1

CANADIAN THESES ON MICROFICHE

I.S.B.N.

THESES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

National Library
of Canada

Bibliothèque nationale
du Canada

CANADIAN THESES
ON MICROFICHE

THÈSES CANADIENNES
SUR MICROFICHE

0-315-12023-1

59936

50

NAME OF AUTHOR/NOM DE L'AUTEUR MARK R CAMPBELL
TITLE OF THESIS/TITRE DE LA THÈSE THE ESTIMATION AND ANALYSIS OF
ENERGY CONSUMPTION IN URBAN
TRANSPORTATION
UNIVERSITY/UNIVERSITÉ CARLETON UNIVERSITY
DEGREE FOR WHICH THESIS WAS PRESENTED/
GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE MASTER OF CIVIL ENGINEERING
YEAR THIS DEGREE CONFERRED/ANNÉE D'OBTENTION DE CE GRADE 1980
NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE PROF. A.M.E. HAN

Permission is hereby granted to the NATIONAL LIBRARY OF
CANADA to microfilm this thesis and to lend or sell copies
of the film.

L'autorisation est, par la présente, accordée à la BIBLIOTHÈ-
QUE NATIONALE DU CANADA de microfilmer cette thèse et
de prêter ou de vendre des exemplaires du film.

The author reserves other publication rights, and neither the
thesis nor extensive extracts from it may be printed or other-
wise reproduced without the author's written permission.

L'auteur se réserve les autres droits de publication; ni la
thèse ni de longs extraits de celle-ci ne doