Overview of light rail transit system

Although light rail is a modern mass transit system for cities, the origin can be traced back to the Tramways in New York City in 1832. For about a century, tramways passed through several episodes. It had a golden time at the beginning, but when motor car and bus became available, it started declining. With time private car became the major mode of transport. This created new concern about traffic congestion and environmental

pollution. Planners began to realize the disadvantages of motorization and marginalization of public transport. Here the tramways came in again with a new look and advanced technology, called LRT. The Canadian city of Edmonton led the way to bring in light rail line in North America in 1978. It was a great success and many North American cities started planning to develop LRT. There has been 39 LRT sytem in North America as of 2007 (Appendix B-1). The recent surge in light rail development in different parts of the world has proven its obvious popularity with the traveling public. As of 2007, there are 91 LRT systems all over the world (Appendix B-2). However, due to lower density of many North American cities, lower LRT speed relative to the automobile, lower ridership levels and questions of cost-effectiveness, the construction of light rail systems has spurred political controversy (Taplin, 1998). Despite that light rail is gaining popularity for its environment friendliness, safety and and long-term sustainability benefits.

4.3 Principal Components of LRT

Regardless of type, all LRT systems have the following basic elements:

- **Infrastructure** - composed of trackways, stations, and storage yards, including any associated structures, such as tunnels and bridges.
- **Rolling Stock** - comprising one or more fleet of railcars that carry passengers along the trackways. Generally, these cars are designed in such a way that they can be assembled into short trains.
- **Fixed Equipment** - consisting of operation and maintenance center, the electric power supply, signals and communications facilities.

The principal elements of LRT systems are briefly discussed below:

4.3.1 Trackways

LRT trackways can be constructed on the ground surface, below the surface in an open cut or in a subway, or above the surface on an embankment or aerial structure. Surface LRT trackways may be constructed on an exclusive right-of-way or along a street right-of-way, commonly in segregated lanes but can be placed within vehicle lanes used by general traffic. Sub-surface trackways are generally positioned below streets and follow the street pattern, but they can also follow an independent alignment and pass under structures, parks, water bodies, or other railways. Aerial trackways may also follow street patterns, but are more likely to trace a different alignment, crossing above streets, rivers, and other rail lines. Types of light rail trackways in few developed countries are shown in Appendix B-3.

4.3.2 Stations

LRT stations are most important components where riders experience its image, service and convenience. Stations range from simple platforms at ground level where passengers can safely board and alight from trains, to elaborate structures above or below ground, which may be accessed via stairways, escalators, and elevators.

4.3.3 Rolling stock

Rail technology allows use of a great variety of vehicles with respect to axle arrangement, body type, dimensions, and dynamic performance. LRT vehicles usually have their body widths limited by conditions in street operation and their distances between truck centers limited by sharp curves. They must also have powerful magnetic brakes for compatibility with other traffic. The main parameters of LRT vehicles that can be varied are the followings:

- length and width and track gauge
- Regular high floors or low floors
- Seating arrangements
- Single unit vehicles, married pairs, articulated vehicles, or units suitable for train consists
- technical elements related to power supply, and control systems

Another set of factors influencing vehicle design are those imposed by local condition such as passenger volumes, station spacing, topography, climate, etc.

4.3.4 Electric power supply

Two basic elements comprise the electric power supply: a network of traction power substations and a distribution system. The power substations receive high-voltage commercial electrical power and convert it to medium voltage direct current. The nominal operation voltage of the substations is either 600V or 750V in North America. The Catenary systems are used to transmit electric power from traction substations to LRVs in LRT systems. Because LRT systems often operate at ground level with other traffic crossing at grade level, overhead contact wires are used to transmit the required electric power. Two types of wires are used in a catenary system: messenger wire serves as the main feed line and contact wire distributes power through contact with the current collector or pantograph of vehicles. Contact shoes or pantographs function as the power pickups for the traction motor. Figure 4.1 is a pictorial view of a typical catenary system. The traction motors may be AC or DC, although most transit systems use DC. The motor sizes are determined as a function of car weight, design speed criteria, and design

acceleration rate requirements. Most Light rail cars are driven by electric traction motors. However, there are few rail systems that utilize diesel traction as well.

Figure 4.1: Light rail power pick up system (Source: APTA, 2008)

4.3.5 Signals

The movement of the cars or trains is guided by signals. On some systems, all of the signals are located alongside the trackway. These trackside signals may include, or be coordinated with, traffic signals along the line. On other systems only certain signals are installed trackside, while others are displayed on a console in front of the train operator.

4.3.6 Operation and maintenance center

The operations and maintenance center is the focal point of an LRT system. It includes a control room from where operations are coordinated, accommodations for train crews preparing for duty, and a maintenance facility where the cars are inspected, cleaned, and repaired. The center can also include administrative and management offices.

4.3.7 Communications facilities

Communications facilities link the operations and maintenance center with the train operators and other personnel. These facilities range from conventional telephone lines to the very newest wireless technologies.

4.4 Capital cost of LRT

Capital costs for LRT systems vary between \$12.7 and \$118.8 million per mile. Table 4.1 shows capital cost of several North American light rail systems. This Table compares the capital costs for construction of LRT in 15 North American cities since 1978. Capital costs shown here have been translated to year 2000 US dollars to facilitate comparison. Cost includes land for rights of way, track work, stations, structures, signals, power, vehicles, maintenance facilities, and project oversight.

Table 4.1: Capital cost comparison of light rail systems (costs in 2000 US Dollars)

City	Total cost (year of expenditure) Million US \$	Year of Line Opening	Total Cost in 2000 Million US \$	Total Length Miles	Cost/mile in 2000 Million US \$	Weekday Boarding in 2000
Sacramento, CA	\$199.0	1987	\$262.1	20.6	\$12.7	28,800
Baltimore, MD	\$470.3	1992	\$536.5	29.4	\$18.2	25,600
St. Louis, MO	\$348.0	1993	\$395.3	19.0	\$20.8	31,700
Salt Lake City, UT	\$312.5	1999	\$320.2	15.0	\$21.4	21,300
Denver, CO	\$292.3	1994	\$305.4	14.0	\$21.8	29,400
Calgary, AB	\$543 (CDN)	1981	\$446.2	18.2	\$24.5	187,700
San Diego, CA	\$776.4	1981	\$1,295.2	46.8	\$27.7	82,600
San Jose, CA	\$725.0	1981	\$882.6	28.6	\$30.9	31,800
Pittsburgh, PA	\$540.0	1985	\$780.0	25.2	\$31.0	24,100
Edmonton, AB	\$310 (CDN)	1978	\$319.0	7.6	\$41.7	36,000
Portland, OR	\$1,245.5	1986	\$1,400.4	32.7	\$42.8	71,100
Dallas, TX	\$840.0	1996	\$909.6	20.0	\$45.5	38,100
Los Angeles, CA	\$1,675.0	1990	\$1,934.8	42.0	\$46.1	81,900
N.E. New Jersey	\$992.1	2000	\$992.1	10.0	\$99.2	22,400
Buffalo, NY	\$510.6	1984	\$760.5	6.4	\$118.8	23,800

(Source: GAO-01-984 Bus Rapid Transit Shows Promise; American Public Transit Association Ridership Statistics; Calgary Transit. Edmonton Transit)

Table 4.1 also includes average weekday boarding passengers for these LRT systems. It is evident that these cities have experienced a wide range of LRT capital costs per mile. The reasons for this wide disparity are likely associated with factors such as the type of LRT rights of way (surface, bridges, and tunnel), number, scale and design of stations, types and number of vehicles, and land costs (Kendrick, 2006).

4.5 Factors affecting LRT energy consumption

The energy consumption of LRT systems is influenced by the following main elements: line, station, vehicle, operation, demand, climate and fixed facilities. The elements and their respective factors are noted below:

Line Characteristics:

Length	:	length operated, length of common trunk
Gradients	:	Gradient (%)
Curves	:	no. of curves, radius
Stations	:	no. of stations, Station Spacing, Station sizes
Underground stations	:	no. of underground stations
Interstations	:	length of interstations
Cross-roads	:	no. of cross-roads, stops per cross-roads (%), average awaiting time per cross-roads
Maneuvering area	:	no. of maneuvering areas and signaling panels
Tunnels	:	length

Station Characteristics:

Station lighting	:	consumption per station
Electronic systems	:	consumption of ticket vending machines, validators, information panels/displays
Electromechanical equipment in tunnel stations	:	consumption of escalators, elevators, ventilation

Vehicles:

Doors	:	number of doors, opening surface area per door
Lighting	:	energy consumption [kwh]
Air Conditioning	:	Passenger cabin, Driver cabin
Ventilation	:	Passenger cabin, Driver cabin
Power used by LRV	:	energy consumption [kwh]
Regenerative Breaking	:	energy regenerated by LRV
LRV weight	:	empty weight of LRV
Volume of the passenger cabin	:	volume [m ³]
Number of places	:	seat capacity, standing capacity
Peak speed	:	speed
Acceleration	:	acceleration

Operation characteristics:

Running frequency and amplitude	:	Weekdays, Saturdays, Sundays
Localization of the depot	:	distance between depot and line, share of dead km
Operating speed	:	off-peak hours, average hours, peak hours
Stops on demand	:	no. of stops on demand
Door operation (average time doors are open at stops)	:	off-peak hours, average hours, peak hours
Awaiting time in stations	:	off-peak hours; average hours; peak hours

Demand Data:

Annual passenger-km	:	Weekdays / Saturdays / Sundays
Annual passenger-trips	:	Weekdays / Saturdays / Sundays

Average Temperature	:	Min. and max. temperature, average temperature
Freezing Days	:	freezing days/year
Humidity	:	average humidity, average precipitation

Fixed electronic facilities	:	cable cross-section [mm ²], cable resistance [Ohm/km] feeder cross-section [mm ²], feeder resistance [Ohm/km]
Substation	:	number of substations, supply voltage [V], power of substations
Switch Heating	:	running time energy consumption of a single switch heating
Facilities at Crossings and Security Equipment	:	energy consumption

The above elements and the respective factors build up a chain of impacts affecting energy consumption and energy efficiency. This is shown in Fig. 4.2.

61

The figure above shows that energy consumption of LRT depends on a number of interlinked factors and the energy efficiency depends on energy consumption and number of passengers transported. The direct factors which influence energy consumption and the number of passengers transported are marked in shaded boxes. Among all these factors, station spacing and operating regime have huge impact on energy, which are discussed below (the effect of some other factors are discussed in Appendix B-4).

4.5.1 The impact of station spacing on energy consumption

The light rail transit system usually serves a series of stations along a line. The travel along a line therefore consists of a discrete stop-and-go movement with station-to-station travel. Short station to station distances are associated with frequent stop-and-go movement and this regime of train operation consumes more energy. Figure 4.3 shows the variation of energy consumption with station spacing (Caltrans, 1983).

Figure 4.3: Relationship between station spacing and energy consumption
(Source: Caltrans, 1983)

It can be seen from Fig.4.3 that when the spacing between stations is less than 1 km, the energy consumption increases exponentially with shorter station spacing. When station spacing is greater than 1 km, the change in energy consumption is not very remarkable.

4.5.2 The impact of operating regime on energy consumption

Station to station movement of train represents a cycle of five different regimes of motion: acceleration, constant speed, coasting, braking and standing. Each of these travel regimes has technical and operational variations that influence energy consumption.

Figure 4.4 shows these regimes of operations.

Fig. 4.4: Different station-to-station travel regime affecting energy consumption of LRT (Source: Vuchic, 2007)

It can be seen in the Fig. 4.4 that the acceleration phase can produce two different energy consumption curves (1& 2). Constant speed and coasting regime represent a direct trade-off between higher top speed under full power and energy saving with coasting, shown by line 3 and 4. Braking method, conventional and regenerative are shown by lines 5 and 6. While convention braking has no influence on energy consumption, regenerative braking results in returning some power to the power line (Vuchic, 2007).

4.6 Energy estimation for LRT vehicle

4.6.1 LRT vehicle life cycle energy consumption

The life cycle of the light rail vehicle (LRV) can be divided in to 6 stages: raw material extraction and processing, LRV component manufacturing and assembling, vehicle delivery, operation, maintenance and end of life (disposal and recycling). Figure 4.5 shows the life cycle stages.

Figure 4.5: The life cycle of light rail vehicle (Source: Struckl, et al. 2006)

Struckl, et al. (2006) conducted a life cycle analysis for rail transit vehicle. The analysis was conducted for 3-car light rail vehicle MX for the Metro Oslo. The train is made of aluminum and the weight is approximately 100 ton. The number of seats per car is 122.

4.6.1.1 Raw materials energy consumption

Light rail vehicle manufacturing is an energy intensive process. It requires different types of material. The principal materials that are used in light rail vehicles are steel, aluminum, plastic, glass, copper and wood. Light rail vehicle is made of thousands of components. To trace the energy and material balance for each component is practically impossible. In order to make the analysis simple, an inventory of principal materials can be prepared. Then the quantity of each material can be determined as percent of total weight of the light rail vehicle. By multiplying the quantity with the energy intensity of each material and summing them up for all materials yields the total material energy for Light rail vehicle. Table 4.2 shows the energy consumption for the production of raw materials of the train MX (approximately 100t of train weight).

Table 4.2 Raw materials and their energy consumption for LRV manufacturing

Raw material	Energy consumption per kg raw material (MJ/kg)	Percentage of vehicle mass	Energy consumption (MJ)
Steel (low alloyed)	45	14 %	630000
Steel (high alloyed)	70	37 %	2590000
Aluminium	96	31%	2976000
Plastics	90	7%	630000
Composite materials	100	3%	300000
Chemicals	90	1 %	90000
Glass	13	2%	26000
Copper	80	3%	240000
Wood	22	2%	44000
Total		100%	7526000

(Source: Struckl, et al. 2006)

4.6.1.2 Manufacturing energy consumption

The train was manufactured at the factory site in Vienna. The data collected form

Siemens Transportation Systems, Vienna. The manufacturing energy was found to be about 100,000 MJ/train. The estimate included 3-car train, utilities, heating, electricity and supplies.

4.6.1.3 Energy consumption for delivery

Energy intensity for delivering the train varies with mode of transportation. The following energy intensities for transportation were used:

By truck: 0.5 MJ/ton-km

By train (diesel): 0.8 MJ/ton-km

By train (electrical): 0.51 MJ/ton-km

By ship: 0.35 MJ/ton-km

Distance from Vienna to Oslo is 1800 km. By truck total energy consumption for delivering the train was 90,000 MJ.

4.6.1.4 Energy consumption for operation

The train operating energy consumption was obtained by the Train Performance Simulation. The average of summer and winter passenger load was considered for the simulation. The total weight of the train with passenger load was 135 ton. The life of the train was considered 30 years and the average annual mileage was estimated to be 120000 km. The life time energy consumption was found as follows:

- Energy consumption per train per kilometer: 44.5 MJ (4.12 kwh/Car)
- Energy consumption per year: 5,340,000 MJ
- Energy consumption for the life-time period of 30 years: 160,200,000 MJ

4.6.1.5 Energy consumption for maintenance: The maintenance energy was estimated as 5.13% of total life cycle energy.

4.6.1.6 Energy consumption for recycling

The material use was reduced to 82% due to losses which are related to the material recycling technology and the recycling rate was considered as 0.9.

Table 4.3 Recycling energy consumption

Raw material	Recycling energy intensity (MJ/kg)	Total energy consumption for material recycling (MJ)
Steel (low alloyed)	12	168000
Steel (high alloyed)	12	444000
Aluminum (50% secondary)	2.5	77500
Glass	9	9000
Copper	12	36000
Total		734500

(Source: Struckl, et al., 2006)

4.6.1.7 Total life cycle energy consumption

Figure 4.6 shows the total life cycle energy consumption of the light rail vehicle. It can be seen that train operating energy consumption constitutes the biggest part of the life cycle energy consumption, which is 90.10% of the total life cycle energy. The energy consumptions for train manufacturing and assembling, delivery and recycling are negligible in comparison to operating energy consumption.

Fig. 4.6: Light rail vehicle life cycle energy consumption (Source: Struckl, et al. 2006).

A few other studies also estimated the major stages of LRV life cycle energy. The transportation laboratory of California Department of Transport (Caltrans) reported the following Light rail vehicle manufacturing and maintenance energy intensity:

Table 4.4 Vehicle manufacturing and maintenance energy intensity

Vehicle	Usable life	Manufacturing energy/Car		Maintenance Energy/Mile
		Total Energy	Energy/Mile	
	(Miles)	(Btu)	(Btu/mile)	(Btu/mile)
LRV	1,240,000*	2,614x10 ⁶	2,108	7,060

(Source: Caltrans, 1983) *30 year usable life/car x 142.5 car miles/weekday x 290 weekdays/year = 1.24x10⁶ miles

In order to determine LRV operating energy consumption, Caltrans used a computer model to simulate LRT system for a normal weekday operation of 16 hours. This model assigns passenger loads throughout a typical weekday according to both passenger demand and the availability of LRV's. The model determined operating energy consumption in Btu for a typical weekday. Table 4.5 shows the simulation result. The average operating energy consumption of LRV was found to be 6.65 Kwh/Car-mile.

Table 4.5 Light rail vehicles direct energy consumption*

Corridor	Weekday Energy Consumption	Annual Energy Consumption	Total Annual System Consumption	Annual VMT	Energy consumption /VMT
	(kwh)	(kwhx10 ⁶)	(Btux10 ⁹)	(miles)	(kwh)
North Area	6,973	2.02	25.19	303,880	6.65
East Area	8,028	2.33	29.00	349,860	6.65
Downtown	4,834	1.40	17.46	210,660	6.65
Deadheading	967	0.28	3.49	42,140	6.65
Total	20,802	6.03	75.14	906,540	6.65

(Source: Caltrans, 1983) *Energy Intensity includes: Energy required for propulsion, auxiliary equipment, heating, and air-conditioning.

The IBI Group (1978) estimated the manufacturing energy of a rail rapid transit vehicle. The estimation was separated into two basic parts; the energy required to produce the materials and the energy consumed in the transformation of these materials into finished

vehicles. A typical Montréal metro transit car was considered in the estimation. The reported manufacturing energy for a rapid transit vehicle was 6,255.49 Mega Btu/car (Appendix B- 5).

The maintenance costs of Montreal Metro type car in 1966\$ per car mile were estimated from industrial source. The cost was estimated as 5 cent per car-mile (1966\$). The energy intensities of vehicle maintenance were assumed as 35000 Btu per 1966 dollar. The calculated maintenance energy per car mile was 1750 Btu.

The direct energy consumption rate was obtained from the Montréal transit officials. The energy consumption was approximately 5 Kilowatt hours per car-mile.

Fels (1975) conducted an analysis to estimate energy consumption for the manufacturing of an auto, bus, rapid rail and personal rapid transit. The result for the manufacturing of a rapid rail car is reported in the table below:

Table 4.6: Energy consumption for the manufacture of a rapid rail car

Type of vehicle	Rapid rail Car
vehicle weight (lbs)	58250
Energy contributions (Kwh):	
Manufacture of metallic materials	855,000
Manufacture of other materials	51,300
Fabrication at parts and assembly of the Vehicle	305,200
Transportation of materials and of the assembled vehicle	20,000
Total energy to manufacture new vehicle (Kwh)	1,231,500

(Source: Fels, 1975)

Fels (1975) also evaluated that the rapid electric rail car consumed an average of 4.25 Kwh of electrical energy per vehicle-mile for propulsion of the system.

Chester and Horvath (2008) conducted a comprehensive lifecycle assessment for

different rail transit systems. They used process-based LCA software SimaPro to estimate manufacturing and maintenance energy of different rail cars. Two light rail train life-cycle inventories were computed by inputting the California and Massachusetts electricity mixes. The maintenance of trains was divided into three categories: routine maintenance, cleaning and flooring replacement. Due to a lack of primary data, SimaPro train maintenance data were used to estimate maintenance energy. The operating energy consumptions were determined from agencies data base. The operating energy consumption was disaggregated into propulsion, idling, and auxiliaries. Table 4.7 shows the result of their analysis for two LRT systems in the USA, namely, Muni in San Francisco and Boston Green Line in Massachusetts.

Table 4.7 Total life cycle energy for two USA light rail systems

Life-Cycle Component	Muni LRT system energy consumption			Boston Green Line LRT system energy consumption		
	TJ/Train- Life	MJ/VMT	MJ/PMT	TJ/Train-Life	MJ/VMT	MJ/PMT
Manufacture	1.4	0.83	0.038	1.6	1.2	0.021
Operation (propulsion)	28	16	0.73	40	29	0.53
Operation (Idling)	14	8.2	0.37	20	15	0.27
Operation (Auxiliary)	4.8	2.8	0.13	6.0	4.3	0.079
Maintenance (Propulsion related)	0.28	0.16	0.0075	0.31	0.22	0.0041
Maintenance (Cleaning)	0.027	0.015	0.0007	0.025	0.018	0.00033
Maintenance (Flooring)	0.044	0.026	0.0012	0.042	0.030	0.00055
Insurance (Employees)	0.71	0.41	0.019	2.3	1.7	0.031
Insurance (Vehicles)	0.88	0.51	0.023	1.4	0.97	0.018

(Source: Chester and Horvath, 2008)

4.6.2 LRT vehicle manufacturing energy using EIO-LCA

To estimate the LRT vehicle manufacturing energy, first the average price of a new vehicle is to be determined. Then the production price of a vehicle is determined by

deducting price discounts, dealer markup and profit (25%) from the base price (Vyas, et al., 2000). This price is then converted to EIOLCA base price (\$1997) and then entered into EIOLCA analysis tool to get the energy consumption for vehicle production. The estimation of LRV manufacturing energy is based on the price shown in Table 4.8.

Table 4.8: Average new light rail vehicle costs in 2008 (U.S.)

Type of Vehicle	Cost*
Rail car, double-articulated, 1 level, 2 cabs	\$3,950,000
Rail car, single-articulated, 1 level, 2 cabs	\$2,850,000

(Source: APTA, 2008)

*Cost includes amount paid to manufacturer or agent.

The average price of LRV is 2.85 million dollar (2008 \$). The price after deducting price discount (5%), dealer markup (17.5%) and profit (2.5%) would be 2.138 million dollar (2008\$). Converting this price into EIOLCA base year price (1997\$) and inputting this in to EIOLCA tool “Rail road rolling stock manufacturing sector” provided 15.9 TJ energy for LRV manufacturing.

4.6.3 Energy consumption to generate electricity

In estimating electric energy consumption, a separation is sometimes made between the electrical energy consumed at the point of use and the energy lost in electricity generation and transmission. At 100% efficiency, the conversion from heat to electricity is at a rate of 3412 Btu per Kwh. But in reality, no conversion process operates at 100% efficiency. Electricity energy at sales differs from net generation due to transmission losses. Transmission and distribution losses amount to be about 8% (USDOE, 1996). The net generation is measured at the output transformer of the power plant. The net generation also differs from the gross electricity generation. The gross electricity generation is the

amount of energy measured at the terminals of the generating unit. They differ by the amount of electricity consumed within the plant itself, roughly 4%. Then comes the primary energy consumed at the generating plant. The primary energy sources can be both nonrenewable such as fossil fuel, coal, nuclear (uranium) and renewable such as hydroelectric, biomass, wind, photovoltaic, and solar thermal. The power plant thermal energy conversion efficiency varies between 32-35%. When all these losses are considered, the energy corresponding to 1 kwh of electricity is typically around 10,272 Btu (USDOE, 1996).

The GREET model provides researchers a good opportunity to evaluate the energy and environmental impacts of electricity generation. This model was used to estimate energy consumption for electricity generation for Ontario's electricity generation mix, which is reported in the later part of this thesis.

4.7 Light rail transit Infrastructure

In Section 4.3, the principal infrastructural components of light rail transit were discussed. Each of these components includes several other elements that are essential for a successful light rail transit system. Figure 4.7 shows those essential components. The energy estimation for all these components is an enormous task, which requires vast information and data. Moreover, some of these components have little impacts on energy. Therefore only the following major infrastructures that have significant impact on energy were considered: Track work, Station, Power distribution system, Train control, Maintenance facilities, Park-and-Ride. The life cycle energy estimation of each of these components is discussed in the following sections.

Figure 4.7: The essential components of LRT infrastructure

4.8 Track construction energy

Track works involve large number activities. The energy consumption in each activity can be calculated by analyzing materials input and energy balance in every step. However this requires detailed information regarding materials input and equipment used in the process. EIOLCA tool can be of great help to overcome these difficulties. Using EIOLCA tool, the construction energy for different types of track works were estimated, which is shown in Table 4.9.

Table 4.9: Track construction cost and energy requirement for selected LRT systems

Location	At-Grade	Elevated Structure	Elevated Retained Fill	Elevated Fill	Subway	Retained Cut
		Cost (million dollars) (1990\$)				
Portland	6.4	16.1	-	-	-	-
Sacramento	2.2	2.2	5.7	-	-	26.3
San Jose	3.2	-	-	-	36.4	-
Pittsburgh	2.4	3.4	5.1	3.7	37.9	25.9
Los Angeles	3.4	15.8	5.0	3.3	36.7	16.5
Average \$1990	3.5	9.3	5.3	3.5	37.0	22.9
\$1997	4.32	11.42	6.54	4.32	45.65	28.25
		Energy				
Energy (TJ)	76.7	204	116	76.7	811	502

(Source for cost: FTA 1992 cited by Hsu, 2003)

Fels (1975) calculated the construction energy for five types of rapid rail guideway based on the Bay Area Rapid Transit District (BARTD) specifications. The per mile construction energy for a single-track was computed from the material constituents such as steel, aluminum, crushed rock and concrete. An additional 35.7% energy was assumed for fuel consumed during construction and transporting the materials (Table 4.10).

Table 4.10: Construction energy requirements for five types of rapid rail guideway

Type	Energy(million kwh)/ single track-mile	Energy (TJ)/ single track-mile
At-grade track	5.0	18
concreted track	5.6	20.16
Aerial structure	16.3	58.68
Subway cut and cover	47.8	172.08
Subway: tunnel	96.2	346.32

(Source: Fels, 1975)

The Transportation Laboratory of California Department of Transport (Caltrans) estimated trackway construction energy as 16.3 Giga Btu/ Track-mile (Caltrans, 1983).

The IBI group (1978) estimated the following construction energy for rail track work

Table 4.11: Rail track construction energy

Infrastructure	Total cost/ unit	Road construction type cost/unit	Non-residential construction type cost/unit	Total construction energy
	1966 \$ x 10 ³	1966 \$ x 10 ³	1966 \$ x 10 ³	BTU's x 10 ⁹
Surface (Track-mile)	2300	500	1800	171
Subway (Track-mile)	6900	3400	3500	706
Elevated(Track-mile)	4500	-	4500	236

(Source: IBI Group, 1978)

4.9 Track maintenance energy

Track needs regular maintenance to remain in good order. Common maintenance jobs include spraying ballast with weedkiller to prevent weeds growing, grinding the surface of the head of each of the two rails by railgrinder and regular inspecting to detect internal flaws in the rails. Very little data exist in the literature regarding track maintenance energy consumption. Some of the available information reported in the literature is shown in Table 4.12.

Table 4.12: Annual track maintenance energy

Track type	Energy (MJ/Track- mile)	Source
Rail rapid transit: Subway, elevated, surface	4220000	IBI Group, 1978
Rail rapid transit: Subway, elevated, surface	917130	Chester & Horvath, 2008

4.10 Station construction energy

The different types of LRT stations construction energy were calculated using the EIOLCA tool (Table 4.13). Station construction energy substantially varies with type of stations. Station construction at tunnel level involves the highest energy consumption.

Table 4.13: Costs and energy requirements by station type for LRT projects

Project Location	Grade-separated	At-Grade	Transit Center	Transit Mall	Tunnel
Costs (1998 U.S. million dollars)					
Dallas(DART) Starter System	4.9	2.6	4.3	-	19.9
Northeast/North Central	5.6	2.6	-	-	-
St. Louis (BSDA) Starter System	2.1	1.0	5.6	-	-
Illinois Extension	-	1.1	-	-	-
Denver(RTD) Southwest Line	-	2.1	-	-	-
Port Land (Tri-Met) Banfield	2.2	-	-	-	-
Westside/ Hillsboro	-	0.9	5.1	2.5	-
Average Cost	3.7	1.7	5.0	2.5	19.9
Energy, TJ (Using EIOLCA)	28.6	12.8	15.8	18.8	154

(Sources for costs: Agency Data; BRW, Inc.; Pilgrim, 2000 cited by Hsu, 2003)

4.11 Station operation and maintenance energy

Fels (1978) analyzed the total energy consumption of four urban rapid rail systems to obtain a detailed breakdown of the traction and station energy contributions. The systems chosen were PATH, PATCO, NYCTA and BART in USA, that span a wide range of characteristics representing age, service region and size. The primary data source for the analysis was monthly bills. The breakdown of the total energy consumption for each system is shown in Table 4.14.

Table 4.14: Energy profile of systems analyzed

	BART	PATCO	PATH	NYCTA
Total energy consumed (Kwh): Annual	219x10 ⁶	40x10 ⁶	69x10 ⁶	2049x10 ⁶
Traction (%)	71%	85.5%	89%	86%
Station (%)	24%	12.5%	5%	9%
Maintenance (%)	5%	2%	6%	5%
Car-miles: Annual	23.4 x10 ⁶	4.2 x10 ⁶	11 x10 ⁶	303 x10 ⁶
# Passenger-miles: Annual	467 x10 ⁶	92 x10 ⁶	183 x10 ⁶	7120 x10 ⁶
Total energy (Kwh/car-mile)	9.4	9.5	6.4	6.8
Energy per passenger-mile (Kwh/pm)	0.47	0.43	0.38	0.29

(Source: Fels, M., 1978)

The analysis also found an average energy consumption of 190,000 Kwh/month per under ground station and 74,000 Kwh/month per aerial station based on BART systems (Appendix B-6).

4.12 Energy consumption for power distribution

4.12.1 Electric Substations

Substations required for LRT to provide traction power are usually located approximately every one mile along the alignment. Usual dimensions are approximately 20' x 60'. Caltrans (1983) estimated the cost for one megawatt (MW) substations as \$300,000 (1982\$). It was assumed that 10% of the total cost was for construction of the concrete slab, walls and roof and the remaining 90% for the electrical equipment, mainly the transformer. The estimated energy consumption, based on above costs, is shown below:

Dollar-to-energy conversions for the structure = 5.01×10^4 Btu/(1973\$)

Dollar-to-energy conversions for Transformer = 8.00×10^4 Btu/(1973\$)

Estimated energy required for substation = 6.91×10^9 Btu/Track-mile

Caltrans (1983) also estimated the energy for supply lines as shown in Table 4.15.

Table 4.15: Energy for overhead electrical distribution system

Item	Density (Ton/TM)	Process Energy (Btu /Ton)	Item Energy (Btu/TMx10 ⁹)
Trolley Line	5.34	1.39×10^8	0.7
Feeder Lines	7.98	1.39×10^8	1.1
Cross Street			
Suspension (Catenary)	2.66	6.67×10^7	0.2
Subtotal			2.0
10% Miscellaneous			0.2
Subtotal Materials			2.2
30% Placement			0.6
Total			2.8

(Source: Caltrans, 1983)

4.13 Energy consumption for Signals

Signal includes the following items:

- Track Circuits
- Impedance Bonds
- Signal Power Supply
- Wayside Indication Apparatus
- Grade Crossing Protection
- Turnout Controls
- Traffic Control Modifications

Energy needed for construction of signals per track mile = 2.87×10^9 Btu /track mile
(Caltrans, 1983)

4.14 Maintenance facilities

Caltrans (1983) also estimated the construction energy for the LRV maintenance facility.

By establishing the total construction cost and energy intensity, the construction energy for maintenance facilities was calculated as follows:

Table 4.16: LRV maintenance facility construction energy

Item	Cost (1982\$)	Cost (1973\$)	Energy Conversion Btu/(1973\$)	Energy (Btu $\times 10^9$)
Shop Building	2,000,000	727,273	5.01×10^4	36.44
Shop Equipment	1,280,000	460,800	1.302×10^4	6.00
Storage Yard	2,700,000	981,818	6.1615×10^4	60.49
Total	5,980,000			102.93

(Source: Caltrans, 1983)

4.15 Parking

Cooper (1983) conducted an extensive study to estimate indirect energy consumption for constructing a park-and-ride lot with 500 car capacity. The study estimated 2.07 Giga Btu energy consumptions for constructing a 500 car capacity park-and-ride lot.

Chapter 5

Comparison of Total Energy Requirements for Bus Rapid Transit and Light Rail Transit for Ottawa East-West via Downtown Transit Corridor

5.1 Introduction

Ottawa is the capital city of Canada, with a population of about 1.1 million and ranks the fourth largest urbanized area of the country. The city of Ottawa and the province of Ontario have invested considerable resources in Ottawa's public transit network, making it one of the best in North America. The Ottawa-Carleton Regional Transit Commission (OC Transpo) is the exclusive provider of public transit in the urban transit area of the City of Ottawa. It operates about 990 standard and articulated buses for regular transit service and a contract service for the physically disabled, called "Para Transpo", through an independent operator. The Commission also operates charter services. The buses use a combination of dedicated bus-only roads (Transitway) and regular roads to deliver the transit service. OC Transpo also operates a diesel-powered light rail rapid transit service (O-Train) that began as a pilot project in 2001 (OC transpo, 2009).

Ottawa's Transitway was opened in 1983 and developed over the next 15 years as one of the world's most successful implementations of a Bus Rapid Transit (BRT) system. Although lauded worldwide as a model BRT facility, the success, however, has led to an emerging congestion problem in the downtown. Ridership growth on the four transitway corridors converging in the downtown has made the system reach its capacity. The current transit system will not be able to accommodate projected increase in population and employment over the next 20 to 30 years. Moreover, the introduction of the new Bus Rapid Transit ("Rapibus") service of Gatineau will deliver a high percentage ridership

into Ottawa's central area. The system will not be able to handle this ridership as well. In order to accommodate future transit ridership, the city has recently approved a study of an underground tunnel project. Four alternatives were initially considered to determine the best feasible option. Extension of existing BRT service was evaluated with a new LRT line construction. The evaluation was conducted considering cost-benefit, environmental and social factors. Energy consumption was not addressed in the evaluation. In this chapter, a life cycle energy assessment (both direct and indirect energy) will be conducted for both BRT and LRT for the Ottawa east-west transit corridor.

5.2 Overview of the Ottawa's existing transit system

Ottawa's BRT system consists of 27 km exclusive busways (transitways) with 26 stations, 2 km CBD reserved bus lanes (on two parallel streets), 3.3 km of mixed-traffic lanes (Ottawa River Parkway); and 11.5 km of freeway shoulder lanes - totaling 46.3 route-km. The BRT system provides transit service to the communities of Ottawa, Nepean, Vanier, Rockcliffe, Gloucester, Kanata, and Orleans. The O-train runs north to south from Bayview through downtown and onto Greenboro and covers 8 km of track (OC Transpo, 2009). The Ottawa's rapid transit networks are shown in Fig. 5.1.

Fig. 5.1: Ottawa's rapid transit network (Source: OC transpo, 2009)

The important service facts of Ottawa's transit system

Service Facts: As of December 31, 2007

Weekday passenger volume	240,000
Peak hour one-way passenger volume	10,500
Buses per peak hour, through central area	180
Number of stations	38
Bike & Ride locations	31
Average passenger trip length in km	9
Total km of routes	6,500
Number of routes (includes school routes)	239
Employees	2,277
Bus Stops	6,417
Bus stops with shelters	1,118
Bus stops with benches	1,525
Park & Ride Spaces	10
Garage	4

Active Fleet: As of December 31, 2007

Number of buses in active fleet	991
Average age of buses (years)	7.1
Average life of a bus (years)	19
Litres of diesel fuel used by active fleet per year	39.1 million
Average km a bus travels per year	60,335
Average km a bus travels in its lifetime	1,086,000

(Source: OC transpo, 2009)

5.3 Transportation Master Plan of Ottawa

The Transportation Master Plan (TMP) of the City of Ottawa is the guiding document to manage growing transportation demand over a certain future horizon. It identifies the transportation facilities and services that the city needs to put in place to meet the travel needs of the residents. The TMP is a key input to the Official Plan that requires revision every five years under the Ontario Planning Act (City of Ottawa, 2009b). The current TMP, have been updated recently. There have been significant changes since previous TMP 2003 that have potential impact on transit options. The updated TMP includes an approved rapid transit network, a schedule for implementation of the transit projects, as well as road projects, pedestrian policies and cycling plans.

5.3.1 Updated transit plan

Making the right transit choice for Ottawa has always been a topic of discussion for many years. The concept for a rapid transit development program in Ottawa-Carleton capital region started in 1973. Following this, a 1976 study confirmed the long-term need for rapid transit in the five major travel corridors in Ottawa-Carleton. Busways were selected as the least costly option for these travel corridors with the recognition of an eventual conversion to a fixed guideway service such as light rail transit (Gault et al. 2003). In June 1986, Regional Council undertook a study to examine the feasibility of grade separating the transitway through the central area. The study examined both above and below-ground alternatives and determined that a tunnel would be the most appropriate grade separated alternative. However, Regional Council decided to continue with further

extensions of the transitway, leaving the expensive grade separation of the downtown section until it was required.

In May 2003, the City of Ottawa adopted a new Official Plan that set a 30% transit modal split target for the year 2021. The TMP identified the expansion of LRT service from North to South (Downtown to Riverside South) as the top priority project to achieving this target. In July 2006, City Council initiated the procurement of the design-build and a 15-year maintenance agreement of the North-South Corridor LRT Project. The federal and provincial governments had each committed \$200 million to the project. But federal government failed to support the project and the concern over the proposed mixed operation of the LRT with buses and general traffic on Albert and Slater Streets led to the decision not to proceed with the contract. As a result the project agreement for the LRT Project was terminated (MRC, 2008).

With the termination of the North-South Corridor LRT Project, the city took the initiative to update the TMP and conducted a transportation infrastructure requirements study. This study identified a series of options for the downtown rapid transit network that would provide Ottawa with a rapid transit system for generations. The primary rapid transit network options considered include:

- Network Option 1: BRT Tunnel - Bus based
- Network Option 2: BRT/LRT Tunnel – Bus based with North-South LRT
- Network Option 3: LRT Tunnel - East& West downtown LRT
- Network Option 4: LRT Tunnel - East& West downtown LRT plus North-South LRT

The basic difference between each of the above network options is the extent to which LRT is incorporated. Options 3 and 4 require the conversion of segments of the existing bus transitway extending east and west of the downtown to LRT. All these four options are shown in Fig. 5.2.

Fig. 5.2: Primary rapid transit options for Ottawa (Source: MRC, 2008)

Having conducted detailed feasibility studies for the above four options, the City Council finally approved a primary rapid transit network (shown in Figure 5.3), that incorporates an East-West light rail transit project between Baseline and Blair stations. The LRT line will pass through 2.5 Km tunnel under the downtown and the rest of the length will be built by converting the existing transitway to LRT. The network also incorporates the conversion of the existing O-Train to electric LRT along with its extension into Riverside South. The network also incorporates ultimate LRT extensions to Kanata and Orléans. These corridors are shown in Figure 5.3 by the red dashed lines. Extensions to the existing bus Transitway system to Orléans, Barrhaven and Kanata are also included in the approved network.

Figure 5.3: Approved rapid transit network (Source: MRC, 2008)

5.4 Corridor selection for this study

The main focus of this research work is to conduct a comprehensive life cycle energy analysis of BRT and LRT by considering both direct and indirect energy consumption. In order to accomplish this objective, the East -West transit corridor of Ottawa was selected for analysis. The transit corridor starts east at Blair station and passes through the tunnel section at Ottawa downtown and ends up west at Baseline station. The total length of the corridor is 21.78 km. The corridor is shown in Fig. 5.4.

Fig. 5.4: Ottawa downtown East-West transit corridor

5.4.1 Case study framework

The study began with a discussion of the city's population and employment growth projections used to forecast city-wide travel demands for the 2031 planning horizon. Using the City's TRANS regional travel demand model, expected ridership levels in 2031 on the transit corridor were established. Then the number of vehicles (standard bus, articulated bus or light rail) required to accommodate the forecasted passenger demand were determined based on the design carrying capacity of the transit vehicles and the forecasted passenger volume. With the number of vehicles, the headways between the transit vehicles were calculated and compared with the way capacity and station capacity of the corridor. Then the final number of vehicles (bus and LRT) and service frequencies required to accommodate 2031 ridership level were established. Using this information, a comprehensive life-cycle assessment (LCA) for energy requirements (raw materials extraction, manufacturing, construction, operation, maintenance & end-of-life) for both vehicles (bus/rail) and infrastructures (transit, rail track) were conducted. A combination of both process based and input-output energy analysis were employed. A micro simulation model was developed using VISSIM to estimate average fuel consumption. The GREET model was used to estimate energy consumption for diesel and electricity production. Several other energy estimation models were also developed. All these are discussed in their respective sections. The study approach for this case study is schematically shown in Fig. 5.5.

Fig. 5.5: Schematic diagram of the case study framework.

5.5 Population and employment growth

Projections of long term growth in population and employment are the backbone for travel demand forecasting. Ottawa City Council has updated population and employment

growth projections recently. In the updated projection, the 2006 mid-year population of 870,800 was used as the basis for the projection of population and employment for 2031. The projections result predicts a 2031 population of 1,135,800 and employment of 703,100 jobs in Ottawa. Table 5.1 and Fig. 5.6 show the population and employment level over the time horizon.

Table 5.1: Population and employment projection

Year	2001	2006	2011	2016	2021	2026	2031
City of Ottawa							
Population	806,600	870,800	923,000	976,800	1,031,300	1,085,300	1,135,800
Households	319,400	351,200	381,800	413,000	443,600	471,700	497,400
Jobs	480,000	529,800	580,200	617,000	648,400	676,300	703,100
Greater Ottawa-Gatineau Area							
Population	1,205,200	1,307,100	1,385,000	1,472,400	1,561,600	1,650,300	1,733,800
Households	454,800	525,000	566,200	611,300	656,200	698,500	737,400
Jobs	n.a.	742,700	807,600	863,500	914,800	962,400	1,008,300

NOTE: Jobs by place of work.

(Source: City of Ottawa, 2009a)

Fig. 5.6: Population and employment growth of city of Ottawa
(Source: City of Ottawa, 2009a)

Table 5.1 indicates that the city of Ottawa is projected to grow by approximately 30% in terms of population (an additional 265,200 persons) and 33% in employment (an

additional 173,300 jobs). This growth in employment is based on the National Capital Region's economic role in serving the greater Ottawa-Gatineau region and outlying areas.

5.6 Travel demands forecast

The travel demand forecast, reported in infrastructure need assessment study for TMP, was used in this analysis. The travel demand over the 2031 planning period was forecasted with the assistance of TRANS model (Appendix C-1). TRANS model is the National Capital Region's transportation model, originally developed in the late 1970's to analyze existing trip patterns and travel choices and to simulate the effects of future scenarios featuring varying growth, alternative transportation facilities, services and policies.

The growth in city wide travel demand and travel pattern over the 2031 planning period were assessed on the basis of the local travel behavior as identified in the 2005 O-D Travel Survey. Trips using the NCR road and transit networks can either be:

- originating from Ottawa and destined to Ottawa;
- originating from Ottawa and destined to Gatineau/MRC;
- originating from Gatineau/MRC and destined to Ottawa; or
- originating from Gatineau/MRC and destined to Gatineau/MRC

To forecast Ottawa city-wide trips, all the above mentioned trips, excluding trips made from Gatineau/MRC to Gatineau/MRC were considered.

The focus of the travel demand analysis was a.m. peak hour, as it represents a period when road networks experience increased levels of congestion. Moreover, a.m. peak hour is the busiest period for transit service. Table 5.2 below presents existing and 2031 forecasted city-wide a.m. peak hour travel by various modes. It can be seen that the city-wide travel will increase by approximately 38% over the planning period. The noticeable fact is that while the share of travel by transit will increase by 76%, the share of travel by auto will increase only by 24 %.

Table 5.2: City wide projected travel demand-all modes

Ottawa Travel* AM Peak Hour	Base year			2031			Percentage Growth
	Person Trips	Mode Share	Mode Split	Person Trips	Mode Share	Mode Split	
Walking/Cycling (Non-Motorized)	23,700	11%	-	35,400	12%	-	49%
Transit Riders	44,500	21%	23%	78,300	26%	30%	76%
Private Auto Trips	146,600	68%	77%	182,300	62%	70%	24%
Total – All Trips	214,800	100%	100%	296,000	100%	100%	38%

**Includes all travel originating or destined to Ottawa (i.e. excludes travel originating and destined to Gatineau/MRC) (Source: MRC, 2008)*

5.6.1 Travel demand in Ottawa's Inner Area

Ottawa's Inner Area is the most significant destination for travel during the a.m. peak period. Figure 5.7 shows major employment nodes located within Ottawa's Inner Area. The high concentration of employment densities occurs along the Wellington and Rideau Street in Ottawa's central business district. The other major employment nodes are Carleton University, University of Ottawa, and Ottawa Hospital Civic Campus. The Carleton University and the University of Ottawa have enrolments of approximately

25,000 and 30,000 students respectively, which generate a substantial amount of a.m. travel demand. Figure 5.7 also indicates the employment levels projected for 2031 for various traffic zones.

Figure 5.7: Major employment nodes and density in Ottawa Inner area: 2031
(Source: MRC, 2008)

Travel demands to and through Ottawa's Inner Area were measured across strategic screenlines. Typically screenlines are established across barriers to transportation, such as rivers, railways and other geographic features which tend to limit the number of crossing points and consequently offer key opportunities to compare transportation demands against various supply options. Ottawa's Inner Area, can be define by three strategic

screenlines, in the north by Ottawa river, east and south by Rideau river and west by the Canadian Pacific Railway (CPR) corridor. The locations of the various screenlines which encompass the Inner Area are shown in Figure 5.8.

Figure 5.8: Ottawa Inner area screenlines
(Source: MRC, 2008)

An assessment of the a.m. peak travel demands to and from and through the Inner Area screen line is shown in Table 5.3.

Table 5.3: Growth in travel by mode – Inner Area cordon (a.m. peak hour)

	Base Year				2031 Forecast			
	Auto		Transit Riders	Transit Mode Split	Auto		Transit Riders	Transit Mode Split
	Veh.	Per.			Veh.	Per.		
Inbound (peak dir)								
Rideau River	15,700	19,100	13,000	40%	16,800	20,100	17,200	46%
CPR	13,300	16,000	9,200	37%	14,000	16,500	14,300	46%
Ottawa River	9,900	11,800	4,900	29%	9,300	11,600	8,500	42%
Inbound Total	38,900	46,900	27,100	37%	40,100	48,200	40,000	45%
Outbound (non-peak dir)								
Rideau River	10,400	12,200	3,200	21%	10,600	12,600	5,500	30%
CPR	8,800	10,400	2,900	22%	9,100	10,800	3,900	27%
Ottawa River	4,900	6,000	1,900	24%	6,400	7,500	5,500	42%
Outbound Total	24,100	28,600	8,000	22%	26,100	30,900	14,900	33%

(Source: MRC, 2008)

It can be seen from the above table that the growth of automobile travel demand over the planning period is relatively low, which reflects the congestion currently experienced on existing roadways, as well as a potential shifting of through travel demand outside the Inner Area. Transit growth is substantial across all three screenlines. In the peak travel direction the transit modal split increases from 37% to 45% by 2031.

Figure 5.9 is a graphical representation of the a.m. peak transit travel demand generated by the TRANS model. It illustrates that by 2031 the majority of transit trips that converge in the downtown will be served by the east- west transit corridor.

Figure 5.9: Transit trip assignments for the year 2031
(Source: MRC, 2008)

5.7 Ridership and service levels in the downtown transit corridor

Being the capital city of Canada, downtown Ottawa is dominated by government

buildings, including the Parliament of Canada and the Supreme Court. Most prominent buildings are situated along Wellington, Sparks and Elgin streets. Most of the buildings are office towers containing the various government departments. The downtown also contains a number of apartments, hotels, and condominiums. Rapid transit ridership into downtown Ottawa flows from four directions: east, west, south, and north. Riders from the east, west, and south currently travel on OC Transpo services entering via the east and west transitways. Riders from the north (Gatineau) travel primarily on STO services entering from the west via the Portage and from the east via the Alexandra bridges. The downtown transit corridor must provide sufficient capacity to accommodate the projected 2031 ridership. The projected 2031 a.m. peak hour passenger load point forecasts are shown in Table 5.4 & Fig. 5.10. The a.m. peak passenger volume differs with the way of how passenger enters downtown from south, either via Hurdman or via O-train corridor.

Table 5.4: Peak hour passenger load point forecasts for two alternative scenarios

Passenger entering from South Through	West of CBD (Le Breton)	East of CBD (Hurdman)	From Gatineau
Southeast Transitway Corridor extension	12,800	13,700	8,500
O-Train Corridor extension	15,600	11,300	8,500

Figure 5.10: Two alternative scenario of transit demands in 2031 on the corridor
(Source: MRC, 2008)

5.8 Accommodating forecasted ridership

To accommodate the forecasted ridership discussed in the previous section, the corridor must carry:

- 12,800 to 15,600 peak hour passenger west of the downtown (at LeBreton)
- 11,300 to 13,700 peak hour passenger east of the downtown (at Hurdman)
- 8,500 from Gatineau.

The range for west of downtown and east of downtown ridership depends on whether the Southeast Transitway or O-Train corridor is used to carry the majority of passengers from the southern areas into the downtown.

Before determining the fleet requirement to accommodate forecasted ridership, it is necessary to determine the line capacity and station capacity. Line capacity is the maximum number of Transit Units (TU) that can be transported on a line past a fixed point during one hour under a given set of conditions. Station capacity is the number of Transit Units that can be processed or served during one hour. Stopping of TUs at a fixed location always increases the minimum headway at which TUs can follow each other with a given regime of safety. For this reason, station capacity is generally lower than way capacity. Headways between successive TUs at a station depends on operating regime and safety requirements of leading TU and following TU, standing time and departure preparation. The theoretical minimum headway can be expressed as:

$$h_{\min} = \text{Max}(h_{\text{wmin}}, h_{\text{smin}}) \dots\dots\dots 5.1$$

where, h_{wmin} is the minimum headway governed by the way capacity and h_{smin} is

the minimum headway governed by the station capacity.

$$h_{wmin} = \frac{nl' + s_0}{v} + t_r + \frac{v(b_1 - b_2)}{2b_1 * b_2} \dots\dots\dots 5.2$$

where, nl' , length of TU; v , speed; t_r , reaction time; S_0 , minimum spacing between stopped TUs; and b_1 and b_2 deceleration rate.

For the most critical safety regime, when leading TU comes to an instantaneous stop ($b_1 = \infty$) and FTU stops without collision by applying normal braking ($b_2 = b_n$)

$$h_{wmin} = \frac{nl' + s_0}{v} + t_r + \frac{v}{2b_n} \dots\dots\dots 5.3$$

$$l' = 12.0m, s_0 = 1.0m, b_n = 1.3m/s^2, t_r = 1.0s, v = 30km/hr = 8.33m/sec$$

$$h_{wmin} = 5.76sec$$

$$\text{When, } b_1 = b_2 = b_n = 1.3m/s^2$$

$$h_{wmin} = \frac{nl' + s_0}{v} + t_r = 2.5sec$$

$$h_{smin} = t_s + t_r + \sqrt{\frac{2nl'}{a}} + \frac{nl'}{v} + \frac{v(K+1)}{2b_n} \dots\dots\dots 5.4$$

$$t_s = t_o + \text{Max}(b'\tau_b, a'\tau_a) \dots\dots\dots 5.5$$

Length of TU, $nl' = 12m$; Reaction time, $t_r = 1.0s$; Dwelling time, $t_s =$

Standing time + time lost prior to opening and closing door, $t_o = 1.0s$ (BRT), $2.0s$ (LRT)

K = Safety factor

$$b' = a' = 7, \tau_b = 1.6s/pass., \tau_a = 2s/pass.)$$

$$t_s = 1.0 + \text{Max}(14, 11.2) = 15$$

$$a = 0.8m/s^2, b_n = 1.3m/s^2, v = 8.33m/sec$$

$$h_{smin} = 15.0 + 1.0 + \sqrt{\frac{2 * 12}{0.8}} + \frac{12}{8.33} + \frac{8.33(1.5 + 1)}{2 * 1.3} = 30.92sec$$

$$h_{\min} = \text{Max}(5.76, 30.92) = 31 \text{ sec}$$

If the length of stations can accommodate four buses at a time, then two vehicles can enter and leave the stations in platoon. The theoretical minimum headway becomes,

$$h_{\min} = 15.5 \text{ sec}$$

The design capacity of various transit units is shown in Table 5.5. This design capacity is used to estimate the required number of buses or LRVs to carry peak hour passenger volume. The number of Transit units (TU) required to carry 2031 peak hour passenger volume is shown in Table 5.6.

Table 5.5: Passenger capacity of BRT & LRT vehicles (No. of passenger/vehicle)

Capacity	40-ft Standard Bus	Articulated Bus	Double- Deck/ Double articulated bus	Light Rail Vehicle (1 car)
Seat capacity	39	54	70	70
Standing capacity	12	32	40	130
Proportion of standing capacity for design	50%	50%	50%	50%
Design capacity	45	70	90	135

(Source: MRC, 2008)

Table 5.6: No of Transit Unit (TU) required in service to accommodate 2031 ridership

	Passenger Design Capacity	From south via Hurdman and from north via separate corridor	From south via Carleton and from north via separate corridor
Peak volume(passenger/hr)		13,700	15,600
40-foot standard bus	45	305	347
60-foot articulated bus	70	196	223
75-80-foot double-articulated bus	90	153	174
2-car light rail train	270	51	58
3-car light rail train	405	34	39
4-car light rail train	540	26	29

For 40-foot standard bus required headway = $3600/347 = 10.4 \text{ s} < 15.5$

For 60-foot articulated bus required headway = $3600/223 = 16.14 > 15.5 \text{ ok}$

But it is not practically possible for the city to provide all 60-foot articulated buses, as currently 70% of buses are standard 40-foot buses. Moreover the peak hour passenger volumes will remain quite low as compared to 2031 forecasted volume at least for the next several years. However, for energy analysis, a theoretically possible maximum number of standard buses were considered to accommodate projected peak hour ridership demand, which is only 10% (23 numbers) standard 40-foot bus and 90% (207 numbers) sixty-foot articulated bus. These buses can accommodate 15,525 passengers/hr.

A study of Transport and Road Research Laboratory (Gardner et. al., 1991) has looked at BRT throughput in a number of systems in developing cities. The research suggested that for a fully segregated, high volume station, with 4 bus bays and fare pre-payment the maximum 217 number of buses per hour can travel on busway.

For light rail transit 58 numbers of 2-car train will be required to accommodate 2031 ridership demand and the headway will be 62 sec, which is within reasonable limit of minimum headway requirement (see Appendix C-2 for ranges of actual capacities of major transit modes).

5.9 Useful life of transit buses

The Federal Transit Administration's (FTA's) service-life policy for transit buses establishes 12 years as the minimum service life or 500,000 VMT (whichever comes first) before a transit bus can be retired without financial penalty (discussed in Section 3.7.2.4 of this thesis). Figure 5.11 shows the actual average retirement age distribution of transit buses in the USA. From this Figure, it can be deduced that average life of bus is around 16

years. The average life of OC Transpo bus is 19 years (OC Transpo, 2007). In the literature, several studies considered the service life of a transit bus as 15 years (IBI Group, 1978; Caltrans, 1983). So, the average life of bus is considered 15 years for this study as well.

Figure 5.11: Average retirement age distribution of transit buses
(Source: Richard et al., 2007)

5.10 Lifetime vehicle-km traveled (VKT) by transit buses

In order to determine average lifetime VKT of transit buses, first VKT/day was calculated. Then annual VKT was established by considering the active running days excluding the days when vehicle is not in service due to maintenance and other reasons. Fleet requirement for a transit service varies with day (weekday and week end) as well as specific time of day (AM/PM peak, midday, evening). The ridership variation of OC Transpo with day as well as time of day is shown in Table 5.7 and Figs. 5.12 and 5.13.

Table 5.7: OC-transpo ridership variation over time

Day and Time of day	1972	1982	1987	1992	1997	2005
Weekday Riders	127,000	283,585	318,961	285,072	264,600	335,468
Saturday Riders	79,000	148,977	144,519	113,744	110,171	147,617
Sunday Riders	24,000	40,395	43,562	44,623	60,362	87,344
Weekday Peak Period Riders (a.m. & p.m)	89,281	155,924	188,506	171,943	155,407	191,400
Weekday Midday Riders	27,178	87,943	95,050	81,949	76,870	101,921
Weekday Evening Riders	9,398	34,232	27,016	28,657	29,946	40,692

(Source: Leroy et al., 2005)

Fig 5.12: Average daily ridership of OC Transpo (Source: Leroy et al., 2005)

Fig. 5.13: Variation of ridership with time of day (Source: Leroy et al., 2005)

It can be inferred from Table 5.7 and Fig. 5.13 that with respect to peak period fleet requirements, midday requires on average 48% fleet and evening hours require 18% fleet. It was assumed that in the early morning, fleet in service would be same as evening hours. The percent of fleet in service during different period of day is shown in Fig 5.14.

Fig 5.14: Percent of fleet in service during different period of day

On the basis of above assumptions, average daily service hour/bus can be calculated as,

$$1.5\text{hr} * 0.18 + 2\text{hr} * 1 + 7.5\text{hr} * 0.48 + 2\text{hr} * 1 + 2\text{hr} * 0.48 + 4\text{hr} * 0.18 = 9.55 \text{ hr} = 10 \text{ hr}$$

The total length of the transit corridor under consideration is 21.675 km. Using micro simulation model VISSIM, average one way travel time was found to be 2790 sec, i.e., 46.5 minute (see Appendix C-3). With a maximum speed of 60km/hr, the average speed of the transit vehicle was found to be 27.96 km/hr, which is close to average speed of OC Transpo service (Fig 5.15). By adding 5 minute lay off time, total time required for one-way travel would be 51.5 minutes. Therefore, time taken to complete a round trip would be 103 minutes. So, one bus can make five round trips per day.

$$\text{VKT /day} = 5 * 2 * 21.675 = 216.75 \text{ km}$$

Total VKT/year = $216.75 \times 298 (365 - 67(\text{one day off/week} + 15 \text{ days maintenance})) = 64591.5 \text{ VKT/year}$

For 15 years service life of a transit bus, total life time VKT would be 968872.5 km. According to OC-Transpo's statistics, average annual kilometerage of a bus is 60,335 and average lifetime kilometerage is 1,086,000. The result is in reasonable agreement with OC-Transpo's statistics. For a 30 year horizon, 2 buses will be required.

Fig. 5.15: Average speed of OC Transpo service (Source: OC Transpo, 2007)

5.11 Service life & life time VKT of LRV

In case of LRT, using micro simulation model VISSIM, average one way travel time was found to be 2195 sec (36.58 minutes). With a maximum speed of 80 km/hr, the average speed of the transit vehicle was found to be 35.55 Km/hr. By adding 5 minute lay off time, total time required for one-way travel would be 40.55 minutes. Therefore, time taken to complete a round trip would be 81 minutes. So one train (2-cars) can make 7 round trips/day.

VKT /day = $7 \times 2 \times 21.675 = 303.45 \text{ km}$

Total VKT/year = $303.45 \times 298 = 90,428 \text{ VKT}$

For 30 years service life of LRV, total life time VKT is 2,712,840 km.

5.12 Bus life cycle energy estimation

5.12.1 Bus manufacturing energy

Bus manufacturing energy was estimated using EIOLCA software (as described in Section 3.7.2). The infrastructure requirement study for the updated TMP of the city of Ottawa assumed a cost of \$630,000 for a standard hybrid bus and \$900,000 for an articulated hybrid bus. These costs are based on recent purchases of similar vehicles. The cost of a standard bus was assumed \$400,000. The production price of a vehicle was determined by deducting price discounts, dealer markup and profit (25%) from the base price. This price is then inputted to EIOLCA analysis tool to get the energy consumption for vehicle production. The result is shown in Table 5.8.

Table 5.8: BRT Bus manufacturing energy using EIOLCA method

Bus Type	Average price	Average price	25% deducted Price	Automobile & light truck manufacturing energy	Heavy duty truck manufacturing energy	Bus Manufacturing Energy (column 5+6)/2
	(\$ 2008)	(\$ 1997)	(\$ 1997)	(TJ)	(TJ)	(TJ)
Standard bus	400,000	312609.8	234457.4	1.77	1.98	1.88
Standard hybrid bus	630,000	492360.5	369270.4	2.79	3.12	2.96
Articulated hybrid bus	900,000	703372.2	527529.1	3.99	4.46	4.23

It can be seen from the Table 5.12 that the energy required to manufacture a conventional Standard bus is 1.88TJ, a Standard hybrid bus is 2.96 TJ and an articulated hybrid bus is 4.23 TJ.

5.12.2 Bus maintenance energy

The annual maintenance cost of buses for Ottawa BRT is shown in Fig 5.16. While annual maintenance cost in 1982 was \$0.33/Bus-km, the cost was increased to \$0.45/bus-

km in 2002. In 1982, most of the buses were new, thereby required less maintenance. With age, the maintenance requirements for buses have been increased. Considering the maintenance cost as 0.45/bus-km and using the EIOLCA software, the maintenance energy per bus-km was estimated as 1.15 MJ.

Fig. 5.16: Annual maintenance cost of OC Transpo buses (Source: Leroy et al., 2005)

5.12.3 Bus operating energy

In order to estimate vehicle operating energy, second by second vehicle velocity and acceleration were obtained using micro simulation model VISSIM. Then Vehicle Specific Power, VSP was calculated with an empirical formula. EPA conducted a study to establish the fuel consumption rate for a standard bus corresponding to eight VSP modes. VSP data were classified into these eight VSP modes using EXCEL. Then fuel consumption for each second was calculated according to its VSP modes. Finally average fuel consumption was determined. The flow diagram of bus operating energy estimation is shown in Fig. 5.17.

Fig. 5.17: Direct energy estimation model

5.12.3.1 Micro simulation model VISSIM

A Traffic simulation model consists of the representation of the road network together with the traffic in the network. The road network includes both the actual infrastructure

and the traffic control systems. Microscopic simulation models consider individual vehicles in the traffic stream. During a simulation run, vehicles are moved through the network on the paths between the vehicles' origin and destination. The interactions between individual vehicles and between vehicles and the infrastructure are modeled during this process through equations designed to mimic real driver behavior.

VISSIM is a microscopic traffic simulation model which is used to model urban traffic and public transit operations. The model can analyze traffic and transit operations under various constraints such as lane configuration, traffic composition, traffic signals, transit stops, etc. VISSIM uses the psycho-physical driver behavior developed by Wideman. VISSIM simulates traffic flow by moving "driver-vehicle-units" through a network. VISSIM can be applied as a useful tool in a variety of transportation problem settings.

5.12.3.2 Simulation in VISSIM

The transit corridor considered in this study was modeled in VISSIM. The first step to develop the model was to build the Traffic/Transit Network in VISSIM. The basic element of a VISSIM traffic/transit network is a link representing a single or multiple lane roadway segments that has a specified direction of flow. Then a network is built by connecting links with connectors. The basic network elements are:

- Links
- Connectors
- Pavement Marker
- Traffic Composition
- Vehicle Inputs
- Routes
- Direction Decisions
- Transit Stops
- Transit Lines
- Non-Signalized Intersections
- Priority Rules
- Stop Sign Control
- Signal Groups and Signal Head
- Detectors

In order to build the transit corridor in VISSIM, a bitmap file of the whole corridor was imported into the program and then the transitway was built based on the background map using links and connectors. The bit map helped to model the road alignment, roadway geometry and station location accurately. After modeling the corridor, transit line was defined. A transit line consisting of buses or LRT serves a fixed sequence of transit stops according to a time table. The stop times are determined by dwell time distributions or calculations of passenger service times. Transit lines were coded similarly as static routes except that transit lines do not distribute arriving vehicles but generate vehicles. The next step was to create transit stop. Transit stops are two type; On Street stop and Bus Lay-by. Vehicles approaching a transit vehicle that has stopped for passenger interchange will attempt to pass it on a multiple lane link, but will wait behind the transit vehicle on a single-lane link. As all the stops in the corridor are transit stations, Bus Lay-by stops were created. The transit stop properties such as bus stop length, boarding and alighting time and dwelling time distribution were also defined in the network. Transit buses or LRT operating in this corridor were input into the model according to peak hour frequencies for the forecasted year 2031. In addition base data for simulation were also entered in to the model. In case of non ability of base data, VISSIM default values were considered. The base information for traffic simulation in VISSIM consists of a range of parameters that are defined as distributions rather than a fixed value. Thus the stochastic nature of traffic situations is reflected realistically. The base information parameters are described in Appendix C-4.

After completion of the network coding, base data input and traffic input, the model was ready for simulation run. Figure 5.18 shows the transit corridor in the VISSIM micro simulation program.

Figure 5.18: Transit corridor in VISSIM model

5.12.3.3 Simulation and results

Numerous measures of effectiveness (MOEs) can be reported from VISSIM. Typical MOEs include instantaneous speed, acceleration, travel times, dwell time, delay, queue length, green time distribution, dynamic signal timing plan, link evaluation etc. In order to calculate average fuel consumption of buses, velocity and acceleration for every second was obtained. Several simulation runs were conducted for peak hour transit operation. VISSIM offers a wide range of simulation output. Data is provided in ASCII or database formats and can be automatically formatted using common software such as Microsoft Access or Excel. Result can also be exported to the transportation planning software such as VISUM for detailed graphical representations. For the purpose of reviewing simulation runs, VISSIM also offers the option of recording simulation sessions and saving them as animation files. In this study output was obtained in database format and then analyzed in Excel. Figure 5.19 shows a typical simulation run.

Fig 5.19: Simulation run in VISSIM

5.12.3.4 VSP-based approach for estimating fuel consumption

The U.S. Environment Protection Agency's (USEPA) mobile source inventory model Motor Vehicle Emissions Simulator (MOVES) uses vehicle specific power (VSP), a road load-based quantity, as the primary variable in modeling emissions (Koupal et al., 2005). VSP, a surrogate for power demand, is generally defined as power per unit mass of the vehicle and is a function of vehicle speed, road grade and acceleration. The calculation of power demand for transit buses was based on emission modeling research performed at West Virginia University. The VSP for transit buses (the curb weight of the bus 12.0 metric tons), can be calculated as follows (Andrei, 2001; Zhai et al., 2006):

$$VSP = Vx(a + g * \sin(\text{grade}) + 0.092) + 0.00021xV^3 \dots\dots\dots 5.6$$

where VSP is the Vehicle Specific Power (kw/ton); V is instantaneous speed at which the vehicle is traveling (m/s); a, is instantaneous acceleration of the vehicle (m/s²); g is

acceleration due to gravity, grade is the instantaneous road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient.

VSP was estimated for every second data obtained from VISSIM simulation. The data were categorized based on ranges of VSP to define VSP-based modes (Table 5.9) using EXCEL.

Table 5.9: Definition of Vehicle Specific Power (VSP) modes

VSP mode	VSP range (kw/ton)	VSP mode	VSP range (kw/ton)
1	$VSP \leq 0$	5	$6 \leq VSP < 8$
2	$0 < VSP < 2$	6	$8 \leq VSP < 10$
3	$2 \leq VSP < 4$	7	$10 \leq VSP < 13$
4	$4 \leq VSP < 6$	8	$VSP \geq 13$

(Source: Zhai, et al., 2006)

Frey et al (2007) conducted a study to estimate instantaneous fuel consumption for diesel and hydrogen fuel cell buses using VSP approach. To evaluate the robustness of the modeling approach, VSP model average fuel consumption rates were compared with diesel and fuel cell buses in the US and Portugal under real-world operating conditions. The data were provided by EPA in collaboration with the Ann Arbor Transportation Authority (AATA) and the Instituto Superior Te'cnico (IST) of Lisbon, Portugal. Each of the AATA diesel buses, Porto diesel bus, and Porto hydrogen fuel cell bus databases were divided into a calibration and validation dataset. The calibration data sets were used to develop VSP-based modal fuel consumption models (Frey et al., 2007).

Using real world speed profiles, second-by-second VSP was calculated using the equation discussed above. Fuel consumption rate by VSP mode for Ann Arbor and Porto diesel buses were established as shown in Fig 5.20.

Fig. 5.20: Variation of bus fuel consumption with VSP mode (Source: Frey et al., 2007)

It was found that the VSP-based approach is able to explain a substantial portion of the short-term variability in fuel consumption. The ability of the VSP modal method to predict total fuel consumption for a trip was evaluated. Relative errors between trip fuel consumption estimates using VSP approach and actual fuel use were generally under 10% for all observations. Therefore, the Vehicle Specific Power-based modeling approach was recommended for estimating instantaneous fuel consumption.

In this study, the VSP based approach was employed to calculate instantaneous fuel consumption. VSP based fuel consumption rate established by above mentioned study was used in the calculation. Second by second velocity and acceleration obtained from micro simulation model VISSIM was used to calculate VSP for each second. Then VSP were categorized according to VSP mode and fuel consumption for each second was

calculated. Finally the average fuel consumption was determined. The average fuel consumption for the corridor was found to be 2.08 km/liter (see Appendix C-5).

5.12.4 Diesel production energy

Petroleum diesel is produced from petroleum and a hydrocarbon mixture, obtained in the fractional distillation of crude oil between 200°C (392°F) and 350°C (662°F) at atmospheric pressure (Fig 5.20).

Fig. 5.21: Diesel production from crude oil distillation (Source: SINTEF, 2006)

The density of petroleum diesel is about 0.85 kg/liter, about 18% more than petrol (gasoline). When burnt, diesel typically releases about 138,700 BTU of energy per US gallon. Diesel is generally simpler to refine from petroleum than gasoline. Due to recent changes in fuel quality regulations, additional refining is required to remove sulfur from diesel, which sometimes contributes to higher cost and energy consumption. Starting in 2006, less than 15 mg/kg Sulfur in on-road diesel fuel has become a legal requirement in Canada (Environment Canada, 2009). Diesel production is an energy intensive process.

The production involves various stages from crude extraction to final use at vehicle. The various production stages of diesel fuel production are discussed in the following section.

5.12.4.1 Diesel production cycles and their stages

Diesel is produced through different fuel production pathways, resulting in different energy efficiencies and emissions from feedstock recovery to vehicle operation. To fully analyze energy impacts of vehicle/fuel systems, a full fuel-cycle analysis from energy feedstock recovery (wells) to fuel use by vehicle (wheels) needs to be conducted. The fuel cycle for a given transportation fuel includes the following processes: feedstock production, transportation and storage (T&S), fuel production, transportation, storage and distribution (T&S&D) and vehicle operations that involve fuel combustion or other chemical conversions (Figure 5.22).

Fig. 5.22: Flowchart of total energy-cycle analysis (Source: Wang, 1999)

The Well to Wheel (WTW) fuel cycle energy analysis can be grouped in to two cycles; “Well-to-Pump” (WTP) or “upstream” stages and “Pump-to-Wheels” (PTW) or “downstream” stage. The feedstock and fuel stages together are called WTP stages and

the vehicle operation stage is called PTW stages. The focus of this study was the estimation of WTP energy consumption of diesel fuel production. The GREET model was used in order to do this.

5.12.4.2 GREET Model

Argonne National laboratory's Transportation Technology R&D Center has developed a full life-cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). The model calculates fuel-cycle energy and emissions for various transportation fuels and vehicle technologies.

GREET was developed in Microsoft Excel. The first version of GREET was released in 1996. Since then, Argonne has been continuing to update and expand the model. The most recent GREET versions are GREET 1.8b version for fuel-cycle analysis and GREET 2.7 version for vehicle-cycle analysis (see Appendix C-6 for GREET model capabilities). GREET 1.8b version was used in this study to estimate diesel production energy.

5.12.4.3 Calculation of fuel cycle energy use

The estimation of fuel cycle energy use is a circuitous calculation process. That is, each upstream stage requires use of process fuels itself for which production energy is to be evaluated. Figure 5.23 shows the circular calculations process for diesel fuel cycle as an example. Petroleum recovery, as one stage of the cycle, requires use of diesel fuel, together with other process fuels. Production of diesel fuel requires petroleum recovery together with other stages (petroleum T&S, petroleum refining, and diesel T&S&D to oil

fields). As the figure shows, other stages require the use of diesel fuel, and together there are four close-loop calculations involved in fully accounting for energy use associated with upstream activities for diesel fuel.

Fig. 5.23: Closed -Loop calculation of upstream energy use (Wang, 1999)

REET model was designed to perform circular calculations by means of the iteration calculation feature in Microsoft Excel. This feature allows REET to draw data to use in one cell from some other cells (Wang, 1999).

REET estimates fuel-cycle energy use in three subcategories: feedstock, fuel, and vehicle operations. The feedstock subcategory includes energy use associated with recovering, transporting, and storing of feedstock; the fuel subcategory includes energy use associated with refining feedstock, transporting, storing, and distributing product fuels; and the vehicle operation subcategory includes energy use directly related to vehicle operations. As the focus of this study is to estimate the well to pump (WTP) cycle

of diesel fuel production energy, only the first two sub categories were considered. The WTP energy estimation process is schematically shown in Fig 5.24.

Fig. 5.24: Flow diagram of diesel production energy estimation

In estimating fuel-cycle energy use, GREET model combines the energy use from all upstream stages. The aggregation also takes into account, among other factors, loss of a

fuel during the fuel cycle. For a given upstream stage, energy input per unit of energy product output is calculated by using the energy efficiency of the stage. The shares of process fuel used are usually estimated on the basis of historical statistical data on fuel use by fuel type. If there is no fuel loss during upstream activities, calculated energy use for each stage can simply be added together to obtain total energy use. However, if there is a fuel loss (from spillage, evaporation, or leakage), the energy use calculated for each upstream stage needs to be adjusted to the actual amount of fuel needed. The GREET model make this adjustment (Wang, 1999).

5.12.4.4 Parametric assumptions for fuel cycle stages

Estimation of fuel-cycle energy consumption requires parametric assumptions in each stage regarding the following: energy efficiencies of upstream stages (which determine the amount of process fuels and feedstock fuels needed); shares of process fuels; and shares of combustion technologies for a given process fuel. This section presents detailed assumptions and data sources for each of these parameters.

5.12.4.5 Crude oil recovery

The crude recovery stage of the petroleum fuel cycle includes well drilling, oil extraction, oil gathering through gathering pipes, crude treatment in production fields, and crude storage in production fields (Wang, 1999).

Energy consumed during the petroleum recovery stage is implicitly contained in the energy efficiency assumptions made for crude recovery. Past published data in the United States showed an energy efficiency of 97% to 99% for petroleum recovery (Wang 1999). In

some parts of the world, the efficiency could be as low as 96%. On the basis of existing studies, GREET assumes an energy efficiency of 98% for petroleum recovery (Table 5.10). Crude oil recovery as well as other fuel production stages use various processed fuel. The share of various processed fuels used in different production stages are presented in Table 5.11.

Table 5.10: Energy efficiencies of petroleum-based fuel-cycle stages (%)

Petroleum-Based Fuel-Cycle Stage	GREET	Nrel et al. 1991	Delucchi 1991	Ecotrafic, AB 1992	Bentley et al. 1992	Acurex 1995
Crude recovery	98.0	99.2	97.5	97.0	NE	NE
Crude T&S	99.5	96.2	99.8	99.3	96.0	NE
CG refining	85.0	NE	NE	84.5	90.0	NE
CG T&S&D	98.5	NE	NE	NE	NE	NE
LPG refining	93.5	NE	94.6	90.0	NE	93.2
LPG T&S&D	97.9	NE	99.0	97.5	NE	NE
Residual refining	95.0	NE	94.9	97.0	NE	NE
Residual T&S&D	99.0	NE	99.0	NE	NE	NE
CD refining	89.0	NE	93.0	NE	NE	NE
CD T&S&D	98.6	NE	99.1	NE	NE	NE
RFD refining	87.0	NE	NE	NE	NE	NE
RFD T&S&D	98.6	NE	NE	NE	NE	NE

CG -conventional gasoline, LPG - liquefied petroleum gas, CD- conventional diesel, RFD- reformulated diesel (Source: Wang, 1999).

Table 5.11: Shares of process fuels for each stage*

Stage	Crude	Diesel	Residual Oil	Gasoline	Still Gas	NG	Coal	Electricity	Fuel Loss
Crude recovery	1	15	1	2	0	62	0	19	0
Crude T&D	0	1	92	0	0	0	0	6	1
Crude refining	0	0	3	0	49	30	13	4	0
T&S&D									
Gasoline	0	39	33	0	0	15	0	11	3
Diesel	0	40	34	0	0	15	0	11	1
LPG	0	39	25	0	0	11	0	25	1
Residual oil	0	20	66	0	0	8	0	5	1

* Values are percentages based on the Btu contained in each fuel (Source: Wang, 1999).

Share of crude feedstock used in Canadian refineries

Canada ranks second largest in terms of global proven crude oil reserves (15% of world reserves) after Saudi Arabia (Gov. of Alberta, 2009a). The majority of these reserves are found in Alberta's oil sands - over 173 billion barrels. The share of petroleum production used in Canadian refineries is shown in Fig.5.25. It can be seen that convention crude oil constitutes the bigger share (78%) of refineries feed stock. The GREET model requires this data as an input. It is assumed that oil sand constitutes 22% of refineries feed stock in Canada and this 22% oil sand comes from equal share of both surface mining and in situ production (Table 5.12).

Fig. 5.25: Share of crude feedstock used in Canadian refineries (Statistics Canada, 2007)

Table 5.12: Share of crude feedstock input to GREET model

Conventional Crude Oil	Oil Sands (Surface Mining)	Oil Sands (In Situ)
78%	11%	11%

Table 5.13: shows oil sands recovery and upgrading efficiency considered in this analysis. The GREET model default values were used for this.

Table 5.13: Oil sands recovery and upgrading efficiency

	Bitumen recovery	Bitumen Upgrading
Surface Mining	94.8%	98.6%
In Situ Production	84.3%	98.6%

5.12.4.6 Crude transportation and storage

This stage includes transportation of crude from oil fields to central storage terminals, storage at the terminals, transportation from the terminals to petroleum refineries, and storage at refineries. Crude is transported from oil fields to central storage terminals by small-size pipelines and tank trucks. Central storage terminals are usually located at major water ports or at the beginning of long-distance pipelines. Crude is transported from the terminals to petroleum refineries via ocean tankers and/or pipelines. Major energy-consuming sources for this stage are ocean tankers and engines that provide pumping and heating for pipelines. Residual oil or bunker fuel is primarily used to provide energy for transportation of crude.

Refineries in Canada use a mix of both imported and domestically produced oil. In 2007, 45% of crude oil consumed in Canada was imported. OPEC accounted for 34% of this volume. Norway and UK supplied an additional 46% of total crude oil imports (Statistic Canada, 2007). Domestic supply of crude oil constituted 55% of total supply. Of which 45% came from Western Canada and 9% came from eastern Canada (Fig 5.26).

Fig. 5.26: Domestic supply of crude oil in Canada (Statistics Canada, 2007)

In the GREET model, for a given feedstock or fuel, its transportation energy is calculated with transportation mode split, transportation distance for each mode, and energy intensity of each mode. First, the types and shares of transportation modes (i.e., ocean tankers, pipelines, barges, rail, and trucks) to be used for transporting a given feedstock or fuel are determined. Then the types and shares of process fuels (residual oil, diesel fuels, natural gas, electricity, etc.) to be used for powering a given transportation mode are identified. And then the energy intensity associated with a given transportation mode fueled with a given process fuel are determined. Finally, the energy use of all transportation to be used for transporting the given feedstock or fuel are added together (Wang, 1999). Figure 5.27 shows the way in which the GREET model simulates transportation of feedstocks and fuels.

Fig.5.27: Calculation logic of energy use for feedstock and fuel transportation

It is assumed that ocean tankers are used to ship imported crude oil from outside North America. Three transportation modes are used for in-land transportation within Canada; pipelines, barge, and rail. As the import counts 45 % crude oil used in Canadian refineries (Fig. 5.26), 45 % crude well was considered to be transported through ocean tanker. The

average distance associated with ocean tanker transportation was calculated according to average port to-port distances. Round trips were considered for ocean tankers and barges because no other goods could be hauled for the back haul. There are about 23,000 km of main trunk pipelines transporting crude oil from the Western Canada to Canadian refineries and international border crossing points. There are also over 12,000 km of gathering lines, transporting crude oil from producers' fields to the main trunk lines, and over 5,000 kilometers of pipeline dedicated to the transport of refined petroleum products (Natural Resources Canada, 2009). All this information was inputted to GREET model. Figure 5.28 shows the flow diagram of crude transportation from oil fields to petroleum refineries.

Figure 5.28: Crude transportation from oil fields to petroleum refineries

5.12.4.7 Crude refining

Refining process from crude oil to petroleum fuels is subjected to the highest energy use.

The petroleum refining industry uses energy to supply both heat and power for plant operations and as a raw material for the production of petrochemicals and other non-fuel products. Canada has a network of 19 refineries across the country. Canadian refineries consumed various type fuel and energy for its operation. Figure 5.29 shows Canadian petroleum refineries fuel use in 2001. Refinery fuel gas make up the largest fraction of consumption (44%), followed by petroleum coke (22%) and natural gas (16%).

Figure 5.29: Petroleum refinery fuel use in 2001 (Source: CIEEDAC, 2002)

Petroleum refineries produce both petroleum-based fuels and petrochemicals. The allocation of energy use from a refinery among all its products is a real difficulty. Usually, a linear programming modeling studies can determine the amount of feedstock and fuels needed to produce a slate of refining products (Wang, 1999). The feedstocks and fuels can then be allocated among different products according to the mass of each product and the refining processes necessary for its production. On the basis of this information, fuel-cycle analyses can then be used to determine the refining energy

efficiency for producing a given product. The GREET model takes this approach in estimating refining energy efficiency for a fuel (Wang, 1999). Table 5.14 presents the refining energy efficiencies for diesel fuels used in the GREET model.

Table 5.14: Fuel specifications and refining efficiencies

	Sulfur Level, ppm	Refining Efficiency
Conventional Diesel	200	90.3%
Low-Sulfur Diesel	11	89.3%

5.12.4.8 Transportation, storage, and distribution of petroleum products

The Transportation, storage, and distribution (T&S&D) of refined fuel is the final stage of WTP analysis, which includes transportation of petroleum products to bulk terminals, storage at the terminals and distribution to refueling stations. The supply and distribution of petroleum products from the refineries to the end-users is a complex system of pipelines, ships, railways and trucks. Often several methods of transportation are utilized to move petroleum products from the refineries, ports and large terminals to tremendously disperse markets all across Canada. In Atlantic Canada, all petroleum product terminals are serviced by marine tanker. In other areas of Canada, railways and trucks are much more important. Highway truck tankers transport all petroleum products from the terminals to underground storage tanks at each retail outlet. In order to reduce transportation costs refiners also enter into a large number of product exchange agreements with one another (Natural Resources Canada, 2009b). The availability of data regarding actual mode share of refined petroleum transportation and transporting distance are very scarce. In the absence of authentic data, the GREET default assumption for USA was used for this study.

Table 5.15: Calculations of energy consumption of petroleum fuels by stage (Btu per MBtu of diesel fuel)

	Crude Oil		Oil Sands Recovery: Surface Mining			Oil Sands Recovery: In-situ production			Conventional Diesel		Low-Sulfur Diesel	
	Recovery	Transportation to Refineries	Bitumen Extraction	Bitumen Upgrading	Transport. to Refin.	Bitumen Extraction	Bitumen Upgrading	Transport. To Refin.	CD Refining	CD T&D	LSD Refining	LSD T&D
Energy efficiency	98.0%		94.8%	98.6%		84.3%	98.60%		90.3%		89.3%	
Loss factor		1,000		1,000	1,000		1,000	1,000	1,000	1,000	1,000	1,000
Shares of process fuels												
Crude oil	1.0%		0.0%	0.0%		0.0%	0.0%		0.0%		0.0%	
Residual oil	1.0%		0.0%	0.0%		0.0%	0.0%		3.0%		3.0%	
Diesel fuel	15.0%		0.6%	0.0%		0.0%	0.0%		0.0%		0.0%	
Gasoline	2.0%		0.0%	0.0%		0.0%	0.0%		0.0%		0.0%	
Natural gas	61.9%		82.3%	97.1%		97.2%	97.1%		30.0%		30.0%	
Coal	0.0%		0.0%	0.0%		0.0%	0.0%		13.0%		13.0%	
Electricity	19.0%		17.1%	2.8%		2.8%	2.8%		4.0%		4.0%	
Hydrogen	0.0%		0.0%	0.0%		0.0%	0.0%		0.0%		0.0%	
Pet coke			0.0%	0.0%		0.0%	0.0%		0.0%			
Refinery still gas	0.0%		0.0%	0.0%		0.0%	0.0%		50.0%		50.0%	
Feed loss	0.1%		0.0%	0.1%		0.0%	0.1%		0.0%		0.0%	
Total energy	28,422	9,781	73,565	58,094	16,146	207,976	32,093	16,146	121,563	6,399	135,597	6,426
Fossil fuels	27,112	9,659	70,413	57,781	15,856	206,147	31,887	15,856	120,000	6,343	133,854	6,369
Coal	6,462	656	15,416	1,539	1,506	8,954	1,011	1,506	21,649	327	24,148	329
Natural gas	15,969	2,000	53,354	55,584	4,512	195,804	30,549	4,512	39,798	992	44,392	996
Petroleum	4,681	7,002	1,643	659	9,838	1,390	326	9,838	58,554	5,024	65,313	5,045

5.12.4.9 Result of diesel production energy analysis

Table 5.15 shows detailed calculations of energy consumption of diesel fuel production by stages. It can be seen from this table that to produce 1MBtu diesel fuel energy, crude oil recovery consumes 28422 Btu energy and transportation of crude oil to refineries consumes additional 9781Btu energy. In total, 38203 Btu of energy is consumed for crude oil recovery and transportation in the production process of 1MBtu diesel energy. The table also shows that the energy consumption in oil sands recovery and transportation (both surface and in situ) as well as diesel fuel refining and transportation energy. The total feedstock energy for diesel production in Canadian refineries is shown in Table 5.16. It can be seen that to produce 1MBtu diesel fuel energy, 74,245 Btu of feedstock energy is consumed.

Table 5.16: Feedstock energy (Btu/MBtu diesel fuel production)

Crude feed stock	Recovery & transportation energy	Share	Share of feed stock energy in Canadian refineries
Conventional Crude Oil	38203	78%	29798.34
Oil Sands (Surface Mining)	147,805	11%	16258.55
Oil Sands (In Situ)	256,215	11%	28183.65
Total Feedstock energy			74240.54

Table 5.17: Summary of energy consumption: Btu/MBtu of fuel throughput at each stage

	Crude for use in Canadian refineries	Conv. Diesel	LS Diesel
Loss factor	1.0	1.0	1.0
Total energy	74,245	127,967	142,028
Fossil fuels	72,459	126,349	140,229
Coal	8,845	21,977	24,478
Natural gas	51,894	40,792	45,390
Petroleum	11,720	63,580	70,361

Well-to-Pump energy consumption: Btu per MBtu of fuel available at fuel station pumps
= 216,277

Energy factor to produce diesel fuel =216,277/1,000,000 = 21.6%

5.13. Light rail vehicle life cycle energy

5.13.1 LRV manufacturing energy

The infrastructure requirement study for updated TMP for the City of Ottawa assumed a cost of \$5,000,000 per LRT vehicle. By deducting price discounts, dealer markup and profit (25%), the production price accounts for \$3.75M. Converting this price to EIOLCA base price and inputted to EIOLCA software “Railroad rolling stock manufacturing (Sector #336500) sector provides total manufacturing energy as 27.2 TJ.

5.13.2 LRV maintenance

Calgary Transit spent \$13.9M for vehicle maintenance in 2006 (Calgary transit, 2009). The number of Light rail car operated in 2006 was 153. Therefore annual maintenance cost/car was \$0.091M. Using EIOLCA tool (Sector #8111A0: Automotive repair and maintenance), the annual maintenance energy was estimated as 0.379 TJ/ car-km.

5.13.3 Light rail vehicle operating energy

Struckl, et al. (2006) estimated energy consumption for light rail vehicle MX for the Metro Oslo. The Energy consumption per train (3 cars) per kilometer was found to be 44.5 MJ (4.12 kwh/car-km). California Department of Transport used a computer model to simulate LRT system for a normal weekday operation of 16 hours (caltrans, 1983). The model determined the energy consumption per car as 6.65 kwh/VMT i.e. 4.13 kwh/car-km. IBI Group (1978) reported the energy consumption rate 5 kwh per car-mile i.e. 3.10Kwh/ car-km based on Montreal transit data. Fels, (1975), reported that the rapid electric rail consumed on average 4.25 kwh of energy per vehicle-mile. Chester and Horvath (2008) divided the operating energy into three parts; active, idling and auxiliary.

They estimated active, idling and auxiliary operating energy as 2.76, 1.42, and 0.48 kwh/VKT respectively for Muni LRT system in San-Francisco and 5.0, 2.58, 0.74 kwh/VKT for Boston Green Line in Massachusetts. Calgary Transit (2009) reported the energy consumption at the rate of 3.23 kwh per vehicle-km of operation. From the above discussion it can be said that light rail vehicle operating energy varies in the range of 3.23 ~ 8.32 kwh/VKT. So a mid range value of 5.77 kwh/VKT was taken for this analysis.

5.13.4 Electricity generation energy

In a typical power plant, electricity is generated by rotating turbines attached to electrical generators. Turbines are driven by a fluid which acts as an intermediate energy carrier. The fluids typically used are steam, water, wind and hot gases. Power plants use steam turbines, internal-combustion engines, gas combustion turbines, water turbines, and wind turbines or other similar machine to drive an electric generator. Most common types of power plants are:

- Steam turbine power plant
- Nuclear power plant
- hydro electric power plant
- Wind power plant
- Gas combustion power plant
- Biomass power plant
- Geothermal power plant
- Solar power plant

The Canadian electricity generation industry is comprised of electricity generators that use water, coal, natural gas, petroleum products, biomass, nuclear, wind and solar energy as fuels to produce electricity (The electricity Forum, 2009).

5.13.4.1 Electricity generation pathways

Electricity generation is a very energy intensive process. Energy consumption mainly depends on electricity generation mix, power plant energy conversion efficiency and feed

stock energy. In order to estimate electricity generation energy, the GREET model was used. The energy estimation starts with feed stock extraction and goes through refining process, power plant input, then electricity generation, transmission and distribution.

Figure 5.30 shows pathways for electricity generation.

Fig. 5.30: Pathway of electricity generation (Source: Wang, 1999)

In GREET model, five types of electric power plants are included for energy estimations: oil-fired, NG-fired, coal-fired, and nuclear power plants and other power plants, such as hydroelectric and windmill power plants. In estimating electricity generation energy, GREET incorporates feed stock and fuel production stages, electricity transmission and distribution losses along with power plant energy use. In this study, five types of power plants are eventually combined together for Ontario electric generation mix to calculate electricity generation energy consumption.

5.13.4.2 Electricity generation mix

One of the key factors determining energy use of electricity generation is electricity generation mix (the mix of the power plants fired with different fuels). Electric generation mix varies with regions. This study is based on Ontario's electricity generation mix. Ontario uses a mix of energy sources for electricity generation. About 52% of Ontario's electricity comes from nuclear power. The remainder comes from a mix of hydroelectric (21%), coal (18%), natural gas (8%), and wind (1%) power plant (see Appendix C-7 for details about Ontario's electricity generation mix).

Fig. 5.31: Ontario's electricity generation mix (Source: Ontario Ministry of Energy and Infrastructure, 2009)

5.13.4.3 Combustion technologies

For each of the fuel used in electricity generation, various combustion technologies can be used. In the GREET model, steam boilers are assumed for oil-fired plants and coal-fired-plant. For NG-fired power plants, the model assumes steam boilers, conventional gas turbines, and advanced combined-cycle gas turbines. For each fuel type, users can change the combustion technology in the GREET model. In this study, the combustion technologies were chosen on the basis of Ontario's electricity generation mix.

5.13.4.4 Power plant conversion efficiencies

The most important factor determining energy requirements of electricity generation pathways is power plant energy conversion efficiencies. Based on published data, the GREET model uses the following conversion efficiencies: 32-35% for steam boilers fired by oil, NG, and coal, 50-60% for NG-fired combined-cycle turbines, and 38- 44% for advanced coal-fired power plants such as integrated gasification combined-cycle turbines (Wang, 1999). In this study, the GREET default energy conversion efficiencies were used. The Table 5.18 summarizes the input data in GREET model regarding electricity generation mixes, combustion technology shares, and power plant energy conversion efficiencies.

Table 5.18: Electricity generation mixes, combustion technology shares and power plant energy conversion efficiencies

Power Plant Type	Electricity Generation Mix	Combustion Technology Shares for a Given Plant Fuel Type	Power Plant Energy Conversion Efficiency
Residual Oil-Fired Power Plants	0.0%		34.8%
Utility boiler		100.0%	34.8%
Natural Gas-Fired Power Plants	8.0%		40.1%
Utility boiler		20.0%	34.8%
Simple-cycle gas turbine		36.0%	33.1%
Combined-cycle gas turbine		44.0%	53.0%
Coal-Fired Power Plants	18.0%		34.1%
Utility boiler		100.0%	34.1%
IGCC		0.0%	46.0%
Biomass Power Plants	0.0%		32.1%
Utility boiler		100.0%	32.1%
IGCC		0.0%	40.0%
Nuclear Power Plants	52.0%		100.0%*
Other Power Plants (hydro, wind, geothermal, etc.)	22.0%		100.0%

*The efficiency of 100% means that Btu accounting starts from Btu contained in electricity. The thermal efficiency of electricity generation in nuclear power plants (LWR) is 35% (Wang, 1999). In this analysis, this information was not used, since there is no alternative use of uranium for other energy application, i.e., it is not the same type of fuel source as fossil fuels (e.g. natural gas).

5.13.4.5 Electricity transmission and distribution efficiency

Transmitting electricity over distance requires cables and power transformers, which create three types of energy losses: i) the Joule effect, where energy is lost as heat in the conductor (a copper wire, for example); ii) magnetic losses, where energy dissipates into a magnetic field (transformer); iii) the dielectric effect, where energy is absorbed in the insulating material (IEC, 2009).

The Joule effect in transmission cables accounts for losses of about 2.5%, while the losses between the power plant and the step-down substation range between 3% and 5%. Between the step-down substation and users the losses are same or even greater. Therefore the overall losses between the power plant and users vary between 8% and 15%. The GREET model assumes transmission and distribution loss 8%. The same assumption was also made for this analysis.

5.13.4.6 Summary of electricity generation energy analysis

Estimation of electricity generation energy can be divided into two parts; power plant energy use and fuel cycle (feedstock) energy use. Power plant energy use (Btu per MBtu of electricity available at user sites) can be estimated as follows:

Power plant energy use

$$= \sum_j \frac{10^6}{\text{power} - \text{plant} - \text{efficiency} * (1 - \%T \& D_Loss)} X_{\text{electricity_gener._mix}(\%)} \dots 5.7$$

where J is the type of power plant (nuclear plant, coal plant, etc.)

Table 5.19 shows the power plant energy use for Ontario electricity generation mix. In order to generate 1 MBtu of electricity available at wall outlets, 1,594,848 Btu of energy is consumed in the power plants. The table also shows power plant energy use with different type of combustion technologies. Figure 5.32 compares the power plant energy use with combustion technology. It can be observed that coal fired power plant consumes the highest energy (although Biomass-fired power plant consumes highest energy, this is not a common technology). Oil-fired power plant consumes a bit less (2%) energy than coal fired power plant. Natural gas power plant consumes approximately 13% less energy than Oil-fired power plant. The nuclear power plant consumes 65% less energy compared to coal power plant. However, if the energy consumption for mining the uranium is included, then the energy consumption of nuclear power plant would be higher. Hydro and wind power plants consume the least amount of energy as they do not go through a thermal work cycle.

Fig. 5.32: Variation of power plant energy use with different technology

Table 5.19: Power plant energy use Btu per Mega Btu of electricity available at user sites (wall outlets)

	Ontario electricity generation mix	Oil-Fired Power Plant	NG-Fired Power Plant	Coal- Fired Power Plant	Biomass- Fired Power Plant	Nuclear Power Plant	Other Power Plants	NGCC Power Plants	Biomass IGCC Power Plants: Woody	Biomass IGCC Power Plants: Herbaceous	Coal IGCC Power Plants
Energy Use: Btu	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total
Residual oil	0	3,123,438	0	0	0	0	0	0	0	0	0
NG	216,740	0	2,709,255	0	0	0	0	2,050,861	0	0	0
Coal	573,760	0	0	3,187,556	0	0	0	0	0	0	2,362,949
Biomass	0	0	0	0	3,386,157	0	0	0	2,717,391	2,717,391	0
Nuclear	565,217	0	0	0	0	1,086,957	0	0	0	0	0
Other energy sources	239,130	0	0	0	0	0	1,086,957	0	0	0	0
Total	1,594,848										

Table 5.20: Fuel-cycle and power plant energy use for electricity generation: Btu per Mega Btu of electricity available at user sites (wall outlets)

	Ontario electricity generation mix		Oil-Fired Power Plant		Nuclear Power Plant		NG-Fired Power Plant		Coal-Fired Power Plant		Other Power Plants	
	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel
Total energy	45,631	1,594,848	378,546	3,123,438	38,618	1,086,957	186,953	2,709,255	58,851	3,187,556	0	1,086,957
Fossil fuels	36,750	790,500	359,465	3,123,438	23,641	0	183,875	2,709,255	54,150	3,187,556	0	0
Coal	6,841	573,760	38,753	0	10,734	0	2,378	0	5,940	3,187,556	0	0
Natural gas	19,474	216,740	163,841	0	9,761	0	170,370	2,709,255	4,274	0	0	0
Petroleum	10,435	0	156,871	3,123,438	3,147	0	11,126	0	43,936	0	0	0

Table 5.20 shows total energy consumption for electric generation (fuel-cycle and power plant energy use). It can be seen that to produce 1 Mega Btu of electricity available at user site, 45,631 Btu feedstock energy and 159,848 Btu fuel cycle energy are required. Therefore, the amount of energy consumption to produce 1 Mega Btu of electricity is 640,479 Btu. The energy conversion factor for Ontario electricity generation mix is 64.05%. The table also shows feedstock and fuel cycle energy consumption for electricity generation of individual power plant. Figure 5.33 compares the result. It can be seen that oil-fired power plant consumes the highest total energy. Feedstock energy consumption for oil-fired power plant is also the highest among all the power plants.

Fig. 5.33: Variation of fuel cycle and power plant energy use in electricity generation with different combustion technologies

5.14 LRT and BRT per km road/track way construction energy

The construction energy for busway and LRT track reported in the literature significantly varies with each other, which have been discussed in the previous chapters. So, the construction energy for 1 km typical busway and LRT track was estimated in this study using process based analysis. The details are discussed in the following sections.

5.14.1 Busway construction energy

Busway can be constructed at grade, under ground or elevated surface. It can be consisted of rigid or flexible pavement. The corridor considered for this analysis is mostly at grade. Therefore construction energy for one kilometer at grade busway was estimated in this study. It was assumed that busway would be made of flexible pavement. The schematic diagram of busway construction energy calculation is shown in Fig. 5.34.

Fig. 5.34: Bus way construction energy estimation process

BRT system requires four basic infrastructural components; busway, station, park and ride lot and maintenance facilities. Busway construction starts with the extraction and manufacturing of raw materials such as cement, asphalt, sand, filler and stone. The

materials are then transported to construction site or mixing plant. Finally the materials are blended, spreaded and compacted on to the prepared surface of the busway. In each step of the process a substantial amount of energy is consumed.

5.14.2 Design parameters

5.14.2.1 Bus way cross-section

A typical at-grade busway should include two through exclusive bus only lanes with an optional two extra lanes at the station areas to allow express buses to bypass other buses while boarding and alighting passengers. Deciding whether to install a median or a side-aligned busway mainly depends on the existing right-of-way configuration, as well as, the characteristics of the corridor on which the busway will be installed. In Fig 5.35, a typical cross-section of a busway that is considered in this study is shown.

Fig. 5.35: Typical cross section of busway at transitway and at station

5.14.2.2 Pavement structural layer

A flexible pavement fundamentally consists of 3 basic layers; surface course, base course and sub grade. Surface course is the layer in contact with traffic loads. It provides characteristics such as friction, smoothness, noise control, rut resistance and drainage. In addition, it prevents entrance of surface water into the underlying layer. This layer is sometimes subdivided into two layers: the wearing course and binder course. Surface courses are most often constructed of HMA (Hot-Mix Asphalt). The layer immediately beneath the surface course is base course. It provides additional load distribution and contributes to drainage. Base courses are usually constructed of crushed aggregate or HMA. Sometimes an additional layer, Subbase course is provided between the base course and subgrade. It functions primarily as structural support but it can also improve drainage. The subbase generally constructed of lower quality crushed aggregate than the base course. The final layer is subgrade layer. It can be made of existing natural soil or can be composed of soil materials treated with Portland cement or Portland-Pozzolan cement. Figure 5.36 shows a typical flexible pavement layer for busway.

Figure 5.36: Typical cross-section of a rigid pavement (Source: Huang 1993)

In this study, the following assumptions were made regarding different pavement layers of busway:

Table 5.21: Characteristics of pavement layers

Road way component	Density (lb/cu.ft)	Thickness (mm)
surface	145	40
binder	145	100
base	135	200
sub base	135	200
sub grade	130	150

The construction energy of one km busway was estimated based on the cross-section and structural layer of pavement discussed above. The details estimation is shown in Appendix C-8. Table 5.22 shows the energy consumption for constructing different layers of pavement. It was assumed that surface and binder course would be constructed with HMAC, base course with emulsion-treated local aggregate and subbase course with crushed stone. The subgrade would be treated with cement.

Table 5.22: Energy use to construct different layers of pavement

Type of pavement Layer	Const. Energy (gal/mi-in)	Transportation energy (gal/mi-in)			Process. Energy (gal/mi-in)	Calorific Energy (gal/mi-in)	Total energy (gal/mi-in)	*Total energy (MBtu/m³)
		Short haul	Long haul	Average				
Hot-mixed asphalt concrete (HMAC) (surface)	1,605	676	4,602	2639	388	10,220	14852	6.90
HMAC (binder)	1,649	781	4,173	2477	452	9,200	13778	6.40
Emulsion-treated local aggregate	126	531	1,376	953.5	1,116	11,412	13607.5	6.33
Crushed Stone	115	545	3,540	2042.5	299	0	2456.5	1.14
Cement-treated subgrade	182	86	86	86	2,445	0	2713	1.26
Cement concrete	246	760	4,236	2498	5,912	0	8656	4.02
Reinforced cement concrete	246	775	4,251	2513	7,289	0	10048	4.67

(Sources: NCHRP: 85) * (gal/mi-in)-Calculation is for 2 lane road (24' width). Converted gal/mi-in into Mbtu/cu.m, on the basis of 139,000 Btu/gal

5.14.3 Construction energy for prime coat and tack coat

The prime coat material is medium cut back bitumen, or bitumen is blended with kerosene or diesel. Tack coat material is rapid curing bitumen of 80/100 or 60/70 grade

bitumen. Prime coat is used over the unbound layer of base, sub-base or subgrade materials. The quantity of prime coat material is 1.0 to 1.5 liter/m² depending on the surface condition. The quantity of tack coat material is 0.25 to 0.4 liter/m². The construction energy for prime coat and tack coat is shown in Table 5.23.

Table 5.23: Construction energy for prime and tack coat

	Type	liter/sq.m	Liters/km busway (2-lane)	Processing energy Btu/gal	Calorific energy Btu/gal	Total Energy Mega Btu	Total Energy TJ
Prime coat	MC-70 Cutback	1.25	10000	59,500	148,000	456.4352	0.48
Tack Coat	C.MS-2 Emulsion	0.33	2640	10,200	115,000	72.70584	0.08

5.14.4 Construction energy for busway shoulder

It was assumed that 2.5m wide shoulder would be constructed on both side of the busway and shoulder would be composed of flexible pavement. The estimates of construction energy for busway shoulder are shown in Table 5.24.

Table 5.24: Construction energy for shoulder

Structural Layer	thickness (mm)	Volume(cu.m)	Energy Intensity (Mega Btu/cu.m)	Total Energy (Mega Btu/Km)	Total Energy TJ/km
surface	25	125	6.90	862.5	0.91
binder	50	250	6.40	1600	1.69
Base/ sub base	100	500	1.14	570	0.60
Total				3032.5	3.20

5.14.5 Construction energy for curb and median block

The construction energy for curb and median was estimated based on a typical cross section shown in Fig 5.37.

$$\text{Curb} = (0.6\text{m} \times 0.2\text{m} \times 1000\text{m}) \times 2 \times 4.02 \text{ MBtu/m}^3 = 964.8 \text{ MBtu} = 1.02 \text{ TJ}$$

$$\text{Median} = (0.6\text{m} \times 0.6\text{m} - 0.3\text{m} \times 0.4\text{m}) \times 1000\text{m} \times 2 \times 4.02 \text{ MBtu/m}^3 = 1929.6 \text{ MBtu} = 2.04 \text{ TJ}$$

Fig. 5.37: Cross section of Curb and Median

5.14.6 Summary of busway construction energy

The result of the busway construction energy estimate is shown in Table 5.25.

Table 5.25: Construction energy for one km busway (2-lane)

Structural Layer	thickness (mm)	Volume(cu.m)	Energy Intensity (Mega Btu/cu.m)	Total Energy (Mega Btu/Km)	Total Energy TJ/km
surface	40	320	6.90	2209.23	2.33
binder	100	800	6.40	5123.67	5.41
base	200	1600	6.33	10120.53	10.68
sub base	200	1600	1.14	1827.01	1.93
Cement treated sub grade	150	1200	1.26	1513.34	1.60
Subtotal					21.94
Tack coat & prime coat					0.56
Total					22.50
Additional lane at station @100m/km					2.25
Shoulder					3.2
Curb					1.02
Median					2.04
Grand Total					31.04

5.14.7 Other road infrastructure components

Busway consists of hundreds of individual items other than pavement. It is not practical to estimate energy consumption for all these individual items. For this reason, the individual items were grouped into main components that were characterized by a set of

characteristic items. The main components and their characteristic items are listed in Table 5.26. In addition to the characteristic items, there are many additional supplementary items that influence the cost and energy consumption. The supplementary items typically occur infrequently. Some of these supplementary items are listed in Table 5.26 as well. The costs of supplementary items are estimated as a percentage of the total cost of the main components.

Table 5.26: Description of characteristics item for all other infrastructure components

Main Component	Characteristic Items		Supplementary Items	
	Description	Unit	Description	Allowance, %
Clearing of vegetation	Clearing and grubbing	m ²	Clearing of brush and trees, removal of top soil.	20
Grading: earth work	Earth excavation or fill	m ³	Rock face work and rock face protection, earth fill or rock fill required, grading of subgrade and subgrade compaction, removal of boulders underneath subgrade	10
	Percent of rock excavation/fill	%		
Landscaping	Sodding and top soil	m ²	Staked and unstaked sodding, water for sod, seeding + mulching + top soil, silt fence barriers, rest areas, flow checks	15
	Top soil	m ³		
Drainage of the right of way	Curb and gutter	m	Culverts of larger diameter or size, excavation bedding and granular back fill for culverts, inspection openings, catch basins, rip-rap on spillways, sedimentation ponds. etc.	25
	500 mm pipe culvert - end sections	m		
	1500 mm wide box culvert	m		
	Storm water sewers	m		
Guard rail and safety appurtenances	Concrete median	m	Anchor blocks for barriers, rumble strips, energy attenuators, warning signs	10
	Steel guardrail at shoulder	m		
	3-cable guide rail at shoulder	m		
Fencing and gates	Chain link fence	m	Farming and walk gates, anti-glare screens, privacy fences, and noise barriers and berms.	10
	Wire fence	m		
Lighting; electrical work	High mast	piece	Concrete foundation for poles, luminaries, wiring (power, lighting, ground), rigid ducts or conduits, power supply points and substations, etc.	50
	Standard mast	piece		
Traffic control	Painting of Traffic control lines	km	Traffic control devices (erected or painted signs, traffic lights, directional and message signs. etc	30

(Source: Applied Research Associates, Inc., 2008)

In a recent published report of Transport Canada, the construction cost of all infrastructure components, other than pavement, of a road in Ontario has been reported (Appendix C-9). This cost was considered to estimate construction energy for all other infrastructural components of busway. The cost was estimated to be \$235,803 per km (2008\$). The cost was converted to EIO LCA tool base year dollar (1997\$) and inputted to EIO LCA tool. The energy consumption to construct all other components was estimated as 2.69 TJ.

5.14.8 Bus way maintenance energy

The life of pavement is usually considered 20 years. However, pavements are seldom rebuilt after their useful life. Instead pavements are rehabilitated or a structural overlay is placed on the top of existing surface. A study of Transport Canada reported that the average age of municipal road in Canada since construction is more than 38 years (Appendix C-10). So, the study assumed a 60 years time horizon for maintenance life cycle cost analysis for a provincial arterial road in Southern Ontario. It was assumed that the same pavement maintenance action plan would also be applicable for busway. The pavement maintenance plan includes both routine maintenance and periodic maintenance. Routine maintenance includes minor repairs of pavement such as filling potholes, route and seal. Periodic maintenance includes resurfacing pavement with asphalt concrete. The study estimated \$514,269/km maintenance cost for 60-years life cycle of an arterial road in Southern Ontario (Appendix C-11). The Net present worth (NPW) of which was calculated as \$100,249. From this NPW, the equivalent uniform annual cost (EUAC) of maintenance can be calculated using the equation below:

$$EUAC = NPW \times \frac{i(1+i)^n}{(1+i)^n - 1} = \$6203 \dots\dots\dots 5.8$$

where NPW = Net present worth value of rehabilitation and maintenance activities, \$;
 i = Discount rate (%/100), the discount rate for public project is usually considered as 0.06; and n = Number of years, which was considered as 60 years.

The annual energy consumption for pavement maintenance was calculated based on this EUAC and using EIOLCA tool (Sector # 230330 - Maintenance and repair of highways, streets, bridges, and tunnels). The annual pavement maintenance energy was estimated as 40 Giga Joule/2-lane-km.

5.14.9 Winter maintenance energy

The winter maintenance costs depends on several factors such as environmental zone, the level of service, traffic volumes, and the application of technology to minimize snow drifting. Applied Research Associates, Inc. (2008) summarized the winter maintenance cost in Canada based on survey data and engineering judgments as shown in Table 5.27.

Table 5.27 Annual unit winter maintenance costs (\$)

Regions	Provincial Winter Maintenance Costs per 2 lane-km (\$)			
	Rural		Urban	
	Freeway	Arterial	Freeway	Arterial
NL	7,500	7,000	8,000	7,500
PE	3,000	2,500	3,500	3,000
NS	4,500	4,000	5,000	4,500
NB	4,500	4,000	5,000	4,500
QC-1	9,334	7,468	11,201	9,334
QC-2	9,334	7,468	11,201	9,334
ON-1	6,000	5,000	6,000	5,500
ON-2	5,500	4,000	5,500	5,000
MB	3,000	2,500	3,500	3,000
SK	3,000	2,500	3,500	3,000
AB	4,500	4,000	5,000	4,500
BC-1	3,000	2,500	3,500	3,000
BC-2	5,500	4,000	5,500	5,000
TR	3,000	2,500	3,500	3,000
Average	5119.1	4245.4	5707.3	5012

(Source: Applied Research Associates, Inc., 2008)

It was assumed that busways need the same winter maintenance as urban freeways in Ontario. Using EIOLCA tool, the annual winter maintenance energy was calculated as 37 Giga Joule/ 2-lane Km.

5.15 LRT track construction energy

The LRT track construction energy was estimated based on a typical LRT track of City of Edmonton. A Typical cross section of LRT track is shown in Fig. 5.38.

Fig 5.38: Typical cross section of LRT track (Source: City of Edmonton's LRT design guide, 2005)

The principal components of LRT track are rail, tie, ballast, sub-ballast, traction power-substations, catenary system and control signals. The LRT track construction energy was estimated using process based approach in a similar manner as busway construction energy estimation. The detailed estimates are shown in Appendix C-12. The summary of LRT track construction energy is shown in Table 5.28.

Table 5.28: Summary of per km trackway construction energy (Double track)

Item of works	Quantity	Energy intensity	Total energy (BtuX10 ⁹)	Total energy (TJ)
Rail	196.05 ton	39.8 MBtu/ton	7.80	8.23
Tie	379.4 m ³	2.01 MBtu/m ³	0.76	0.80
Anchoring bolt	11.72(ton)	39.8 MBtu/ton	0.47	0.49
Sub total				9.52
Placement (30%)				2.86
Ballast	3144.1 m ³	1.14MBtu/m ³	3.58	3.78
Sub Ballast	2557.5 m ³	1.14MBtu/m ³	2.91	3.07
Sub grade	1395 m ³	1.26MBtu/m ³	1.76	1.86
Total				21.09

5.16 Tunnel construction energy

In the infrastructure requirement study for TMP of Ottawa, a 2.5 km length twin tunnels for BRT under the down town has been considered to meet the growing transit service requirements of the City (MRC, 2008). Each of the twin tunnels would have one through lane and one passing lane. The passing lane would allow buses to pass any disabled vehicle in the tunnel without any service disruption. To accommodate these two lanes, a 10m diameter tunnel would be required (Fig. 5.39).

Fig. 5.39: 10.0 m diameter BRT tunnel (Source: MRC, 2008)

For LRT, each of the twin tunnels would incorporate a single track throughout its length, including through the station areas. The rationale for a single-track tunnel is that if a train breaks down in the tunnel area the next train can physically push it through the tunnel to an outside track beyond the tunnel area. A 6.0m diameter tunnel can accommodate a single rail and required safety/maintenance walk (Fig. 5.40).

Fig. 5.40: 6.0 m diameter LRT tunnel (Source: MRC, 2008)

The transportation master plan infrastructure requirement study prepared preliminary cost estimates for 2.5 km tunnel for both BRT and LRT (Table 5.29)

Table 5.29: The construction cost of the downtown tunnel

Items of work	Length	LRT		BRT	
		Cost /km (Million \$)	Total Cost (Million \$)	Cost /km (Million \$)	Total Cost (Million \$)
Twin bore	2.5 km	45.0	112.5	125.0	312.5
Tracks/ electrical	2.5 km	55.0	137.5	-	-
Asphalt/ventilation	2.5 km	-	-	35.0	87.5
Sub total			250.0		400.0
30% contingency			75.0		120.0
Total			325.0		520.0
Cost/km -single bore			65.0		104.0

(Source: MRC, 2008)

The tunnel construction energy was estimated based on this cost estimate. The EIOLCA tool was used for energy estimation. The cost is in 2008\$. The cost was converted to EIOLCA base year (1997) value and then fed in to the “Highway, Street, Bridge, and

Tunnel Construction” (Sector #230230) sector of the software. The calculated energy is shown below:

- LRT tunnel construction energy: *1800TJ/km*
- BRT tunnel construction energy: *2890 TJ/km*

The twin tunnels would be drilled through the bedrock using tunnel-boring machines, and a combination of open-cut and/or standard mining techniques would be used to construct the stations. To address air quality concerns it is assumed that minimal emission buses, such as hybrid-electric, will be used for bus operations in a tunnel.

5.17 Stations construction energy

There would be 16 surface stations and 3 underground stations on the corridor. Station functional design and sizing largely depends on frequency of buses or LRV's, physical characteristics of vehicle, number of passengers boarding and alighting and degrees of integration with other developments and functions. All the underground stations will serve the downtown core. Therefore the size of stations and other functional elements and amenities should be same for these 3 underground stations. Blair and Baseline stations would act as terminal stations. Hurdman station would act as a transit hub. So these three stations need to be integrated with other feeder services. The size and functional elements for these stations would be more extensive than others. The Infrastructure requirement study for Ottawa transit estimated the preliminary construction costs for all the stations. On the basis of these costs, the construction energy was estimated using EIO-LCA software. The costs are in 2008\$. The costs were converted to EIO-LCA base year (1997) dollar value and then fed in to the “Commercial and Institutional Buildings Construction” (Sector #230220) sector of the software. The calculated energy results are shown below:

Table 5.30: Construction cost and construction energy of stations

Stations	Qt.	Cost (\$)/station	Energy (TJ)/station	Total energy TJ
Under ground Stations	3	40,000,000	241.33	723.99
Baseline (below grade station all in including approaches)	1	20,000,000	120.67	120.67
Iris	1	1,000,000	6.03	6.03
Queensway	1	1,000,000	6.03	6.03
Lincoln Fields	1	3,000,000	18.10	18.10
Dominion	1	1,000,000	6.03	6.03
Westboro	1	1,000,000	6.03	6.03
Tunney's Pasture	1	1,000,000	6.03	6.03
Bay View	1	7,000,000	42.23	42.23
Lebreton	1	5,000,000	30.17	30.17
Campus	1	1,000,000	6.03	6.03
Lees	1	4,000,000	24.13	24.13
Hurdman	1	8,000,000	48.27	48.27
Train	1	3,000,000	18.10	18.10
St. Laurent	1	2,000,000	12.07	12.07
Cyrville	1	1,000,000	6.03	6.03
Blair	1	10,000,000	60.33	60.33
Total				1140.27

(Source for costs: MRC, 2008)

The station costs were determined on the basis of size and function requirements of the stations to meet the projected ridership. It was assumed that there would be no variation of ridership with mode of choice i.e. whether the transit system is BRT or LRT. In that case the provision for stations functional elements would mostly be same for BRT or LRT. Therefore, it was assumed that the construction energy for stations would be same for BRT or LRT.

5.18 Station operation and maintenance

The main energy consumption for station operation is electricity. The major part of the electricity is consumed for lighting. Based on BART system, Fels (1983) estimated that underground station lighting consumes as much as 64% of station total energy

consumption. The other consumptions of electricity at stations are for escalators, elevator, heating, air conditioning and several small miscellaneous items. It was assumed that all the underground stations would have at least two elevators, two escalators, 40 electric lights (150W). The energy consumption for station lighting is shown below.

$$\text{Lighting} = 12 \text{ hr operation/day} * 40 \text{ nos. of light} * 0.150 \text{ KW} * 365 = 26280 \text{ Kwh/year} = 0.09461 \text{ TJ/year}$$

The escalators energy consumption accounts for up to 24% of station electricity consumption (Fels, 1978). The electricity consumption of escalators is 4.7KW (EERE, 2007). It was assumed that on average escalator would be operated 15 hr/day.

- Escalator energy = 15 hr operation* 2* 4.7*365 = 51465 Kwh/year =0.185 TJ/year
- Total electricity consumption for lighting and escalator = 0.279 TJ/year

It was assumed that other electric devices accounted for 10% of total electricity consumption. Then total station electricity consumption/year stands for 0.31TJ. Considering electricity production energy, the total station electricity consumption/year would be $1.6405 * 0.31 = 0.508 \text{ TJ/year}$

It was also assumed that the electricity consumption for surface station would be 39% of the underground station (based on Fels, 1983 study). The electricity consumption for surface station would be 0.203TJ/year.

The electricity consumptions of all other stations were estimated based on their cost of construction (Table 5.31). The equation used for this estimate is shown below:

$$\begin{aligned} & \text{Electricity - consumption}_{station} \\ & = 0.203 + \frac{\text{Construction - Cost}_{station} (M\$) - 1(M\$)}{40(M\$) - 1(M\$)} X (0.508 - 0.203) \dots\dots\dots 5.9 \end{aligned}$$

Table 5.31: Annual operating energy consumption of stations

Stations	Quantity	Cost (\$)/station	Annual energy consumption (TJ)
Under ground Station	3@ 0.508 TJ	40,000,000.00	1.524
Baseline (below grade station all in including approaches)	1	20,000,000	0.352
Blair,	1	10,000,000	0.273
Iris	1	1,000,000	0.203
Queensway	1	1,000,000	0.203
Lincoln Fields	1	3,000,000	0.219
Dominion	1	1,000,000	0.203
Westboro	1	1,000,000	0.203
Tunney's Pasture	1	1,000,000	0.203
Bay View	1	7,000,000	0.250
Lebreton	1	5,000,000	0.234
Campus	1	1,000,000	0.203
Lees	1	4,000,000	0.226
Hurdman	1	8,000,000	0.258
Train	1	3,000,000	0.219
St. Laurent	1	2,000,000	0.211
Cyrville	1	1,000,000	0.203
Total			5.186

5.19 Maintenance facilities

In the infrastructure requirement study for Transportation Master Plan of the City of Ottawa, the construction cost for maintenance yard and shop was estimated as \$60M per 250 buses. For LRT, the construction cost of maintenance yard and shop were considered as \$100M per 150 light rail vehicles (MRC, 2008). The same assumption was considered in this study. Using EIOLCA software (Sector #230210: Manufacturing and industrial buildings), the construction energy for maintenance yard and shop were calculated as follows:

Construction energy for BRT Maintenance facilities: 458TJ

Construction energy for LRT Maintenance facilities: 763TJ

Chapter 6

Results and Discussions

6.1 Introduction

In the previous chapter detailed analyses for establishing energy intensities of different components of BRT and LRT for the transit corridor have been reported. This chapter will describe the results of the analysis. The total length of the corridor is 21.78 km, including a 2.5 km tunnel. The projected maximum peak hour passenger volume for the year 2031 is 15,600. To accommodate this passenger volume by BRT, the theoretical minimum headway (by considering way capacity and station capacity) was found as 15.5sec. For 40' standard buses, the required headway to accommodate peak hour passenger volume would be 10.4sec, which is less than the theoretical minimum headway i.e., 15.5sec. For 60' articulated buses, the required headway would be 16.14 sec, which satisfies the minimum headway criteria. Providing services with only articulated buses, however, would be more energy intensive on a vehicle-km basis. Moreover, during off peak hour, service provided by articulated bus would not be cost effective. Therefore in this analysis, a theoretically possible maximum number of standard buses were considered to accommodate projected peak hour ridership demand, which is only 10% (23) of total fleet. The rest 90% are sixty-foot articulated buses (207). For light rail transit, 58 trains (2-car unit) per hour would be required to accommodate the 2031 ridership demand and the headway would be 62 sec, which is within reasonable limit of minimum headway requirement. In this chapter, the results of the life cycle energy consumption for both BRT and LRT vehicles will be presented first. Then the total transit system (vehicle and infrastructure) energy requirements for both LRT and BRT will be evaluated. Finally the energy intensities per vehicle-km and passenger-km for BRT and

LRT will be compared considering both direct and indirect energy.

6.2 Life cycle energy consumption for transit bus

The energy intensity for different stages of bus life cycle reported in this thesis, obtained from literature sources and own analysis, are summarized below:

Table 6.1: Summary of bus life cycle energy intensities

Lifecycle stages	Energy	Source
Manufacturing energy for standard bus	1,406.44 X10 ⁶ Btu = 1.48 TJ	(IBI Group, 1978)
	1.099 TJ	(Herbert et al. 1984)
	1040.5X10 ⁶ Btu =1.098 TJ	(Caltrans, 1983)
	300,000 Kwh =1.080 TJ	(Fels, 1975)
	2 TJ	(Chester & Horvath, 2008)
	1564.28 X10 ⁶ Btu = 1.65 TJ	Own analysis (EIOLCA)
Manufacturing energy for standard hybrid bus	1779.03 X10 ⁶ Btu =1.87 TJ	Own analysis (EIOLCA)
	2801.97X10 ⁶ Btu =2.95 TJ	Own analysis (EIOLCA)
Manufacturing energy for articulated hybrid bus	4006.20 X10 ⁶ Btu = 4.22 TJ	Own analysis (EIOLCA)
Maintenance energy for standard bus	1952.98 Btu/mile = 1.28 Mega Joule/km	Own analysis (EIOLCA)
	13,142 Btu/mile = 8.61 Mega Joule/km	(Caltrans, 1983)
	3,360 Btu/mile =2.20 Mega Joule/km	(IBI Group, 1978)
Operating energy for standard bus	1.4-2.34 km / liter	(Caltrans, 1983)
	1.84 km /liter(1960) -2.44 km /liter (2002)	(RITA, 2004) Historical data
	Diesel: 2.28 km /liter 2.38 km /liter CNG: 1.70 km /liter Hybrid: 3.19 km /liter	(Barnitt & Battelle 2006) based on NYCT data
	2.08 km /liter	Own analysis using Micro-Simulation (VISSIM)
Service life of buses	Minimum 12 years	(Richard et al., 2007) FTA Recommended
	15+	(Calgary transit, 2002)
	19 years	(OC transpo, 2007)
	Average 16 years	(Source: Richard et al., 2007) Based on historical data
Lifetime VMT of buses	500,000 mile	(Richard et al., 2007) FTA Recommended
	1,086,000 Km	(OC Transpo, 2007)
	968880 km.	Own analysis

6.2.1 Manufacturing energy

It can be seen from the above table that bus manufacturing energy estimated by Herbert et al. (1984), Caltrans (1983) and Fels (1975) are close to each other. The IBI Group (1978) estimated a bit higher value than others. All these study were conducted 25-30 years ago. There have been some technological changes. Moreover buses today have more amenities, including ITS technologies and safety devices. Therefore bus manufacturing process has become more energy intensive. In a recent analysis Chester & Horvath (2008) reported 2 TJ manufacturing energy for a conventional bus. Therefore it is reasonable to consider standard bus manufacturing energy as 1.87 TJ which was obtained using EIOLCA. For a standard hybrid bus, the manufacturing energy was estimated as 2.95 TJ using EIOLCA. Manufacturing energy for an articulated bus can be obtained by considering ratio of vehicle weights with conventional bus. Weight of an articulated bus is 18,597 kg (41,000 lbs). A standard 40' bus weighs 12,156 kg (26,800 lbs). Therefore the manufacturing energy for an articulated bus would be 2.86 TJ. Manufacturing energy for an articulated hybrid bus was estimated using same manner, which was 4.51 TJ. This value is a bit higher than the value obtained using EIOLCA (4.22 TJ). Therefore the manufacturing energy for an articulated hybrid bus was considered as 4.22 TJ.

6.2.2 Maintenance energy

Bus maintenance energy reported by Caltrans (1983) and IBI Group (1978) remarkably differ with each other. In this research bus maintenance energy was estimated based on a recent (2008) Federal Transit Administration (FTA) sponsored research that evaluated life cycle maintenance cost for a transit bus using data supplied by the local transit

operators and vehicle manufacturers. The bus maintenance energy was estimated as 1.28 MJ/km (Section 3.8). This can be considered reasonable. For 968,872.5 km life time VKT, the total life cycle maintenance energy for a standard bus would be 1.24 TJ.

For hybrid bus, propulsion related maintenance energy is considered as same as standard bus. But hybrid bus requires battery replacement, which consumes substantial energy. Clark et al. (2007) conducted a study for evaluating transit bus life cycle cost (LCC) for 2007 year model buses. It covers four bus types: diesel buses, diesel buses using B20 biodiesel, compressed natural gas (CNG) buses, and hybrid diesel-electric buses. Based on FTA electric drive study, the researchers found that, for lead-acid battery packs, hybrid buses need battery replacements in every three years at a price of \$25,000. For NiMH battery packs, hybrid buses need battery replacements in every 5-7 years at a cost of \$35,000 - \$45,000. For 15 years life cycle, hybrid bus requires 4 lead-acid batteries or at least two NiMH batteries. The average life cycle battery replacement cost can be considered as \$ 90,000 (\$2007). Converting this cost to 1997\$ and feeding it in EIOLCA tool “Primary Battery Manufacturing” (Sector #335912) sector, provided 0.535 TJ battery replacement energy consumption. Therefore, Life cycle maintenance energy for a hybrid bus would be 1.78 (i.e., 1.24+ 0.54) TJ.

During the literature review, no reliable information was found regarding maintenance cost of articulated buses and hybrid articulated buses. Therefore, life cycle maintenance energy for an articulated bus and hybrid articulated bus were estimated on the basis of ratio of vehicle weights with conventional bus.

Life cycle maintenance energy for an articulated bus =1.89 TJ

Life cycle maintenance energy for an articulated hybrid bus =2.72 TJ

6.2.3 Operating energy

Historical trend of bus fuel economy shows that the fuel efficiency of buses has been increasing over time. In 1960, while the average fuel consumption of transit bus was 1.84 km/liter, it was 2.44 km/liter in 2002 (RITA, 2009). A recent study conducted by Barnitt & Battelle (2006) for New York City Transit (NYCT) confirmed this fact. In this study, fuel economy of two groups of standard diesel buses was found to be 2.28 km/liter and 2.38 km/liter. The fuel economy for standard CNG bus and hybrid bus was found to be 1.70 km/liter and 3.19 km/liter respectively. In this thesis, fuel consumption rate for a standard bus was determined using micro-simulation model VISSIM. Having obtained second by second vehicle velocity and acceleration from micro simulation model, the Vehicle Specific Power, VSP was calculated with an empirical formula. EPA conducted a study to establish the fuel consumption rate for a standard bus corresponding to eight VSP modes. VSP data were classified into these eight VSP modes using EXCEL. Then fuel consumption for each second was calculated according to its VSP modes. Finally average fuel consumption was determined. The average fuel consumption for the corridor was found to be 2.08 km/liter. This is a bit lower than the other values reported above. However, the fuel consumption rate obtained from simulation is usually adjusted by over the road factor in order to reflect the real world driving condition. If the average fuel consumption rate obtained from simulation is adjusted by a factor of 12%, the average fuel consumption rate would be 2.33 km/liter, which is same as the average fuel consumption rate for the two groups of buses obtained by Barnitt & Battelle (2006) for New York City Transit (NYCT). Therefore, this rate was considered to estimate lifetime operating energy for a standard bus. For standard hybrid bus, the fuel consumption rate

obtained in New York City Transit study was used. The life time operating energy for a standard bus and standard hybrid bus was calculated as follows:

The rate of fuel consumption for a standard bus = 2.33 km/liter

The rate of fuel consumption for a standard hybrid bus = 3.19 km/liter

Life time VKT = 968880 km

Life time fuel consumption for standard bus = $968880/2.33 = 415828.35$ liters

= 109846.58 gallons

Life time fuel consumption for standard hybrid bus = $968880/3.19 = 303724.14$ liters

= 80232.76 gallons

Calorific value of low-sulfur diesel fuel = 138,490 Btu/gallon (Wang, 1999)

Lifetime operating energy for standard bus = $138,490 \times 109846.58 = 15.21$ Giga Btu

= 16.04 TJ

Lifetime operating energy for standard hybrid bus = $138,490 \times 80232.76 = 11.11$ Giga Btu

= 11.72 TJ

The fuel consumption rate for a standard articulated bus and articulated hybrid bus were established based on Caltrans (1983) study. In this study, it was found that the fuel consumption for a standard Non-AC articulated bus varies in the range of 1.65~1.95 km/liter with different pay loads, whereas fuel consumption for standard Non-AC bus varies at the range of 1.99 ~2.34 km/liter. It can be deduced that the fuel consumption for a standard Non-AC articulated bus is on average 20% higher than standard Non-AC bus. For standard articulated AC bus, fuel consumption varies in the range of 1.45~1.71 km/liter with different pay loads, whereas fuel consumption for standard AC bus varies in the range of 1.77~2.23 km/liter. It shows that the fuel consumption for a standard articulated AC bus is on average 25% higher than standard AC bus. So fuel consumption for an articulated bus was considered 25% higher than the Standard bus. The same

consideration was also made for articulated hybrid bus. The fuel consumption for articulated hybrid buses would be 25% more than that of standard hybrid buses. The life time operating energy for a standard articulated bus and articulated hybrid bus were calculated as follows:

The rate of fuel consumption for articulated bus = $2.33/1.25 = 1.86$ km/liter

The rate of fuel consumption for articulated hybrid bus = $3.19/1.25 = 2.55$ km/liter

Life time VKT = 968880 km

*Life time fuel consumption for articulated bus = $968880/1.86 = 520903.23$ liters
= 137603.50 gallons*

*Life time fuel consumption for articulated hybrid bus = $968880/2.55 = 379952.94$ liters
= 100369.61 gallons*

Calorific value of low-sulfur diesel fuel = 138,490 Btu/gallon (Wang, 1999)

Lifetime operating energy for articulated bus = 20.10 TJ

Lifetime operating energy for articulated hybrid bus = 14.66 TJ

6.2.4 Fuel production energy

The energy consumption for diesel fuel production was obtained by conducting a life cycle assessment (LCA) for diesel fuel using GREET model. The WTP (Well to Pump) analysis was conducted for both conventional diesel and Low Sulfur Diesel (LSD). It was found that to produce 1 Mega Btu conventional diesel, 202,212 Btu of energy is required. For Low Sulfur Diesel (LSD), the production energy was found to be 216,277 Btu. Therefore, the energy conversion factor for conventional diesel fuel production is 0.202 and for LSD 0.216.

Conventional diesel fuel is hardly used in transportation now. There is a legal requirement for the sulfur concentration in on-road diesel fuels. It was assumed that transit buses would use LSD only. The production energy for life time LSD requirements

for different transit buses were calculated as follows:

Lifetime LSD production energy for standard bus = $16.04 \times 0.216 \text{ TJ} = 3.46 \text{ TJ}$

Lifetime LSD production energy for standard hybrid bus = $11.72 \times 0.216 \text{ TJ} = 2.53 \text{ TJ}$

Lifetime LSD production energy for articulated bus = $20.10 \times 0.216 \text{ TJ} = 4.34 \text{ TJ}$

Lifetime LSD production energy for articulated hybrid bus = $14.66 \times 0.216 \text{ TJ} = 3.16 \text{ TJ}$

The life cycle energy consumption of different transit buses are summarized below. It is clear from the Table 6.2 that the total life cycle energy consumption for a standard hybrid bus requires the least amount of energy among four types of buses. Articulated bus consumes maximum energy (29.19 TJ) during its lifecycle. Figure 6.1 compares the life cycle energy consumption of different transit buses.

Table 6.2: Summary of life cycle energy consumption for transit buses

Type of Bus	Energy Consumption (TJ)				
	Manufacturing	Operation (Direct energy)	Maintenance	Fuel production	Total energy
Standard bus	1.87	16.04	1.24	3.46	22.61
Standard hybrid bus	2.95	11.72	1.78	2.53	18.98
Articulated bus	2.86	20.10	1.89	4.34	29.19
Articulated hybrid bus	4.22	14.66	2.72	3.16	24.76

Fig. 6.1: Life cycle energy consumption of different transit buses

Fig. 6.2: Direct and indirect energy consumption of different transit buses

Figure 6.2 shows the direct and indirect energy consumption of four types of transit buses. It is evident that direct and indirect energy significantly varies with type of buses. While direct energy consumption for a standard bus is 71%, indirect energy constitutes only 29%. In the case of articulated hybrid bus, indirect energy constitutes a significant part (41%) of life cycle energy.

6.3 Life cycle energy consumption for light rail vehicle

6.3.1 Light rail vehicle manufacturing

Struckl, et al. (2006) estimated manufacturing energy for 3-car light rail train as 7,626,000MJ i.e., 2.54 TJ/car. Caltrans (1983) reported light rail vehicle manufacturing energy as $2,614 \times 10^6$ Btu /car i.e. 2.76 TJ/car. The IBI Group (1978) estimated manufacturing energy for Montreal metro type car as $6,255.48 \times 10^6$ Btu/car i.e., 6.6 TJ/car. Fels (1975) estimated energy consumption for the manufacturing of a rapid rail

car as 1,231,500 kwh/car i.e., 4.43 TJ/car. Chester and Horvath (2008) estimated light rail vehicle manufacturing energy for Muni LRT system in San-Francisco as 1.4 TJ/car and for Boston Green Line in Massachusetts as 1.6 TJ/car. Considering the current light rail vehicle cost of Calgary transit, \$3.9 Million/car (Calgary transit, 2009) and using EIOLCA tool, the manufacturing energy was estimated as 29 TJ/car. It is clear from the above discussion that there are differences among the light rail vehicle manufacturing energy reported in the literature. The manufacturing energy calculated using EIOLCA enormously differs with other values. By judging the energy intensity of other vehicles, the LRV manufacturing energy estimated by the IBI Group was found to be reasonable. The manufacturing energy for light rail vehicle was considered as 6.6 TJ/car in this study.

6.3.2 Light rail vehicle maintenance energy

Caltrans, (1983) calculated 7,060Btu/car-mile maintenance energy for light rail vehicles. On the basis of 142.5 car miles/weekday and 290 weekdays/year, the annual maintenance energy was estimated as 291.75 MBtu/car-mile i.e. 0.308TJ/car-km. The maintenance energy calculated by the IBI Group (1978) was 1750Btu/car-mile. With the same assumption above, the annual maintenance energy would be 0.047TJ/car-km. Chester and Horvath (2008) divided the maintenance of LRVs into three categories: routine maintenance, cleaning and flooring replacement. They calculated total maintenance energy as 0.351TJ/car-km for Muni LRT system in San Francisco and 0.377TJ/car-km for Boston Green Line in Massachusetts. Calgary Transit spent \$13.9M for vehicle maintenance in 2006. The number of light rail cars operated in 2006 was 153. Therefore, annual maintenance cost/car was \$0.091M. Using the EIOLCA tool (Sector #8111A0:

Automotive repair and maintenance), the annual maintenance energy was estimated as 0.379 TJ/car-km. Most of the above analyses are reasonably close to each other. Therefore the annual maintenance energy per car was considered as 0.37 TJ. Considering 30 years of usable life of LRV, the life cycle maintenance energy would be 11.1 TJ.

6.3.3 Light rail vehicle operating energy

Struckl, et al. (2006) estimated the operating energy consumption for light rail vehicle as 4.12 kwh/car. California Department of Transport determined the energy consumption of LRVs as 4.13 kwh/car-km (Caltrans, 1983). The IBI Group (1978) reported the energy consumption rate as 3.10 kwh/car-km based on Montreal transit data. Fels (1975) reported that the rapid electric rail consumed on average 4.25 kwh of energy per vehicle-mile. Chester and Horvath (2008) estimated active, idling and auxiliary operating energy as 2.76, 1.42, and 0.48 kwh/VKT for Muni LRT system in San-Francisco and 5.0, 2.58, 0.74 kwh/VKT for Boston Green Line in Massachusetts. Calgary Transit (2009) reported the energy consumption at the rate of 3.23 kwh/vehicle-km of operation. From the above discussion, it can be deduced that light rail vehicle operating energy varies in the range of 3.23 ~ 8.32 kwh/vehicle-km. Therefore, an average value of 5.77 kwh/vehicle-km was taken for this study.

It was calculated in Chapter 5 that one train (2-cars) can make 7 round trips/day in the transit corridor. The VKT/day was estimated as 303.45 km. It was assumed that each train would be in service for 298 days/year and the yearly VKT was calculated as 90,428km. For a 30 years service life, the total life time VKT would be 2,712,843 km.

The lifetime energy consumption = $2712843 \times 5.77 = 15.65 \times 10^6$ kwh/car = 56.35 TJ/car

6.3.4 Electricity generation energy

Electricity generation energy consumption was estimated using the GREET model based on Ontario's electricity generation mix (Section 5.13.4). It was found that to produce one Mega Btu of electricity 640,479 Btu energy would be consumed. Therefore, the energy conversion factor is 0.6405. The energy consumption to produce lifetime electricity demand for a LRV would be 36.09 TJ/car ($56.35 \times 0.6405 = 36.09$ TJ/car).

Table 6.3 summarizes the life cycle energy consumption of a light rail vehicle and Figure 6.3 (a) compares the energy consumption of different stages of life cycle. It can be seen that that electricity production energy has a large impact on life cycle energy consumption. Figure 6.3 (b) shows that indirect energy constitutes a substantial part (49%) of the life cycle energy of a light rail vehicle.

Table 6.3: Summary of life cycle energy consumption of a LRV

Life Cycle Stages	Energy consumption/ LRV
Manufacturing	6.6 TJ
Operating	56.35 TJ
Electricity production	36.09 TJ
Maintenance	11.1 TJ

(a)

(b)

Fig. 6.3: (a) Life cycle energy consumption of light rail vehicle, (b) Direct and indirect energy consumption.

6.4 Infrastructure energy consumption

BRT and LRT require a large number of different types of infrastructural components. Incorporating all these components for energy analysis is a very difficult endeavor. Therefore, only the basic components that have significant energy impact were considered in this analysis.

6.4.1 Busway construction energy

Busway construction energy greatly varies with type of busways. On the basis of average cost of several busways and using EIOLCA, the construction energy consumption for at grade busway was found as 80.17 TJ/Lane-km, for below grade (tunnel) busway 795.52 TJ/lane-km and for aerial busway 201.98 TJ/lane-km. In the literature there are large differences in energy intensity for bus way construction. While the IBI Group (1978) reported busway (at grade) construction energy as 77.69/Lane-km, Herbert et al. (1984) estimated construction energy for a freeway as 12.132 TJ/lane-km. Other studies also came up with different energy intensities (Caltrans, 1983, Zapata et al., 2005). These variations of energy intensities might be due to site specific design requirements, level of service and underlying assumptions.

In the above context, a process based analysis was adopted in this study to estimate the construction energy for the basic elements of a busway. As the objective of this research is to evaluate the energy consumption of both BRT and LRT, the same approach was adopted in calculating light rail track construction energy as well. This way the comparison between two systems will be more rational. The total length of the transit corridor is 21.78 km, of which 2.5 km is tunnel and the rest is at grade busway. The estimated construction energy for the at grade busway components (excluding tunnel) are

summarized below:

Table 6.4: Summary of busway construction energy

Road way component	Energy TJ/km(2-lane)
2-lane busway	22.50
Additional lane at station	2.25
Shoulder	3.20
Curb	1.02
Median	2.04
Total	31.00
All other components (Clearing of vegetation, Grading, earth work, Landscaping, Drainage, Fencing and gates, Lighting, Traffic control etc.)	2.69
Total	33.69 TJ

6.4.2 Maintenance energy

Herbert et al.(1984) reported the following annual maintenance energy for 3 types of road.

Freeway- 4 Lane	: 19.1 GJ/lane-km
Rural Road-2 Lane	: 41.1 GJ/lane-km
Urban Arterial-2 Lane	: 81.0 GJ/lane-km

IBI Group (1978) reported 983.53 GJ/lane-km annual maintenance energy for busway.

Caltrans (1983) reported 116.45 GJ/lane-km annual maintenance energy for urban road.

All these reported maintenance energy estimates in the literature significantly vary with each other. In this research the following maintenance energy was estimated based on an urban freeway road in southern Ontario (Section 5.14.8 & 5.14.9):

<i>The annual pavement maintenance energy</i>	: 40 GJ/km (2-lane)
<i>The annual winter maintenance energy</i>	: 37 GJ/km (2-lane)
<i>Total annual maintenance energy</i>	: 77 GJ/km (2-lane)

It was assumed that busways require the same regular and winter maintenance as urban freeways.

6.4.3 Trackway construction

Trackway construction energy also substantially varies with type. On the basis of average costs of different LRT systems and using EIOLCA tool, the track construction energy was estimated in this research. Table 6.5 summarizes various types of trackways construction energy intensities obtained from literature sources and own analysis.

Table 6.5: Construction energy of different LRT trackways

Type of trackway	Construction energy (TJ/Track-km)		
	Own analysis using EIOLCA	Fels (1975)	IBI Group (1978)
At-Grade	76.71	11.19	112.12
Elevated Structure	204.04	36.47	154.74
Elevated Retained Fill	116.02	-	-
Elevated Fill	76.71	-	-
Subway	811.15	215.24	462.91
Retained Cut	502.10	106.95	-

It is evident that there are wide variations in track construction energy estimates reported in the literature. The approach taken in this research was to quantify the basic elements of track works (same as busway) and estimate the energy consumption on the basis of their energy intensity. The following trackway construction energy was estimated.

Table 6.6: Summary of trackway construction energy

Item of works	Energy TJ/ km (Double-track)
Rail, tie and anchoring bolt	12.38
Ballast	3.78
Sub ballast	3.07
Sub grade	1.86
Substation*	4.53
Overhead electrical distribution*	1.83
Signals*	1.88
Total	29.33

* Value obtained from section 4.12 and 4.13

6.4.4 Track maintenance energy

Tracks need regular maintenance to remain in good order. Very little information exists in the literature regarding track maintenance energy consumption. Among the few available literature sources, however, there are wide disagreements on reported track maintenance energy. While the IBI Group (1978) estimated the annual track maintenance energy for rail rapid transit (Subway, elevated, surface) as 4,220,000 MJ/Track- mile, Chester and Horvath (2008) reported the same as 91,713 MJ/Track-mile. Therefore, in this research, track maintenance energy was estimated based on Calgary transit report. Calgary transit reported the annual track maintenance cost as \$2.9M in 2006. With 44.5 km tracks, annual maintenance cost/Track-km would be \$65168.53. Using EIOLCA software the annual track maintenance energy was estimated as 0.551TJ/Track-km (double track).

6.4.5 Tunnel construction energy

The transit corridor includes 2.5 km length twin tunnels below Ottawa down town. For BRT, each of the 10m diameter twin tunnels will accommodate one through lane and one passing lane. For LRT, each of the 6.0m diameter twin tunnels will incorporate a single rail track and required safety/maintenance walk. In the previous chapter, the tunnel construction energy was calculated based on the cost estimates using EIOLCA software. The calculated tunnel construction energy for BRT was 2890TJ/km and for LRT 1800TJ/km. As the length of the tunnel is 2.5 km, the total tunnel construction energy for BRT would be 7225 TJ and for LRT would be 4500 TJ.

6.4.6 Stations construction energy

There are 16 surface and 3 underground stations in the corridor. The construction energy

of these stations were determined in the previous Chapter using EIOLCA software. It was assumed that there would be no variation of ridership with mode of choice i.e., whether the transit system is BRT or LRT. In that case the provision for stations' functional elements would mostly be the same for BRT or LRT. Therefore, the construction energy for stations was assumed to be the same for BRT or LRT. The total construction energy consumption for all stations was estimated as 1140.27TJ.

6.4.7 Station operation

The main energy consumption for station operation is electricity. On the basis of a typical under ground station, the annual operating energy for all stations was estimated in the previous chapter as 5.19 TJ.

6.4.8 Maintenance facilities

Based on the cost of maintenance facilities reported in the infrastructure requirement study for TMP of Ottawa (MRC, 2008) and using the EIOLCA software, the construction energy for maintenance yard and shop were calculated as follows:

Construction energy for BRT maintenance facilities: 458TJ

Construction energy for LRT maintenance facilities: 763TJ

6.5 BRT/LRT total system life cycle energy

In order to evaluate and compare the BRT and LRT total system (both vehicle and infrastructure) life cycle energy requirements, a 30-year analysis period was considered. The reason behind this consideration is that the time horizon should cover at least the life of a light rail vehicle, which is 30 years. Within these 30 years, two buses will be

required (usable life of bus is 15 years). Moreover the analysis was done with the projected ridership volume in 2031. A 30-year analysis period therefore justifies the functional requirements of the transit system.

6.5.1 BRT 30-year life cycle energy

Since the transit corridor passes through the tunnel under downtown, vehicular emission have to be kept at a minimal level. In order to address this air quality concerns, it was assumed that only hybrid-electric bus will be running through the corridor. The 30 years life cycle energy calculation for BRT system is shown below:

Total length of the transit corridor under consideration is 21.675 km.

Vehicle requirement: 23 Standard hybrid bus and 207 articulated hybrid bus

Busway construction energy 33.69 TJ/km

Total busway construction energy = $33.69 \times (21.675 - 2.5) = 646.00 \text{ TJ}$

Annual busway maintenance energy: 77 GJ/km

Total busway maintenance energy = $77 \times 21.675 = 1.669 \text{ TJ/year} = 50.06 \text{ TJ/30 years}$

BRT tunnel construction energy: 2890 TJ/km

Total BRT tunnel construction energy: $2890 \times 2.5 = 7225 \text{ TJ}$

Total stations construction energy = 1140.27 TJ

Total stations operating energy = $5.186 \times 30 = 155.58 \text{ TJ/30 years}$

Construction energy for BRT Maintenance facilities: 458TJ

The result of the analysis is summarized in Table 6.7. It can be seen in Table 6.7 and Fig. 6.4 that while vehicle operating energy consumption has the largest impact on total life cycle energy consumption, construction energy for infrastructures, such as tunnel, also has a high impact. The total life cycle energy consumption for the BRT system is 19313.1TJ.

Table 6.7: BRT total system (vehicle and infrastructure) life cycle energy

Row #	Component	Energy (TJ)				
		Manufacturing/ construction	Operation	Maintenance	Fuel production	Total energy
1	Vehicle					
2	1-Standard hybrid bus	2.95	11.72	1.78	2.53	18.98
3	For 30 years, $23 \times 2 = 46$ Standard hybrid bus	135.7	539.12	81.88	116.38	873.08
4	1-Articulated hybrid bus	4.22	14.66	2.72	3.16	24.76
5	For 30 years, $207 \times 2 = 414$ Articulated hybrid bus	1747.08	6069.24	1126.08	1308.24	10250.6
6	Sub total (vehicle energy) Row (3+5)	1882.78	6608.36	1207.96	1424.62	11123.7
7	Infrastructure					
8	Bus way (20 years life)	646.00		33.38		
9	Bus way energy for 30 years (row # 8) $\times 30/20$	969		50.06		1019.06
10	Tunnel (40 years life)	7225				
11	Tunnel energy for 30 years (row # 10) $\times 30/40$	5416.5				5416.5
12	Stations (30 years life)	1140.27	155.58			1295.85
13	Maintenance facility (30 years life)	458				458.0
14	Sub total (Infrastructure) (Row # 9+11+12+13)					8189.41
15	Total (Row # 6+ 14)					19313.1

*Spare vehicle is not considered

Figure 6.4: BRT system life cycle energy consumption

Figure 6.5: (a) Share of BRT system components energy consumption, (b) Direct and indirect energy consumption

It can be seen in Figure 6.5 (a) that while BRT vehicle life cycle constitutes 58% of the total BRT system's life cycle energy, infrastructure components constitute 42%. Indirect energy accounts for the larger share (66%) of total life cycle energy, mainly due to the tunnel (Figure 6.5 (b)).

6.5.2 LRT 30-years life cycle energy

The 30 years life cycle energy estimation for LRT system is shown below:

Track way construction energy 29.33 TJ/km (Double track)

Total trackway construction energy $29.33 \times (21.675 - 2.5) = 562.40 \text{ TJ}$

Trackway maintenance energy: 0.551 TJ/Track-km (Double track)

Total track way maintenance energy $0.551 \times 21.675 = 11.94 \text{ TJ/year} = 358.28 \text{ TJ/30 years}$

LRT tunnel construction energy: 1800 TJ/km

Total LRT tunnel construction energy: $2890 \times 2.5 = 4500 \text{ TJ}$

Total stations construction energy = 1140.27 TJ

Total stations operating energy = $5.186 \times 30 = 155.58 \text{ TJ/30 years}$

Construction energy for LRT maintenance facilities: 763 TJ

The result of the analysis is summarized in Table 6.8. It can be seen in Table 6.8 and Figure 6.6 that while light rail vehicle operating energy consumption has the largest impact on the total life cycle energy consumption, electricity generation also has very significant impact on energy. The construction energy for infrastructures, such as a tunnel, has no way less importance. The total life cycle energy consumption for LRT system is 18990.17 TJ.

Table 6.8: LRT total system (vehicle and infrastructure) life cycle energy

Row #	Component	Energy (TJ)				
		Manufacturing/ construction	Operation	Maintenance	Electricity generation	Total energy
1	1-LRV (30 years life)	6.6	56.35	11.1	36.09	110.14
2	58*2 =116 LRV	765.6	6536.6	1287.6	4186.44	12776.24
3	Track way (40 years life)	562.40		477.60		
4	For 30 years, Track way energy = Row # 3 *30/40	421.80		358.28		780.08
5	Tunnel (40 years life)	4500				
6	For 30 years, Tunnel energy = Row # 5 *30/40	3375				3375
7	Stations (30 years life)	1140.27	155.58			1295.85
8	Maintenance facilities (30 years life)	763				763
9	Subtotal (Infrastructure) (Row # 4+ 6+ 7+ 8)					6213.93
	Total					18990.17

Figure 6.6: LRT system life cycle energy consumption

Figure 6.7: (a) Share of LRT system components energy consumption, (b) Direct and indirect energy consumption.

It is evident in Fig. 6.7 (a) that LRT vehicles life cycle energy consumption constitutes the major part (67%) of the total LRT system's life cycle energy. While indirect energy consumption accounts for the largest share (66%) of the total LRT system's life cycle energy, direct energy only accounts for 34% (Fig. 6.7 b). It can be noted that both BRT and LRT systems have nearly the same proportion of direct and indirect energy consumption.

6.6 Energy intensity per unit output (Vehicle life cycle)

The energy intensity enables fair comparison of energy consumption among transportation modes. It is generally expressed as energy consumption per passenger-km. There are other indicators, however, such as energy/seat-km, or energy/vehicle-km. The most important factor for energy intensity is the vehicle occupancies, which is usually stated as passenger load factor. Transit vehicles load factor enormously varies with peak and off peak hour operation. Higher average load factor corresponds to lower energy consumption per passenger. The energy intensity per unit output for different BRT and LRT transit vehicles life cycle are shown in Table 6.9. In this analysis, the average load factor for all the transit vehicles was considered as 0.28.

Table 6.9: Energy intensity per unit output

Vehicle type	Life cycle stage	Energy (TJ) Per bus-life	Energy (KJ)/VKT	Pass./Veh. (Load factor 0.28)	Energy/PKT (KJ/PKT)
Standard bus	Manufacturing	1.87	1930.08	13	148.47
	Operation	16.04	16555.33		1273.49
	maintenance	1.24	1279.84		98.45
	Fuel production	3.46	3571.16		274.70
	Total	22.61	23336.40		1795.11
Standard hybrid bus	Manufacturing	2.95	3044.78	13	234.21
	Operation	11.72	12096.53		930.50
	maintenance	1.78	1837.19		141.32
	Fuel production	2.53	2611.28		200.87
	Total	18.98	19589.78		1506.91
Articulated bus	Manufacturing	2.86	2951.88	20	147.59
	Operation	20.1	20745.76		1037.29
	maintenance	1.89	1950.72		97.54
	Fuel production	4.34	4479.43		223.97
	Total	29.19	30127.80		1506.39
Articulated hybrid bus	Manufacturing	4.22	4355.58	20	217.78
	Operation	14.66	15130.99		756.55
	maintenance	2.72	2807.39		140.37
	Fuel production	3.16	3261.52		163.08
	Total	24.76	25555.48		1277.77
LRV	Manufacturing	6.6	2432.87	38	64.02
	Operation	56.35	20771.57		546.62
	maintenance	11.1	4091.65		107.67
	Fuel production	36.09	13303.39		350.09
	Total	110.14	40599.47		1068.40

Figure 6.8: Energy intensity per vehicle-km traveled for BRT and LRT vehicles

Figure 6.9: Energy intensity per passenger-km traveled for BRT and LRT vehicles

It can be seen in Fig. 6.8 that the total life cycle energy intensity of LRV per vehicle-km is the highest among all the transit vehicles and the total life cycle energy intensity of LRV per passenger-km is the lowest in Fig 6.9.

6.7 Energy intensity per unit output (Vehicle and Infrastructure)

In order to determine the total system energy intensity of BRT and LRT, both vehicle and infrastructure lifecycle energy were considered. The impacts of infrastructure energy consumption on vehicle were calculated as follows:

Impact of bus way construction energy per bus-life =

$$\frac{\text{Busway} - \text{construction} - \text{energy}}{\text{Busway} - \text{life}} \times \frac{\text{Annual} - \text{VKT}_{\text{vehicle}}}{\text{Annual} - \text{busway} - \text{usage}} \times \text{Bus} - \text{life} \dots\dots\dots 6.1$$

In the previous chapter, the annual VKT of a bus was estimated as 64591.5 km. It was assumed that the corridor would be exclusively used by the transit buses. Therefore a total of 230 buses would make 14, 856,045 = (230* 64591.5) vehicle-km annual usages of the busway.

Therefore, the impact of bus way construction energy per bus-life =

$$= \frac{646.0TJ}{20years} \times \frac{64591.5km}{14,856,045km} \times 15years = 2.106TJ$$

The impact of other infrastructure energy consumption were estimated in a similar manner. The equations are shown below:

Impact of bus way maintenance energy per bus-life =

$$Annual - Busway - maintenance - energy \times \frac{Annual - VKT_{vehicle}}{Annual - busway - usage} \times Bus - life \dots\dots 6.2$$

Impact of tunnel construction energy per bus-life =

$$\frac{tunnel - construction - energy}{tunnel - life} \times \frac{Annual - VKT_{vehicle}}{Annual - busway - usage} \times Bus - life \dots\dots\dots 6.3$$

Impact of station construction energy per bus-life =

$$\frac{Station - construction - energy}{Station - life} \times \frac{Annual - VKT_{vehicle}}{Annual - busway - usage} \times Bus - life \dots\dots\dots 6.4$$

Impact of stations operation energy per bus-life =

$$Annual - Stations - operation - energy \times \frac{Annual - VKT_{vehicle}}{Annual - busway - usage} \times Bus - life \dots\dots\dots 6.5$$

Impact of maintenance facilities construction energy per bus-life =

$$\frac{Maintenance - yard/ shop - const - energy}{Maintenance - yard/ shop - life} \times \frac{Annual - VKT_{vehicle}}{Annual - busway - usage} \times Bus - life \dots\dots\dots 6.6$$

The result of the analysis is shown in Table 6.10. It can be seen from the table that the energy intensity of standard hybrid bus is 2934.81 KJ/Passenger-km and articulated hybrid bus is 1918.19 KJ/Passenger-km, which indicates that articulated hybrid bus is more energy efficient than standard hybrid bus.

Table 6.10: Energy intensity (vehicle and infrastructure) for standard hybrid and articulated hybrid bus

Component	Life cycle stages	Standard hybrid bus energy intensity		Articulated hybrid bus energy intensity	
		(TJ)/bus-life	*KJ/PKT	(TJ)/bus-life	*KJ/PKT
Vehicle	Manufacturing	2.95	234.21	4.22	217.78
	Operation	11.72	930.50	14.66	756.55
	maintenance	1.78	141.32	2.72	140.37
	Fuel production	2.53	200.87	3.16	163.08
		18.98	1506.91	24.76	1277.77
Busway	Construction	2.106	167.20	2.106	108.68
	Maintenance	0.109	8.65	0.109	5.63
Tunnel	Construction	11.77	934.47	11.77	607.41
Station	Construction	2.47	196.10	2.47	127.47
	Operation	0.34	26.99	0.34	17.55
Maintenance facilities	Construction	1.19	94.48	1.19	61.41
	Subtotal	17.99	1427.91	17.99	928.40
	Total	36.97	2934.81	42.75	2206.17

* Considering Load factor = 0.28 (Passenger volume/bus: 13 for standard hybrid bus and 20 for articulated hybrid bus)

Light rail vehicle

The annual VKT for LRV was estimated as 90,428 vehicle-km. A total of 116 light rail cars would make 10,489,648 vehicle-km annual usages of the trackway.

Impact of track way construction energy per car-life =

$$\frac{\text{Trackway - construction - energy}}{\text{Trackway - life}} \times \frac{\text{Annual - VKT}_{\text{vehicle}}}{\text{Annual - Trackway - usage}} \times \text{car - life} \dots\dots\dots 6.7$$

$$= \frac{532.48TJ}{40 \text{ years}} \times \frac{90428 \text{ km}}{10,489,648 \text{ km}} \times 30 \text{ years} = 3.44TJ$$

Impact of track way maintenance energy per car-life =

$$\text{Annual - Trackway - maintenance - energy} \times \frac{\text{Annual - VKT}_{\text{vehicle}}}{\text{Annual - Trackway - usage}} \times \text{car - life} \dots\dots\dots 6.8$$

Impact of tunnel construction energy per car-life =

$$\frac{\text{tunnel} - \text{construction} - \text{energy}}{\text{tunnel} - \text{life}} \times \frac{\text{Annual} - \text{VKT}_{\text{vehicle}}}{\text{Annual} - \text{trackway} - \text{usage}} \times \text{car} - \text{life} \dots\dots\dots 6.9$$

Impact of station construction energy per car-life =

$$\frac{\text{Station} - \text{construction} - \text{energy}}{\text{Station} - \text{life}} \times \frac{\text{Annual} - \text{VKT}_{\text{vehicle}}}{\text{Annual} - \text{trackway} - \text{usage}} \times \text{car} - \text{life} \dots\dots\dots 6.10$$

Impact of stations operation energy per bus-life =

$$\text{Annual} - \text{staion} - \text{operation} - \text{energy} \times \frac{\text{Annual} - \text{VKT}_{\text{vehicle}}}{\text{Annual} - \text{trackway} - \text{usage}} \times \text{Car} - \text{life} \dots\dots 6.11$$

Impact of maintenance facilities construction energy per bus-life =

$$\frac{\text{Maintenance} - \text{yard/ shop} - \text{construction} - \text{energy}}{\text{Maintenance} - \text{yard/ shop} - \text{life}} \times \frac{\text{Annual} - \text{VKT}_{\text{vehicle}}}{\text{Annual} - \text{trackway} - \text{usage}} \times \text{Car} - \text{life} \dots\dots 6.12$$

The result of the analysis is shown in Table 6.11. It can be seen that the energy intensity of light rail vehicles is 1586.02 KJ/Passenger-km. Table 6.12 summarizes the result for both BRT and LRT vehicles.

Table 6.11: Energy intensity (vehicle and infrastructure) for light rail vehicle

		Energy (TJ) Per train-life	Energy (KJ)/VKT	Energy/PKT*
Vehicle	Manufacturing	6.6	2432.87	64.02
	Operation	56.35	20771.59	546.62
	maintenance	11.1	4091.65	107.68
	Fuel production	36.09	13303.40	350.09
	Sub total	110.14	40599.52	1068.41
Trackway	Construction	3.44	1268.04	33.37
	Maintenance	3.08	1135.34	29.88
Tunnel	Construction	29.09	10723.08	282.19
Station	Construction	9.83	3623.51	95.36
	Maintenance	1.34	493.95	13.00
Maintenance facilities	Construction	6.58	2425.50	63.83
	Sub total	53.36	19669.42	517.62
Total		163.5	60268.94	1586.02

* Considering Load factor = 0.28 (38 passenger/car)

Table 6.12: Summary of energy intensity (vehicle and infrastructure)

Vehicle type	Energy impact category	Energy (TJ) Per train-life	Energy (KJ)/VKT	Energy/PKT*
Standard hybrid bus	Vehicle	18.98	19589.78	1506.91
	Infrastructure	17.985	18562.81	1427.91
	Total	36.965	38152.59	2934.81
Articulated hybrid bus	Vehicle	24.76	25555.48	1277.77
	Infrastructure	17.985	18562.81	928.14
	Total	42.745	44118.29	2205.91
Light rail vehicle	Vehicle	110.14	40599.52	1068.41
	Infrastructure	53.36	19669.42	517.62
	Total	163.5	60268.94	1586.02

*Load factor = 0.28

Figure 6.10: Energy intensity per vehicle-km traveled for BRT and LRT vehicles considering both vehicle and infrastructure life cycle energy

Figure 6.10 shows energy consumption per vehicle-km for standard hybrid bus, articulated hybrid bus and light rail vehicle. It can be seen that the impact of infrastructure energy on vehicle is nearly same for all three types of vehicle. The vehicle life cycle energy consumption for standard bus is the least and LRV is the highest. The total energy (vehicle and infrastructure) also follows the same trend.

Figure 6.11: Energy intensity per passenger-km traveled for BRT and LRT vehicles considering both vehicle and infrastructure life cycle energy

Figure 6.11 shows energy consumption per passenger-km for standard hybrid bus, articulated hybrid bus and light rail vehicle. With the assumption of average load factor 0.28, i.e., passenger volume of a hybrid standard bus as 13 and hybrid articulated bus as 20 and Light rail vehicle as 38, the energy intensity for a hybrid standard bus shows the highest among the three types of vehicles. The energy intensity for light rail vehicle is found to be the lowest, which is 1586.02 KJ/Passenger-km.

Transportation energy intensity expressed in per passenger-km largely depends on load factor. When a vehicle is lightly loaded, energy intensity goes up because the vehicle consumes nearly the same amount of energy, regardless of the number of occupants. Therefore load factor is the most important consideration. Table 6.13 shows the energy intensity of standard hybrid bus, articulated hybrid bus and light rail vehicle at 3 different load factors. It can be seen that at seat capacity the energy intensity for articulated bus is the lowest among three types of vehicle, which is 817.01 KJ/passenger. At design capacity, however, the energy intensity for light rail vehicle becomes the lowest.

Table 6.13: Energy intensity (vehicle and infrastructure) at different load factor

Vehicle type	Energy intensity at seat capacity		Energy intensity at design capacity		Energy intensity at full capacity (Seat + Standing)	
	Seats/ vehicle	KJ/PKT	Passengers/ vehicle	KJ/PKT	Passenger/ vehicle	KJ/PKT
Standard hybrid bus	39	978.27	45	847.84	51	748.09
Articulated hybrid bus	54	817.01	70	630.26	86	513.00
Light rail vehicle	70	860.98	135	446.44	200	301.34

Fig. 6.12 (a) shows the variation of energy intensity with the number of passengers and (b) shows the variation with different load factors for three types of transit vehicles. It can be seen that light rail vehicle is more energy intensive if the passenger volume is low (Fig. 6.12(a)). If the passenger volume is high, light rail vehicle would be the most energy efficient option. In Fig. 6.12(b), it can be seen that the energy intensity substantially goes down with the increasing load factor for all types of vehicles. The variation is relatively less significant beyond 0.5 load factor. The energy intensity for standard hybrid bus is the highest for any load factor. The energy intensity of light rail vehicle is the lowest and articulated hybrid bus falls in between.

Fig 6.12: Variation of energy intensity of transit vehicles (a) with different passenger volume and (b) with load factor.

6.8 BRT and LRT energy consumption (without Tunnel)

It has been found in the previous analyses that tunnel construction has a large impact on total energy consumption for the transit corridor, but tunnel construction may not be necessary in some other places. Therefore, in this section, an analysis is conducted assuming that there would be no tunnel in the corridor. The busway or trackway would be built on surface throughout the corridor. It is also assumed that the projected travel demand and all other attributes will remain same. Therefore, there would be no variation for vehicle life cycle analysis. The result obtained in the previous section for vehicle life cycle energy consumption can directly be applied here. The only difference would be with infrastructure lifecycle energy estimation.

6.8.1 BRT infrastructure energy estimation

The total length of the transit corridor is 21.675 km. With the busway construction energy intensity of 33.69 TJ/km, the total busway construction energy would be 730.23 TJ. The annual maintenance energy of busway is 77 GJ/2-lane km. For 30 years, the total busway maintenance energy for busway would be 50.06 TJ. There are a total of 19 stations. It was assumed that the construction cost of 3 down town stations and 2 terminal stations at Blair and Baseline will cost \$10 Million each. The construction cost for other stations will remain same as considered in the previous analysis. Using EIOLCA tool, the total construction energy for all the stations was estimated as 536.93 TJ. Following the same procedure discussed in Section 5.18, the annual operation energy consumption for all the stations was estimated as 4.403 TJ. The summary of the energy analysis is shown in Table 6.14.

Table 6.14: BRT total system (vehicle and infrastructure) life cycle energy

Row #	Component	Energy (TJ)				
		Manufacturing/ construction	Operation	Maintenance	Fuel production	Total energy
1	Vehicle					
2	1-Standard hybrid bus	2.95	11.72	1.78	2.53	
3	For 30 years, $23 \times 2 = 46$ Standard hybrid bus	135.7	539.12	81.88	116.38	873.08
4	1-Articulated hybrid bus	4.22	14.66	2.72	3.16	
5	For 30 years, $207 \times 2 = 414$ Articulated hybrid bus	1747.08	6069.24	1126.08	1308.24	10250.6
6	Sub total (vehicle energy) Row (3+5)	1882.78	6608.36	1207.96	1424.62	11123.7
7	Infrastructure					
8	Bus way (20 years life)	730.23		33.38		
9	Bus way energy for 30 years (row # 8) $\times 30/20$	1095.35		50.06		1145.405
12	Stations (30 years life)	536.93	132.09			669.02
13	Maintenance facility (30 years life)	458.00				458.00
14	Sub total (Infrastructure) (Row # 9+11+12+13)					2272.425
15	Total (Row # 6+ 14)					13396.125

*Spare vehicle is not considered

(a)

(b)

Figure 6.13: (a) Share of BRT system components energy consumption, (b) Direct and indirect energy consumption

It can be seen in Fig 6.13 (a) that vehicle life cycle energy constitutes lion share of the total BRT system energy consumption. The share of direct and indirect energy consumption for the total system is nearly equal (Fig. 6.13 (b)).

6.8.2 LRT infrastructure energy estimation

The construction energy for trackway was estimated as 635.72 TJ based on the construction energy intensity of 29.33 TJ/km. The trackway maintenance energy for 30 years was estimated as 358.28 TJ. The station construction and operating energy was considered as same as BRT station. Since there is no variation of ridership with mode of choice, the provision for stations functional elements would be same for BRT or LRT. The construction energy for LRT maintenance facilities was considered as same as previous analysis i.e. 763TJ. The result of the estimation is summarized in Table 6.15.

Table 6.15: LRT total system (vehicle and infrastructure) life cycle energy

Row #	Component	Energy (TJ)				
		Manufacturing/ construction	Operation	Maintenance	Electricity generation	Total energy
1	1-LRV (30 years life)	6.6	56.35	11.1	36.09	110.15
2	58*2 =116 LRV	765.6	6536.6	1287.6	4186.44	12776.24
3	Track way (40 years life)	635.72		477.60		
4	For 30 years, Track way energy = Row # 3 *30/40	476.79		358.28		835.07
7	Stations (30 years life)	536.93	132.09			669.02
8	Maintenance facilities (30 years life)	763.00				763.00
9	Subtotal (Infrastructure) (Row # 4+ 6+ 7+ 8)					2267.09
10	Total					15043.33

Figure 6.14: (a) Share of LRT system components energy consumption, (b) Direct and indirect energy consumption.

It can be seen in Fig 6.14 (a) that vehicle life cycle energy constitutes a major part of the total LRT system energy consumption. The share of indirect energy is larger than direct energy (Fig. 6.14(b)).

It can be concluded from the above analysis that while BRT system consumes 13396.125TJ of energy for a 30 years life, LRT system consumes 15043.33 TJ of energy. This indicates that LRT system is more energy intensive than BRT. In the previous analysis, where a tunnel was considered, it was found that LRT system is a bit less energy intensive than BRT. It is really difficult to say which mode would be more energy intensive without conducting a detailed analysis. It is evident that the energy consumption of both BRT and LRT system is close to each other.

6.9 Energy intensity per unit output (Vehicle and Infrastructure)

Table 6.16 and Table 6.17 show the energy intensity (vehicle and infrastructure) for the standard hybrid bus, articulated hybrid bus and LRV. With the consideration of average passenger volume for the standard hybrid bus 13, for the articulated hybrid bus 20 and the light rail vehicle 38, it was found that the energy intensity for standard hybrid bus is the

highest. The energy intensity for LRV is the lowest and the energy intensity for the articulated hybrid bus falls in between.

Table 6.16: Energy intensity (vehicle and infrastructure) for standard hybrid bus and articulated hybrid bus

Components	Life cycle stages	Standard hybrid bus energy intensity		Articulated hybrid bus energy intensity	
		(TJ)/bus-life	*KJ/PKT	(TJ)/bus-life	*KJ/PKT
Vehicle	Manufacturing	2.95	234.21	4.22	217.78
	Operation	11.72	930.50	14.66	756.55
	maintenance	1.78	141.32	2.72	140.37
	Fuel production	2.53	200.87	3.16	163.08
Subtotal		18.98	1506.91	24.76	1277.77
Busway	Construction	2.38	188.96	2.38	122.82
	Maintenance	0.109	8.65	0.109	5.63
Station	Construction	1.16	92.10	1.16	59.86
	Operation	0.29	23.02	0.29	14.97
Maintenance facilities	Construction	0.99	78.60	0.99	51.09
Subtotal		4.929	391.34	4.929	254.37
Total		23.909	1898.24	29.689	1532.14

* Considering Load factor = 0.28 (No of passengers are 13 for standard hybrid bus and 20 for articulated hybrid bus).

Table 6.17: Energy intensity (vehicle and infrastructure) for light rail vehicle

Components	Life cycle stages	Energy (TJ) Per train-life	Energy/PKT*
Vehicle	Manufacturing	6.6	64.02
	Operation	56.35	546.62
	maintenance	11.1	107.68
	Fuel production	36.09	350.09
Subtotal		110.15	1068.50
Trackway	Construction	4.11	39.87
	Maintenance	3.09	29.97
Station	Construction	4.63	44.91
	Maintenance	1.14	11.06
Maintenance facilities	Construction	6.58	63.83
Subtotal		19.55	189.64
Total		129.70	1258.14

* Considering Load factor = 0.28

Chapter 7

Life Cycle Energy Estimation for an Automobile

7.1 Introduction

In the previous chapters the energy estimates for BRT and LRT systems have been reported. The transit systems necessary to accommodate the 2031 travel demand of City of Ottawa have been considered in the analysis. In this chapter, the energy requirements for an automobile commuting to downtown and related infrastructures will be analyzed. The analysis assumes that all the required transit infrastructures to accommodate the 2031 transit ridership demand will be in place, and the goal of 30% city-wide peak hour transit modal split will be achieved. It is also assumed that the major road network elements will be in place by that time to accommodate peak hour travel demand.

7.2 Future automobile travel demand

In the City of Ottawa's 2008 TMP, a detailed assessment of long-term transit and road infrastructure needed to accommodate the 2031 projected travel demand is presented. The growth in travel demand over the 2031 planning period was forecasted with the assistance of TRANS Model. The basis of this assessment was 2005 O-D survey. Table 7.1 compares the city-wide modal splits and person-trip volumes for transit and automobile use for the year 2005 and 2031. It shows that while peak hour transit person-trips will increase by 76%, automobile person-trips will only increase by 24%.

Table 7.1: Projected transit and automobile travel demand (Morning peak hour)

Mode	Modal Split		Person-Trips		
	2005	2031	2005	2031	Change
Transit	23%	30%	44,500	78,300	+76%
Automobile	77%	70%	146,600	182,300	+24%
Total motorized trips	100%	100%	191,100	260,600	36%

(Source: TRANS, 2009)

7.3 Major travel flows

The analysis of major travel flows between planning districts in the National Capital Region during weekday mornings shows that downtown Ottawa is a dominant destination (23% of trips) (Appendix D-1). The Alta Vista and Merivale districts are the second top destinations, which are 10% and 8% of all trips, respectively. The primary destinations of trips in the morning from Orléans district are: Ottawa Inner Area (34%), Ottawa East/Beacon Hill (23%) and the Alta Vista District (14%). The primary destinations of trips from South Nepean are: Ottawa Inner Area (25%) and the Merivale district (20%). The primary destinations of trips from the Kanata/ Stittsville district in the morning are: Ottawa Inner Area (26%), Bayshore/Cedarview (19%) and the Merivale District (15%) (Source: TRANS, 2009)

7.4 Selection of vehicle

The focus of this analysis was to estimate the lifecycle energy requirements for an automobile used for travel to downtown Ottawa. The type of car considered for this analysis was a compact commuter car. Compact cars can carry four adults and a reasonable amount of luggage. It is relatively cheaper to buy and operate and suitable for commuting and other urban uses. Compact cars were the strongest sellers in Canada

during the past years. Table 7.2 shows the top 10 best-selling compact cars in Canada in 2007 (Sympatic, 2009). It can be seen from the table that the best selling car in Canada is Honda Civic. Therefore this car was considered for the analysis.

Table 7.2: The top 10 best-selling compact cars in Canada in 2007

Rank	Model	Total sales	Rank	Model	Total sales
1	Honda Civic	70,838	6	Toyota Camry	28,218
2	Mazda3	48,236	7	Pontiac G5	25,211
3	Toyota Corolla	40,474	8	Ford Focus	24,013
4	Toyota Yaris	34,424	9	Honda Accord	22,102
5	Chevrolet Cobalt	32,613	10	Nissan Versa	21,940

Vehicle Specification

Table 7.3: Honda Civic specification

Vehicle	Base Retail Price (2009\$)	Horse power	Length in.	Curb Weight, lb.	Cargo Volume, cu. ft.	Fuel Capacity, gal.
Honda Civic 2-dr. Cpe.	\$17,190 - 26,880	140 - 197	174.8	2593	11.5	13.2

(Source: Consumer guide automotive, 2009)

7.5 Energy estimation

7.5.1 Automobile manufacturing energy

Automobile manufacturing energy can be estimated using process based or input-output approach or a combination of both of them in a like manner described in Chapter 3. However, the recent version of GREET model 2.7 has incorporated the energy estimation of vehicle-cycle model for three types of vehicles: passenger car, SUV, and light truck. The vehicle-cycle model evaluates the energy and emission effects associated with vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling. In this analysis the GREET 2.7 model was used to estimate vehicle cycle energy for a Honda Civic car.

The first step of the vehicle-cycle analysis is to estimate vehicle component weights. This estimate takes into account the weight of the major components of a vehicle, such as the body, chassis, batteries, fluids, powertrain and transmission or gearbox. The second step of the analysis is to break down each major vehicle component into its material composition (i.e., breakdowns of component weight into steel, aluminum, iron, plastic, rubber, and any other materials). The model then develops replacement schedules for components that are subjected to replacement during a vehicle's lifetime. The model also takes into account the energy required for disposal and recycling of scrap materials back into original materials for reuse. Finally, the model estimates energy used in each step of the process from raw material recovery to vehicle assembly and finally disposal. The simulation logic for estimating vehicle energy use and emissions of the GREET vehicle-cycle model is shown in Figure 7.1.

Figure 7.1: Simulation logic for GREET vehicle-cycle analysis (Source: Wang, 2006)

The key Input Parameter

- Total vehicle weight = 2,593 pounds (ICEV: Conventional material)
- Vehicle battery weight = 36.0 pounds (Lead-Acid battery)
- Fluids weight (pounds):

Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Fluid	Adhesives
8.5	0.0	2.0	24.0	23.0	6.0	30.0

- Vehicle components composition:

Components	% by wt
Powertrain system	25.7%
Transmission system	6.3%
Chassis (w/o battery)	23.9%
Traction Motor	0.0%
Generator	0.0%
Electronic Controller	0.0%
Fuel Cell Auxiliary System	0.0%
Body: including BIW, interior, exterior, and glass	44.1%

- Vehicle material composition:

Material	% by wt
Steel	61.7%
Cast Iron	11.1%
Wrought Aluminum	2.2%
Cast Aluminum	4.7%
Copper/Brass	1.9%
Magnesium	0.02%
Glass	2.9%
Average Plastic	11.2%
Rubber	2.4%
Platinum	0.0005%
Others	1.9%

- Fluids replacements during lifetime of vehicle

Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Fluid	Adhesives
40	0	3	1	3	20	0

- Lifetime VMT of a vehicle, miles =160,000

Summary of automobile manufacturing energy consumption

Table 7.4: Summary of energy consumption: Mega Btu per-vehicle lifetime

Item	Components	ADR*	Batteries	Fluids	Total
Total energy	54.819	15.856	4.439	11.665	86.779

*ADR: Assembly, disposal and recycling

It can be seen from Table 7.4 that the vehicle cycle energy consumption for a typical Honda Civic automobile is 86.78 Mega Btu or 91.55 GJ. The vehicle manufacturing energy was also calculated using EIOLCA approach in order to check the consistency of the result. Using an average base price of a Honda Civic as \$22,035 (\$2009) and converting the price in to EIOLCA base year price (1997\$) and then inputting it to Automobile and Light Truck Manufacturing (Sector #336110) sector of EIOLCA tool provided 94 GJ manufacturing energy. The result is quite similar to the result obtained from GREET model.

7.5.2 Automobile maintenance energy

In order to estimate vehicle maintenance energy, the life cycle cost of driving an automobile was first obtained from a publication of the American Automobile Association (Your Driving Costs, 2005 Edition). The Vehicle maintenance was separated into maintenance of the vehicle and tire replacement. The maintenance cost of an automobile is \$0.047/VMT and the tire replacement cost is \$0.005/VMT (Table 7.5). Multiplying lifetime VMT by these factors yielded lifetime costs for the two components. To estimate energy consumption for automobile maintenance, the EIOLCA tool was used. The Automotive Repair and Maintenance (sector #8111A0) and Tire

Manufacturing (sector #326210) sectors were used for these two components. The energy consumption for life time maintenance and tire replacement of an automobile was found to be 0.033TJ and 0.012TJ, respectively.

Table 7.5: Automobile driving costs, 2005

Category	Small Car	Midsize Car	Large Car	Sport Utility Vehicle	Van
Operating Costs (cents per mile)					
Gasoline & Oil	6.9	8.5	9.3	10.8	8.9
Maintenance	4.7	5.8	5.4	5.3	5.7
Tires	0.5	0.7	0.5	0.9	0.6
Ownership Costs (cost per year, dollars)					
Insurance	1,456	1,195	1,212	1,398	1,130
License, registration, taxes	333	390	445	435	389
Depreciation (15,000 miles annually)	2,985	4,005	4,647	4,300	3,755

(Source: APTA, 2005)

7.5.3 Automobile operating energy

The automobile life time operating energy was estimated using the Fuel Consumption Calculator developed by the Office of Energy efficiency, Natural resource of Canada. The fuel consumption ratings are developed for typically equipped vehicles and are adjusted to reflect average real-world driving conditions in Canada. The fuel consumption, however, may vary from this rating, depending on factors such as driving style and behaviors, vehicle acceleration and driving speed, the overall age and operating condition of the vehicle, temperature, weather, traffic and road conditions. The estimated fuel efficiency for a Honda Civic automobile obtained from Fuel Consumption Calculator is shown in the table below:

Table 7.6: Average fuel consumption of Honda Civic automobile

Make/Model	Class	Eng. Size /Cylinder	Tran # gear	Fuel Consumption (L/100km)	
				City	Highway
HONDA CIVIC	S	1.8L/4	M5+	7.4	5.4

(Source: NRC, 2009c)

It was assumed that the lifetime VMT of a car is 160,000 mile or 258,000 Km (wang, 2006). It was also assumed that for a car used in an urban area, 52% of the lifetime VKT can be attributed to highway and the rest to city roads (based on Table 7.9). On the basis of these assumptions, the lifetime operating energy was calculated as follows:

$$\text{Lifetime gasoline consumption} = (0.52 * 5.4/100 + 0.48 * 7.4/100) * 258,000$$

$$= 16,408.8 \text{ Liters} = 4340.9 \text{ gallon}$$

The calorific value of Reformulated or low-sulfur gasoline is 121848 Btu/Gallon (Wang, 1999). Therefore, the lifetime vehicle operating energy = $4340.9 * 121848 \text{ Btu/Gallon} = 528.93 \text{ Mega Btu} = 558.02 \text{ GJ}$

7.5.4 Gasoline production energy

The energy consumption for gasoline fuel production was obtained by conducting a life cycle assessment (LCA) for gasoline fuel using the GREET model in a similar manner as diesel fuel production described in Section 5.12.4. The WTP (Well to Pump) analysis was conducted for reformulated or low-sulfur gasoline. It was found that to produce 1 Mega Btu reformulated gasoline, 247,628 Btu of energy is required to expend. The energy conversion factor for reformulated gasoline fuel production = $247,628/1000000 = 0.248$ (24.8%). Therefore, energy consumption for vehicle lifetime gasoline fuel production would be $0.248 * 558.02 \text{ GJ} = 138.39 \text{ GJ}$.

7.5.5 Insurance

Car insurance provides the critical support in the event of a car accident. The service requires facilities and operations which consume energy. The average cost of insuring a small car is \$1456 (2005\$) per year (Table 7.5). The EIOLCA sector “Insurance Carriers” was used to estimate the energy consumption for this service. The lifetime insurance costs (in \$1997) is computed and inputted to the EIOLCA tool for the energy estimate. If the service life of an automobile is assumed as 10 years then lifetime insurance cost would be \$12,294.05 (1997\$). Therefore the impact of energy for vehicle insurance would be 0.013TJ.

7.6 Infrastructure construction energy

Modern urban road systems consist of a wide array of infrastructures. These include roads, bridges and culverts, traffic signals, parking lots, lighting, ITS technologies and other components. Ottawa residents are served by an extensive, multi-modal transportation system. In the Ottawa region, there are about 6,000 kilometers of roads including arterial roads, collector roads and local roads as well as freeways. While arterials account for about 1,300 kms, collectors make up about 1,700 kms and the remainders are mostly local roads. The City also operates 15 off-street parking lots with 1,600 spaces, and 3,750 on-street parking meters. There are private sectors parking providers as well, that provides spaces in all types of structures and surface lots. The estimation of energy to construct all these components is a difficult task. Moreover, there are some components which have little impact on energy. Therefore, only the major components that have significant impacts on energy were considered in this analysis. The infrastructure components included in this analysis were:

- Roadway construction
- Roadway maintenance
- Parking facilities construction

7.6.1 Roadway construction

Roadways are usually classified based on the function of the roads, the projected traffic volumes and vehicle speed limit. A typical roadway system includes the following four classes of roads:

Freeways, expressways and parkways: These carry large volumes of rapid, through traffic between and across urban areas. They have limited access with grade separated interchanges. They have design speeds of 80-100 km per hour.

Arterial roads: These carry through traffic between and across developed areas with some direct access to abutting properties. They are subjected to control of exits, entrances and curb use. They have design speeds of 50 to 70 km per hour.

Collector roads: These carry traffic between arterial and local roads, with direct access to abutting properties. Traffic control is provided by stop signs on side roads. They have design speeds of 50 km per hour.

Local roads: These carry local traffic and offer direct access to abutting property. They have design speeds of 30 km per hour.

In this study, the road construction energy was estimated based on this classification. Specifications for each roadway type were taken from the American Association of State Highway and Transportation Officials design manual (AASHTO, 2001). These specifications are shown in Table 7.7.

Table 7.7: AASHTO specifications for roadway design

Functional class	Travel way width (ft)	Shoulders width (ft)	Parking width (ft)	Total width (ft)	Note
Freeway	48	28	0	76	Two lanes in each direction
Urban Arterial	23	12	0	35	One lane in each direction
Urban Collectors	22	10	10	42	One lane in each direction and parking
Urban Local	22	4	11	37	One lane in each direction, parking

(Source: AASHTO 2001)

Herbert et al. (1984) estimated the construction energy of different roadways following AASHTO specifications and using a pavement life-cycle assessment tool, PaLATE. The result of this estimation is shown in Table 7.8.

Table 7.8: PaLATE roadway construction energy factors

Road type	Energy (MJ/mile)	Energy (TJ/KM)
Freeway	19,297,459	11.99
Urban Arterial	12,528,103	7.79
Urban Collector	10,977,135	6.82
Urban Local	9,277,977	5.77

(Source: Herbert et al. 1984)

Roadway Usages: In this study, an analysis was conducted to estimate the percent usages of different classes of roads by automobiles commuting to downtown Ottawa from different urban and suburban region based on fastest road. The result is shown in Table 7.9.

Table 7.9: Roadway usages by commuters (Based on fastest route)

Travel from	Local		Arterial		Expressway		Total	Time
	(km)	(%)	(km)	(%)	(km)	(%)	(km)	(min.)
Barrhaven	5	22.12%	87	38.50%	8.9	39.38%	22.6	29
Riverside S	6.1	23.55%	19.8	76.45%	-	0.00%	25.9	31
Nepean	3.2	20.65%	3.4	21.94%	8.9	57.42%	15.5	17
Bells Corner	1.0	5.10%	6.1	31.12%	12.5	63.78%	19.6	20
Kanata	0.8	3.07%	3.9	11.88%	22.2	85.06%	26.1	19
Greenboro	2.55	15.09%	6.65	39.35%	7.7	45.56%	16.9	18
Gloucester	1.1	12.36%	2.7	30.34%	5.1	57.30%	8.9	9
Orleans	1.5	8.15%	2.7	14.67%	14.2	77.17%	18.4	16
Hull	0.6	9.09%	3	45.45%	3	45.45%	6.6	11
Gatineau	1.7	17.00%	3.5	35.00%	4.8	48.00%	10	13
Average		13.62%		34.47%		51.91%		

It can be seen from the above table that commuters travel through the expressway to get into downtown on average 51.91% of their total trip lengths. The length of their travel through arterials is 34.47 % and through local and collector 13.62% of their total trip length. The impact of road construction energy on vehicle energy use was calculated on the basis of these percentages of road usages.

Annual roadway usages

Expressway: The Highway 417 (Queensway) is the major controlled-access freeway running from Kanata in the west to Orléans in the east and passe through the downtown business core of the City of Ottawa. It is the primary east-west transportation artery in the Ottawa-Gatineau area. The section of Highway 417 that carries most of the commuter traffic is from west of Highway 416 to Anderson Road in the east. The AADT significantly varies through out the section of this highway. The AADT's for three horizon years on the Highway 417 mainline is shown in Fig 7.2.

Figure 7.2: Highway 417 current and projected AADT (Source: MTO, 2009)

It can be seen from the above figure that the AADT substantially varies throughout the section of the highway. The portion of this highway has mostly 3 lanes in each direction. The Average AADT for this section was calculated as 120,000. Therefore the annual usage can be calculated as $=120,000 \times 365/6 = 7,300,000$ PCU/lane-km

Arterial Road: Figure 7.3 shows the average volume of traffic on the major roads in different municipalities of Ontario. It shows the number of times (in thousands) that a vehicle travels over each lane kilometer of road. Ottawa is near the median, which is 1,485,000 pcu/lane-km/year. The large rural component of Ottawa's geography has an impact on the result as it contributes to an increased number of lane kilometers.

Figure 7.3: Vehicle-km traveled per lane km in different major roads of municipalities of Ontario in 2005 (Source: City of Ottawa, 2009)

Collector and Local road: It was assumed that an arterial road has four (2 intersections /km in each direction) intersections per km with collector roads and collector road has six (3 intersections/km in each direction) intersections with local roads. Based on this

assumption, the average volume of traffic on the collector would be 25% of arterial road, which is 371,250 pcu/lane-km/year and the average volume of traffic on the collector would be 16.67% of collector roads, which is 61,875 pcu/lane-km/year. It was also assumed that a typical commuter would travel on express way 51.91%, on arterials 34.47% and on local and collector 13.62% of her/his trip length. The share of trips on collector and local roads would be equal.

On the basis of the above assumptions, the impact of road construction energy per vehicle life can be calculated by the following equation:

Impact of road way construction energy per vehicle life:

$$\begin{aligned}
& 0.519 * \frac{\text{Freeway - construction - energy}}{\text{Freeway - life}} \times \frac{\text{Lifetime - VKT}_{\text{vehicle}}}{\text{Annual - Freeway - usage}} \\
& + 0.345 * \frac{\text{Arterial - construction - energy}}{\text{Arterail - life}} \times \frac{\text{Lifetime - VKT}_{\text{vehicle}}}{\text{Annual - Arterial - usage}} \\
& + 0.068 * \frac{\text{Collector - road - construction - energy}}{\text{Collector - road - life}} \times \frac{\text{Lifetime - VKT}_{\text{vehicle}}}{\text{Annual - collector - road - usage}} \\
& + 0.068 * \frac{\text{Local - road - construction - energy}}{\text{Local - road - life}} \times \frac{\text{Lifetime - VKT}_{\text{vehicle}}}{\text{Annual - Local - road - usage}} \dots\dots 7.1 \\
& = 0.519 * \frac{11.99}{20} \times \frac{258,000}{7,300,000} + 0.345 * \frac{7.79}{20} \times \frac{258000}{1485000} + 0.068 * \frac{6.82}{20} \times \frac{258000}{371,250} \\
& + 0.068 * \frac{5.77}{20} \times \frac{258000}{61,875} \\
& = 0.011 + 0.0234 + 0.0161 + 0.0818 = 0.13328 \text{ TJ} = 132.30 \text{ GJ/per car life}
\end{aligned}$$

7.6.2 Road maintenance energy

Figure 7.4 shows the maintenance cost per lane kilometer paved roads in different

municipalities in Ontario. Maintenance cost includes surface maintenance, such as sealing cracks or patching sections. They do not include costs for major repairs, winter maintenance, streetlights, and street cleaning. Ottawa's road maintenance cost is a bit lower than the median. It is \$1,211 per lane-km. Using EIOLCA software (Sector #230330: Maintenance and Repair of Highways, Streets, Bridges) the annual maintenance energy was estimated as 0.009 TJ /Lane-km

Figure 7.4: 2005 - Maintenance cost per lane-km in different municipalities of Ontario (Source: OMBI, 2009)

The impact of road maintenance energy per vehicle life =

$$\left(\frac{0.519}{7300000} + \frac{0.345}{1485000} + \frac{0.068}{371250} + \frac{0.068}{61875} \right) \times 0.009 \times 258000 = 0.003681 \text{ TJ} = 3.681 \text{ GJ}$$

7.6.3 Winter maintenance energy

Figure 7.5 shows the cost of winter road maintenance in different municipalities of Ontario. Winter maintenance costs include snow plowing, snow removal, ice control, combination plowing/salting/sanding, snow fencing, spring clean-up, winter drainage, winter patrol, winter standby and administration. Ottawa's winter maintenance costs of

roads are \$4,224 per lane km, which is above the median. Ottawa's is located in a zone of severe winter weather conditions. Snow removal forms a significant portion of the cost in Ottawa. Using EIOLCA tool, the annual winter maintenance energy consumption was found to be 38 GJ/ lane-km.

Figure 7.5: 2005-Winter maintenance cost per lane km in different municipalities of Ontario. (Source: OMBI, 2009)

The impact of road winter maintenance energy per vehicle life =

$$\left(\frac{0.519}{7300000} + \frac{0.345}{1485000} + \frac{0.068}{371250} + \frac{0.068}{61875} \right) \times 0.038 \times 258000 = 0.015545 \text{ TJ} = 15.54 \text{ GJ}$$

7.6.4 Parking

Parking is the termination of a trip. Parking can be provided on-street or off-street. Adjacent land use may create a demand for on-street parking along an urban street. However, on-street parking reduces capacity, impedes traffic flow and increases the crash potential. Off-street parking plays an important role in the efficiency of the overall transportation system. Off street parking can be provided in surface parking lot or in parking garage. In this study the construction energy for parking facilities for the

commuters were evaluated. The parking for the commuters is usually provided by surface parking lot or parking garage. Therefore on street parking is not considered. Moreover, construction energy for on street parking lane was implicitly considered in the road construction energy estimates.

Surface parking lot: Typically, surface parking lots consist of asphalt pavement. The hot mix asphalt surface course is placed on the asphalt concrete base course. An asphalt concrete base course is constructed on a prepared subgrade over the entire area that will become parking areas. The subgrade must be properly shaped to meet true lines and elevations. All vegetation rocks, debris, and topsoil should be removed from the area to be paved. The construction process of the asphalt paved surface parking lot follows the same procedure as for asphalt road construction. The only difference is the pavement structural layer thickness. Cooper (1982) conducted a study to estimate indirect energy consumption for constructing a surface parking lot with 500 car capacity. The study estimated a total of 2.07 Giga Btu or 2183.85GJ energy consumptions for constructing a 500 car capacity parking lot. This study finding was considered in this analysis to estimate the impact of parking lot construction energy on automobile lifecycle energy use. If the service life of a parking lot is assumed as 20 years, the following energy estimate can be obtained.

$$\text{Construction energy per parking space} = 2183.85\text{GJ}/500 = 4.36 \text{ GJ}$$

$$\text{The impact of parking lot construction energy per car life} = 4.36*(10/20) = 2.18 \text{ GJ}$$

Parking garage: Parking is always a crucial problem in the city centre especially in the downtown. When the available space for the surface lot is limited, a parking garage can provide an effective solution to accommodate a large number of vehicles. Parking garage

is a multi-storied building designed specifically for automobile parking and generally constructed by concrete or steel structure. The design loads for car parking are often less than the office building (50 psf versus 80 psf), leading to long floor spans of 55-60 feet that permit cars to park in rows without supporting columns in between. The parking garage construction energy was estimated on the basis of average costing for a typical parking garage. Table 7.10 shows the construction cost of a 5 storied parking garage.

Location	: US
Stories	: 5
Story height	: 10.00
Floor area (S.F.)	: 145000
Basement included	: No
Data release	: Year 2008
Cost per sq ft	: \$54.78
Building cost	: \$7,942,530

Table 7.10: Construction cost of a 5 storied parking garage

Square foot cost estimate	% of Total	Cost per SF	Cost
Total		\$41.81	\$6,063,000
Contractor Fees (GC, Overhead, Profit)	25%	\$10.45	\$1,515,750
Architectural Fees	6%	\$2.51	\$363,780
Total Building Cost		\$54.78	\$7,942,530

(Source: Reed Construction Data, 2006)

On the basis of this cost, the construction energy for the parking garage was estimated using EIO LCA tool (Sector #230220: Commercial and Institutional Buildings). It was assumed that one car requires about 100 sq ft of parking space and the service life of a parking garage is 30 years. The estimated construction energy is reported below:

$$\text{Construction energy for the parking garage} = 47.9 \text{ TJ}$$

$$\text{Construction energy per space} = 47900 \text{ GJ} / 1450 = 33.03 \text{ GJ}$$

$$\text{Construction energy per-car life} = 33.03 * (10/30) = 11.01 \text{ GJ}$$

7.7 Summary of direct and indirect energy consumption

Table 7.11 shows the summary of automobile lifecycle energy consumption.

Table 7.11 Summary of automobile lifecycle energy consumption

Item	Energy consumption		
	Per car life	Per VKT	Per PKT*
	GJ	KJ	KJ
Vehicle manufacturing	91.55	354.84	253.46
Vehicle maintenance	33	127.91	91.36
Tier replacement	12	46.51	33.22
Vehicle operation	558.02	2162.87	1544.91
Gasoline production	138.09	535.23	382.31
vehicle insurance	13	50.39	35.99
Roadway construction	133.28	516.59	368.99
Roadway maintenance	3.68	14.26	10.19
Roadway winter maintenance	15.54	60.23	43.02
Parking lot construction Surface: 4.36 GJ; Garage: 11.01 GJ	11.01	42.67	30.48
Total	1009.17	3911.51	2793.94

*Based on load factor of 1.4

Figure 7.6: Life cycle energy consumption for an automobile

It can be seen in Table 7.11 and Figure 7.6 that the vehicle operation accounts for the largest share of automobile life cycle energy consumption. The second largest share of energy consumption stands for gasoline fuel production. The impact of roadway construction energy is also significant. The life cycle energy consumption of a

automobile is 1009.17 GJ. If the load factor for an automobile is considered as 1.4, the energy intensity per passenger-km amounts to 2793.94 KJ.

Figure 7.7: Direct and indirect energy consumption of an automobile

Figure 7.7 shows the direct and indirect energy consumption of an automobile. It is evident that indirect energy constitutes a significant part of total life cycle energy consumption of an automobile.

7.8 Comparison of direct and indirect energy consumption of BRT, LRT and automobile

Figure 7.8 compares the direct and indirect lifecycle energy consumption of 4 types of vehicles. It can be seen that while direct energy consumption for automobile constitutes

Figure 7.8: Direct and Indirect energy consumption of BRT, LRT and automobile

a major part of the life cycle energy for automobile (55.3%), indirect energy is the major part of the life cycle energy for other types of vehicle. The consideration of indirect energy is therefore very important in transportation energy analysis.

7.9 Comparison of energy intensity of BRT, LRT and automobile

Table 7.12 summarizes the energy intensity (vehicle and infrastructure) of different types of vehicles.

Table 7.12: Energy intensity (vehicle and infrastructure) for different types of vehicle

Energy	Standard hybrid bus		Articulated hybrid bus		Light rail vehicle		automobile	
	(TJ)/ bus-life	KJ/VKT	(TJ)/ bus-life	KJ/VKT	(TJ)/ car-life	KJ/VKT	(GJ)/ car-life	KJ/VKT
Direct energy	11.72	12096.53	14.66	15130.99	56.35	20771.6	558.02	2162.87
Indirect energy	25.25	26056.1	28.09	28987.3	107.15	39497.35	451.15	1748.64
Total	36.97	38152.59	42.75	44118.29	163.5	60268.94	1009.17	3911.51

Considering average load factor for automobile as 1.4, for standard hybrid bus 13, for articulated hybrid bus 20 and light rail vehicle 38, the following energy intensity/passenger-km was obtained (Table 7.13). It can be seen that energy intensity for standard hybrid bus and automobile is nearly same. The energy intensity for LRV is the lowest and energy intensity for hybrid bus falls in between.

Table 7.13: Energy intensity (KJ per passenger-km)*

Energy	Standard hybrid bus	Art. hybrid bus	Light rail vehicle	Automobile
Direct energy	930.5	756.55	546.62	1544.90
Indirect energy	2004.3	1449.37	1039.40	1249.03
Total	2934.8	2205.91	1586.02	2793.93

*Load factor: Standard hybrid bus =13; Articulated hybrid bus =20 and Light rail vehicle =38; Automobile =1.4

Figure 7.9: Comparison of energy intensity of bus, LRV and automobile

As the passenger load highly varies with time, it is some time reasonable to compare energy intensity of various transportation modes on the basis per seat-km. Table 7.14 compares the energy intensity per seat-km for four types of vehicles. There is a noticeable difference from Table 7.13. The energy intensity for automobile and standard bus nearly same and the energy intensity for articulated hybrid bus is the lowest. Figure 7.10 compares the energy intensity of these four types of vehicle.

Table 7.14: Energy intensity (KJ per seat-km)

Energy	Standard hybrid bus	Articulated hybrid bus	Light rail vehicle	Automobile
Direct energy	310.2	280.20	296.7	540.72
Indirect energy	668.1	536.80	564.24	437.16
Total	978.3	817.01	860.94	977.88

Figure 7.10: Comparison of energy intensity of vehicles per seat-km

Table 7.15: Energy intensity per passenger-km at design capacity

Energy	Standard hybrid bus	Articulated hybrid bus	Light rail vehicle	Automobile
Direct energy	268.8	216.157	153.9	540.72
Indirect energy	579.0	414.104	292.57	437.16
Total	847.8	630.261	446.47	977.88

Figure 7.11: Comparison of energy intensity of bus, LRV and automobile at design capacity passenger load

It can be seen from the above tables and figures that energy intensity for a particular vehicle substantially varies with passenger load. In general, the energy intensity of automobile is the highest among four types of vehicle. The energy intensity of standard hybrid bus is a bit lower than automobile. The energy intensity of light rail vehicle is the lowest.

Chapter 8

Conclusions and Recommendations

Energy is a key sustainability issue for both the transportation industry and our planet. Moving people and freight in an environmentally sustainable manner will be one of the biggest challenges for the 21st Century. Transportation energy consumption and environmental health are interrelated issues. The transportation energy consumption is associated with greenhouse gas (GHG) emissions, air, water and noise pollution. If vehicle fuel economy were doubled, for example, transportation emissions would be essentially cut in half. If petroleum consumption were cut in half, reserves would be effectively doubled. The key to the sustainability concept is therefore reduction of energy use.

In the transportation sector, automobile alone consumes the major share of energy. So the most fundamental thing for energy conservation is to place emphasis on reducing the role of the private automobile as the prime mode of transportation and shifting travel toward other sustainable modes such as public transit. In recent years Bus Rapid Transit (BRT) has emerged as a competitor of Light rail Transit (LRT). Promoters of BRT claim that it can provide all the benefits of LRT and it is cheaper. On the other hand promoters of LRT claim that LRT is safer, energy efficient and environment friendly. Choosing between Light Rail Transit (LRT) and Bus Rapid Transit (BRT) systems is often controversial and not an easy task for transportation planners who are contemplating the upgrade of their public transportation services. Moreover transportation systems are usually analyzed based on economic, social and environmental criteria. Transportation

energy consumption is not given due importance. Now with the pressure of increasing transportation energy consumption, the uncertainty of future supply of energy and the growing concern about the environmental protection, attempts are being made to include energy in transportation planning and policy. Transportation energy, however, is being analyzed on the basis of direct energy consumption alone. But in order to evaluate transportation system in its proper energy context, both direct and indirect energy consumption need to be considered. This research was aimed at developing a method to assist transportation planners and decision makers in comparing the direct and indirect energy consumption characteristics of LRT and BRT in a real world situation.

The purpose of this research was two-fold. Firstly, it demonstrated a systematic energy analysis method for both direct and indirect energy, which can be applied to any transportation system. Secondly, it attempted to evaluate the BRT and LRT systems in an identical context in order to resolve the controversy of which mode is really more energy efficient. For reference purposes, this study also evaluated the direct and indirect energy requirements for an automobile.

In order to achieve the goal, the research investigated contemporary energy analysis techniques for transportation system and established energy intensities for various elements of BRT and LRT. This research also examined the factors affecting energy consumption. Finally the research conducted a comprehensive life-cycle assessment (LCA) for energy requirements for both vehicles and infrastructures of LRT and BRT systems for a transit corridor in Ottawa. In addition, this research also conducted a lifecycle energy assessment for an automobile commuting to downtown Ottawa. The

objectives set up in chapter one were fully met. The major conclusions of the research are described below.

Conclusions

LCA analysis technique

The key to an energy analysis is the Life Cycle Assessment (LCA). The LCA analysis requires detailed input-output information for every stage of a transportation system element's life. Within the framework of cradle-to-grave analyses of LCA, the main step is the preparation of a life cycle inventory (LCI) and setting the system boundary. The selection of an appropriate system boundary is critical in any LCA. The system boundary in this analysis includes all the important components of BRT and LRT. It was not possible, however, to include all possible components such as energy used in offices where vehicles are designed and disposal of vehicles at the end of service life. Components with the largest expected contributions to total energy consumption were mostly considered. In this thesis a combination of process based and input-output analysis were employed. In process based analysis, tracing the energy requirements in each step of the production process all way back to the original production of primary materials is not an easy task and sometimes practically impossible. Defining the boundary of the analysis i.e., what should be included and what should be excluded or ignored, is a real difficulty. Therefore, in some cases the energy consumption in producing a good or service was traced back one or two steps. Then the various input materials and services were identified and the remaining energy inputs to the entire process were determined using input-output analysis.

The “Economic Input–Output based LCA” (EIO-LCA) model, developed by researchers of Carnegie Mellon University was used in this analysis. Economic input-output (EIO) analysis estimates the energy requirements from activities in the economy on the basis of dollar value of the output. The basic problem with using the input-output analysis is that it provides aggregate view of a sector. The energy requirements of a particular process cannot be obtained. The advantage of the input-output analysis is that it does not need to draw any boundary and thus covers the entire economy, including all the material and energy inputs. The use of the input-output analysis without discrimination or judgment, however, could lead to large errors or anomalies in the estimation of total energy. This method is very helpful in getting quick energy estimates when the life cycle inventory is difficult to produce or not available. The only information required is the dollar value of the output. As the input-output analysis divides the entire economy into certain distinct sectors, it is often difficult to find the appropriate representative sector for a life cycle process.

Direct and indirect energy

Energy consumption of a transportation system can be divided in two parts; direct energy consumption and indirect energy consumption. Direct energy is the energy required to propel the vehicle and indirect energy is all the remaining energy needed to produce direct energy, construct, operate, and maintain the infrastructure and manufacture and maintain the vehicles. Direct energy consumption substantially varies with characteristics of vehicle as well as facilities. Vehicle related variables include such features as engine size, fuel type, weight, speed and cold or hot starts, engine tune, tire type and pressure

and aerodynamics, etc. Facility related variables affecting energy consumption include grade, pavements type, texture, roadway curvature, etc. Indirect energy consumption enormously varies with type of infrastructure. In order to calculate indirect energy to construct, operate and maintain the facilities and to manufacture and maintain the vehicles, various factors are required to consider. To collect the required data for indirect energy calculation is a big challenge. Moreover, there are wide disparities about energy intensities among available sources. Therefore, it is often prudent to use the same source of information in evaluating different mode of transports. Direct energy can be estimated with reasonable accuracy but indirect energy estimates are highly uncertain. Therefore careful observations and judgments are required.

Elements of transportation for energy analysis

Each mode of transportation requires some basic components to move people and goods. These can be divided broadly into two parts; infrastructure and vehicles. Infrastructure consists of a network of fixed installations such as roads, railways, stations, refueling depots, etc. Vehicles traveling on these networks include vehicles of appropriate types such as automobiles, buses, trucks and trains, etc. The energy consumption of modes of transport differ with each other due to their infrastructure requirements, vehicle performance and way of operation. Therefore, it is sometimes difficult to set the boundary as to which elements should be considered in the analysis. The most logical way to deal with this matter is to consider only the basic elements that are necessary for the provision of transport facilities and that have a significant impact on energy consumption. In this research the various elements of BRT and LRT were first identified

and their energy intensities were determined. Finally, the elements that had significant impact on energy were considered in the analysis.

Transit bus life cycle energy

While bus manufacturing energy for a standard bus accounts for 8% of total life cycle energy, the manufacturing energy for a standard hybrid bus is 16% of total life cycle energy (Table 6.2). Production of battery for hybrid bus consumes substantial energy. Bus manufacturing energy estimation is complex. There are wide variations among reported energy intensities of bus manufacturing in the literature. This variation might be due to the energy analysis approach and underlying assumptions. The EIOLCA approach gives an approximate energy intensity based on dollar value of the product. In order to get an accurate assessment, an intensive process based analysis is required.

Bus operation has the biggest share of vehicle life cycle energy. While operating energy for a standard bus accounts for 71% of vehicle life cycle energy, the operating energy for standard hybrid bus is 62% of vehicle life cycle energy. The operating energy of an articulated bus is 20% more than standard bus.

Bus operating energy can be estimated accurately using micro simulation model. In this research fuel consumption rate for a standard bus was determined using micro-simulation model VISSIM. The average fuel consumption for a standard bus was found to be 2.08km/liter. The accuracy of the micro-simulation model depends on how precisely the model represents the real operation. A large number of inputs are required to make the

model represents the real world. The more the model can replicate the real world operation, the more accurate the result would be.

Fuel production energy consumption is the next energy intensive process after vehicle operating energy. Fuel production energy consumption varies in the range of 13% to 15% of the total life cycle energy consumption, depending on type of buses.

REET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model can effectively be used to estimate fuel life cycle energy consumption. In this research the WTP (Well to Pump) analysis was conducted for both conventional diesel and Low sulfur Diesel (LSD). It was found that 0.202 Mega Btu of energy is required to produce 1 Mega Btu of conventional diesel. For Low Sulfur Diesel (LSD), the production energy was found to be 0.216 Mega Btu/Mega Btu of LSD. Therefore, the energy conversion factor for conventional diesel fuel production is 0.20 and the same for Low Sulfur Diesel fuel is 0.21.

Direct and indirect energy consumption significantly varies with types of buses. While direct energy consumption is 71% for a standard bus, indirect energy is only 29%. But for an articulated bus, while direct energy consumption is 59%, the indirect energy is 41%. Therefore it is important to consider both direct and indirect energy in understanding the energy characteristics of vehicle technologies.

Total life cycle energy for a standard hybrid bus is approximately 16% less than for a standard bus. The same is also true for articulated hybrid bus. The total life cycle energy

of an articulated hybrid bus is approximately 15% less than articulated diesel bus. So introducing more hybrid buses will significantly reduce the energy consumption.

Light rail vehicle life cycle energy

Light rail vehicle manufacturing energy constitutes a relatively small part (5%) of the total life cycle energy consumption. Light rail vehicle maintenance consumes 10% of total life cycle energy. The biggest share is the vehicle operating energy consumption, which is 51% (Table 6.3). The most remarkable item is the energy consumption to generate electricity for light rail vehicle operation. The electricity generation energy accounts for 33% of the lifecycle energy consumption.

The GREET model can effectively be used in order to estimate electricity generation energy. In this research electricity generation energy was estimated using the GREET model. One of the key factors in estimating electricity generation energy is the electricity generation mix. Ontario's electricity generation mix was used in this research. It was found that to produce 1 Mega Btu of electricity available at user site, 640,479 Btu of energy is consumed. The energy conversion factor for Ontario electricity generation mix is 0.64.

For light rail vehicle, the direct and indirect energy consumption are nearly equally important. While direct energy consumption for light rail vehicle is 51%, indirect energy constitutes 49% of total life cycle energy. Therefore without the consideration of indirect energy for light rail vehicle, the energy intensity value cannot be compared with other modes of transport.

BRT and LRT vehicle life cycle energy

The total life cycle energy (15 years life) for various buses was estimated in this research. The estimated total life cycle energy is as follows: standard bus 22.61 TJ, standard hybrid bus 18.98TJ, articulated bus 29.19 TJ and hybrid articulated bus 24.76 TJ. The total life cycle energy (30 years life) for light rail vehicle was estimated as 110.14 TJ. For a 30 years horizon, to carry same design passenger volume as the light rail, the total life cycle energy would be 135.66 TJ for standard bus, 113.88TJ for standard hybrid bus, 112.59TJ for articulated bus and 95.50 TJ for hybrid articulated bus. It can be deduced that if the passenger volume is high enough to justify operating articulated hybrid bus, the total life cycle energy consumption of BRT vehicle would be less than the light rail vehicle. If the infrastructure component were included, the scenario might be different.

BRT infrastructure

Among the various infrastructure components of BRT, busway, stations and maintenance yard were found to be the most important components that have significant impact on energy consumption.

Busway construction and maintenance energy varies much with the types i.e., busway at grade, aerial or in tunnel. Tunnel construction consumes the highest energy. There are wide differences among busway construction energy intensity reported in the literature. The variation might be due to the structural design and the assumption made in the analysis. In this research, a process based analysis was made based on a typical cross-section of a busway. The analysis provides a systematic energy analysis procedure which

can be adopted for any other type of cross section. The construction energy for at grade busway was calculated as 33.69 TJ/km (2-lane) (Table 6.4).

BRT stations range from enhanced shelters to large complex facilities with extensive amenities and features. The wide range of station types and features influences both performance and energy consumption. As the energy estimation for stations is highly dependent on specific site condition and functional elements, the construction energy was estimated based on cost of construction.

LRT infrastructure

Among the various infrastructure components of LRT, trackways, stations, power substation, power distribution system and maintenance yard were found to be the most important components that have significant impact on energy consumption.

LRT trackways can be constructed on the ground surface, below the surface in an open cut or in a subway, or above the surface on an embankment or on aerial structure. The energy consumption for trackway construction immensely varies with types. There is very little information regarding the track construction energy consumption in the literature. In this research, a process based energy analysis was conducted for a typical at grade trackway construction. The construction energy consumption was calculated as 29.33 TJ/ track- km (Double track) (Table 6.6).

BRT and LRT system comparison (with tunnel)

The BRT and LRT total system energy consumption for a 30-year life cycle period was

estimated. By considering a 2.5 km tunnel section in the corridor, it was found that BRT system consumes nearly 2% more energy than LRT system. It can be inferred that for a long time planning horizon, BRT could be more energy intensive than LRT. It should be noted that the BRT tunnel has a larger cross-section area than that of the corresponding LRT tunnel due to differences in technologies and way of operation.

Energy consumption per unit output

Transportation energy intensity is a measure of the energy consumed per passenger kilometer traveled. When a vehicle is lightly loaded, energy intensity goes up because the vehicle consumes nearly the same amount of energy, regardless of the number of occupants. Therefore energy consumption per passenger kilometer largely depends on load factor. In this analysis, a load factor of 0.28 was considered to compare the energy intensities of different transit vehicles. With this load factor, the number of passengers in a hybrid standard bus would be 13, in a hybrid articulated bus 20 and in a light rail car 38. On the basis of these assumptions and the consideration of both the vehicle and infrastructure life cycle energy, the energy intensity for a hybrid standard bus was found to be the highest among the three types of vehicles, which was 2934.81 KJ/Passenger-km. The light rail vehicle consumed the least amount of energy, which is 1586.02 KJ/Passenger-km. The energy intensity for the hybrid articulated bus was found to be 2205.91 KJ/Passenger-km. Therefore it could be deduced that if the passenger volume is high, light rail vehicle could be the most attractive option from the energy consumption point of view.

BRT and LRT system comparison (without Tunnel)

The transit corridor considered in this research includes a 2.5 km tunnel section under the Ottawa downtown. It was found that tunnel construction has a large impact on total energy analysis. Tunnel construction may not be necessary in some other places. Therefore, an analysis was conducted assuming that there would be no tunnel in the corridor. It was found that while BRT system consumes 13396.13TJ (Table 6.14) of energy for 30 years life cycle, LRT system consumes 15043.33 TJ of energy (Table 6.15). This indicates that LRT system is 12% more energy intensive than BRT. In the previous analysis, where tunnel was considered, it was found that LRT system is approximately 2% less energy intensive than BRT. It is really difficult to say which mode would be more energy intensive without conducting detailed analysis. But it is clear that the total energy consumption of both BRT and LRT system is close to each other.

Comparison of energy intensity of BRT, LRT and automobile

On the basis of the average load factor for automobile as 1.4, for standard hybrid bus 13, for articulated hybrid bus 20 and light rail vehicle 38, it was found that the energy intensity for standard hybrid bus is the highest. The energy intensity for light rail vehicle is the lowest and energy intensity for articulated hybrid bus falls in between. Since passenger volumes vary highly with time, it is sometimes reasonable to compare energy intensity among various transportation modes on the basis of per seat-km. The energy intensity per seat-km for four types of vehicles was found to be different than the above estimates. The energy intensity for standard hybrid bus and automobile is nearly same and the energy intensity for articulated hybrid bus is found to be the lowest. The energy intensity for light rail vehicle falls in between.

Limitation of the research

Lifecycle analysis is a cradle to grave analysis for a product or service. Hundreds of processes are sometimes involved during the life cycle of an element of transportation system. The analysis could not cover all the stages of life cycle of the elements of transportation systems analyzed.

In order to conduct a life cycle analysis, the preparation of life cycle inventory is the key. Due to limitation of data availability, several assumptions were made in this research, which may hinder the credibility of the result.

The scope of this research was very extensive. Within the scope, it was not possible to conduct in depth life cycle assessment for every element of the transportation systems.

There are wide disparities about energy intensities of different materials and processes of transportation systems reported in the literature. The reliability of those results could not be judged by mere observation. Use of these results might lead to erroneous conclusion.

Using different software, analysis technique and sources of information sometimes leads to contradictory results. It is better to conduct LCA with the same analytical procedure, sources or software. No software or analytical technique, however, covers all the aspects of a transportation system. This research employed different techniques, sources and software, which may limit the accuracy of the analysis.

The EIOLCA model is based on the USA economy. Energy intensity estimates obtained using EIOLCA model might not be directly applicable to the Canadian context.

In some instances the energy estimation was done based on cost. The cost of different elements of transportation systems is highly dependent on functional and design requirements and geographical location. The variability of cost estimates might influence the energy estimation results.

Recommendation for future work

The energy estimation, specifically indirect energy estimation, has not been given due importance in the research domain. More research needs to be conducted to integrate indirect energy analysis in the transportation planning process.

LRT and BRT are two transit systems providing comparable services from the suburban neighborhood to the CBD, and both utilize similar ROW categories. These two systems are viable options for medium-sized cities that are looking to invest in transit to solve their traffic congestion problems. There are many possible transportation planning and operation scenarios; either the LRT or the BRT could be the optimal urban public transportation mode that satisfies the specific requirements of transit services. This research analyzed BRT and LRT systems from an energy point of view. These two systems could be analyzed for their total environmental burden as well as for level of service and cost.

This research is based on data obtained from literature review and other secondary sources. An extensive energy analysis could be conducted by collecting data from real field observation.

Direct energy estimation could usually be done with good accuracy. Indirect energy estimation, however, is very difficult to conduct, as there is no system in place to observe and monitor the energy and materials balances in different processes. Research could be done for finding a better way to capture the data for indirect energy analysis.

References:

AASHTO, (2001), American Association of State Highway and Transportation Officials design manual,
<https://www.nysdot.gov/portal/page/portal/divisions/engineering/design/dqab/hdm>
Last accessed on July, 2009.

Ally, J., Pryor, T., (2007), Life-Cycle Assessment of Diesel, Natural Gas and Hydrogen Fuel Cell Bus Transportation Systems, Journal of Power Sources, v 170, n 2, p 401-11.

American Public Transportation Association (APTA), (2009), <http://www.apta.com/>;
Last accessed on March, 2009.

Andrei, P., (2001), Real World Heavy-Duty Vehicle Emissions Modeling, Master's Thesis, West Virginia University, Morgantown.

APTA, (2008), U.S. Average New Vehicle Costs for 2007 and 2008 Vehicles by Type
http://www.apta.com/research/stats/documents/table22_vehvosttransitlength.pdf ; Last accessed on May, 2009.

APTA, (2009), Automobile Driving Costs, 2005
<http://www.apta.com/research/stats/fares/drivcost.cfm>; Last accessed on July, 2009.

Applied Research Associates, Inc., (2008), Estimation of The Representative Annualized Capital and Maintenance Costs of Roads by Functional Class, Revised Final Report, Toronto, Ontario.

Argonne National Laboratory (ANL), (2009), The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model,
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html ; Last accessed on March, 2009.

Association of German Transport Undertakings, (2000), Light Rail in Germany.

Barnitt, R., Battelle, K. Chandler, (2006), New York City Transit (NYCT) Hybrid and CNG Transit Buses, Final Evaluation Results, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado.

Berry, G.D., Pasternak, A.D., Rambach, G.D., Smith, J.R.; Schock, R.N., (1996), Hydrogen as a Future Transportation Fuel, Energy, v 21, n 4, 289-303.

Bester, C J, (1984), Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles, Transportation Research Record No. 1000, p. 28-32.

Bladikas, A.K., Papadimitriou, C., (1986), Analysis of Bus Transit's Maintenance Efficiency Using Section 15 Data, Transportation Research Record 1066.

Bonnafous A., Raux C., (2003), Transport Energy and Emissions: Rail, Handbook of Transport and Environment, Oxford: Elsevier. pp. 293-307.

Boorse, Jack W., (2000), This is Light Rail Transit, Conference proceedings, The Eighth National Conference on Light Rail Transit in Dallas, Texas, in November 2000

BP Statistical Historical Data Work Book, (2008),
<http://www.bp.com/subsection.do?categoryId=9023761&contentId=7044545>; Last accessed on June, 2009.

Bradley (MJ) and Associates, (2008), Updated Comparison of Energy Use & CO2 Emissions from Different Transportation Modes, American Bus Association Foundation.

Bruun, Eric, (2005), Bus Rapid Transit and Light Rail Comparing Operating Costs with A Parametric Cost Model, Transportation Research Record, n 1927, p 11-21.

Chester, M., Horvath, A., (2008), Environmental Life-cycle Assessment of Passenger Transportation, Working Paper, Institute of Transportation Studies, University of California, Berkeley.

Clark, Nigel N., Zhen, Feng, Wayne, W. Scott, and Lyons, Donald W., (2007), Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation , Center for Alternative Fuels, Engines & Emissions Dept. of Mechanical & Aerospace Engineering West Virginia University Morgantown, WV 26506; Website URL: (cafee.wvu.edu)

Calgary Transit, (2002), A Review of Bus Rapid Transit, Calgary Transit Planning Division.

Calgary transit, (2009), LRT Technical Data,
http://www.calgarytransit.com/html/technical_information.html Last accessed on May, 2009.

Caltrans, (1983), Energy and Transportation Systems, Office of Transportation Laboratory, Department of transportation, California.

Claffey, P. J., (1971), Running Costs of Motor Vehicles as Affected by Road Design and Traffic. NCHRP, Report 111.

Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC), (2002),
<http://www.cieedac.sfu.ca/CIEEDACweb/index.php?menu=1>; Last accessed on May, 2009

City of Ottawa, (2009a), New Growth Projections for 2006-2031,
http://www.ottawa.ca/residents/statistics/new_growth/projections/index_en.html; Last accessed on May, 2009

City of Ottawa, (2009b), Transportation Master Plan (2008),

http://www.ottawa.ca/city_hall/master_plans/tmp/index_en.html ; Last accessed on May, 2009.

City of Edmonton, (2005), LRT Design Guidelines
http://www.edmonton.ca/transportation/ets/lrt_projects/lrt-route.aspx; Last accessed on February, 2009.

Consumer Guide Automotive, (2009),
<http://consumerguideauto.howstuffworks.com/featured-article-archive-cga.htm>; Last accessed on July, 2009.

Cooper, C. Lawrence, (1982), Indirect Energy Considerations of Park-and-Ride Lots, Transportation Research Record 870, Transportation Research Board, Washington D.C.

Davis Stacy C., Diegel Susan W., (2008), Transportation Energy Data Book: Edition 27, Center for Transportation Analysis, Oak Ridge National Laboratory.

EERE, (2007), Buildings Energy Data Book, Chapter 7, U.S. Department of Energy, Energy Efficiency and Renewable Energy.

Energy Information Administration (EIA), 2005, International Energy Outlook 2005, Office of Integrated Analysis and Forecasting U.S. Department of Energy, Washington, DC 20585;
[http://tonto.eia.doe.gov/FTPROOT/forecasting/0484\(2005\).pdf](http://tonto.eia.doe.gov/FTPROOT/forecasting/0484(2005).pdf); Last accessed on February, 2009.

Environment Canada, (2009), Sulphur in Diesel Fuel Regulations,
<http://www.ec.gc.ca/cleanair-airpur/default.asp?lang=En&n=5B4D506F-1>; Last accessed on March, 2009

Environment Canada, (2009), http://www.ec.gc.ca/cleanair-airpur/Home-WS8C3F7D55-1_En.htm; Last accessed on May, 2009.

Federal Transit Administration (FTA), (1992). Characteristic of Urban Transportation Systems-Final Report.

Federal Transit Administration (FTA), (2009), Creating Better Bus Systems,
http://www.fta.dot.gov/assistance/technology/research_4393.html; Last accessed on May, 2009.

Fels, M. F., (1978), Breakdown of Rapid Rail Energy Costs: A Study of Three Systems, Energy, V3, p 507-522.

Fels, M. F., (1975), Comparative Energy Costs of Urban Transportation Systems, Transportation Research, v 9, n 5, p 297-308.

Florida International University (2001), Florida Transit Information System.

- Frederic R. Ross, (1982), Effect of Pavement Roughness on Vehicle Fuel Consumption, Transportation Research Record 846, pp 1-6.
- Frey, H.C., Roupail, N., Zhai, H., Farias, T.L. and Goncalves, G.A., (2007) "Comparing Real-World Fuel Consumption for Diesel-and Hydrogen-fueled Transit Buses and Implication for Emissions, Transportation Research Part-D, volume 12, pages 281–291.
- Fulton, H, (2000), Fuel Economy Improvement: Policies and Measures to Save Oil and Reduce CO Emissions, COP-6, Hague, Netherlands.
- Gault, Helen and Leach, Colin, (2003), BRT Case Study, Ottawa, Ontario, TCRP report 90, Volume 1.
- Geography of Transport Systems, (2009), Transportation and Energy; <http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html>; Last accessed on May, 2009.
- Government of Alberta, (2009a) Oil Sands Consultations, <http://www.oilsandsconsultations.gov.ab.ca/index.html>; Last accessed on May, 2009.
- Government of Alberta, (2009b), What is Oil Sands, <http://www.energy.gov.ab.ca/OilSands/793.asp>; Last accessed on April, 2009.
- Grava, Sigurd, (2003), Urban Transportation Systems : Choices for Communities, New York, McGraw-Hill, p. 303.
- Gardner, G, Cornwell, P.R and Cracknell, J.A, (1991), “The Performance of Busway Transit in Developing Cities”, Transport and Road Research Laboratory, research Report 329.
- Haidong, L., Baohua, M., Yong, D., Wenzheng, J., Shukun, L., (2007), Train Energy-saving Scheme with Evaluation in Urban Mass Transit Systems, Journal of Transportation Systems Engineering and Information Technology, v 7, n 5, p 68-73.
- Hendrickson, Chris T., Lester B. Lave, Matthews, H. Scott, (2006), Environmental Life Cycle Assessment of Goods and Services : An Input-Output Approach, Resources for the Future, Washington, DC.
- Horvath, A. and Hendrickson, C. (1998), Comparison of Environmental Implications of Asphalt and Steel-Reinforced Pavements, Transportation Research Record 1626, Transportation Research Board, Washington, D.C. page 105-113.
- Hsu, Jinu-jia, (2003), Development of a Medium-Capacity Guideway Transit Planning Guide, A Doctor of Philosophy in Civil Engineering Thesis, Florida International University, Miami, Florida.
- Huang, Y. (1993), Pavement Analysis and Design, Prentice Hall, Englewood Cliffs,

New Jersey 07632.

IBI Group, (1978), Indirect Energy in Transportation, A Report Prepared for the Strategic Studies Branch of Transport Canada.

IEC, (2009), Efficient Electrical Energy Transmission and Distribution, http://www.iec.ch/news_centre/onlinepubs/efficient_transmission/#section1; Last accessed on May, 2009

International Energy Agency (2009), <http://www.iea.org/>; Last accessed on May, 2009.

ISO - International Organization for Standardization, (2009), <http://www.iso.org/iso/home.htm>; Last accessed on May, 2009.

Industry Canada, (2009), <http://www.ic.gc.ca/eic/site/ic1.nsf/eng/home>; Last accessed on June, 2009.

Kendrick, Neil Mc., (2006), Calgary's C-Train - Effective Capital Utilization, Presented at the 2006 Joint International Light Rail Conference, St. Louis, Missouri.

Khan, Ata. M., (1980), Energy Efficiency of Electrified Passenger Railway in the Canadian Context, Journal of Advanced Transportation, Vol.4, No. 3.

Koupal, J., Landman, L., Nam E., Warila, J., Scarbro, C., (2005), MOVES 2004- Energy and Emission Inputs, Draft Report, Office of Transportation and Air Quality, U.S. Environmental Protection Agency.

Laganier R, Lucas J, (1990), The Influence of Pavement Evenness and Macrottexture on Fuel Consumption, The First International Symposium on Surface Characteristics, held June 8-9, 1988 in State College, Pa., Sponsored by the ASTM Committee.

Leroy, W. Demery, Jr., Michael, D. Setty , (2005), Ottawa: Transit Productivity and Bus Rapid Transit, publictransit.us, Special Report No. 8, A web-based publication of www.publictransit.us, Vallejo, CA.

Levinson, Herbert S., (2001), Bus Transit in The 21st Century: Some Perspectives and Prospects, Transportation Research Record, n 1760, p 42-46.

Levinson, Herbert S, Harry E S., Syd, R.E., Dickson, W., (1984), Indirect Transportation Energy, Journal of Transportation Engineering, V 110, n 2, p 159-174.

Levinson, H., Samuel Z., Jennifer C., Scott R., Rodney L. Smith, J. C., and Richard S., (2003), TCRP Report 90, Bus Rapid Transit, Volume 1: Case Studies in Bus Rapid Transit. Washington, D.C.: Transportation Research Board.

Litman, Todd, Burwell, David, (2006), Issues in Sustainable Transportation, International Journal of Global Environmental Issues, v 6, n 4, p 331-347.

Mccormick Rankin Corporation (MRC), (2008), Transportation Infrastructure Requirement Study: Development of a Downtown Transit Solution and Network Implications, City of Ottawa.

MALTESE, (2008), Energy Consumption Criteria
<http://www.ivv-aachen.de/maltese/english/start.htm>; Last accessed on May, 2009.

MTO, (2009), Traffic Operations Report,
<http://www.mto.gov.on.ca/english/engineering/417ea/traffic/summary.shtml>; Last accessed on July, 2009.

Murugesan, A.; Umarani, C.; Subramanian, R.; Nedunchezian, N., (2009), Bio-Diesel as an Alternative Fuel for Diesel Engines-A review, Renewable and Sustainable Energy Reviews, v 13, n 3, p 653-662.

Natural Resources Canada, (2008), Statistics and Analysis,
<http://nrcan.gc.ca/eneene/statstat/index-eng.php>; Last accessed on May, 2009.

Natural Resources Canada, (2009), Transportation Sector – Energy Use Analysis
http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablesanalysis2/tran_00_1_e_4.cfm?attr=0; Last accessed on May, 2009.

Natural Resources Canada, (2009a), Infrastructure – Pipeline and Refineries,
<http://nrcan.gc.ca/eneene/sources/infinf/pipgaz-eng.php>; Last accessed on April, 2009.

Natural Resources Canada, (2009b), Petroleum Products Distribution Networks,
<http://nrcan.gc.ca/eneene/sources/infinf/netres-eng.php>; Last accessed on May, 2009.

Natural Resources Canada, (2009c), Fuel Consumption Calculator,
<http://oee.nrcan.gc.ca/transportation/tools/fuel-trip-calculator/fuel-calculator-input.cfm?attr=16>; Last accessed on July, 2009.

Natural Resource Canada, (1997), Canada's Energy Outlook 1996-2020,
<http://www.nrcan.gc.ca/es/ceo/toc-96E.html>; Last accessed on April, 2009.

Natural Resource Canada, (2009c), Electricity In Canada,
<http://www.theimo.com/imoweb/EmergencyPrep/blackout2003/ElectricityCanada.pdf>;
Last accessed on June, 2009.

NRCan, (2009d), GHGenius-A model for lifecycle assessment of transportation fuels,
<http://www.ghgenius.ca/>; Last accessed on August, 2009.

NCHRP 85, (1981), Energy Involved in Construction Materials and Procedures, Transportation Research Board, National Research Council, Washington, D.C.

Nichols, Jenna; Garrick, Norman; Atkinson-Palombo, Carol, (2009), Framework for Developing Indicators of Sustainability for Transportation Planning, Conference paper, Transportation Research Board 88th Annual Meeting.

OC traspo, (2009),
http://www.octranspo.com/about_OC/Mission_Vision/Mission_Vision_menuE.htm;
Last accessed on June, 2009.

OC Transpo, (2007), Transit Services Annual Performance Report 2007, Ottawa.

Ogden, J.M.; Steinbugler, M.M. Kreutz, T.G., (1999), A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development, Journal of Power Sources, v 79, n 2, 143-68,

Ontario Power Generation (OPG), (2009), <http://www.opg.com/about/>; Last accessed on May, 2009.

Ontario Ministry of Energy and Infrastructure (OMEI), (2009)
<http://www.mei.gov.on.ca.wsd6.korax.net/english/energy/electricity/index.cfm?page=nuclear-electricite-demand>; Last accessed on June, 2009.

Ontario Municipal Benchmarking Initiative (OMBI), (2009),
http://www.ottawa.ca/city_hall/ottawa_performance/ombi/index_en.html;
Last accessed on July, 2009.

Petro-Canada, (2002), Annual Information Form 1999, <http://www.petro-canada.ca/pdfs/investors/aif-99-e.pdf>; Last accessed on May, 2009.

Pisarski, Alan, (2009), The Nexus of Energy, Environment and the Economy: A Win, Win, Win Opportunity, ITE Journal, Vol. 79 No. 1, pp 30-32.

Puchalsky, Christopher M, (2005), Comparison of Emissions from Light Rail Transit and Bus Rapid Transit, Transportation Research Record No. 1927, Transportation Research Board.

Purdy, J.E., Wiegmann, J.D., (1987), Vehicle Maintenance: Cost Relationship and Estimating Methodology, Transportation Research Record 1140.

Reed Construction Data, (2009), Quick Construction Cost Estimate for a Parking Garage, <http://www.reedconstructiondata.com/rsmeans/models/garage/>; Last accessed on July, 2009.

Research and Innovative Technology Administration (RITA), (2004), National Transportation Statistics 2004, The Bureau of Transportation Statistics (BTS),
http://www.bts.gov/publications/national_transportation_statistics/2003/index.html;
Last accessed on January, 2009.

Research and Innovative Technology Administration (RITA), (2009), Bureau of Transportation statistics, Table 4-15: Bus Fuel Consumption and Travel;
http://www.bts.gov/publications/national_transportation_statistics/html/table_04_15.html;
Last accessed on July, 2009.

Richard, Laver, Schneck, D., Skorupski, D., Brady, S., Cham, L., (2007), Useful Life of Transit Buses and Vans, Federal Transit Administration, U.S. Department of Transportation, Washington, DC 20590, <http://www.fta.dot.gov>; Last accessed on May, 2009.

Rodrigue, J.P., Comtois, C., 2008, The Geography of Transport Systems-Transportation and Energy, <http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/ch8c2en.html> Last accessed on May, 2009

Sandberg, (2001), Heavy Truck Modeling for Fuel Consumption. Simulations and Measurements, Linköping University, Sweden.

Sandberg, Ulf, (1990), Road Macro- and Megatexture Influence on Fuel Consumption, ASTM STP 1031 page 460-479.

Schumann, W. John, (1992), Status of North American LRT Systems: 1992 Update, Transportation Research Record No. 1361, Transportation Research Board, Washington D.C. pp 3-13.

Scientific Applications International Corporation (SAIC), (2006), Life Cycle Assessment: Principles and Practice, National Risk Management Research Laboratory, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

SINTEF, (2006), Residual Fuel Oils - Weathering and Behaviour at Sea, Presentation, <http://www.cedre.fr/fr/publication/colloque/vhfo/moldestad.pdf>; Last accessed on May, 2009.

South Yorkshire Passenger Transport Executive, (2004), Comparative Performance Data from French Tramway Systems, Egis Semaly ltd and Faber Maunsell for SYPTE.

Sreedhar, V., (2006), Plug-In Hybrid Electric Vehicles with Full Performance, 2006 IEEE Conference on Electric & Hybrid Vehicles, 18-20 Dec. 2006, Pune, India.

Statistic Canada, (2007), The Supply and Disposition of Refined Petroleum Products in Canada, <http://www.statcan.gc.ca/pub/45-004-x/45-004-x2007005-eng.pdf>; Last accessed on March, 2009.

Stutsman, John M., (2002), Bus Rapid Transit or Light Rail Transit - How to Decide? Los Angeles case study, Transportation Research Record, n 1793, p 55-61.

Stripple, Håkan, (2001), Life Cycle Assessment of Road: A Pilot Study for Inventory Analysis, IVL Swedish Environmental Research Institute Ltd, Gothenburg, Sweden <http://www.ivl.se/download/18.2f3a7b311a7c806443800055078/B1210E.pdf>; Last accessed on December, 2008.

Struckl, W., Stribersky, A., (2006), Life Cycle Analysis of the Energy Consumption of a Rail Vehicle, Workshop of the Allianz pro Schiene, Hotel Sylter Hof, Berlin, September 19, 2006; <http://www.allianz-pro-schiene.de/cms/upload/media/themen/umweltbericht/workshops/20060919/08-Vortrag%20Stribersky-060919.pdf> ; Last accessed on May, 2009.

Sympatic, (2009), The Top 10 Best-Selling cars in Canada for 2007 http://en.autos.sympatico.msn.ca/guides_and_advice/article.aspx?cp-documentid=6198519, Last accessed on July, 2009.

TCRP Report 57, (1999), Track Design Handbook for Light Rail Transit, Transportation Research Board, National Research Council, National Academy Press Washington, D.C. 2000.

TCRP Report 118, (2007), Bus Rapid Transit Practitioner's Guide, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C. 2000.

Taplin, Michael, (1998), The History of Tramways and Evolution of Light Rail <http://www.lrta.org/mrthistory.html>; Last accessed on may, 2009.

Taplin, Michael, (2006), A World of Trams and Urban Transit, <http://www.lrta.org/world/worldind.html>; Last accessed on May, 2009.

Taylor, G.W., Patten, J.D. P., (2006), Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III, Test Report, Centre for Surface Transportation Technology (CSTT), National Research Council of Canada (NRC), Ottawa, Canada.

Taylor, G.W., (2002), Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption, Final Report, Prepared for Action Plan 2000 on Climate Change Concrete Roads Advisory Committee, Government of Canada.

The electricity Forum, (2009), Electricity Production, <http://www.electricityforum.com/electricity-production.html>; Last accessed on May, 2009.

Tolley, R. and Turton, B., (1995) Transport Systems, Policy and Planning: A Geographical Approach, Burnt Mill, Harlow Essex: Longman Scientific & Technical, p. 268.

TRANS, (2009), 2005 O-D Survey in the National Capital Region; www.O-DSurvey.ca Last accessed on July, 2009.

Trans, (2008) Trans Model Redevelopment, Technical report, <http://www.ncr-trans-rcn.ca/index.php?toc=content&ID=213&lang=en>; Last accessed on May, 2009.

United States General Accounting Office, GAO, (2001), “Bus Rapid Transit Shows Promise” <http://www.gao.gov/>; Last accessed on May, 2009.

U.S. Department of Energy (2009), <http://www.energy.gov/energysources/index.htm>;
Last accessed on April, 2009.

U.S. Department of Energy, (1996), Annual Energy Review 1995, Energy Information Administration Report DOE/EIA-0384(95), Washington, D.C.

US Environmental Protection Agency, (2009), Life-Cycle Assessment (LCA)
<http://www.epa.gov/nrmrl/lcaccess/>; Last accessed on June, 2009.

Victoria Transport Policy Institute, <http://www.vtpi.org/> ; Last accessed on May, 2009.

VISSIM 4.10 User Manual, (2005), PTV Planung Transport Verkehr AG, Germany.

Vuchic, Vukan R., (2007), Urban Transit Systems and Technology, John Wiley & Sons Inc. Hoboken, New Jersey.

Vyas, A., Santini, D., and Cuenca, R., (2000), Comparison of Indirect Cost Multipliers for Vehicle Manufacturing, Technical Memorandum, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.

Wang M.Q., (1999), GREET 1.5 - Transportation Fuel-Cycle Model
Volume 1: Methodology, Development, Use, and Results, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

Wang, (2006), Development and Applications of GREET 2.7 -The Transportation Vehicle-Cycle Model, U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, TN 37831-0062.

Whitaker M. B., (2007), Life Cycle Assessment of Transit Systems in the U.S. and India: Implications for a Carbon-Constrained Future, A Doctor of Philosophy in Civil Engineering Thesis, Submitted to the University of Colorado at Denver and Health Sciences Center.

Wilbur Smith & Associates (1981), Metropolitan Toronto Area Transportation Energy Study, Toronto Planning Department.

Wikipedia, (2008), List of United States Light Rail Systems by Ridership
http://en.wikipedia.org/wiki/List_of_United_States_Light_Rail_systems_by_ridership
Last accessed on May, 2009.

Wright, Lloyd, (2007), Bus Rapid Transit Planning Guide, Transportation & Development Policy, 127 W. 26th Street, Suite 1002, New York, NY 10001 USA.

Zaniewski, J.P, and others, (1979), Fuel Consumption Related to Vehicle Type and

Road Conditions. TRB, Transportation Research Record 702, pp. 328-334.

Zniewski, (1982), Effect of Pavement Surface Type on Fuel Consumption, Published in "Vehicle Operating Costs, Fuel Consumption and Pavement Type and Condition Factors" report, FHWA.

Zapata, Pablo and Gambatese, John A. (2005), Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction, Journal of Infrastructure System, Volume 11, Issue 1, pp. 9-20.

Zhai, H., Frey, H.C., Roupail, N.M., (2006), Speed and Facility-Specific Emissions Estimates for Transit Buses Based on Measured Speed Profiles, Proceedings of the Annual Meeting of the Air & Waste Management Association, New Orleans, Paper No. 195.

-----, (2004), Environmental Impacts and Fuel Efficiency of Road Pavements, Industry Report, European Asphalt Pavement Association (EAPA).

-----, The Tyre Encyclopedia, Vol. 3, Michelin, France 2003.

Appendix A-1

Table A-1.1: Cities with BRT systems, as of March 2007

Continent	Country	Cities with BRT systems
Asia	China	Beijing, Hangzhou, Kunming
	India	Pune
	Indonesia	Jakarta (TransJakarta)
	Japan	Nagoya (Yutorito Line)
	South Korea	Seoul
	Taiwan	Taipei
Europe	France	Caen (Twisto), Clermont Ferrand (Léo 2000), Lyon, Nancy (TVR line 1), Nantes (Line 4), Nice (Busway), Paris (RN305 busway, Mobilien, and Val de Marne busway), Rouen (TEOR), Toulouse (RN88)
	Netherlands	Amsterdam (Zuidtangent), Eindhoven, Utrecht
	UK	Bradford (Quality Bus), Crawley (Fastway), Edinburgh (Fastlink), Leeds (Superbus and Elite)
	Germany	Essen (O-Bahn)
Latin America and Caribbean	Brazil	Curitiba (Rede Integrada), Goiânia (METROBUS), Porto Alegre (EPTC), São Paulo (Interligado)
	Chile	Santiago (Transantiago)
	Colombia	Bogotá (TransMilenio), Pereira (Megabus)
	Ecuador	Quito (Trolé, Ecovía, Central Norte), Guayaquil (Metrovía)
	Guatemala	Guatemala City (Transmetro)
	Mexico	León (Optibus SIT), Mexico City (Metrobús)
North America	Canada	Ottawa (Transitway)
	United States	Boston (Silver Line Waterfront), Eugene (EmX), Los Angeles (Orange Line), Miami (South Miami-Dade Busway), Orlando (Lynx Lymmo),
Oceania	Australia	Pittsburgh (Busway) Adelaide (O-Bahn), Brisbane (Busway), Sydney (T-Ways)

(Source: Bus Rapid Transit Planning Guide, 2007)

Table A-1.2: Cities with BRT systems under construction, as of March 2007

Continent	Country	Cities with systems under construction
Africa	Tanzania	Dar es Salaam
Asia	China	Jinan, Xi'an
Europe	France	Evry-Sénart, Douai, Clermont-Ferrand (Line 1 Lohr system)
	Italy	Bologna
Latin America and Caribbean	Colombia	Bucaramanga, Cali, Cartagena, Medellín
	Venezuela	Barquisimeto, Mérida (Trolmérida)
North America	United States	Cleveland
Ocean	Australia	Canberra
	New Zealand	Auckland (Northern Busway)

(Source: Bus Rapid Transit Planning Guide, 2007)

Table A-1.3: Cities with BRT systems in the planning process, as of March 2007

Continent	Country	Cities with systems in the planning process
Africa	South Africa	Cape Town, Johannesburg, Port Elizabeth, Pretoria
	Other Africa	Accra (Ghana), Dakar (Senegal), Lagos (Nigeria)
Asia	China	Chengdu, Chongqing, Guangzhou, Shanghai, Shenyang, Shenzhen, Wuhan, Wuxi
	India	Ahmedabad, Bangalore, Delhi, Indore, Jaipur
	Taiwan	Chiayi, Kaohsiung, Taoyuan, Taichung, Tainan
	Other Asia	Bangkok (Thailand), Colombo (Sri Lanka), Haifa (Israel), Hanoi (Vietnam), Ho Chi Minh (Vietnam), Jerusalem (Israel)
Europe	France	Cannes, Montbéliard, Besançon, Lorient, Amiens, Metz, Nancy (Line 2), Caen (Line 2), Valenciennes/Pays de Condé, Nîmes, Le Havre
	UK	Cambridge, Coventry, Kent Thames-side, Leigh
Latin America and Caribbean	Colombia	Barranquilla, Soacha (Bogotá)
	Mexico	Aguas Calientes, Chihuahua, Guanajuato, Monterrey, Querétaro, Torreón, Zapopan
	Other Latin America and Caribbean	Lima (Peru), Managua (Nicaragua), Fort-de-France (Martinique, France), Posadas (Argentina), Rio de Janeiro (Brazil), San José, (Costa Rica), Tegucigalpa (Honduras)
North America	Canada	Brampton, Calgary, Durham region, Edmonton, Mississauga, St. John, Toronto, Victoria, Winnipeg
	United States	Albany, Atlanta, Baton Rouge, Charlotte, Chicago, Denver, Detroit, El Paso, Fort Collins, Hartford, Houston, Louisville, Milwaukee, Minneapolis and St. Paul, Montgomery County, New York City, Reno, Sacramento, St. Petersburg, Salt Lake City, San Diego, San Francisco, San Jose, Seattle, South Brunswick, Tampa Bay
Ocean	Australia	Melbourne

(Source: Bus Rapid Transit Planning Guide, 2007)

Appendix A-2

Components of BRT:

Levinson et al., (2003), put forward seven principal components of BRT:

1. Runways
2. Stations
3. Vehicles
4. Services
5. Route Structure
6. Fare Collection and
7. Intelligent Transportation Systems.

1. Running way: BRT vehicles may operate on exclusive Busways (Transitways), Arterial bus lanes, Transit signal priority lane, Queue jumps/bypass lanes or Curb extensions. Bus way can be built at grade, grade separated or in tunnel. Busways, especially when off-street and grade-separated are the most effective BRT running way option in terms of operating speed, service reliability and BRT identity. The construction and maintenance energy requirement greatly varies with the type of running way.

2. Stations: BRT stations, ranging from enhanced shelters to large complex facilities with extensive amenities and features. They are conveniently located and integrated into the community they serve. The wide range of station types and features influences both costs performance and energy consumption. The important features include the following:

- Type of running way (busway, arterial bus lane etc.)
- Type of construction (at-grade, elevated, or subway)
- Platform length and height
- Auxiliary features (such as telephones, temperature control, automated passenger information, and security provisions)
- Passenger amenities (such as benches, restrooms, and drinking fountains)

- Need for stairs, escalators, and pedestrian bridges
- Station building type and design

The construction and maintenance energy for a station largely depends on the all above factors.

3. Vehicles: BRT vehicles have important bearing on ridership attraction, system performance, environmental compatibility and energy consumption. Propulsion systems impact revenue, service times, emissions, and operating and maintenance costs. Seating arrangements, floor height, and door configuration impact on dwell time at stations, travel time, and passenger comfort. Physical vehicle size, aisle width and number, width and arrangement of doors influence BRT system capacity. Vehicle fleet selection, provision and operation are complex and depend on legal, operational, institutional, and strategic factors particular to each individual case. In general, the basic characteristics of a vehicle include:

1. Vehicle size
2. Chassis and body configuration
3. Interior design options
4. Fuel and propulsion technology
5. Aesthetic options

Among all the factors, sizes of vehicle and fuel and propulsion technology are the important factors for energy consideration. From a customer perspective, the interior of the bus, color and aesthetic features is more important than the mechanical components propelling the bus. The interior design will directly affect comfort, passenger capacity, security and safety. The sizes of bus, fuel and propulsion technology are briefly described below:

Size of Vehicle: Bus size should be based on BRT passenger capacity and operations requirements. Bus dimensions have become fairly standard with small variations, and most buses can be classified into one of three categories: small buses (around 30 to 35 feet in length) typically used in small communities or as feeders or shuttles; standard

buses (40 to 45 feet), which are the most commonly used buses for transit service; and articulated buses (60 feet and longer), which are used for heavy patronage routes and for BRT service. Double-articulated buses with a length of 80 feet are used in some places (such as Curitiba). Table 1 shows typical bus sizes and capacity.

Table A-2.1: Typical bus sizes and capacity

Length	Width	Floor Height	Number of Door Channels	Number of Seats (including seats in wheelchair tie-down areas)	Maximum Passenger Capacity (seated plus standing)
40 ft (12.2 m)	96-102 in	13-36 in	2-5	35-44	50-60
45 ft (13.8 m)	96-102 in	13-36 in	2-5	35-52	60-70
60 ft (18 m)	96-102 in	13-36 in	4-7	31-65	80-90
80 ft (24 m)	96-102 in	13-36 in	7-9	40-70	110-130

(Source: Grava, 2003)

Propulsion/Fuel Technologies: Propulsion technologies are constantly changing to meet stricter emissions standards as well as provide higher energy efficiency. Diesel buses currently dominate most BRT operations. However, other propulsion technologies are also available and becoming increasingly popular such as natural gas and diesel-electric hybrids. Type of propulsion technology has a large impact on life cycle energy consumption. The following is a list of some of the most common fuel options currently being considered for public transport vehicles:

- Standard diesel
- Clean diesel
- Compressed natural gas (CNG)
- Liquid petroleum gas (LPG)
- Electric trolley-bus
- Bio-diesel
- Ethanol
- Hybrid-electric
- Hydrogen (fuel cell technology).

4. Services: Service frequency is an important attribute for BRT. High-frequency, all-day service means less waiting and no need to consult schedules. The integration of local and express service can reduce long-distance travel times. Service is also greatly influenced by the station spacing. Short station spacing means frequent stop and longer travel time. Longer station spacing reduces travel but passenger may require long walking distance. The underlying goals of service plan are to provide rapid and reliable service, ensure passenger safety and security, and provide a pleasant, comfortable, and convenient ride.

5. Route Structure: BRT uses simple, often color-coded routes. They can be laid out to provide direct, no-transfer rides to multiple destinations.

6. Fare Collection: Fare payment has a large influence on dwell time and speed of service. Fares may be collected in a number of ways, either on or off the vehicle at each transit station. On-board fare collections include exact change of payments, use of proof-of-purchase tickets, and pass scanners. Off-board payment methods include payment booths located at each station, ticket vending machines, and prepayment boarding areas. The use of advanced payment methods such as electronic smart cards increases boarding speed and can contribute to a considerable decrease in dwell time.

7. Intelligent Transportation Systems: BRT uses advanced digital technologies that improve customer convenience, speed, reliability, and operations safety. A cornerstone of a modern control system is automated vehicle location (AVL) technology which allows the tracking of the vehicles along the corridor.

In addition to the above 7 components, BRT also needs some other components which are necessary for efficient operation. These includes transfer stations, terminals, depots, control center and park and ride facilities.

Appendix A-3

Table A-3.1: "Orion" small bus manufacturing energy

Material	Weight (Lbs.)	Value (1974 \$)	Energy Intensity (Btu's)/ Unit	Total Energy Requirement (Btu's X10 ³)
Rolled Steel	10,321	1,135	15,600/lb.	161,008
Steel Ingots	3,461	305	11,900/lb.	41,186
Pig Iron	927	45	6,000/lb.	5,562
Aluminum Ingots	539	183	55,900/lb.	30,130
Other Non-Ferrous Ingots	685	473	40,800/lb.	27,948
Glass	997	598	47,400/lb.	47,258
Plastic Resins	75	35	47,300/lb.	3,548
Rubber	830	241	17,500/lb.	14,525
Tires	330	182	34,600/lb.	11,418
Plywood	580	116	4,600/lb.	2,668
Arborite	257	324	87,500/lb.	22,488
Paint	50	28	35,000/lb.	1,750
Fluids and Lubricants	248	24	23,000/lb.	5,704
Total materials	19,300	3,689		375,193
Producer's price		45,9000		
Less total materials		3,689		375,193
Value added		41,311	17,000/1974\$	702,287
Total energy				1,077,480

(Source: IBI Group, 1978)

Table A-3.2: Standard 40' urban bus manufacturing energy

Material	Weight (Lbs.)	Value (1974 \$)	Energy Intensity (Btu's)/ Unit	Total Energy Requirement (Btu's X10 ³)
Total Materials*	21,330	4,077	15,600/lb.	414,656
Producer's Price		62,417		
Less Total Materials		4,077		414,656
Value Added		58,340	17,000/1974 \$	991,780
Total Energy				1,406,436

(Source: IBI Group, 1978)

*Based on Orion material contents and computed by ratio of vehicle weights.

Appendix A-4

Vehicle Manufacturing Energy Toronto Metropolitan Area':

Vehicle	Rate, in Mega joules / ton	Total consumption in Mega joules
Automobile	78,000	125,000-140,000
Diesel bus	111,000	1,099,000
Trolley bus	114,000	1,023,000
"PCC car	146,000	2,395, 000
Subway car (H-5)	198,000	4,946,000

(Source: Herbert et al. 1984)

Appendix A-5

Energy consumption for the manufacture of a bus:

Type of vehicle	40' City bus
vehicle weight (lbs)	19,960
Energy contributions (kwh)	
Manufacture of metallic materials	208,00
Manufacture of other materials	11,800
Fabrication at parts and assembly of the Vehicle	74,400
Transportation of materials and of the assembled vehicle	5,800
Total energy to manufacture new vehicle (kwh)	300,000
Total energy to manufacture new vehicle (Giga Btu)	1.023

(Source: Fels, 1975)

Appendix A-6

Minimum service-life categories for buses and vans:

Category	Typical Characteristics			Minimum Life (Whichever comes first)	
	Length	Approx. GVW	Seats	Years	Miles
Heavy-Duty Large Bus	35 to 48 ft and 60 ft articulated	33,000 ~ 40,000	27 ~ 40	12	500,000
Heavy-Duty Small Bus	30 ft	26,000 ~ 33,000	26 ~ 35	10	350,000
Medium-Duty and Purpose-Built Bus	30 ft	16,000 ~ 26,000	22 ~ 30	7	200,000
Light-Duty Mid-Sized Bus	25 to 35 ft	10,000 ~ 16,000	16 ~ 25	5	150,000
Light-Duty Small Bus, Cutaways, and Modified Van	16 to 28 ft	6,000 ~ 14,000	10 ~ 22	4	100,000

(Source: Richard et al., 2007)

Appendix A-7

Transit bus life cycle maintenance cost (No Major Rehab):

Comp ID	Group	Component	Replacement Cost	Expected Life (years)	Repl. Freq.	Total Repl. Cost
1	Body	Structure		12	0	0
2	Body	Exterior and Applied Panels	\$180.26	12	0	0
3	Body	Paint	\$3,000.00	6	1	3000
4	Body	Interior		12	0	0
5	Body	Floor		12	0	0
6	Body	Steps and Stepwells		12	0	0
7	Body	Wheel Housings		12	0	0
8	Body	Exit Passenger Doors	\$1,742.44	6	1	1742.44
9	Body	Service Compartment		12	0	0
10	Body	Engine door Access Doors	\$2,350.71	6	1	2350.71
11	Operating Components	Doors	\$332.23	4	2	664.46
12	Operating Components	Windshield Wipers and Washers	\$247.06	1	11	2717.66
13	Operating Components	Headlight Assy Lighting	\$108.28	1	11	1191.08
14	Operating Components	Dimmer switch Controls	\$89.62	3	3	268.86
15	Operating Components	Speedometer Instruments	\$101.68	3	3	305.04
16	Interior	Trim Panels		12	0	0
17	Interior	Headlining		12	0	0
18	Interior	Front End		12	0	0
19	Interior	Rear End		12	0	0
20	Interior	Passenger Info and Advertising		12	0	0
21	Interior	One Seat Insert Passenger Seats	\$1,836.80	6	1	1836.8
22	Interior	Driver's Seat	\$2,237.33	4	2	4474.66
23	Interior	Rubber Floor Covering		12	0	0
24	Windows	Windshield	\$2,500.00	12	0	0
25	Windows	Driver's Side Window	\$1,334.21	12	0	0
26	Windows	Side Windows	\$2,281.84	12	0	0
27	Insulation	Insulation			0	0
28	Ancillary Items	Dash Panels	\$102.88	12	0	0
29	Ancillary Items	Visors	\$232.34	6	1	232.34
30	Ancillary Items	Chime Exit Signal	\$187.56	6	1	187.56
31	Ancillary Items	Outside Mirrors	\$402.28	1	11	4425.08
32	Ancillary Items	Inside Mirrors	\$36.55	6	1	36.55
33	Passenger Assists	Front Doorway		12	0	0

Comp ID	Group	Component	Replacement Cost	Expected Life (years)	Repl. Freq.	Total Repl. Cost
34	Passenger Assists	Vestibule		12	0	0
35	Passenger Assists	Overhead		12	0	0
36	Passenger Assists	One Set Insert Longitudinal Seats	\$45.92	6	1	45.92
37	Passenger Assists	Rear Doorway		12	0	0
38	Bumpers	Front Bumper	\$1,091.12	12	0	0
39	Bumpers	Rear Bumper	\$1,393.36	12	0	0
40	Destination Signs	Run Box Run Numbers		1	11	0
41	Destination Signs	Rear Route # Route Numbers	\$4,223.00	3	3	12669
42	Destination Signs	Front Main Auxiliary Destination Sign	\$6,071.00	6	1	6071
43	Destination Signs	Fare Collection Device			0	0
44	Destination Signs	Wheelchair Lift	\$21,000.00	12	0	0
45	Destination Signs	Wheelchair Restraints	\$95.44	6	1	95.44
46	ITS Components	AVL			0	0
47	ITS Components	APC			0	0
48	ITS Components	Others			0	0
49	Propulsion System	Engine Mounts	\$88.96	3	3	266.88
50	Propulsion System	Accessories			0	0
51	Propulsion System	Pump Hydraulic Drive	\$1,056.76	3	3	3170.28
52	Propulsion System	Engine	\$19,320.00	6	1	19320
53	Propulsion System	Radiator Cooling System	\$3,865.00	6	1	3865
54	Propulsion System	Transmission	\$18,232.00	4	2	36464
55	Propulsion System	Muffler Cat Conv Exhaust System	\$2,742.39	6	1	2742.39
56	Propulsion System	EGR Emissions Control Devices	\$396.19	3	3	1188.57
57	Propulsion System	Reman Diff Axles and Differential	\$2,014.75	6	1	2014.75
58	Propulsion System	Sway Bar Suspension	\$382.22	4	2	764.44
59	Propulsion System	Air Springs	\$118.42	4	2	236.84
60	Propulsion System	Shock Absorbers	\$119.23	4	2	238.46

Comp ID	Group	Component	Replacement Cost	Expected Life (years)	Repl. Freq.	Total Repl. Cost
61	Propulsion System	Steering Gear			0	0
62	Propulsion System	Steering	\$995.86	6	1	995.86
63	Brakes	Brake Chamber Actuators	\$109.72	3	3	329.16
64	Brakes	Rear Axel Set Friction Material	\$140.00	1	11	1540
65	Brakes	Hubs	\$890.87	6	1	890.87
66	Brakes	One Drums or Rotors	\$110.00	1	11	1210
67	Brakes	Compressor Air System	\$1,008.66	3	3	3025.98
68	Brakes	Wheels	\$169.68	6	1	169.68
69	Brakes	Tires	\$400.00	0.5	23	9200
70	Fuel System	Fuel Tank	\$2,027.08	6	1	2027.08
71	Fuel System	Fuel Filler	\$288.28	12	0	0
72	Electrical Components	Batteries	\$89.35	2	5	446.75
73	Electrical Components	Master Battery Switch	\$16.24	6	1	16.24
74	Electrical Components	Fire Detectors	\$453.69	4	2	907.38
75	Electrical Components	Radio Noise Suppression			0	0
76	Interior Climate Control	Master control a/c heat Controls	\$1,000.00	6	1	1000
77	Interior Climate Control	Plenums and Vents		12	0	0
78	Interior Climate Control	Filter Air Intakes	\$10.66	1	11	117.26
79	Interior Climate Control	Radio & Public Address System	\$164.23	4	2	328.46
99	Body/Structure	Other Overhaul Costs		12	0	0
99	Body/Body	Other Overhaul Costs	\$180.26	12	0	0
99	Interior	Other Overhaul Costs	\$3,000.00	6	1	3000
99	Fare Collection	Other Overhaul Costs		12	0	0
99	Suspension	Other Overhaul Costs		12	0	0
99	Brakes	Other Overhaul Costs		12	0	0
99	Fuel System	Other Overhaul Costs		12	0	0
99	Electrical Components	Other Overhaul Costs	\$1,742.44	6	1	1742.44
99	Interior Climate Control	Other Overhaul Costs		12	0	0
Total Life Cycle Maintenance Cost						\$139,533.4

(Source: Richard, et al. 2007)

Appendix A-8

Factors effecting fuel consumption of a vehicle

The fuel consumption of a vehicle depends on several of factors. Broadly, these can be divided into two categories. The first category is concerned primarily with the relationship between fuel consumption and factors that are directly related to vehicle speed profiles. These include: average speed, acceleration, traffic density, road topography, road layout, traffic management controls, weather, visibility, driving behavior, etc.

The second category is concerned with speed independent factors. These factors are basically related with vehicle performance and road-vehicle interaction. These factors can be divided into following parts (EAPA, Industry Report, 2004):

- Thermodynamic efficiency of the engine to transfer heat into mechanical power;
- Rolling resistance: due to tire/pavement effect;
- Air resistance: effect of speed and aerodynamic shape;
- Gradient resistance: effect of road slope and vehicle mass;
- Inertia resistance: effect of vehicle mass and acceleration; and
- Driveline losses in the vehicle.

The potential energy available in the fuel is transferred into mechanical power for the engine crankshaft. This mechanical power is then used to overcome driveline, air drag and rolling resistance losses at a constant speed. The potential left over mechanical power is then available for climbing and/or acceleration of the vehicle. Figure A-8.1 shows an example of energy distribution for a 40-ton truck driving at a constant speed of 80 km/h (Sandberg, 2001).

Fig. A-8.1: Energy distribution of the potential energy available in the fuel for a 40-ton truck (Source: Sandberg, 2001).

It can be seen in Fig. A-8.1 that the efficiency of the engine is only approximately 40%, since the thermodynamic loss is 60%. Out of this 40% available energy, the driveline loss accounts for 3%, air drag 9%, rolling resistance 12%. The left over mechanical power, 16%, is potentially available for climbing a slope and/or acceleration of the vehicle mass.

Figure A-8.2 shows how mechanical power available at the engine crankshaft is distributed as a function of the vehicle speed for a passenger car. At a constant speed of 100 km/h on a horizontal road, air drag represents 60% of energy loss while rolling resistance accounts for 25% and internal friction (drive line loss) for 15%. At higher speeds, air drag becomes the largely predominant factor (Michelin, France 2003).

Fig.A-8.2: Variation of energy distribution of the available power output at the crankshaft in a passenger car with speed. (F_D = Air drag, F_v = Internal friction and F_{RR} = Rolling resistance), (Source: Michelin, France 2003).

Impact of pavement surface characteristics on fuel consumption

Road surface characteristics affect both the rolling resistance and the suspension losses of a vehicle. Both of these factors affect the fuel consumption. Laganier and Lucas (1990) conducted a study to comprehend the influence of pavement evenness and macrotexture on fuel consumption. Three practical tests were made: in the laboratory, with a vibrator bench to simulate unevenness; on a track to test the extreme values of the macrotexture of pavements; and on open roads with both unevenness and macrotexture. They found that both unevenness and macrotexture showed measurable extra fuel consumption.

Swedish Road and Traffic Research Institute (VTI) performed an extensive experiment on the influence of road macro- and megatexture on fuel consumption (Sandberg, 1990). In this experiment a Volvo passenger car was run at 50, 60 and 70 km/h constant speed over 20 test sites with various surfaces textures. Road surface macro- and megatexture as well as shorter wavelengths of unevenness were measured by a mobile laser profilometer. The fuel consumption data at each speed were reported. The study concluded that there is a good correlation between vehicle fuel consumption and pavement macrotexture and unevenness. An uneven road may increase fuel consumption by up to 12% relative to an even road. A rough macrotexture may increase fuel consumption by 7% relative to a very smooth macrotexture.

Surface roughness and vehicle fuel consumption

In the past several research investigations found that fuel consumption increases as pavement roughness increases (Claffey 1971, Zaniewski et al., 1979). However, there is substantial disagreement in the findings. Some reported the increase in fuel consumption between a broken asphalt pavement and a smooth surface of 30% (Claffey, 1971), while others reported only 10%.

The Wisconsin Department of Transportation (WDOT) in 1980 conducted an extensive study to find the relation between fuel consumption and pavement roughness (Frederic, 1982). The study was conducted on five 2-lane bituminous concrete pavements with a

minimum of 5000 ft in length. The road segments were straight, level, lightly traveled, uniformly rough or smooth. The roads had varied levels of roughness. Pavement roughness was measured in terms of serviceability index (SI). The study found that automobile fuel consumption increases as pavement roughness increases. However, the increase was very modest and non linear. The relation between fuel consumption and pavement roughness was not an apparent function of vehicle size.

It is clear that the finding of the WDOT study differs from other earlier studies in terms of magnitude of the variation of fuel consumption with roughness. As the WDOT study was very extensive and controls of influential factors on fuel consumption other than pavement roughness were more rigid, the findings of this study can be considered as more reliable.

Pavement types and vehicle fuel consumption

Several researchers have also reported that the type of road surface can significantly affect vehicle fuel consumption. However, Zniewski (1982), having conducted several tests with both cars and trucks traveling on a variety of pavement types, reported that fuel consumption was not influenced by pavement surface type for cars, but bus and trucks consumed less fuel on concrete pavements than on asphalt pavements.

Bester (1984), investigated the effect of pavement type and condition (roughness) on the rolling resistance of vehicles. It was found that, except for gravel surfaces, pavement type has a minor effect on fuel consumption. However, the test reported that roughness correlates strongly with rolling resistance and therefore with vehicle fuel consumption.

The Centre for Surface Transportation Technology (CSTT), a business unit of the National Research Council of Canada, conducted an extensive study (Phase III) to determine the effect of pavement types on vehicle fuel consumption.

Three types of pavement i.e., concrete, asphalt and composite (an asphalt coat over concrete), were tested. The tests were done in all seasons at two speeds (60 km/h and 100km/h) with both loaded and empty trailers. The tests measured the International

Roughness Index (IRI), road curvature, grade and the strength of the road bed. The tests were conducted on routes run in Ontario and Québec. The study found that concrete generally provided fuel savings over asphalt and composite pavements. However, under certain conditions during summer days, composite pavements provided fuel savings over concrete pavements. Fuel savings ranged from 0.8 per cent to 6 per cent for tandem drive tractors pulling van semi trailers on concrete over asphalt or composite pavements. This study also found that for passenger vehicles, concrete only showed significant fuel savings over asphalt in winter and over composite pavements in summer (Taylor et al., 2006).

Appendix A-9

Energy intensities of materials and life cycle processes of continuously reinforced concrete pavements and asphalt pavements:

Energy consumption J / t of material	Source	Comments
Process: Extraction of aggregates (coarse and fine aggregate)		
53 x 10 ⁶	NCSA (1977)	Consumption of energy between 21.1x10 ⁶ J/t—63.3x10 ⁶ J/t with a common value of 53 x 10 ⁶ J/t
22.2 x 10 ⁶	Berthiaume and Bouchard (1999)	—
74 x 10 ⁶	Stammer and Stodolsky (1995)	—
24 x 10 ⁶ (gravel) 52 x 10 ⁶ (crushed aggregates for asphalt)	Häkkinen and Mäkelä (1996)	In the case of gravel the process includes extraction and transportation. In the case of crushed aggregates for asphalt the process includes: (1) quarrying and breaking, (2) transportation of broken rock, (3) crushing, and (4) transportation of crushed materials.
38.18x 10 ⁶ (crushed aggregates)	Stripple (2001)	In the case of crushed aggregates from rock mass the process includes: (1) blast rock, (2) transportation of blasted rock, and (3) crushing blasted rock.
Process: Cement manufacturing		
6.33 x 10 ⁹	School of Resources, Environment and Society based on Portland Cement Association, 1990 data)	The 6.33x10 ⁹ J / t includes the direct fuel use for mining and transporting raw materials. It takes about 1.75 kg of raw materials to produce 1 kg of finished cement, according to the Environmental Research.
5.35 x 10 ⁹ –10.2 x 10 ⁹	Berthiaume and Bouchard (1999)	5.35x 10 ⁹ J/t (dry process) 10.2 x 10 ⁹ J/t (wet process)
6.7x 10 ⁹	Stammer and Stodolsky (1995)	—
6.36 x 10 ⁹	Twinshare (2003)	It takes about 1,600 kg of raw material to produce a ton of cement.
5.35 x 10 ⁹	Häkkinen and Mäkelä (1996)	The data are received from Finncement (Stefan Lindfors). The system includes: (1) extraction and transportation of energy raw materials, (2) extraction of cement raw materials, (3) transportation of cement raw materials to the cement factory, (4) production of raw meal, (5) burning of clinker, and (6) grinding of cement.
4.77 x 10 ⁹	Stripple (2001)	
Process: Steel manufacturing		
1.90 x 10 ¹⁰	Stubbles (2000)	Total use of energy for steel tapped
1.8x 10 ¹⁰ –2.3x10 ¹⁰ 0.62 x 10 ¹⁰	Stammer and Stodolsky (1995) Häkkinen and Mäkelä (1996)	1 t of reinforcing steel Production of reinforcement steel for the Norwegian market at Fundia Norsk Jernverk in Mo. Data from 1992, based on assumption of 100% Norwegian scrap iron.
2.53 x 10 ¹⁰	Stripple (2001)	
Process: Concrete mixing		
6.875x 10 ⁶	Contractor survey	The consumption of energy during mixing will depend on the

		amount of diesel fuel necessary to mix the total amount of concrete. In this case, it has been assumed a mixing plant with a capacity of 230 m ³ / h. It takes a 550 kW generator to run, and the generator burns 102 L of fuel phr.
Energy consumption J / t of material	Source	Comments
Process: Portland cement concrete pavement placement		
3.40 x 10 ⁷ (concrete) 0 (steel)	Contractor survey	The consumption of energy during placement will depend on the amount of diesel fuel used by the equipment necessary for the operation. CRCP pavement will typically be placed at approximately 21 m ² / manhour. Equipment necessary for placement and approximate fuel consumption: (1) 2 pavers= 41.6 L / h each (2) 1 tiner/cure machine = 13.2 L / h (3) 2 pickup trucks= 4.2 L / h each (4) 1 small loaders(CAT 950 size) = 26.5 L / h
Process: Production of bitumen		
0.63 x 10 ⁹	Stammer and Stodolsky (1995)	
0.42 x 10 ⁹	NCSA (1977)	
6 x 10 ⁹	Häkkinen and Mäkelä(1996)	The data are received from Neste (Jouko Nikkonen). The production process includes: (1) production of raw oil, (2) transportation of raw oil, and (3) refining.
2.93 x10 ⁹	Stripple(2001)	The production process included: (1) crude oil extraction in Venezuela, (2) transport of crude oil to refinery, (3) refining. The allocation of energy consumption for the refining process is 40% for bitumen and 60% for lighter products.
Process: Asphalt storage		
5.43 x 10 ⁸	Stripple (2001)	
Process: Asphalt mixing and drying of aggregates		
0.32 x 10 ⁹ –0.39X10 ⁹ (per ton of asphalt mixture)	Ang et al. (1993)	310x 10 ³ J / t for continuous plant; 375x 10 ³ J / t for batch plant. A large part of the process energy use is for drying and heating aggregates. Statistical analysis historical energy-consumption data show a high correlation between specific energy requirements and rainfall level.
Process: Asphalt pavement placement		
1.34 x 10 ⁷	Contractor survey	The consumption of energy during placement will depend on the amount of diesel fuel used by the equipment necessary for the operation. It has been assumed an asphalt plant with a capacity of approximately 360 t / h. Equipment necessary for placement and approximate fuel consumption: (1) 1 asphalt paver = 15.1 L / h (2) 3 rollers(if in Oregon, two anywhere else) = 17.0 L / h each (3) 1 tack truck= 26.5 L / h (4) 3 pickup trucks= 4.2 L / h each (5) 1 small loaders(CAT 950 size) = 26.5 L / h (6) 1 small broom= 17.0 L / h

(Source: Zapata et.al. 2005)

Appendix A-10

Table A-10.1: Typical BRT Station component cost

Item	Cost (US\$) per unit
Station construction	
3 meter wide stations	200'000
5 meter wide stations	350'000
Station air conditioning / heating	
Full air conditioning / heating	100'000
Air conditioned / heated shelter inside station	30'000
Mist generators / fans	5'000
Automatic sliding doors at boarding interface	
Sliding doors (8 doors per station)	40'000
Sliding doors (16 doors per station)	80'000
Station identification - sign post	
Station identification post	800
Maps and information	
Maps at stations	3'000
Maps at stations and in vehicles	6'000
Information kiosks	30'000
Recycling receptacles at stations	
Receptacles at station	1'000
Station security	
Emergency callbox	1'500
Security cameras	8'000
Fare collection turnstiles	
Gate-arm turnstile (per turnstile)	2'800

(Source: Wright, 2007)

Table A-10.2: Fare and ITS costs

Item	Cost (US\$) per unit
Fare collection readers	
Smart card system (4 readers per station)	10'000
Magnetic strip system (4 readers per station)	7'000
Coin-based system (2 readers per station)	1'500
Fare collection turnstiles	
Rotating turnstile (per turnstile)	7'000
Gate-arm turnstile (per turnstile)	2'800
Fare registering unit / vending machine	
Smart card system (per machine)	15'000
Magnetic strip system (per machine)	10'000
Coin-based system (per machine)	0
Fare media	
Smart card system with micro-processing ability (per card)	3.50
Smart cards w/o micro-processing ability(per card)	1.20
Magnetic strip cards (per card)	0.05
Coin-based system (per card)	0.00
Fare system software	
Smart card system (per software)	500'000

Magnetic strip system (per software)	300'000
Coin-based system	100'000
Intelligent Transportation Systems (ITS)	
Green light phase extension for BRT (per intersection)	20'000
Real-time information displays (per station)	7'500
Broad-band service at stations/terminals (per station)	750

(Source: Wright, 2007)

Table A-10.3: Integration infrastructure costs

Item	Cost (US\$) per unit
Pedestrian crossings	
Pedestrian crosswalk with signal	20'000
Pedestrian bridge	300'000
Pedestrian access to station areas	
Improvements to pedestrian access ways	35'000
Bicycle integration	
Bicycle parking at stations	8'000
Taxi integration	
Formal taxi stands at stations	60'000
Park-and-ride facilities	
Kiss-and-ride facilities only	40'000
Park-and-ride facility (open lot parking)	1'500'000
Park-and-ride facility (multi-level parking)	10'000'000

(Source: Wright, 2007)

Table A-10.4: Other infrastructure cost items

Item	Cost per unit US\$	Units
Feeder system		
Feeder busway/station improvements	75'000	US\$ per kilometer
Control centre (including software)		
Control centre physical construction	1'500'000	US\$
Radio-based control only (equipment)	100'000	US\$
GPS system (equipment)	1'000'000	US\$
Software	3'000'000	US\$
Terminals and depots		
Terminal facilities	3'000'000	US\$ per terminal
Depot facilities	5'000'000	US\$ per depot
Restrooms at terminals	15'000	US\$ per terminal
Intermediate transfer stations		
Standard intermediate transfer station	400'000	US\$ per corridor
Large intermediate transfer station for multiple feeder services	1'500'000	US\$ per corridor
Property acquisition		
Terminal site in peripheral area1	3'000'000	US\$ per site
Depot site in peripheral area2	5'000'000	US\$ per site
Park-and-ride site in peripheral area3	2'000'000	US\$ per site
Terminal site in central area1	60'000'000	US\$ per site
Street widening in central district (2 lanes eqv.)	40'000'000	per kilometer

(Source: Wright, 2007)

Appendix B-1

North American LRT systems:

Sl.	System	city served	Daily ridership	Route miles	Opened
1	MBTA Green Line	Boston	267,100	25.4	1897
	Ashmont–Mattapan High Speed line			2.6	
2	Muni Metro* and F/Market Line*	San Francisco	147,800	71.5	1912
	Muni Cable Cars			8.8	1878
3	Los Angeles County Metro Rail Blue, Green, and Gold lines*	Los Angeles	144,900	55.7	1990
4	MAX Light Rail	Portland	113,700	44	1986
	Portland Streetcar			4.0	
5	San Diego Trolley	San Diego	113,300	53.5	1981
6	SEPTA Subway-Surface Lines, Suburban Trolley Lines, and Girard Avenue Trolley*	Philadelphia	111,500	60	
7	Metro Link	St. Louis	67,300	46	1993
8	DART: Red and Blue lines	Dallas	65,900	45	1996
	MATA streetcar			3.6	
9	Denver RTD, The Ride Light Rail	Denver	65,300	35	1994
10	Sacramento Regional Transit District LRT	Sacramento	63,700	36.9	1987
11	UTA TRAX	Salt Lake City	51,849	19	1999
12	METRO Rail	Houston	39,500	7.5	2004
13	Hudson-Bergen Light Rail*	Jersey City	38,200	27.2	2000
14	Santa Clara VTA Light Rail	San Jose	34,000	28.6	1987
15	Baltimore Light Rail*	Baltimore	31,900	30.0	1992
16	Hiawatha Line	Minneapolis	30,300	12	2004
17	The T	Pittsburgh	26,300	25	1987
18	Buffalo Metro Rail	Buffalo	25,700	6.4	1984
19	LYNX Rapid Transit Services	Charlotte	20,300	9.6	2007
20	Newark City Subway and Newark LRT	Newark	19,050	9.9	
21	Streetcars in New Orleans	New Orleans	13,600	21.5	1835
22	The Rapid Blue and Green Lines	Cleveland	8,900	15	1913
23	River Line	Trenton/Camden	7,900	69.7	2004
24	South Lake Union Streetcar	Seattle	4,200	1.3	2007
25	Memphis RTA Trolley	Memphis	3,300	6.7	1993
26	Tacoma Link	Tacoma	2,900	1.6	2003
27	TECO Line Streetcar System	Tampa	1,100	2.3	2002
28	River Rail Streetcar	Little Rock	340	2.5	2004
29	Kenosha Transit	Kenosha	200	2.0	2000
30	Galveston Island Trolley	Galveston	100	5.2	1988
31	C-Train	Calgary	276,800	27.8	1985
32	Toronto streetcar system	Toronto	246,700	190.0	1861
33	Sky Train (Vancouver)	Vancouver	220,000	30.8	1985
34	Scarborough RT	Toronto	47,600	4.0	1985
35	Edmonton LRT	Edmonton	42,000	8.0	1978
36	O-Train	Ottawa	9,800	5.0	2001
37	Monterrey Metro	Monterrey	217,700	25	1991
38	Guadalajara Metro	Guadalajara	190,000	9.6	1989
				5.5	1994
39	Xochimilco Light Rail	Mexico City			1980

(*) Systems marked with an asterisk are integrated with a heavy rail rapid transit system; the above numbers represent ridership on light rail lines only. (Source: Wikipedia, 2008)

Appendix B-2

LRT system in the world as of 2007:

Country	No of Light rail Transit system	Country	No of Light rail Transit system
Argentina	1	Norway	(+1)
Austria	1	Philippines	1
Brazil	1	Poland	1
Canada	3 (+1p)	Portugal	1 (+1 +1p)
China	2	Russia	2
Czech Republic	(+1p)	Singapore	3
Denmark	(+1p)	Spain	5 (+1p)
France	(+1 +1p)	Sweden	1
Germany	16	Switzerland	2
Hungary	1	Tunisia	1
Italy	2	Turkey	5 (+1)
Japan	7	Ukraine	1
Malaysia	1	United Kingdom	4*
Mexico	2	United States	23 (+2)(+2p)
Netherlands	4	Venezuela	(+2)
World Totals (31 countries):		91 (+8 +8p)	

Items in brackets + = under construction or + p = planned/proposed; (Source: Taplin, 2006)

Appendix B-3

Table B-3.1: Types of light rail tracks in USA

Light Rail System	Direct track miles by type of right -of -way					
	At Grade Exclusive ROW	At Grade With Cross Traffic	At Grade Mixed ROW	Elevated ROW	Tunnel ROW	Total
San Diego	-	80.2	8.0	7.8	0.6	96.6
Los Angeles	3.7	27.6	-	35.1	16.0	82.4
San Francisco	4.5	6.0	47.9	-	14.9	73.3
Philadelphia	-	23.6	41.3	-	4.4	69.3
St. Louis	39.0	0.8	-	15.4	13.6	68.8
Portland	6.1	41.7	0.2	1.0	15.9	64.9
San Jose	12.2	36.5	-	8.6	1.1	58.4
Baltimore	40.4	11.5	3.1	2.6	-	57.6
Boston	19.2	19.1	1.3	2.4	9.0	51.0
Dallas	1.5	30.4	2.5	5.0	7.7	47.1
Sacramento	8.1	21.7	6.8	4.1	-	40.7
Pittsburgh	24.3	-	4.4	1.9	4.2	34.8
Salt Lake City	-	25.6	8.6	-	-	34.2
Cleveland	10.3	14.5	-	2.9	3.1	30.8
Denver	10.6	4.8	-	10.4	2.2	28.0
Newark	7.6	7.1	1.9	-	-	16.6
New Orleans	16.0	-	-	-	-	16.0
Buffalo	-	2.8	-	-	9.6	12.4
Newark	5.8	-	-	-	2.5	8.3
Memphis	-	2.4	3.4	-	-	5.8
Galveston	-	-	4.9	-	-	9.8
Seattle	-	3.7	-	-	-	3.7
Kenosha	-	0.5	1.4	-	-	1.9
Detroit	-	-	1.3	-	-	1.3
Total	209.3	360.5	137.0	97.2	104.8	913.7
	23%	40%	15%	11%	12%	

(Source: Analysis of the Florida Transit Information System database, Florida International University, 2001)

Table B-3.2: Types of light rail right of way – French, German & UK Systems

Light Rail System	Track kms by type of right of way			
	Segregated ROW	Dedicated ROW	Mixed Traffic	Total
France	14.8	155.2	0.8	170.8
Germany	424.5	442.1	361.0	1,227.5
United Kingdom	175.2	1.7	28.8	205.7

Source: South Yorkshire Passenger Transport Executive, 2004 and Association of German Transport Undertakings, 2000

Appendix B-4

Impact of curve, slope, speed and weight of a train on energy consumption

Haidong, et al. (2007) conducted a study to analyze the effect of the curve, slope, speed and weight of a train on energy consumption. Figure B-4.1 shows the energy consumption of a train with different curve radius at three speed limits. It can be seen that the energy consumption exhibits a similar pattern under different speed limits. When the radius of curve is longer than 500 m, the effect of energy consumption is nearly the same as that of the energy consumption of the straight section of the line (∞ radius). The effect of energy consumption is obvious, when the curve radius is shorter than 300 m.

Figure B-4.1: Variation of energy consumption with different radius of curves of LRT track (Source: Haidong, et al. 2007)

Figure B-4.2 (a), (b) shows the impact of ascending and descending slope on energy consumption. It can be seen that the energy consumption shows a linear variation with the grade of the slope. For ascending gradient the energy consumption increases with increasing gradient and for descending gradient the energy consumption decreases with increasing gradient.

Figure B-4.2: The variation of energy consumption with different (a) ascending and (b) descending grades (Source: Haidong, et al. 2007)

The impact of the weight of the train on energy consumption is very obvious. It can be seen in Fig. B-4.3 that the relationship between energy consumption and the weight of the train is linear. The energy consumption increases with the increasing weight of train.

Figure B-4.3: Variation of energy consumption with train weight (Source: Haidong, et al. 2007)

Electric train propulsion efficiency also depends on primary energy sources. Khan (1980) conducted a study to estimate energy efficiency of electric train propulsion. In his study, it was found that sources of primary energy have a significant effect on train propulsion efficiency. Traction efficiency substantially varies with electricity generation mix. He demonstrated that traction efficiency drops 38% to 21% with the change of electricity mix of 34% hydro-electric and 66% thermal and nuclear power to 100% thermal and nuclear power.

Appendix B-5

The energy consumption for manufacturing Montréal metro type car:

Material	Weight (Lbs.)	Value (1974\$)	Energy intensity (BT U's Per Unit)	Total Energy Requirement (BTU's X 10 ³)
Rolled Steel	37,922	4,172	15,600/lb.	591,593
Steel Ingots	9,000	M	11,900/lb.	107,100
Pig iron	1,219	60	6,000/lb.	7,314
Aluminum Ingots	1,800	612	55,900/lb.	100,620
Other Non-Ferrous hoots	2,874	1,983	40,800/lb.	117,259
Fiber glass Sheets	1,612	650	44,000/lb.	70,928
Plastic Resins	1,984	1,024	47,300/lb.	93,843
Paint	850	476	35,00/lb	29,750
Glass	480	288	47,400/lb.	22,752
Tires	1,250	688	34,600/lb	43,250
Plywood	119	24	4,600/lb.	547
Arborite	150	189	87,500/lb.	13,125
Porcelain	50	1	2,400/lb.	120
Total Materials	59,310	13,959		1,198,191
Producer's Price		348,112		
Less Total Materials		10,959		1,198,191
Value Added		337,153	15,000/1974\$	5,057,295
Total Energy				6,255,486

(Source: IBI Group, 1979)

Appendix B-6

Table B-6.1: Breakdown of energy consumption for sample underground and aerial stations in BART system

Component	Underground Station	Aerial Station
Station lighting	64%	13%
Escalators	24%	17%
Train control	8%	17%
Parking lot lighting	-	50%
Miscellaneous	4%	3%

(Source: Fels, M., 1978)

Table B-6.2: Breakdown of total energy consumption for BART's 34 stations

Component	14 Underground stations (million Kwh/month)	20 Aerial stations (million Kwh/month)	Overall breakdown for 34 stations
Interior lighting	2.0	0.2	54%
Escalators	0.5	0.3	20%
Train control	0.2	0.3	12%
Parking	-	0.6	15%
Total	2.7	1.4	
Average energy consumption / station	190,000 Kwh/month	74,000 Kwh/month	
Overall average energy consumption / station	120,000 Kwh/month		
Total estimated energy for stations	4.1 million Kwh/month		

(Source: Fels, 1978)

Appendix C-1

TRANS model

The TRANS model is the National Capital Region (NCR) transportation model, originally developed in the late 1970's to analyze existing trip patterns and travel choices and to simulate the effects of future scenarios featuring varying growth, alternative transportation facilities, services and policies. The TRANS model is almost entirely implemented in EMME software, which is developed and distributed by INRO, Montreal, Canada. Over the years various forms of a TRANS model were updated. Having completed a regional origin-destination survey as well as a number of related transportation data collection activities in 2005, the TRANS agencies updated modeling techniques and practices. The redevelopment of the TRANS Model involved a full update of key demographic and land-use variables, as well as both the auto and transit networks that reflect 2005 conditions. The model architecture includes many entirely-tour-based and half-tour-based procedures. The introduction of these advanced modeling procedures is restricted to the trip generation and trip distribution stages. Thus, the developed model is not a full tour-based model (Trans, 2008). A flow chart highlighting each of the elements and sub-elements of the TRANS model system design is shown in Fig. C-1.1.

The major new features of the TRANS Model are the addition of trip chaining procedures, daily tour generation and distribution, and more detailed mode choice models to consider a variety of transit modes (bus, Transitway, rail/LRT) and access options (walk, park & ride, kiss & ride) (Trans, 2008).

Appendix C-2

Ranges of actual capacities of major transit modes*

Mode	Maximum or Moderate Values	Min. Ave. Headway- h_{min} (s)	Vehicle Line capacity, (veh/h)	Typical Vehicle Capacity, (sps / veh)	Maximum Offered Capacity, (sps/h)	Operating Speed at Capacity, V (km/h)
Regular or express bus on streets, with or without reserved lane	Maximum	30	120	75	6,000-9,000	8-12
	Moderate	40	90	75	4,000-6,300	20-40
Articulated buses, ROW as above	Maximum	33	110	110	8,500-12,000	7-11
	Moderate	45	80	110	5,000-8,500	18-36
Streetcar on street or curbed median	Maximum	33	110 x2=220	100	14,000-22,000	8-10
	Moderate	40	90 x2=180	100	10,000-16,000	10-14
LRT on private ROW, regulated crossings	Maximum	60	60 x2=120	180	12,000-20,000	18-30
	Moderate	80	45 x2=90	180	8,000-15,000	20-35
Rail rapid transit, urban	Maximum	100	36 x 10=360	175	40,000-63,000	22-40
	Moderate	120	30 x8=240	175	30,000-42,000	25-45
Regional rail, electrified	Maximum	120	30 X9=270	180	30,000-48,000	25-45
	Moderate	180	20 x9=180	180	20,000-32,000	30-50
Way capacity of buses on freeways without stops	(Capacity of off-line terminals governs)					

(Source: Vuchic, 2007)

*This table presents upper limits of capacities of modes. The "maximum" lines represent capacities that can be achieved with careful design and strict, competent operation; the "moderate" lines are capacities achievable under most conditions without special efforts.

Appendix C-3

Sample of travel time calculation in VISSIM for BRT

Time	No_	Veh	VehTy	Trav
2123.131	1	1	300	2069.202
2210.513	1	2	300	2144.588
2231.385	1	3	300	2160.147
2313.379	1	4	300	2222.28
2372.087	1	5	300	2230.464
2375.567	1	6	300	2222.598
2380.209	1	7	300	2211.133
2447.231	1	8	300	2273.642
2449.476	1	9	300	2239.43
2451.741	1	10	300	2220.21
2507.65	1	11	300	2272.492
2530.818	1	12	300	2292.18
2533.801	1	13	300	2246.332
2546.987	1	14	300	2255.645
2605.431	1	15	300	2310.619
2618.002	1	16	300	2316.188
2634.269	1	17	300	2291.991
2640.787	1	18	300	2295.362
2702.663	1	19	300	2342.286
2712.685	1	20	300	2342.459
2738.429	1	21	300	2321.651
2740.762	1	22	300	2320.677
2784.875	1	23	300	2361.519
2798.127	1	24	300	2371.064
2811.814	1	25	300	2335.932
2836.16	1	26	300	2357.018
2860.819	1	27	300	2371.056
2865.909	1	28	300	2371.369
2868.565	1	29	300	2331.172
2894.134	1	30	300	2345.563
2939.166	1	31	300	2375.382
2945.969	1	32	300	2376.04
2964.425	1	33	300	2347.587
2969.821	1	34	300	2349.626
3021.67	1	35	300	2396.874
3033.732	1	36	300	2403.983
3036.809	1	37	300	2370.415
3039.813	1	38	300	2370.39
3071.153	1	39	300	2379.308
3076.166	1	40	300	2380.956
3114.669	1	41	300	2382.105
3119.893	1	42	300	2365.99
3151.525	1	43	300	2394.606
3195.962	1	44	300	2435.398
3205.019	1	45	300	2404.926

3211.338	1	46	300	2401.919
3250.379	1	47	300	2428.853
3274.929	1	48	300	2450.127
3336.447	1	49	300	2474.447
3338.527	1	50	300	2472.799
3344.521	1	51	300	2475.212
3346.965	1	52	300	2459.421
3390.62	1	53	300	2432.11
3423.939	1	54	300	2461.717
3428.152	1	55	300	2462.676
3472.82	1	56	300	2503.522
3499.895	1	57	300	2495.07
3526.196	1	58	300	2503.569
3536.307	1	59	300	2510.019
3544.598	1	60	300	2500.11
3604.688	1	61	300	2525.444
3610.9	1	62	300	2518.856
3633.121	1	63	300	2525.867
3656.839	1	64	300	2546.258
3706.308	1	65	300	2542.48
3713.222	1	66	300	2537.199
3724.334	1	67	300	2544.591
3746.432	1	68	300	2563.708
3798.072	1	69	300	2571.653
3815.98	1	70	300	2573.937
3819.319	1	71	300	2574.006
3821.935	1	72	300	2573.295
3870.008	1	73	300	2552.106
3873.353	1	74	300	2548.698
3890.796	1	75	300	2562.106
3893.892	1	76	300	2562.23
3937.557	1	77	300	2544.977
3949.046	1	78	300	2553.078
3964.817	1	79	300	2564.802
3991.616	1	80	300	2588.001
4032.08	1	81	300	2576.31
4040.292	1	82	300	2579.9
4043.115	1	83	300	2579.729
4046.702	1	84	300	2579.452
4086.372	1	85	300	2572.226
4089.775	1	86	300	2569.197
4097.354	1	87	300	2573.051
4147.63	1	88	300	2619.174
4159.239	1	89	300	2590.191
4173.322	1	90	300	2588.928
4176.433	1	91	300	2588.423
4182.121	1	92	300	2590.075
4244.157	1	93	300	2603.767
4255.438	1	94	300	2611.982
4257.989	1	95	300	2608.049

4262.208	1	96	300	2609.164
4308.159	1	97	300	2617.615
4319.249	1	98	300	2618.583
4327.041	1	99	300	2606.537
4330.43	1	100	300	2606.334
4385.174	1	101	300	2628.493
4388.54	1	102	300	2621.484
4391.912	1	103	300	2600.694
4395.127	1	104	300	2600.653
4453.113	1	105	300	2601.017
4456.542	1	106	300	2601.349
4461.78	1	107	300	2602.659
4466.809	1	108	300	2603.829
4509.185	1	109	300	2591.786
4512.736	1	110	300	2591.626
4554.71	1	111	300	2630.241
4559.131	1	112	300	2630.948
4603.68	1	113	300	2620.703
4606.263	1	114	300	2612.077
4609.235	1	115	300	2611.957
4612.271	1	116	300	2611.901
4666.892	1	117	300	2628.555
4669.72	1	118	300	2626.012
4673.609	1	119	300	2621.09
4675.477	1	120	300	2619.519
4717.139	1	121	300	2599.027
4720.256	1	122	300	2599.483
4731.988	1	123	300	2607.56
4759.058	1	124	300	2621.09
4779.827	1	125	300	2595.804
4793.02	1	126	300	2602.302
4815.56	1	127	300	2621.282
4820.851	1	128	300	2622.17
4865.326	1	129	300	2624.912
4870.319	1	130	300	2608.835
4873.465	1	131	300	2608.395
4886.603	1	132	300	2617.779
4931.18	1	133	300	2602.447
4945.36	1	134	300	2607.831
4948.082	1	135	300	2607.263
4964.682	1	136	300	2620.679
5023.482	1	137	300	2656.19
5026.165	1	138	300	2626.522
5028.48	1	139	300	2625.634
5033.466	1	140	300	2626.91
5085.811	1	141	300	2642.474
5088.308	1	142	300	2616.159
5113.274	1	143	300	2636.75
5115.552	1	144	300	2635.085
5171.97	1	145	300	2647.688

5174.752	1	146	300	2639.468
5178.77	1	147	300	2639.56
5182.932	1	148	300	2632.987
5238.461	1	149	300	2641.766
5246.838	1	150	300	2647.204
5253.48	1	151	300	2650.094
5259.083	1	152	300	2651.364
5303.663	1	153	300	2654.082
5325.763	1	154	300	2672.695
5331.19	1	155	300	2674.007
5373.918	1	156	300	2713.053
5392.537	1	157	300	2696.787
5398.496	1	158	300	2679.865
5401.057	1	159	300	2678.815
5405.895	1	160	300	2677.224
5450.723	1	161	300	2676.607
5461.796	1	162	300	2679.489
5473.472	1	163	300	2685.438
5477.114	1	164	300	2679.395
5523.436	1	165	300	2659.023
5525.202	1	166	300	2657.596
5528.804	1	167	300	2657.636
5546.437	1	168	300	2671.303
5598.021	1	169	300	2676.818
5601.87	1	170	300	2671.905
5616.566	1	171	300	2683.761
5625.892	1	172	300	2688.469
5682.022	1	173	300	2702.316
5685.238	1	174	300	2694.807
5718.371	1	175	300	2724.933
5723.546	1	176	300	2727.007
5757.363	1	177	300	2694.898
5760.005	1	178	300	2694.019
5764.625	1	179	300	2694.072
5774.98	1	180	300	2702.029
5817.257	1	181	300	2692.865
5823.182	1	182	300	2694.85
5837.533	1	183	300	2704.914
5841.921	1	184	300	2704.099
5893.168	1	185	300	2715.503
5896.586	1	186	300	2708.146
5902.596	1	187	300	2706.287
5904.988	1	188	300	2705.625
5943.278	1	189	300	2701.18
5959.726	1	190	300	2700.325
5994.974	1	191	300	2722.369
5997.579	1	192	300	2722.376
6001.606	1	193	300	2696.094
6004.327	1	194	300	2681.881
6059.262	1	195	300	2733.279

6066.822	1	196	300	2712.395
6071.771	1	197	300	2670.65
6112.502	1	198	300	2707.554
6123.586	1	199	300	2712.618
6128.414	1	200	300	2707.9
6135.553	1	201	300	2668.761
6146.974	1	202	300	2666.275
6185.347	1	203	300	2701.396
6188.833	1	204	300	2700.613
6217.561	1	205	300	2670.917
6244.297	1	206	300	2694.136
6278.856	1	207	300	2725.369
6282.096	1	208	300	2725.164
6296.153	1	209	300	2714.391
6324.75	1	210	300	2716.548
6364.556	1	211	300	2743.686
6372.556	1	212	300	2740.689
6382.759	1	213	300	2694.91
6392.383	1	214	300	2701.16
6442.481	1	215	300	2747.346
6444.302	1	216	300	2746.415
6465.103	1	217	300	2720.231
6467.721	1	218	300	2707.56
6512.482	1	219	300	2748.101
6540.828	1	220	300	2773.06
6543.787	1	221	300	2730.16
6548.245	1	222	300	2721.921
6612.331	1	223	300	2782.735
6615.071	1	224	300	2777.779
6622.821	1	225	300	2740.219
6624.837	1	226	300	2730.571
6668.014	1	227	300	2770.428
6671.238	1	228	300	2769.769
6694.078	1	229	300	2755.816
6698.623	1	230	300	2755.941
6737.336	1	231	300	2776.53
6759.136	1	232	300	2795.434
6770.229	1	233	300	2740.591
6782.739	1	234	300	2749.735
6805.619	1	235	300	2769.528
6811.923	1	236	300	2772.966
6824.601	1	237	300	2740.605
6831.655	1	238	300	2741.978
6886.078	1	239	300	2790.909
6895.34	1	240	300	2788.604
6911.149	1	241	300	2753.779
6914.125	1	242	300	2749.283
6970.37	1	243	300	2801.861
6977.02	1	244	300	2805.415
6987.713	1	245	300	2789.56

6991.455	1	246	300	2766.543
7051.953	1	247	300	2817.21
7056.54	1	248	300	2814.057
7061.263	1	249	300	2761.37
7065.378	1	250	300	2761.827
7112.988	1	251	300	2806.39
7120.032	1	252	300	2807.861
7123.445	1	253	300	2757.794
7130	1	254	300	2760.859
7164.723	1	255	300	2785.177
7172.418	1	256	300	2789.9
7178.238	1	257	300	2749.673
7220.665	1	258	300	2772.61
7231.788	1	259	300	2780.281
7237.185	1	260	300	2782.936
7259.346	1	261	300	2769.451
7316.547	1	262	300	2814.809
7318.487	1	263	300	2798.074
7320.971	1	264	300	2797.102
7325.444	1	265	300	2762.877
7372.069	1	266	300	2803.512
7393.279	1	267	300	2805.758
7401.685	1	268	300	2809.914
7404.623	1	269	300	2763.115
7437.349	1	270	300	2782.28
7456.857	1	271	300	2799.05
7461.685	1	272	300	2789.651
7500.461	1	273	300	2780.938
7510.848	1	274	300	2787.775
7521.432	1	275	300	2793.664
7525.515	1	276	300	2786.083
7533.973	1	277	300	2730.245
7572.099	1	278	300	2764.878
7578.472	1	279	300	2766.823
7584.816	1	280	300	2769.969
7615.386	1	281	300	2761.179
7652.289	1	282	300	2793.912
7659.894	1	283	300	2795.844
7697.893	1	284	300	2817.116
7701.902	1	285	300	2780.931
7742.002	1	286	300	2817.52
7750.348	1	287	300	2823.219
7757.329	1	288	300	2814.176
7759.362	1	289	300	2763.706
7822.747	1	290	300	2823.186
7824.504	1	291	300	2811.701
7826.517	1	292	300	2810.186
7829	1	293	300	2774.666
7870.715	1	294	300	2803.604
7873.736	1	295	300	2804.169

7878.857	1	296	300	2801.595
7907.678	1	297	300	2789.945
7955.827	1	298	300	2823.114
7959.13	1	299	300	2823.07
7961.098	1	300	300	2821.743
7963.6	1	301	300	2884.252
8014.825	1	302	300	2813.051
8030.622	1	303	300	2825.54
8040.794	1	304	300	2832.493
8066.831	1	305	300	2808.574
8092.676	1	306	300	2830.924
8095.811	1	307	300	2825.978
8099.294	1	308	300	2825.732
8106.833	1	309	300	2878.598
8157.515	1	310	300	2813.144
8166.1	1	311	300	2817.623
8168.707	1	312	300	2817.33
8174.045	1	313	300	2774.337
8223.474	1	314	300	2820.121
8235.816	1	315	300	2825.786
8245.598	1	316	300	2831.753
8249.529	1	317	300	2781.939
8289.536	1	318	300	2818.771
8302.049	1	319	300	2827.286
8307.214	1	320	300	2828.876
8309.238	1	321	300	2766.746
8335.562	1	322	300	2789.044
8361.136	1	323	300	2811.245
8367.932	1	324	300	2814.128
8377.322	1	325	300	2777.166
8411.731	1	326	300	2807.478
8461.687	1	327	300	2850.131
8468.35	1	328	300	2852.657
8471.656	1	329	300	2812.258
8515.843	1	330	300	2842.292
8523.511	1	331	300	2845.879
8528.742	1	332	300	2847.263
8530.896	1	333	300	2805.72
8577.667	1	334	300	2833.93
8595.179	1	335	300	2847.256
8597.245	1	336	300	2846.313
8600.65	1	337	300	2787.617
8663.854	1	338	300	2845.678
8666.187	1	339	300	2844.581
8673.131	1	340	300	2848.064
8675.722	1	341	300	2787.115
8736.861	1	342	300	2844.946
8739.92	1	343	300	2844.8
8743.162	1	344	300	2844.653
8747.309	1	345	300	2818.997

8791.825	1	346	300	2858.292
8803.967	1	347	300	2853.805
8807.134	1	348	300	2843.485
8817.512	1	349	300	2803.831
8876.152	1	350	300	2858.637
8887.602	1	351	300	2853.624
8902.943	1	352	300	2865.933
8905.344	1	353	300	2814.057
8965.543	1	354	300	2867.554
8972.424	1	355	300	2871.062
8974.852	1	356	300	2870.079
8976.865	1	357	300	2837.27
9033.799	1	358	300	2881.805
9037.296	1	359	300	2882.342
9042.79	1	360	300	2875.808
9054.162	1	361	300	2847.499
9112.462	1	362	300	2899.935
9116.398	1	363	300	2887.682
9119.27	1	364	300	2876.07
9122.339	1	365	300	2843.021
9172.838	1	366	300	2889.961
9180.288	1	367	300	2859.197
9185.907	1	368	300	2861.988
9212.75	1	369	300	2839.12
9247.587	1	370	300	2870.167
9251.077	1	371	300	2870.013
9254.358	1	372	300	2870.13
9262.157	1	373	300	2833.441
9321.533	1	374	300	2877.478
9325.771	1	375	300	2878.62
9330.309	1	376	300	2879.654
9336.679	1	377	300	2827.847
9385.521	1	378	300	2872.356
9389.049	1	379	300	2872.659
9393.825	1	380	300	2874.602
9395.894	1	381	300	2923.444
9439.171	1	382	300	2958.754
9467.532	1	383	300	2981.384
9469.713	1	384	300	2900.22
9471.868	1	385	300	2834.717
9533.268	1	386	300	2888.591
9535.346	1	387	300	2880.614
9537.646	1	388	300	2876.891
9540.653	1	389	300	2831.104
9583.878	1	390	300	2863.943
9599.118	1	391	300	2875.575
9603.602	1	392	300	2877.024
9644.402	1	393	300	2853.599
9651.743	1	394	300	2858.083
9655.424	1	395	300	2858.579

9661.902	1	396	300	2861.508
9672.937	1	397	300	2809.517
9716.772	1	398	300	2849.855
9720.607	1	399	300	2841.515
9723.639	1	400	300	2841.267
9728.727	1	401	300	2789.406
9761.493	1	402	300	2818.18
9809.167	1	403	300	2861.693
9811.823	1	404	300	2860.86
9814.466	1	405	300	2821.006
9819.33	1	406	300	2814.526
9880.705	1	407	300	2869.258
9883.501	1	408	300	2869.148
9886.297	1	409	300	2820.885
9888.592	1	410	300	2817.013
9936.594	1	411	300	2861.498
9944.815	1	412	300	2866.537
9960.813	1	413	300	2820.353
9965.338	1	414	300	2815.591
10021.28	1	415	300	2868.133
10025.41	1	416	300	2868.307
10027.41	1	417	300	2820.998
10029.57	1	418	300	2819.051
10086.33	1	419	300	2872.392
10090.4	1	420	300	2967.471
10094.69	1	421	300	2824.151
10099.74	1	422	300	2825.292
10141.79	1	423	300	2863.755
10145.51	1	424	300	2962.01
10161.83	1	425	300	3015.121
10205.93	1	426	300	2957.466
10211.95	1	427	300	2957.014
10215.31	1	428	300	2957.248
10221.43	1	429	300	2994.81
10233.44	1	430	300	2954.69
10299.35	1	431	300	2964.703
10309.06	1	432	300	2965.179
10311.92	1	433	300	3008.394
10316.67	1	434	300	2950.671
10365.38	1	435	300	2949.237
10372.27	1	436	300	2948.827
10376.95	1	437	300	2996.812
10380.91	1	438	300	2947.073
10433.56	1	439	300	2945.11
10440.58	1	440	300	2962.123
10443.23	1	441	300	2992.817
10446.3	1	442	300	2943.186
10504.14	1	443	300	2949.835
10506.99	1	444	300	2962.863
10509.37	1	445	300	2966.939

10521.77	1	446	300	2856.034
10575.12	1	447	300	2896.633
10578.7	1	448	300	2895.115
10582.35	1	449	300	2844.738
10586.28	1	450	300	2845.743
10632.75	1	451	300	2888.186
10638.19	1	452	300	2890.704
10652.72	1	453	300	2844.204
10690.33	1	454	300	2878.321
10724.53	1	455	300	2909.483
10732.96	1	456	300	2913.408
10736.49	1	457	300	2865.579
10741.38	1	458	300	2860.948
10805.46	1	459	300	2921.457
10808.23	1	460	300	2921.017
10817.19	1	461	300	2978.59
10820.69	1	462	300	2977.05
10868.87	1	463	300	2921.115
10893.72	1	464	300	2939.666
10912.77	1	465	300	2894.513
10915.54	1	466	300	2894.411
10977.07	1	467	300	2951.38
10979.2	1	468	300	2951.092
10981.15	1	469	300	2909.707
10984.3	1	470	300	2903.865
11042.06	1	471	300	2950.846
11044.8	1	472	300	2947.086
11047.43	1	473	300	2898.373
11050.02	1	474	300	2895.311
11093.91	1	475	300	2935.594
11117.75	1	476	300	2956.511
11122.76	1	477	300	2919.043
11140.39	1	478	300	2920.11
11155.05	1	479	300	2921.339
11158.04	1	480	300	2921.297
11182.67	1	481	300	2904.84
11186.71	1	482	300	2890.361
11229.23	1	483	300	2928.637
11236.1	1	484	300	2931.03
11256.02	1	485	300	2903.288
11259.1	1	486	300	2903.133
11289.81	1	487	300	2929.492
11311.42	1	488	300	2947.329
11316.64	1	489	300	2903.013
11326.09	1	490	300	2909.539
11361.96	1	491	300	2939.845
11368.15	1	492	300	2942.773
11391.38	1	493	300	2917.032
11394.56	1	494	300	2916.301
11450.84	1	495	300	2951.523

11453.82	1	496	300	2951.898
11464.07	1	497	300	2897.874
11467.4	1	498	300	2897.268
11531.03	1	499	300	2956.459
11533.99	1	500	300	2956.565
11539.29	1	501	300	2909.042
11584.05	1	502	300	2950.074
11590.01	1	503	300	2949.789
11594.03	1	504	300	2948.968
11599.15	1	505	300	2916.752
11608.09	1	506	300	2917.093
11657.38	1	507	300	2944.562
11662.18	1	508	300	2945.906
11665.32	1	509	300	2890.78
11676.69	1	510	300	2898.293
11721.77	1	511	300	2940.434
11738.73	1	512	300	2953.915
11741.58	1	513	300	2912.229
11744.89	1	514	300	2912.2
11785.21	1	515	300	2940.63
11789.65	1	516	300	2942.037
11822.51	1	517	300	2919.787
11827.06	1	518	300	2921.265
11849.96	1	519	300	2939.724
11853.74	1	520	300	2940.882
11879.37	1	521	300	2898.328
11900.69	1	522	300	2916.091
11925.35	1	523	300	2937.089
11942.26	1	524	300	2951.127
11945.54	1	525	300	2894.228
11951.42	1	526	300	2895.772
11994.27	1	527	300	2935.947
12016.3	1	528	300	2953.935
12018.8	1	529	300	2918.424
12022.21	1	530	300	2894.638
12069.93	1	531	300	2938.161
12072.27	1	532	300	2937.728
12076.78	1	533	300	2874.266
12081.26	1	534	300	2875.385
12117.26	1	535	300	2907.72
12121.71	1	536	300	2908.85
12146.21	1	537	300	2897.388
12149.31	1	538	300	2862.997
12182.15	1	539	300	2891.289
12184.66	1	540	300	2891.346
12229.29	1	541	300	2907.719
12231.23	1	542	300	2887.136
12249.1	1	543	300	2901.817
12292.2	1	544	300	2941.707
12309.9	1	545	300	2918.602

12311.94	1	546	300	2916.446
12333.5	1	547	300	2925.171
12376.97	1	548	300	2963.141
12381.8	1	549	300	2919.981
12401.19	1	550	300	2915.745
12417.2	1	551	300	2928.808
12472.07	1	552	300	2978.475
12478.34	1	553	300	2936.685
12486.82	1	554	300	2939.816
12490.89	1	555	300	2938.823
12543.52	1	556	300	2987.267
12547.45	1	557	300	2934.652
12551.66	1	558	300	2935.1
12577.07	1	559	300	2947.03
12632.66	1	560	300	2999.004
12637.88	1	561	300	2966.338
12644.05	1	562	300	2960.081
12651.85	1	563	300	2959.987
12718.44	1	564	300	3023.149
12722.99	1	565	300	2991.241
12726.25	1	566	300	2969.423
12727.73	1	567	300	2965.161
12773.17	1	568	300	3006.563
12777.88	1	569	300	2956.13
12794	1	570	300	2968.969
12800.46	1	571	300	2971.458
12859.61	1	572	300	3027.158
12861.83	1	573	300	2984.959
12863.79	1	574	300	2983.321
12869.03	1	575	300	2956.833
12911.06	1	576	300	2994.978
12914.96	1	577	300	2940.117
12923.28	1	578	300	2944.745
12958.09	1	579	300	2976.1
12966.09	1	580	300	2981.222
12970.91	1	581	300	2948.318
12976.23	1	582	300	2939.105
12988.27	1	583	300	2945.458
13050.12	1	584	300	3004.241
13060.73	1	585	300	2962.684
13062.87	1	586	300	2961.869
13066.6	1	587	300	2962.633
13119.04	1	588	300	3010.402
13122.61	1	589	300	2953.728
13125.87	1	590	300	2954.371
13130.11	1	591	300	2955.421
13168.19	1	592	300	2989.375
13175.03	1	593	300	2948.467
13201.41	1	594	300	2971.445
13203.57	1	595	300	2971.024

13257.08	1	596	300	3004.875
13277.91	1	597	300	2993.844
13279.76	1	598	300	2973.991
13281.9	1	599	300	2972.618
13325.06	1	600	300	2997.071
13337.01	1	601	300	2964.68
13345.01	1	602	300	2969.336
13392.88	1	603	300	3002.542
13410.56	1	604	300	3016
13413.1	1	605	300	2954.525
13415.95	1	606	300	2953.966
13446.21	1	607	300	2980.292
13505.89	1	608	300	3037.308
13508.63	1	609	300	2999.965
13512.51	1	610	300	2993.871
13518.39	1	611	300	2981.758
13543.25	1	612	300	2930.279
13567.66	1	613	300	2972.02
13573.17	1	614	300	2900.399
13606.25	1	615	300	2898.327
13619.91	1	616	300	2858.196
13622.67	1	617	300	2879.643
13637.76	1	618	300	2979.6
13644.25	1	619	300	2864.699
13695.44	1	620	300	2844.282
13697.98	1	621	300	2880.413
13701.11	1	622	300	2881.858
13704.1	1	623	300	2863.784
13744.79	1	624	300	2822.23
13765.29	1	625	300	2829.952
13778.52	1	626	300	2891.992
13782.79	1	627	300	2898.547
13829.5	1	628	300	2854.195
13842.55	1	629	300	2855.482
13844.35	1	630	300	2892.261
13846.93	1	631	300	2895.001
13898.29	1	632	300	2846.059
13901.84	1	633	300	2846.413
13903.52	1	634	300	2887.829
13923.85	1	635	300	2890.164
13958.12	1	636	300	2838.935
13976.78	1	637	300	2837.45
13987.15	1	638	300	2892.266
14002.96	1	639	300	2891.4
14010.59	1	640	300	2848.341
14038.89	1	641	300	2955.147

1775982

Average Travel time 2770.642

By conducting several simulation run,
average travel time was found as 2790.0sec

Appendix C-4

Base Data for Simulation in VISSIM

Parameters	Description
Vehicle Acceleration and deceleration functions	VISSIM does not use a single acceleration and deceleration value but uses functions to represent the differences in driver behavior. For each vehicle type there are two acceleration and two deceleration functions represented as graphs.
Desired Speed Distribution	The minimum and maximum values for the desired speed distribution can be entered. Intermediate points can be created by dragging.
Weight Distribution	The weight of vehicle categorized as HGV can be defined as a weight distribution.
Power Distribution	The power of vehicles categorized as HGV can be defined as a power distribution. Along with a weight distribution it affects the driving behavior on lopes.
Color Distribution	The color distribution is used to differentiate various vehicle types.
Vehicle Model Distribution	This distribution defines the variety of vehicle dimensions within a vehicle type.
Dwell Time Distribution	The dwell time distribution is used for dwell times at parking lots, transit stops, stop signs and toll counters.
Model Year Distribution	The model year of vehicles can be defined as a model year distribution.
Mileage Distribution	The mileage of vehicles can be defined as a mileage distribution.
Temperature Distribution	The temperature of the coolant and of a catalytic converter of vehicles can be defined as a temperature distribution.
Vehicle Type, Class and Category	Group of vehicles with similar technical characteristic and physical driving behavior. Typically the following are vehicle types: car, LGV, HGV (truck), articulated Bus, Tram, Bike, and Pedestrian.
Driving Behavior	Both the car following and lane change models are used in VISSIM (The Wiedemann" Approach and Vehicle Following Behavior)
Lane Change	There are basically two kinds of lane changes in VISSIM: Necessary lane change and Free lane change
Lateral Behavior	By default, in VISSIM one vehicle occupies the entire width of one lane. The lateral behavior parameters enable vehicles to travel at different lateral positions and also overtake other vehicles within the same lane if it is wide enough.
Reaction to Amber Signal	These parameters define the vehicle behavior in front of a signal control showing amber.

(Source: VISSIM 4.10 User Manual, 2005)

Appendix C-5

Sample of second by second speed and acceleration of conventional bus obtained from VISSIM

a	v	Veh Nr	t
0.116348	16.83404	1	1
-7.46501	9.369023	1	2
-1.66662	7.702399	1	3
-0.93566	6.766743	1	4
-0.93566	5.831087	1	5
-0.93566	4.895431	1	6
-0.93566	3.959775	1	7
-1.05947	2.900307	1	8
-1.05947	1.84084	1	9
-1.05947	0.781372	1	10
-0.30527	0.476101	1	11
-0.31661	0.159489	1	12
-0.3086	0	1	13
0	0	1	14
0	0	1	15
0.983102	5.521746	2	16
0	0	1	16
0.918295	6.440041	2	17
0	0	1	17
0.844718	7.284759	2	18
0	0	1	18
0.437705	7.722464	2	19
0	0	1	19
-0.83867	6.883796	2	20
0	0	1	20
-0.83867	6.045128	2	21
0	0	1	21
-0.83867	5.20646	2	22
0	0	1	22
-0.83867	4.367792	2	23
0	0	1	23
-0.83867	3.529124	2	24
0	0	1	24
-0.97844	2.550687	2	25
0	0	1	25
-0.97844	1.57225	2	26
0	0	1	26
-0.97844	0.593814	2	27
0	0	1	27
-0.17631	0.417506	2	28
0	0	1	28
-0.24128	0.176228	2	29
0	0	1	29
-0.27011	0	2	30

0	0	1	30
1.010285	5.027874	3	31
0	0	2	31
0	0	1	31
0.949957	5.97783	3	32
0	0	2	32
0	0	1	32
0.87782	6.85565	3	33
0	0	2	33
0	0	1	33
-0.53333	6.322318	3	34
0	0	2	34
0	0	1	34
-0.86295	5.459373	3	35
0	0	2	35
0	0	1	35
-0.86295	4.596428	3	36
0	0	2	36
0	0	1	36
-0.86295	3.733483	3	37
0	0	2	37
0	0	1	37
-0.86295	2.870538	3	38
0	0	2	38
0	0	1	38
-1.16819	1.702344	3	39
0	0	2	39
0	0	1	39
-1.16819	0.534151	3	40
0	0	2	40
0	0	1	40
-0.14266	0.391492	3	41
0	0	2	41
0	0	1	41
-0.19375	0.197745	3	42
0	0	2	42
0	0	1	42
-0.23564	0	3	43
0	0	2	43
0	0	1	43
0	0	3	44
0	0	2	44
1.157184	1.157184	1	44
0	0	3	45
0	0	2	45
1.099279	2.256464	1	45
1.101092	3.995151	4	46
0	0	3	46
0	0	2	46
1.044271	3.300735	1	46

1.058969	5.054121	4	47
0	0	3	47
0	0	2	47
0.986957	4.287692	1	47
0.453066	5.507187	4	48
0	0	3	48
0	0	2	48
0.928022	5.215714	1	48
-0.87136	4.635828	4	49
0	0	3	49
0	0	2	49
0.872606	6.08832	1	49
-0.87136	3.76447	4	50
0	0	3	50
0	0	2	50
0.802833	6.891153	1	50
-0.87136	2.893111	4	51
0	0	3	51
0	0	2	51
0.738507	7.62966	1	51
-1.18458	1.708533	4	52
0	0	3	52
0	0	2	52
0.682415	8.312076	1	52
-1.18458	0.523955	4	53
0	0	3	53
0	0	2	53
0.652328	8.964403	1	53
-0.13726	0.386691	4	54
0	0	3	54
0	0	2	54
0.623568	9.587971	1	54
-0.18726	0.199426	4	55
0	0	3	55
1.22725	1.22725	2	55
0.596075	10.18405	1	55
-0.23042	0	4	56
0	0	3	56
1.165838	2.393089	2	56
0.569795	10.75384	1	56
0	0	4	57
0	0	3	57
1.1075	3.500588	2	57
0.542145	11.29599	1	57
0	0	4	58
0	0	3	58
1.045088	4.545677	2	58
0.505419	11.8014	1	58
0	0	4	59
1.223318	1.223318	3	59

0.982682	5.528359	2	59
0.47118	12.27258	1	59
0	0	4	60
1.162104	2.385422	3	60
0.917765	6.446125	2	60
0.439261	12.71185	1	60
1.129924	3.036932	5	61
0	0	4	61
1.103952	3.489374	3	61
0.84423	7.290355	2	61
0.409505	13.12135	1	61
1.034872	4.071805	5	62
0	0	4	62
1.041826	4.5312	3	62
0.776587	8.066941	2	62
0.381764	13.50311	1	62
-0.87697	3.194833	5	63
0	0	4	63
0.979615	5.510815	3	63
0.73189	8.798831	2	63
0.361798	13.86491	1	63
-1.09334	2.101489	5	64
0	0	4	64
0.91524	6.426054	3	64
0.697785	9.496616	2	64
0.348256	14.21317	1	64
-1.09334	1.008146	5	65
0	0	4	65
0.841906	7.267961	3	65
0.66527	10.16189	2	65
0.335221	14.54839	1	65
-0.50818	0.499967	5	66
0	0	4	66
0.774449	8.04241	3	66
0.634269	10.79615	2	66
0.322673	14.87106	1	66
-0.24539	0.254573	5	67
0	0	4	67
0.729171	8.771582	3	67
0.601241	11.3974	2	67
0.310596	15.18166	1	67
-0.2983	0	5	68
0	0	4	68
0.695296	9.466877	3	68
0.559233	11.95663	2	68
0.29897	15.48063	1	68
0	0	5	69
0	0	4	69
0.662995	10.12987	3	69
0.520159	12.47679	2	69

0.28778	15.76841	1	69
0	0	5	70
0	0	4	70
0.632194	10.76207	3	70
0.483816	12.9606	2	70
0.277008	16.04542	1	70
0	0	5	71
0	0	4	71
0.600142	11.36221	3	71
0.450012	13.41062	2	71
0.26144	16.30686	1	71
0	0	5	72
0	0	4	72
0.558282	11.92049	3	72
0.421657	13.83227	2	72
0.241739	16.5486	1	72
0	0	5	73
0	0	4	73
0.519342	12.43983	3	73
0.404956	14.23723	2	73
0.223522	16.77212	1	73
0	0	5	74
0	0	4	74
0.483117	12.92295	3	74
0.388916	14.62615	2	74
0.206678	16.9788	1	74
0	0	5	75
0	0	4	75
0.44942	13.37237	3	75
0.373512	14.99966	2	75
0.191104	17.1699	1	75
0	0	5	76
0	0	4	76
0.420002	13.79237	3	76
0.358718	15.35838	2	76
0.176703	17.3466	1	76
0	0	5	77
0	0	4	77
0.403418	14.19579	3	77
0.34451	15.70289	2	77
0.163387	17.50999	1	77
0	0	5	78
1.279823	1.279823	4	78
0.387489	14.58328	3	78
0.330865	16.03375	2	78
0.151075	17.66106	1	78
0	0	5	79
1.215781	2.495604	4	79
0.372189	14.95547	3	79
0.31238	16.34613	2	79

0.13969	17.80075	1	79
1.204397	1.204397	5	80
1.154943	3.650548	4	80
0.357493	15.31296	3	80
0.286608	16.63274	2	80
0.129163	17.92992	1	80
0.910668	2.115065	5	81
1.088707	4.739254	4	81
0.343377	15.65634	3	81
0.262962	16.8957	2	81
0.1217	18.05162	1	81
1.119513	3.234578	5	82
1.023696	5.762951	4	82
0.329818	15.98615	3	82
0.241267	17.13697	2	82
0.119306	18.17092	1	82
-0.19862	4.05623	6	83
1.059074	4.293652	5	83
0.951542	6.714493	4	83
0.313479	16.29963	3	83
0.221362	17.35833	2	83
0.11696	18.28788	1	83
0.727204	4.783434	6	84
0.995832	5.289485	5	84
0.8753	7.589794	4	84
0.287741	16.58737	3	84
0.203099	17.56143	2	84
0.114659	18.40254	1	84
0.5714	5.354834	6	85
0.935006	6.22449	5	85
0.80661	8.396404	4	85
0.264117	16.85149	3	85
0.186342	17.74777	2	85
0.112405	18.51495	1	85
0.644636	5.99947	6	86
0.860089	7.084579	5	86
0.767487	9.163891	4	86
0.242433	17.09393	3	86
0.170969	17.91874	2	86
0.110194	18.62514	1	86
0.797491	6.79696	6	87
-0.59036	6.494223	5	87
0.730261	9.894152	4	87
0.222529	17.31645	3	87
0.158697	18.07743	2	87
0.108027	18.73317	1	87
-0.02231	6.774647	6	88
-0.87697	5.617251	5	88
0.69484	10.58899	4	88
0.204259	17.52071	3	88

0.155443	18.23288	2	88
0.105902	18.83907	1	88
-0.34477	6.429878	6	89
-0.87697	4.740279	5	89
0.661138	11.25013	4	89
0.187489	17.7082	3	89
0.152256	18.38514	2	89
0.103819	18.94289	1	89
-1.20072	5.229162	6	90
-0.87697	3.863307	5	90
0.615222	11.86535	4	90
0.172096	17.8803	3	90
0.149135	18.53427	2	90
0.101778	19.04467	1	90
-0.66395	6.387703	7	91
-0.93278	4.296382	6	91
-0.87697	2.986335	5	91
0.571256	12.43661	4	91
0.157966	18.03826	3	91
0.146077	18.68035	2	91
0.099776	19.14444	1	91
-0.12705	6.260655	7	92
-1.0307	3.265681	6	92
-1.13377	1.852569	5	92
0.530432	12.96704	4	92
0.154188	18.19245	3	92
0.143082	18.82343	2	92
0.097814	19.24226	1	92
-0.79325	5.467408	7	93
-1.37199	1.893689	6	93
-1.13377	0.718802	5	93
0.492525	13.45956	4	93
0.151034	18.34348	3	93
0.140149	18.96358	2	93
0.09589	19.33815	1	93
-0.98246	4.484953	7	94
-1.25706	0.636626	6	94
-0.25834	0.460464	5	94
0.46189	13.92145	4	94
0.147945	18.49143	3	94
0.137275	19.10085	2	94
0.094004	19.43215	1	94
0.907264	5.392217	7	95
0.968202	1.604828	6	95
-0.25987	0.200597	5	95
0.442842	14.3643	4	95
0.144919	18.63635	3	95
0.134461	19.23531	2	95
0.092155	19.52431	1	95
-0.49819	4.894027	7	96

-0.98593	0.618895	6	96
-0.28425	0	5	96
0.42458	14.78888	4	96
0.141954	18.7783	3	96
0.131704	19.36702	2	96
0.090343	19.61465	1	96
-0.44919	4.44484	7	97
-0.40391	0.214988	6	97
0	0	5	97
0.40707	15.19595	4	97
0.13905	18.91735	3	97
0.129004	19.49602	2	97
0.088566	19.70322	1	97
-0.871	3.573839	7	98
-0.36604	0	6	98
0	0	5	98
0.390283	15.58623	4	98
0.136206	19.05356	3	98
-0.18712	19.3089	2	98
0.086824	19.79004	1	98
-1.15738	2.41646	7	99
0	0	6	99
0	0	5	99
0.374187	15.96042	4	99
0.13342	19.18698	3	99
-0.18712	19.12178	2	99
0.085117	19.87516	1	99
-1.15738	1.259081	7	100
0	0	6	100
0	0	5	100
0.356455	16.31687	4	100
0.130691	19.31767	3	100
-0.18712	18.93466	2	100
0.083443	19.9586	1	100
-0.79264	0.466438	7	101
0	0	6	101
0	0	5	101
0.326005	16.64288	4	101
0.128018	19.44569	3	101
-0.18712	18.74754	2	101
0.081802	20.0404	1	101
-0.17993	0.286509	7	102
0	0	6	102
0	0	5	102
0.298156	16.94103	4	102
0.125399	19.57109	3	102
-0.18712	18.56042	2	102
0.080193	20.1206	1	102
-0.27213	0.014378	7	103
0	0	6	103

0	0	5	103
0.272686	17.21372	4	103
0.122834	19.69392	3	103
0.145541	18.70596	2	103
0.078616	20.19921	1	103
-0.01438	0	7	104
0	0	6	104
0	0	5	104
0.249392	17.46311	4	104
0.120321	19.81424	3	104
0.142557	18.84851	2	104
0.07707	20.27628	1	104
0	0	7	105
0	0	6	105
0	0	5	105
0.228088	17.6912	4	105
0.11786	19.9321	3	105
0.139634	18.98815	2	105
-0.11635	20.15993	1	105
1.079247	4.171898	8	106
0	0	7	106
0	0	6	106
0	0	5	106
0.208604	17.8998	4	106
0.115449	20.04755	3	106
0.136772	19.12492	2	106
-0.72691	19.43302	1	106
1.014801	5.186698	8	107
0	0	7	107
0	0	6	107
0	0	5	107
0.191393	18.0912	4	107
0.113088	20.16064	3	107
0.133968	19.25889	2	107
-0.93566	18.49737	1	107
0.08146	5.268158	8	108
0	0	7	108
0	0	6	108
0	0	5	108
0.185998	18.27719	4	108
0.110775	20.27141	3	108
0.131221	19.39011	2	108
-0.93566	17.56171	1	108
-0.80323	4.464928	8	109
0	0	7	109
0	0	6	109
0	0	5	109
0.180755	18.45795	4	109
0.108509	20.37992	3	109
0.128531	19.51864	2	109

Sample of second by second fuel consumption estimation for conventional bus

Equation for calculating VSP for transit buses:

$$VSP = V \times (a + g \times \sin(\text{grade}) + 0.092) + 0.00021 \times V^3$$

Where VSP is the Vehicle Specific Power (kw/ton); v is instantaneous speed at which the vehicle is traveling (m/s); a, is instantaneous acceleration of the vehicle (m/s²); grade is the instantaneous road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient.

EXCEL code for VSP Classification

=IF(E2<=0,"1",IF(AND(E2>0,E2<2),"2",IF(AND(E2>=2,E2<4),"3",IF(AND(E2>=4,E2<6),"4",IF(AND(E2>=6,E2<8),"5",IF(AND(E2>=8,E2<10),"6",IF(AND(E2>=10,E2<13),"7","8"))))))))

EXCEL code for second by second fuel consumption estimation based on VSP bin

=IF(F2="1","1",IF(F2="2","3.5",IF(F2="3","4.8",IF(F2="4","5.2",IF(F2="5","8.2",IF(F2="6","9.5",IF(F2="7","10.8","11.9"))))))))

a	vMS	VehNr	t	VSP VSP bin	Fuel Cons.
0.593724	7.234189	10	169	5.040161 4	5.2
-0.10775	7.126437	10	170	-0.03625 1	1
-0.74878	6.377656	10	171	-4.13425 1	1
-0.91942	5.458236	10	172	-4.48211 1	1
-0.95472	4.503515	10	173	-3.8661 1	1
-0.97955	3.523963	10	174	-3.11851 1	1
-1.24481	2.279151	10	175	-2.62495 1	1
-1.2158	1.063348	10	176	-1.19474 1	1
0.51841	1.581759	10	177	0.966353 2	3.5
-0.51139	1.070364	10	178	-0.44865 1	1
-0.80125	0.269118	10	179	-0.19087 1	1
-0.40907	0	10	180	0 1	1
0	0	10	181	0 1	1
0	0	10	182	0 1	1
0	0	10	183	0 1	1
0	0	10	184	0 1	1
0	0	10	185	0 1	1
0	0	10	186	0 1	1
0	0	10	187	0 1	1
0	0	10	188	0 1	1

0	0	10	189	0 1	1
0	0	10	190	0 1	1
0	0	10	191	0 1	1
0	0	10	192	0 1	1
0	0	10	193	0 1	1
0	0	10	194	0 1	1
0	0	10	195	0 1	1
0	0	10	196	0 1	1
0	0	10	197	0 1	1
0	0	10	198	0 1	1
0	0	10	199	0 1	1
0	0	10	200	0 1	1
0	0	10	201	0 1	1
0	0	10	202	0 1	1
0	0	10	203	0 1	1
0	0	10	204	0 1	1
0	0	10	205	0 1	1
0	0	10	206	0 1	1
0	0	10	207	0 1	1
0	0	10	208	0 1	1
0	0	10	209	0 1	1
0	0	10	210	0 1	1
0	0	10	211	0 1	1
0	0	10	212	0 1	1
0	0	10	213	0 1	1
0	0	10	214	0 1	1
0	0	10	215	0 1	1
0	0	10	216	0 1	1
0	0	10	217	0 1	1
0	0	10	218	0 1	1
0	0	10	219	0 1	1
0	0	10	220	0 1	1
1.318133	1.318133	10	221	1.859222 2	3.5
1.252173	2.570306	10	222	3.458502 3	4.8
1.189514	3.75982	10	223	4.829425 4	5.2
1.120491	4.880311	10	224	5.941744 4	5.2
1.053583	5.933894	10	225	6.841642 5	8.2
0.976155	6.910048	10	226	7.45029 5	8.2
0.897941	7.80799	10	227	7.829411 5	8.2
0.833968	8.641958	10	228	8.137717 6	9.5
0.792355	9.434313	10	229	8.519624 6	9.5
0.752819	10.18713	10	230	8.82829 6	9.5
0.715255	10.90239	10	231	9.073138 6	9.5
0.67376	11.57615	10	232	9.190318 6	9.5
0.624829	12.20098	10	233	9.127429 6	9.5
0.579451	12.78043	10	234	9.019816 6	9.5
0.537369	13.3178	10	235	8.877848 6	9.5
0.49862	13.81642	10	236	8.714125 6	9.5
0.477465	14.29388	10	237	8.75316 6	9.5
0.457207	14.75109	10	238	8.775452 6	9.5
0.437809	15.1889	10	239	8.783075 6	9.5
0.419233	15.60813	10	240	8.777892 6	9.5

0.401446	16.00958	10	241	8.761569 6	9.5
0.379903	16.38948	10	242	8.658754 6	9.5
0.346857	16.73634	10	243	8.329325 6	9.5
0.316686	17.05302	10	244	8.010747 6	9.5
0.289139	17.34216	10	245	7.70507 5	8.2
0.263989	17.60615	10	246	7.413667 5	8.2
0.241026	17.84718	10	247	7.137364 5	8.2
0.220061	18.06724	10	248	6.876568 5	8.2
0.210098	18.27733	10	249	6.803758 5	8.2
0.202654	18.47999	10	250	6.770526 5	8.2
0.195473	18.67546	10	251	6.736519 5	8.2
0.188546	18.86401	10	252	6.701908 5	8.2
0.181865	19.04587	10	253	6.66685 5	8.2
0.175421	19.22129	10	254	6.631484 5	8.2
0.169205	19.3905	10	255	6.595934 5	8.2
0.163209	19.55371	10	256	6.560313 5	8.2
0.157426	19.71113	10	257	6.524723 5	8.2
0.151848	19.86298	10	258	6.489252 5	8.2
0.146467	20.00945	10	259	6.453979 5	8.2
0.141277	20.15073	10	260	6.418975 5	8.2
0.136271	20.287	10	261	6.384301 5	8.2
0.131442	20.41844	10	262	6.350014 5	8.2
0.126785	20.54523	10	263	6.31616 5	8.2
0.122292	20.66752	10	264	6.282781 5	8.2
0.117959	20.78548	10	265	6.249913 5	8.2
0.113779	20.89926	10	266	6.217585 5	8.2
0.109747	21.009	10	267	6.185825 5	8.2
0.105859	21.11486	10	268	6.154654 5	8.2
0.102108	21.21697	10	269	6.12409 5	8.2
0.098489	21.31546	10	270	6.094147 5	8.2
0.095291	21.41075	10	271	6.071225 5	8.2
0.092664	21.50341	10	272	6.058958 5	8.2
0.090109	21.59352	10	273	6.046786 5	8.2
0.087624	21.68115	10	274	6.034719 5	8.2
0.085208	21.76636	10	275	6.022769 5	8.2
0.082859	21.84921	10	276	6.010945 5	8.2
0.080574	21.92979	10	277	5.999254 4	5.2
-1.51056	20.41923	10	278	-27.1781 1	1
-3.25248	17.16674	10	279	-53.1928 1	1
-1.12621	16.04053	10	280	-15.7225 1	1
-0.60943	15.43111	10	281	-7.21283 1	1
-1.38729	14.04382	10	282	-17.6091 1	1
-0.60811	13.43571	10	283	-6.42492 1	1
-0.80442	12.6313	10	284	-8.57551 1	1
-0.76385	11.86745	10	285	-7.62216 1	1
-0.77071	11.09674	10	286	-7.24448 1	1
-0.77205	10.32469	10	287	-6.79015 1	1
-0.77205	9.552649	10	288	-6.31319 1	1
-0.77205	8.780602	10	289	-5.82906 1	1
-0.77205	8.008554	10	290	-5.33833 1	1
-0.77205	7.236508	10	291	-4.84158 1	1
-0.77205	6.464461	10	292	-4.33941 1	1

-0.77205	5.692414	10	293	-3.83237 1	1
-0.77205	4.920367	10	294	-3.32106 1	1
-0.77205	4.148321	10	295	-2.80606 1	1
-0.77205	3.376274	10	296	-2.28794 1	1
-0.77205	2.604227	10	297	-1.76729 1	1
-1.04598	1.558245	10	298	-1.48574 1	1
-1.04598	0.512263	10	299	-0.48866 1	1
-0.13121	0.381057	10	300	-0.01493 1	1
-0.19927	0.181785	10	301	-0.0195 1	1
-0.23973	0	10	302	0 1	1
0	0	10	303	0 1	1
0	0	10	304	0 1	1
0	0	10	305	0 1	1
0	0	10	306	0 1	1
0	0	10	307	0 1	1
0	0	10	308	0 1	1
0	0	10	309	0 1	1
0	0	10	310	0 1	1
0	0	10	311	0 1	1
0	0	10	312	0 1	1
0	0	10	313	0 1	1
0	0	10	314	0 1	1
0	0	10	315	0 1	1
0	0	10	316	0 1	1
0	0	10	317	0 1	1
0	0	10	318	0 1	1
0	0	10	319	0 1	1
1.318133	1.318133	10	320	1.859222 2	3.5
1.252173	2.570306	10	321	3.458502 3	4.8
1.189514	3.75982	10	322	4.829425 4	5.2
1.120491	4.880311	10	323	5.941744 4	5.2
1.053583	5.933894	10	324	6.841642 5	8.2
0.976155	6.910048	10	325	7.45029 5	8.2
0.897941	7.80799	10	326	7.829411 5	8.2
0.833968	8.641958	10	327	8.137717 6	9.5
0.792355	9.434313	10	328	8.519624 6	9.5
0.752819	10.18713	10	329	8.82829 6	9.5
0.715255	10.90239	10	330	9.073138 6	9.5
0.67376	11.57615	10	331	9.190318 6	9.5
0.624829	12.20098	10	332	9.127429 6	9.5
0.579451	12.78043	10	333	9.019816 6	9.5
0.537369	13.3178	10	334	8.877848 6	9.5
0.49862	13.81642	10	335	8.714125 6	9.5
0.477465	14.29388	10	336	8.75316 6	9.5
0.457207	14.75109	10	337	8.775452 6	9.5
0.437809	15.1889	10	338	8.783075 6	9.5
0.419233	15.60813	10	339	8.777892 6	9.5
0.401446	16.00958	10	340	8.761569 6	9.5
-0.01873	15.99084	10	341	2.030308 3	4.8
-0.05285	15.938	10	342	1.474207 2	3.5
-0.58535	15.35265	10	343	-6.81427 1	1
-0.77205	14.5806	10	344	-9.26455 1	1

-0.77205	13.80856	10	345	-8.83754	1
-0.77205	13.03651	10	346	-8.40017	1
-0.77205	12.26446	10	347	-7.953	1
-0.77205	11.49242	10	348	-7.49663	1
-0.77205	10.72037	10	349	-7.03162	1
-0.77205	9.948321	10	350	-6.55856	1
-0.77205	9.176274	10	351	-6.07803	1
-0.77205	8.404228	10	352	-5.59061	1
-0.77205	7.632181	10	353	-5.09688	1
-0.95808	6.674097	10	354	-5.7179	1
-1.48028	5.193817	10	355	-7.18105	1
-2.90657	2.287251	10	356	-6.43511	1
-0.18125	2.105999	10	357	-0.186	1
-0.1106	1.995396	10	358	-0.03545	1
-0.03559	1.959811	10	359	0.112142	2
0.210476	2.170287	10	360	0.658608	2
1.209531	3.379819	10	361	4.407048	4
1.143183	4.523001	10	362	5.606163	4
1.074919	5.59792	10	363	6.569157	5
1.003075	6.600995	10	364	7.288982	5
-0.07985	6.521146	10	365	0.137479	2
-0.14785	6.373292	10	366	-0.30161	1
-1.27134	5.101951	10	367	-5.98905	1
-1.13329	3.968665	10	368	-4.11939	1
-1.98809	1.980573	10	369	-3.75372	1
-0.02045	1.960126	10	370	0.141836	2
0.877185	2.837312	10	371	2.754678	3
-1.96729	0.870024	10	372	-1.63141	1
0.889455	1.759479	10	373	1.727994	2
-1.54788	0.211596	10	374	-0.30806	1
-0.06749	0.144109	10	375	0.003533	2
-0.11971	0.024398	10	376	-0.00068	1
-0.0244	0	10	377	0	1
0	0	10	378	0	1
0	0	10	379	0	1
0	0	10	380	0	1
0	0	10	381	0	1
0	0	10	382	0	1
0	0	10	383	0	1
0	0	10	384	0	1
0	0	10	385	0	1
0	0	10	386	0	1
0	0	10	387	0	1
0	0	10	388	0	1
0	0	10	389	0	1
0	0	10	390	0	1
0	0	10	391	0	1
0	0	10	392	0	1
0	0	10	393	0	1
0	0	10	394	0	1
0	0	10	395	0	1
0	0	10	396	0	1

0	0	10	397	0 1	1
0	0	10	398	0 1	1
0	0	10	399	0 1	1
0	0	10	400	0 1	1
0	0	10	401	0 1	1
0	0	10	402	0 1	1
0	0	10	403	0 1	1
0	0	10	404	0 1	1
0	0	10	405	0 1	1
0	0	10	406	0 1	1
0	0	10	407	0 1	1
0	0	10	408	0 1	1
0	0	10	409	0 1	1
0	0	10	410	0 1	1
0	0	10	411	0 1	1
0	0	10	412	0 1	1
0	0	10	413	0 1	1
0	0	10	414	0 1	1
1.318133	1.318133	10	415	1.859222 2	3.5
1.252173	2.570306	10	416	3.458502 3	4.8
1.189514	3.75982	10	417	4.829425 4	5.2
1.120491	4.880311	10	418	5.941744 4	5.2
1.053583	5.933894	10	419	6.841642 5	8.2
0.976155	6.910048	10	420	7.45029 5	8.2
0.897941	7.80799	10	421	7.829411 5	8.2
0.833968	8.641958	10	422	8.137717 6	9.5
0.792355	9.434313	10	423	8.519624 6	9.5
0.752819	10.18713	10	424	8.82829 6	9.5
0.715255	10.90239	10	425	9.073138 6	9.5
0.67376	11.57615	10	426	9.190318 6	9.5
0.624829	12.20098	10	427	9.127429 6	9.5
0.579451	12.78043	10	428	9.019816 6	9.5
0.537369	13.3178	10	429	8.877848 6	9.5
0.49862	13.81642	10	430	8.714125 6	9.5
0.477465	14.29388	10	431	8.75316 6	9.5
0.457207	14.75109	10	432	8.775452 6	9.5
0.437809	15.1889	10	433	8.783075 6	9.5
0.419233	15.60813	10	434	8.777892 6	9.5
0.401446	16.00958	10	435	8.761569 6	9.5
0.379903	16.38948	10	436	8.658754 6	9.5
0.346857	16.73634	10	437	8.329325 6	9.5
0.316686	17.05302	10	438	8.010747 6	9.5
0.289139	17.34216	10	439	7.70507 5	8.2
0.263989	17.60615	10	440	7.413667 5	8.2
0.241026	17.84718	10	441	7.137364 5	8.2
0.220061	18.06724	10	442	6.876568 5	8.2
0.210098	18.27733	10	443	6.803758 5	8.2
0.202654	18.47999	10	444	6.770526 5	8.2
0.195473	18.67546	10	445	6.736519 5	8.2
0.188546	18.86401	10	446	6.701908 5	8.2
0.181865	19.04587	10	447	6.66685 5	8.2
0.175421	19.22129	10	448	6.631484 5	8.2

0.169205	19.3905	10	449	6.595934 5	8.2
0.163209	19.55371	10	450	6.560313 5	8.2
0.157426	19.71113	10	451	6.524723 5	8.2
0.151848	19.86298	10	452	6.489252 5	8.2
0.146467	20.00945	10	453	6.453979 5	8.2
0.141277	20.15073	10	454	6.418975 5	8.2
0.136271	20.287	10	455	6.384301 5	8.2
0.131442	20.41844	10	456	6.350014 5	8.2
0.126785	20.54523	10	457	6.31616 5	8.2
0.122292	20.66752	10	458	6.282781 5	8.2
0.117959	20.78548	10	459	6.249913 5	8.2
0.113779	20.89926	10	460	6.217585 5	8.2
0.109747	21.009	10	461	6.185825 5	8.2
0.105859	21.11486	10	462	6.154654 5	8.2
0.102108	21.21697	10	463	6.12409 5	8.2
0.098489	21.31546	10	464	6.094147 5	8.2
0.095291	21.41075	10	465	6.071225 5	8.2
0.092664	21.50341	10	466	6.058958 5	8.2
0.090109	21.59352	10	467	6.046786 5	8.2
0.087624	21.68115	10	468	6.034719 5	8.2
0.085208	21.76636	10	469	6.022769 5	8.2
0.082859	21.84921	10	470	6.010945 5	8.2
0.080574	21.92979	10	471	5.999254 4	5.2
0.078352	22.00814	10	472	5.987705 4	5.2
0.076192	22.08433	10	473	5.976303 4	5.2
0.074091	22.15842	10	474	5.965055 4	5.2
-0.26301	21.89541	10	475	-1.54 1	1
-0.26301	21.6324	10	476	-1.5735 1	1
-0.26301	21.36939	10	477	-1.60513 1	1
-0.26301	21.10638	10	478	-1.63489 1	1
-0.26301	20.84337	10	479	-1.66281 1	1
0.111728	20.9551	10	480	6.201495 5	8.2
-0.4118	20.5433	10	481	-4.74913 1	1
-2.77975	17.76355	10	482	-46.5669 1	1
-0.77205	16.9915	10	483	-10.5248 1	1
-0.77205	16.21945	10	484	-10.1339 1	1
-0.77205	15.44741	10	485	-9.73088 1	1
-0.77205	14.67536	10	486	-9.31621 1	1
-0.77205	13.90331	10	487	-8.89052 1	1
-0.77205	13.13126	10	488	-8.45439 1	1
-1.19119	11.94007	10	489	-12.767 1	1
-1.25051	10.68956	10	490	-12.1275 1	1
-0.88639	9.803167	10	491	-7.58974 1	1
-0.73858	9.06459	10	492	-5.70455 1	1
-0.75147	8.313119	10	493	-5.36161 1	1
-0.76919	7.543927	10	494	-5.01853 1	1
-0.77205	6.77188	10	495	-4.53998 1	1
-0.56898	6.202901	10	496	-2.90853 1	1
-0.5708	5.632105	10	497	-2.65911 1	1
-0.29829	5.333815	10	498	-1.06845 1	1
-0.09379	5.240022	10	499	0.02082 2	3.5
-0.00266	5.237361	10	500	0.498071 2	3.5

1.031964	6.269325	10	501	7.098243	5	8.2
0.949279	7.218604	10	502	7.595568	5	8.2
-0.08938	7.12922	10	503	0.09474	2	3.5
-0.15331	6.975909	10	504	-0.35641	1	1
-0.2372	6.738706	10	505	-0.91422	1	1
-1.1061	5.632603	10	506	-5.67451	1	1
-2.24804	3.38456	10	507	-7.28911	1	1
-0.15125	3.233311	10	508	-0.18447	1	1
-1.55139	1.681916	10	509	-2.45358	1	1
0.26301	1.944927	10	510	0.692014	2	3.5
0.17465	2.119576	10	511	0.567184	2	3.5
-1.06221	1.057362	10	512	-1.02562	1	1
-0.55901	0.498355	10	513	-0.23271	1	1
-0.29165	0.206704	10	514	-0.04127	1	1
-0.30443	0	10	515	0	1	1
0	0	10	516	0	1	1
0	0	10	517	0	1	1
0	0	10	518	0	1	1
0	0	10	519	0	1	1
0	0	10	520	0	1	1
0	0	10	521	0	1	1
0	0	10	522	0	1	1
0	0	10	523	0	1	1
0	0	10	524	0	1	1
0	0	10	525	0	1	1
0	0	10	526	0	1	1
0	0	10	527	0	1	1
0	0	10	528	0	1	1
0	0	10	529	0	1	1
0	0	10	530	0	1	1
0	0	10	531	0	1	1
0	0	10	532	0	1	1
0	0	10	533	0	1	1
0	0	10	534	0	1	1
0	0	10	535	0	1	1
0	0	10	536	0	1	1
0	0	10	537	0	1	1
0	0	10	538	0	1	1
0	0	10	539	0	1	1
0	0	10	540	0	1	1
0	0	10	541	0	1	1
0	0	10	542	0	1	1
0	0	10	543	0	1	1
0	0	10	544	0	1	1
0	0	10	545	0	1	1
0	0	10	546	0	1	1
0	0	10	547	0	1	1
0	0	10	548	0	1	1
0	0	10	549	0	1	1
0	0	10	550	0	1	1
0	0	10	551	0	1	1
0	0	10	552	0	1	1

0	0	10	553	0 1	1
0	0	10	554	0 1	1
0	0	10	555	0 1	1
0	0	10	556	0 1	1
0	0	10	557	0 1	1
0	0	10	558	0 1	1
0	0	10	559	0 1	1
0	0	10	560	0 1	1
0	0	10	561	0 1	1
1.318133	1.318133	10	562	1.859222 2	3.5
1.252173	2.570306	10	563	3.458502 3	4.8
1.189514	3.75982	10	564	4.829425 4	5.2
1.120491	4.880311	10	565	5.941744 4	5.2
1.053583	5.933894	10	566	6.841642 5	8.2
0.976155	6.910048	10	567	7.45029 5	8.2
0.897941	7.80799	10	568	7.829411 5	8.2
0.833968	8.641958	10	569	8.137717 6	9.5
0.792355	9.434313	10	570	8.519624 6	9.5
0.752819	10.18713	10	571	8.82829 6	9.5
0.715255	10.90239	10	572	9.073138 6	9.5
0.67376	11.57615	10	573	9.190318 6	9.5
0.624829	12.20098	10	574	9.127429 6	9.5
0.579451	12.78043	10	575	9.019816 6	9.5
0.537369	13.3178	10	576	8.877848 6	9.5
0.49862	13.81642	10	577	8.714125 6	9.5
0.477465	14.29388	10	578	8.75316 6	9.5
0.457207	14.75109	10	579	8.775452 6	9.5
0.437809	15.1889	10	580	8.783075 6	9.5
0.419233	15.60813	10	581	8.777892 6	9.5
0.401446	16.00958	10	582	8.761569 6	9.5
0.379903	16.38948	10	583	8.658754 6	9.5
0.346857	16.73634	10	584	8.329325 6	9.5
0.316686	17.05302	10	585	8.010747 6	9.5
0.289139	17.34216	10	586	7.70507 5	8.2
0.263989	17.60615	10	587	7.413667 5	8.2
0.241026	17.84718	10	588	7.137364 5	8.2
0.220061	18.06724	10	589	6.876568 5	8.2
0.210098	18.27733	10	590	6.803758 5	8.2
0.202654	18.47999	10	591	6.770526 5	8.2
0.195473	18.67546	10	592	6.736519 5	8.2
0.188546	18.86401	10	593	6.701908 5	8.2
0.181865	19.04587	10	594	6.66685 5	8.2
0.175421	19.22129	10	595	6.631484 5	8.2
0.169205	19.3905	10	596	6.595934 5	8.2
0.163209	19.55371	10	597	6.560313 5	8.2
0.157426	19.71113	10	598	6.524723 5	8.2
0.151848	19.86298	10	599	6.489252 5	8.2
0.146467	20.00945	10	600	6.453979 5	8.2
0.141277	20.15073	10	601	6.418975 5	8.2
0.136271	20.287	10	602	6.384301 5	8.2
0.131442	20.41844	10	603	6.350014 5	8.2
0.126785	20.54523	10	604	6.31616 5	8.2

0.122292	20.66752	10	605	6.282781 5	8.2
0.117959	20.78548	10	606	6.249913 5	8.2
0.113779	20.89926	10	607	6.217585 5	8.2
0.109747	21.009	10	608	6.185825 5	8.2
0.105859	21.11486	10	609	6.154654 5	8.2
0.102108	21.21697	10	610	6.12409 5	8.2
0.098489	21.31546	10	611	6.094147 5	8.2
0.095291	21.41075	10	612	6.071225 5	8.2
0.092664	21.50341	10	613	6.058958 5	8.2
0.090109	21.59352	10	614	6.046786 5	8.2
0.087624	21.68115	10	615	6.034719 5	8.2
0.085208	21.76636	10	616	6.022769 5	8.2
0.082859	21.84921	10	617	6.010945 5	8.2
0.080574	21.92979	10	618	5.999254 4	5.2
0.078352	22.00814	10	619	5.987705 4	5.2
0.076192	22.08433	10	620	5.976303 4	5.2
0.074091	22.15842	10	621	5.965055 4	5.2
-0.26301	21.89541	10	622	-1.54 1	1
-0.26301	21.6324	10	623	-1.5735 1	1
-0.26301	21.36939	10	624	-1.60513 1	1
-0.26301	21.10638	10	625	-1.63489 1	1
-0.26301	20.84337	10	626	-1.66281 1	1
0.111728	20.9551	10	627	6.201495 5	8.2
0.107769	21.06287	10	628	6.170029 5	8.2
0.10395	21.16682	10	629	6.139162 5	8.2
0.100266	21.26709	10	630	6.10891 5	8.2
0.096714	21.3638	10	631	6.079285 5	8.2
0.093958	21.45776	10	632	6.065034 5	8.2
0.091368	21.54913	10	633	6.052813 5	8.2
0.088848	21.63797	10	634	6.040693 5	8.2
0.086399	21.72437	10	635	6.028684 5	8.2
0.084016	21.80839	10	636	6.016796 5	8.2
0.0817	21.89009	10	637	6.005038 5	8.2
0.079447	21.96954	10	638	5.993417 4	5.2
0.077257	22.04679	10	639	5.981942 4	5.2
0.075126	22.12192	10	640	5.970617 4	5.2
0.073055	22.19497	10	641	5.959448 4	5.2
-0.26301	21.93196	10	642	-1.53519 1	1
-0.26301	21.66895	10	643	-1.56896 1	1
-0.26301	21.40594	10	644	-1.60085 1	1
-0.26301	21.14293	10	645	-1.63086 1	1
-0.26301	20.87992	10	646	-1.65904 1	1
0.110432	20.99036	10	647	6.191262 5	8.2
0.106519	21.09687	10	648	6.159987 5	8.2
0.102745	21.19962	10	649	6.129317 5	8.2
0.099104	21.29873	10	650	6.099267 5	8.2
0.095753	21.39448	10	651	6.073353 5	8.2
0.093113	21.48759	10	652	6.06107 5	8.2
0.090545	21.57813	10	653	6.048881 5	8.2
0.088049	21.66618	10	654	6.036796 5	8.2
0.085621	21.7518	10	655	6.024825 5	8.2
0.08326	21.83506	10	656	6.012978 5	8.2

0.080964	21.91603	10	657	6.001264	5	8.2
0.078732	21.99476	10	658	5.98969	4	5.2
0.076561	22.07132	10	659	5.978262	4	5.2
0.07445	22.14577	10	660	5.966987	4	5.2
0.072397	22.21817	10	661	5.95587	4	5.2
-0.26301	21.95516	10	662	-1.53212	1	1
-0.26301	21.69215	10	663	-1.56606	1	1
-0.26301	21.42914	10	664	-1.59811	1	1
-0.26301	21.16613	10	665	-1.62829	1	1
-0.26301	20.90312	10	666	-1.65663	1	1
0.109611	21.01273	10	667	6.184736	5	8.2
0.105727	21.11846	10	668	6.153587	5	8.2
0.10198	21.22044	10	669	6.123044	5	8.2
0.098367	21.3188	10	670	6.093123	5	8.2
0.095199	21.414	10	671	6.070799	5	8.2
0.092574	21.50658	10	672	6.058535	5	8.2
0.090022	21.5966	10	673	6.046366	5	8.2
0.08754	21.68414	10	674	6.034304	5	8.2
0.085126	21.76926	10	675	6.022357	5	8.2
0.082779	21.85204	10	676	6.010538	5	8.2
0.080496	21.93254	10	677	5.998852	4	5.2
0.078277	22.01081	10	678	5.987308	4	5.2
0.076118	22.08693	10	679	5.975911	4	5.2
0.07402	22.16095	10	680	5.964668	4	5.2
-0.26301	21.89794	10	681	-1.53967	1	1
-0.26301	21.63493	10	682	-1.57319	1	1
-0.26301	21.37192	10	683	-1.60483	1	1

.....

.....

0	0	10	2498	0	1	1
0	0	10	2499	0	1	1
0	0	10	2500	0	1	1
0	0	10	2501	0	1	1
0	0	10	2502	0	1	1
0	0	10	2503	0	1	1
1.318133	1.318133	10	2504	1.859222	2	3.5
1.038345	2.356477	10	2505	2.66638	3	4.8
1.200214	3.556692	10	2506	4.605457	4	5.2
1.132621	4.689312	10	2507	5.764284	4	5.2
1.064988	5.7543	10	2508	6.697668	5	8.2
0.990545	6.744845	10	2509	7.366033	5	8.2
0.911178	7.656023	10	2510	7.77459	5	8.2
0.841551	8.497574	10	2511	8.061776	6	9.5
0.79956	9.297133	10	2512	8.457709	6	9.5
0.759664	10.0568	10	2513	8.778606	6	9.5

10321.4.2

Average fuel consumption =21.675/10.32 = 2.10 km/liter

Appendix C-6

GREET Model

Argonne National laboratory's Transportation Technology R&D Center has developed a full life-cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). The model calculates fuel-cycle energy and emissions for various transportation fuels and vehicle technologies. For a given vehicle and fuel system, GREET separately calculates the following:

- consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal and natural gas;
- emissions of CO₂-equivalent greenhouse gases - primarily carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O); and
- emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NO_x), particulate matter with size smaller than 10 micron (PM₁₀), particulate matter with size smaller than 2.5 micron (PM_{2.5}), and sulfur oxides (SO_x).

GREET was developed in Microsoft Excel. It is available free of charge on the web. The model has been continuously improved since first release in 1996. There are two models, one for fuel-cycle analysis and another for vehicle-cycle analysis. The most recent GREET version for fuel-cycle analysis is GREET 1.8b and for vehicle-cycle analysis is GREET 2.7.

GREET includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems. General fuel production pathways are shown in the Figure below.

Figure: Fuel production pathways in GREET model (Source: ANL, 2009)

GREET covers the following vehicle technologies:

- conventional spark-ignition engines;
- direct-injection, spark-ignition engines;
- direct injection, compression-ignition engines;
- grid-independent hybrid electric vehicles;
- grid-connected (or plug-in) hybrid electric vehicles;
- battery-powered electric vehicles; and
- fuel-cell vehicles.

Appendix C-7

Ontario's Electricity Generation Mix

Ontario Power Generation operates is one of the largest producers of electricity in North America. Ontario Power Generation operates 64 hydroelectric, 5 fossil, 3 nuclear and one wind stations producing more than 22,000 megawatts of electricity. Figure C-7.1 shows Power Generation stations in Ontario and their capacity.

Fig. C-7.1: Ontario's Power Generation stations and their capacity (Source: OPG, 2009)

Ontario uses a mix of energy sources for electricity generation. Half of Ontario's electricity comes from nuclear power. The remainder comes from a mix of hydroelectric, coal, natural gas and wind. The energy sources of electricity generation are briefly described below:

Nuclear Energy: Nuclear plants account for 52 per cent of Ontario's electricity generation mix. The three nuclear power plants are Pickering Generating Station, Darlington Generating Station and Bruce Power.

Hydroelectric Energy: Hydroelectric generation accounts for 21 per cent of Ontario's generating mix. There are currently about 180 hydroelectric stations in Ontario, of which 58 are connected to the grid.

Coal: Ontario currently has four coal-fired fuel stations: Nanticoke, Lambton, Thunder Bay, and Atikokan. Together they account for approximately eighteen per cent of Ontario's generating capacity.

Natural Gas: Natural gas accounts for approximately 8 per cent of Ontario's generating mix. There are currently about 60 natural gas stations of varying sizes, of which 19 are connected to the grid.

Wind: Huron Wind plant is the Ontario's first commercial wind farm located on the shore of Lake Huron in Bruce County, Ontario. This nine megawatt wind farm was commissioned in December 2002 and accounts for one per cent of Ontario's generating capacity.

Appendix C-8

Detailed calculation of construction energy for surface, base, sub base and subgrade course of flexible pavement

Table C-8.1: Processing and calorific energy factors

Processing Energy (E _p)	Conversion Factor
Portland Cement	7.232 x 10 ⁶ Btu /ton
Asphalt Cement	587,000 Btu/ton
Crushed Aggregate	58,100 Btu/ton
Sand, Gravel	15,000 Btu/ton
Filler	58,100 Btu/ton
C.MS-2 Emulsion	10,200 Btu/gal 241 gal/ton
MC-70 Cutback	59,500 Btu/gal
Reinforcing Steel	24 x 10 ⁶ Btu/ton
Calorific Energy (E _h)	
Asphalt Cement	37.1 x 10 ⁶ Btu/ton
CMS-2 Emulsion	115,000 Btu/gal
MC-70 Cutback	148,000 Btu/gal

(Source: NCHRP 85)

Table C-8.2: Energy required for processing crushed stone

Type of Stone	Electricity (kwh/ton)	Fuel (gal/ton)	Total Energy	
			NCSA ^a (Btu/ton)	Adjusted values (Btu/ton)
Limestone (open pit)	3.241	0.195	38,400	62,800
Limestone (underground)	3.901	0.198	40,600	70,400
Trap rock (open pit)	2.901	0.268	35,400	69,200
Granite (open pit)	1.738	0.116	30,400	44,000
Total	2.830	0.194	35,600	58,100

(Source: NCHRP 85) ^aNCSA- National Crushed Stone Association

Table C-8.3: Estimates of fuel use by trucks hauling highway construction materials

Material Hauled	Type of Equipment	Fuel Economy (mpg)	Assumed Full Load (tons)	Fuel Use ^a	
				(gal/ton-mi)	(Btu/ton-mi)
Aggregate, sand, asphalt cement, Portland cement	Diesel 5 axle	5	22	0.0182	2,500
Asphalt hot mix, recycled material, portland cement concrete	Diesel 3 axle	7	10	0.0286	4,000
	Gasoline 3 axle	5	10	0.0400	5,560

(Source: NCHRP 85)

^aVehicles are assumed to move one way fully loaded and return empty.

Table C-8.4: Total fuel use factors for highway construction activities

Item of Work	Unit	Equivalent gallons of diesel fuel		
		Low	Average	High
Excavation				
Earth	ton	0.37	0.42	0.49
Rock	ton	0.52	0.55	0.62
Other	ton	0.46	0.49	0.54
Aggregates				
Production	ton	0.32	0.36	0.46
0-10 mi haul ¹	ton	0.44	0.49	0.58
11-20 mi haul ¹	ton	0.59	0.77	0.98
Asphalt Concrete				
Production	ton	1.81	2.56	3.66
0-10 mi haul	ton	0.28	0.33	0.34
11-20 mi haul	ton	0.30	0.49	0.56
Placement	ton	0.06	0.14	0.20
Portland Cement Concrete ²				
Production	yd ³	0.26	0.41	0.64
Hauling	yd ³	0.33	0.48	0.67
Placement	yd ³	0.13	0.22	0.31

(Source: NCHRP 85)

¹Includes hauling, spreading, compacting, and finishing of base.²A cubic yard of concrete is assumed to weigh 2 tons.

Table C-8.5: Fuel required to dry aggregate (Asphalt Plants)

Moisture Content of aggregate (%)	Fuel Oil (gal)/ton of aggregate
10	3.04
9	2.82
8	2.61
7	2.40
6	2.19
5	1.98
4	1.76
3	1.55
2	1.34

(Source: NCHRP 85)

Table C-8.6: Energy use in conventional asphalt plant operations

Item	Hot-Mixed Asphalt Concrete (Btu/ton)
Asphalt Storage	6,400
Cold Feed	4,730
Dryer and Exhaust Fans, etc.	4,770
Mixing Plant	3,920
Total	19,820

(Source: NCHRP 85)

Energy estimates for Subgrade improvement: Cement-treated

Assumptions:

Calculation for 2-lane road (24' wide)/mile

Subgrade to be treated with 6% cement

Amount of cement required: $14,082 \text{ yd}^2 \times 36 \times 2 \text{ ton/yd}^3 \times 0.06 = 47 \text{ ton/mi-in.}$

Construction energy:

$33 \text{ Btu/sq. yd -in. per pass} \times 9 \text{ passes} = 300 \text{ Btu/sq. yd -in.}$

$= 0.00216 \text{ gal/yd}^2 \text{ -in.}$

$1760 \text{ yd} \times 8 \text{ yd} \times 6 \text{ in} \times 0.00216 = 182 \text{ gal/mi-in}$

Transport energy

$\text{Haul cement} = 47 \times 50 \text{ mi} \times 2 \times 0.0182 \text{ (Table C-8.3)} = 86 \text{ gal/mi-in}$

Processing energy

$\text{Cement} = 47 \times 52.03 \text{ (Table C-8.1)} =$	<u>2445 gal/mi-in</u>
Total	2713 gal/mi-in

Sub base: Crushed Stone Aggregate

Assumptions:

Processing energy = 58,100 Btu/ton (Table C-8.2)

Aggregate is hauled at 0.0182 gal/ton-mi (Table C-8.3)

Aggregate contains 5% moisture when hauled

Energy for loading = 4,400 Btu/ton

Energy for spreading and compacting = 17,000 Btu/ton

Base compacted to 135 lb/ft = 712.8 tons/mi-in. (24-ft width)

Convert Btu to equivalent gallons diesel fuel by dividing by 139,000 Btu/gal

Construction energy

(loading, spreading, and compacting)

$= 4,400 + 17,000 = 21,400 \text{ Btu/ton}$

$(21,400 \times 1.05 \times 712.8) / 139,000 = 115 \text{ gal/mi-in}$

Transport energy

Short haul (20 mi)

$= 712.8 \text{ tons} \times 1.05 \times 20 \times 2 \times 0.0182 \text{ (Table C-8.3)} = 545 \text{ gal/mi-in}$

Long haul (130 mi)

$= 712.8 \times 1.05 \times 130 \times 2 \times 0.0182 = 3540 \text{ gal/mi-in}$

Processing energy

$= 712.8 \times 0.42 \text{ (Table C-8.1)} = 299 \text{ gal/mi-in}$

Emulsion-Treated Base (Local Aggregates)

Assumptions:

Processing energy (local aggregate) = 15,000 Btu/ton

8% emulsion mixed in plant at local quarry pit

CMS-2 emulsion used

Energy for plant operation = 6,630 Btu/ton

Assume base compacted to $140 \text{ lb/ft}^3 = 739.2 \text{ ton/mi-in.}$ ($140 \times 5,280 \times 24/12/2000$)

Energy for compaction = 17,000 Btu/ton

Emulsion is hauled 50 mi to plant (both short and long haul) (plant at aggregate source)

Mix hauled at 0.0286 gal/ton-mi (Table C-8.3)

Construction energy

(handling, mixing, compaction) = $6,630 + 17,000 = 23,630 \text{ Btu/ton}$

= $(23,630 \times 739.2) / 139,000 =$

126 gal/mi-in

Transport energy

Short haul (10 mi)

For hauling emulsion = $0.08 \times 739.2 \times 50 \times 2 \times 0.0182 =$

108 gal/mi-in

For hauling mixture (10 mi) = $739.2 \times 10 \times 2 \times 0.0286 =$

423 gal/mi-in

Long haul (30 mi)

For hauling emulsion (as above) =

108 gal/mi-in

For hauling mixture (30 mi) = $739.2 \times 30 \times 2 \times 0.0286 =$

1268 gal/mi-in

Processing energy

Emulsion

= $0.08 \times 739.2 \times 17.60$ (Table C-8.1)

1041 gal/mi-in

Aggregate

= (92% of mix) = $0.92 \times 739.2 \times 0.11$ (Table C-8.1) =

75 gal/mi-in

Calorific energy (CMS-2 emulsion)

0.827 (table-B-1) $\times 241 \times 739.2 \times 0.08 =$

11786 gal/mi-in

Hot-Mixed Asphalt Concrete

Assumptions:

Crushed stone = 58,100 Btu/ton

4.5% asphalt content

Aggregate hauled at 5% moisture

Asphalt hauled 50 mi (both long and short haul)

Energy for heating and drying aggregate = 1.98 gal/ton (Table C-8.5)

Energy for mixing = 19,800 Btu/ton

Energy for spreading and compacting mix = 16,700 Btu/ton

Base compacted to $145 \text{ lb/ft}^3 = 766 \text{ ton/mi-in.}$

Construction energy

Heating and drying aggregate = $766 \times 0.955 \times 1.98 =$

1448 gal/mi-in

Mixing = $766 \times 19,800 / 139,000 =$

109 gal/mi-in

Spreading and compacting = $766 \times 16,700 / 139,000 =$

92 gal/mi-in

Transport energy

Asphalt (short and long haul)

$$= 766 \times 0.045 \times 50 \times 2 \times 0.0182 \text{ (Table C-8.3)} = 63 \text{ gal/mi-in}$$

Aggregate

$$\text{Short haul (10 mi)} = 766 \times 0.955 \times 1.05 \times 10 \times 2 \times 0.0182 = 280 \text{ gal/mi-in.}$$

$$\text{Long haul (100 mi)} = 766 \times 0.955 \times 1.05 \times 100 \times 2 \times 0.0182 = 2796 \text{ gal/mi-in}$$

Mix

$$\text{Short haul (10 mi)} = 766 \times 10 \times 2 \times 0.0286 = 438 \text{ gal/mi-in.}$$

$$\text{Long haul (30 mi)} = 766 \times 30 \times 2 \times 0.0286 = 1,314 \text{ gal/mi-in.}$$

Total transport energy

$$\text{Short haul (63 + 280 + 438)} = 781 \text{ gal/mi-in.}$$

$$\text{Long haul (63 + 2,796 + 1,314)} = 4,173 \text{ gal/mi-in}$$

Processing energy

Aggregate

$$= 766 \times 0.955 \times 0.42 \text{ (Table C-8.1)} = 307 \text{ gal/mi-in.}$$

Asphalt

$$= 766 \times 0.045 \times 4.22 \text{ (Table C-8.1)} = 145 \text{ gal/mi-in.}$$

$$\text{Total processing energy} = 452 \text{ gal/mi-in.}$$

Calorific energy

Asphalt

$$= 766 \times 0.045 \times 266.9 \text{ (Table C-8.1)} = 9,200 \text{ gal/mi-in.}$$

Asphalt Concrete

Assumptions:

Composition of hot-mixed asphalt concrete HMAC -5% asphalt (mix basis)

Aggregate

60% crushed stone

35% natural sand

5% filler

Asphalt cement is hauled 50 mi to the plant. Aggregate is hauled 10 mi to plant for short haul and 100 mi to plant for long haul (aggregate contains 5% moisture when hauled and when introduced into dryer; initial temperature is 70° F; temperature of mix at discharge is 300°F) Asphalt concrete is hauled an average distance of 7.5 mi for short haul and 40 mi for long haul (compacted density of the asphalt concrete is 145 lb/ft³). All energy computed on basis of equivalent gallons of diesel fuel at 139,000 Btu/gal.

Calculations:

Asphalt concrete required for 1 mile pavement

$$145 \text{ lb/cu. ft} \times 27 = 3,915 \text{ lb/cu. yd} = 108.75 \text{ lb/sq. yd -in.}$$

$$14,080 \text{ yd}^2 \times 108.75 / 2,000 = 765.6 \text{ ton/mi-in.}$$

Asphalt cement

$$765.6 \times 0.05 = 38.28 \text{ ton/mi-in.}$$

Aggregate

$$= 765.6 \times 0.95 = 727.3 \text{ total ton/mi-in.}$$

$$\text{Coarse aggregate} = 436.4 \text{ ton/mi-in.}$$

Sand = 254.5 ton/mi-in.

Filler = 36.4 ton/mi-in.

Construction energy

For heating and drying aggregate (exclude filler)

= 690.9 ton x 1.98 (from Table C-8.5) = 1,368 gal/mi-in.

For heating filler (assume 1 gal/ton) = 36 gal/mi-in.

Total for heating and drying aggregate = 1,404 gal/mi-in.

For operating asphalt plant

= 765.6 ton x 19,800 Btu/ton (Table C-8.6)/139,000 = 109 gal/mi-in.

For laydown and compacting HMA

= 765.6 ton x 16,700 Btu/ton (4)/139,000 = 92 gal/mi-in.

Total construction energy = 1,605 gal/mi-in.

Transport energy

For hauling asphalt cement

= 38.28 ton x 50 mi x 2 x 0.0182 = 70 gal/mi-in.

For hauling aggregate

Short haul: 727.3 ton x 1.05 (5% moisture) x 10 mi x 2 x 0.0182 = 278 gal/mi-in.

Long haul: 727.3 ton x 1.05 (5% moisture) x 100 mi x 2 x 0.0182 = 2,780 gal/mi-in.

For hauling HMA to job site

Short haul: 765.5 ton x 7.5 mi x 2 x 0.0286 = 328 gal/mi-in.

Long haul: 765.6 ton x 40 mi x 2 x 0.0286 = 1,752 gal/mi-in.

Total transport energy

Short haul = 676 gal/mi-in.

Long haul = 4,602 gal/mi-in.

Processing energy

38.28 ton asphalt cement x 4.22 gal/ton (Table C-8.1) = 162 gal/mi-in.

436.4 ton crushed aggregate x 0.42 gal/ton (Table C-8.1) = 183 gal/mi-in.

254.5 ton sand x 0.11 gal/ton (Table C-8.1) = 28 gal/mi-in.

36.4 ton filler x 0.42 gal/ton (Table C-8.1) = 15 gal/mi-in.

Total processing energy = 388 gal/mi-in.

Calorific energy

38.28 ton asphalt cement x 266.9 gal/ton (Table C-8.1) = 10,220 gal/mi-in.

Portland Cement Concrete

Assumptions:

PCC composition (materials in 1 yd³)

Cement = 564 lb = 0.282 ton/yd³

Coarse aggregate = 2,000 lb = 1.0 ton/yd³

Sand = 1,154 lb = 0.577 ton/yd³

Water = 282 lb = 0.141 ton/yd³

Amount each material for 1 mi/in. thickness

Cubic yards required 14,080 yd² /36 = 391.1 yd³/mi-in.

Cement = 391.1 x 0.282 = 110 ton/mi-in.

Coarse aggregate = 391.1 x 1.0 = 391 ton/mi-in.

Sand = $391.1 \times 0.577 = 226$ ton/mi-in.	
Total = $391.1 \times 2 = 782$ ton/mi-in.	
<u>Construction energy</u>	
Batch concrete = 391.1×0.41 gal/ yd ³ (Table C-8.4) =	160 gal/mi-in.
Place and consolidate concrete	
= 391.1 yd x 0.22 gal/ yd ³ (average from Table C-8.4)	<u>86 gal/mi-in.</u>
Total construction energy	246 gal/mi-in.
<u>Transport energy</u>	
Haul cement = 110×50 mi x 2×0.0182 (Table C-8.3) =	200 gal/mi-in.
Haul coarse aggregate	
Short haul 391×10 mi x $2 \times .0182 =$	142 gal/mi-in.
Long haul 391×100 mi x $2 \times 0.0182 =$	1,423 gal/mi-in.
Haul sand	
Short haul 226×10 mi x $2 \times 0.0182 =$	82 gal/mi-in.
Long haul 226×100 mi x $2 \times 0.0182 =$	823 gal/mi-in.
Haul concrete	
Short haul 782.2 ton x 7.5 mi x 2×0.0286 (Table C-8.3) =	336 gal/mi-in.
Long haul 782.2 ton x 40 mi x 2×0.0286 (Table C-8.3) =	1,790 gal/mi-in.
Total transport energy	
Short haul ($200 + 142 + 82 + 336$)	760 gal/mi-in.
Long haul ($200 + 1,423 + 823 + 1,790$)	4,236 gal/mi-in.
<u>Processing energy</u>	
Cement = 110×52.03 (Table C-8.1) =	5,723 gal/mi-in.
Coarse aggregate = 820×0.42 (Table C-8.1)	164 gal/mi-in.
Sand = 226×0.11 (Table C-8.1)	25 gal/mi-in.
<hr/>	
(Source: NCHRP 85)	

Appendix C-9

Example of cost estimates for construction of all other components (excluding pavement) of a road in Ontario

Main component	Characteristic items	Unit	Unit cost	Per two-lane equivalent km	
				Quantity	Cost
1	2	3	4	5	6 = 4 x 5
Clearing of vegetation	Clearing and grubbing	m ²	2.30	4000	9200
Grading; earth work	Earth excavation or fill	m ³	7.87	4000	31480
	Percent of rock excavation or fill	%	44.00	10	440
Landscaping	Sodding and top soil	m ²	3.65	500	1825
	Top soil	m ³	11.00	9500	104500
Drainage of the right-of-way	Curb and gutter (PCC, straight)	m	55.00	70	3850
	500 mm pipe culvert + end sections	m	123.43	50	6171.5
	1500 mm wide box culvert	m	1,688.17	15	25322.55
	Storm water sewers	m	55.00	90	4950
Guard rail and safety appurtenances	Concrete median	m	220.20	0	0
	Steel guardrail at shoulder	m	72.58	160	11612.8
	3-cable guide rail at shoulder	m	16.94	260	4404.4
Fencing and gates	Chain link fence	m	48.88	0	0
	Wire fence	m	9.39	0	0
Lighting	High mast	piece	\$ 32,599.36	0	0
	Standard	piece	1,427.37	20	28547.4
Traffic control	Painting of traffic control lines	m	1.00	3500	3500
					235803.65

(Source: Applied Research Associates, Inc., 2008)

Appendix C-10

Age of infrastructure of Canadian provincial and municipal road and bridges

Region	Average Pavement Age, years				Average Bridge Age, years			
	Provincial		Municipal		Provincial		Municipal	
	Since Constr.	Since Rehabilitation	Since Constr.	Since Rehabilitation	Since Constr.	Since Rehabilitation	Since Constr.	Since Rehab.
PE			75	28				
NS		16	24	12	53			
NB			30	25				
QC		12.5	22		38.2	20		
ON	30.9	17.6	37	22	36	25	34	23
MB	45	25	75	35			32	32
SK	30	13	33	23	37		42	
AB	34	9.9			34	25	34	
TR	12	12	15	15	23	6.5	20	20
Average	30.4	15.1	38.9	22.9	36.9	19.1	32.4	25.0

(Source: Applied Research Associates, Inc., 2008)

Origin of municipal data:

PE- City of Summerside;

NS- Regional Municipality of Halifax;

NB -City of Edmunston;

QC- City of Ville de Longueuil

ON- Average of cities of Brampton, Niagara Falls, Ottawa, and Toronto;

MB- City of Winnipeg;

SK- Average of cities of Regina and Saskatoon;

AB- City of Edmonton;

TR -City of Yellowknife, NT

Appendix C-11

Pavement maintenance action plan for an arterial road in Southern Ontario:

Years after initial construction	Description of pavement layer, Amount (Quantity)	Amount	Quantity per km	Price/ unit of quantity	Cost (\$)	Net present worth
5	Rout and seal, m (m)		500	\$ 2.00	1,000	\$ 747
9	Spot repairs - mill and patch, % Area (m2)	10	750	\$ 7.70	5,775	\$ 3,418
15	Mill AC, mm (t)	40	750	\$ 11.00	8,250	\$ 3,442
15	Resurface with SP 12.5mm FC1, mm (t)	40	750	\$ 68.75	51,563	\$ 21,515
15	Resurface with SP 19mm (MDBC), mm (t)	50	938	\$ 53.70	50,344	\$ 21,007
19	Rout and seal, m (m)		500	\$ 2.00	1,000	\$ 331
19	Spot repairs - mill and patch, % Area (m2)	20	1500	\$ 7.70	11,550	\$ 3,817
27	Mill AC, mm (t)	40	750	\$ 11.00	8,250	\$ 1,711
27	Resurface with SP 12.5mm FC1, mm (t)	40	750	\$ 68.75	51,563	\$ 10,692
27	Resurface with SP 19mm (MDBC), mm (t)	50	938	\$ 53.70	50,344	\$ 10,440
31	Rout and seal, m (m)		500	\$ 2.00	1,000	\$ 164
35	Spot repairs - mill and patch, % Area (m2)	20	1500	\$ 7.70	11,550	\$ 1,503
38	Mill AC, mm (t)	40	750	\$ 11.00	8,250	\$ 901
38	Resurface with SP 12.5mm FC1, mm (t)	40	750	\$ 68.75	51,563	\$ 5,633
38	Resurface with SP 19mm (MDBC), mm (t)	50	938	\$ 53.70	50,344	\$ 5,499
42	Rout and seal, m (m)		500	\$ 2.00	1,000	\$ 87
42	Spot repairs - mill and patch, % Area (m2)	20	1500	\$ 7.70	11,550	\$ 999
48	Mill AC, mm (t)	100	1875	\$ 11.00	20,625	\$ 1,258
48	Resurface with SP 12.5mm FC1, mm (t)	40	750	\$ 68.75	51,563	\$ 3,145
48	Resurface with SP 19mm (MDBC), mm (t)	60	1125	\$ 53.70	60,413	\$ 3,685
53	Rout and seal, m (m)		500	\$ 2.00	1,000	\$ 46
57	Spot repairs - mill and patch, % Area (m2)	10	750	\$ 7.70	5,775	\$ 209
60	End of life (Dismantling, recycling and disposal)					
Total					514,269	\$ 100,249

(Source: Applied Research Associates, Inc., 2008)

Appendix C-12

The energy consumption for construction of one km LRT track was estimated using processed based approach. The principal components of LRT track work such as rail, tie, ballast, sub-ballast and subgrade were considered in the estimation.

Rail for Track work

Rail used for the construction of LRT tracks is rolled 100 lb ARA-A (49.8 kg/m) rail.

Fastening Devices

Rail fastening devices vary with the type of track structure provided. Figure C-12.1 shows typical fastening devices.

Fig. C-12.1: Fastening devices for LRT (Source: City of Edmonton, 2005)

Ties: The classification of ties used in LRT System is as follows:

Wood Crossties: Wood crossties used on mainline and in yard track is pressured treated softwood, preferably fir, conforming to AREMA recommendations.

The standard nominal dimensions for wood crossties are:

- Depth – 180 mm (7")
- Width – 230 mm (9")
- Length – 2600 mm (8'-6")

Concrete Crossties: Concrete crossties should be mono-block pre-stressed reinforced concrete ties conforming to the AREMA Manual for Rail Engineering. Spacing for concrete ties are 675 mm and wood ties are 560 mm.

Fig. C-12.2: Dimension of concrete ties (Source: City of Edmonton, 2005).

Ballast:

Ballast should be a clean 100% crushed rock with a hard, durable, dense, angular particle stone providing sharp corners with a minimum of flat and elongated pieces. These properties will provide stability, durability and proper drainage. Granites, quartzites and dolomites are the preferred aggregate types. The ballast should be 100% crushed stone conforming to the AREMA. Ballast depth should be placed to a minimum of 225 mm below the bottom of the tie.

Sub-ballast:

Sub-ballast should have suitable mechanical, permeability, chemical and environmental characteristics and comply with the AREMA Manual for Railway Engineering. Acceptable sub-ballast materials include crushed stone or crushed gravel and sands, or a mixture of these materials. A minimum depth of 275 mm of sub-ballast should be placed on top of the subgrade, extending a minimum of 600 mm beyond the edge of the ballast.

Subgrade:

The subgrade's stability and its ability to sustain and distribute loads are dependent on the soil characteristics, its geometric configuration and the system drainage design. The width of the subgrade is determined by the width of the ballast. The sub-grade should be compacted to 100% of the maximum density as per the Standard Proctor Compaction Test.

Calculation of construction energy**Rail:**

$$49.8 \text{ Kg/m} \times 1000 \text{ m} \times 4 = 199,200 \text{ kg/km} = 196.05 \text{ ton}$$

Concrete tie:

$$\text{Length } 2515 \text{ mm} \times \text{width } 265 \text{ mm} \times \text{height } 210 \text{ mm} - \{(1162 + 305 \times 2) / 2 \times (210 - 160)\} \times \text{width } 265 \text{ mm} = 128.22 \times 10^6 \text{ mm}^3 = 0.128 \text{ m}^3$$

$$\begin{aligned} \text{No. of tie required/ km with } 675 \text{ mm Spacing} &= 106/675 = 1482 \\ \text{Total volume of tie/km} &= 189.7 \text{ m}^3 \end{aligned}$$

Total volume of tie/km for both way = $189.7 \times 2 = 379.4 \text{ m}^3$

Anchoring and Joints:

Joint bars, bolts, spikes for 120lb/yd (49.8kg/m)
 $(13.6 + 1.27 \times 4) \text{ ton / mile} = 11.72 \text{ ton/km}$

Ballast:

Volume of Ballast = $1000 \times (8.1 + 0.6 \times 2) \times 0.275 = 3144.1 \text{ m}^3$

Sub ballast:

Volume of Ballast = $1000 \times 8.1 \times 0.225 + 1000 \times 8.1 \times 0.210 - 379.4 = 2557.5 \text{ m}^3$

Table C-12.1: Summary of per km track work construction energy (Double track)

Item of works	Quantity	Energy intensity	Total energy (BtuX10 ⁹)	Total energy (TJ)
Rail	196.05 ton	39.8 MBtu/ton	7.80	8.23
Tie	379.4 m ³	2.01 MBtu/m ³	0.76	0.80
Anchoring bolt	11.72(ton)	39.8 MBtu/ton	0.47	0.49
Sub total				9.52
Placement (30%)				2.86
Ballast	3144.1 m ³	1.14MBtu/m ³	3.58	3.78
Sub Ballast	2557.5 m ³	1.14MBtu/m ³	2.91	3.07
Sub grade	1395 m ³	1.26Btu/m ³	1.76	1.86
Total				21.09

Major Travel Flows

[illegible]

320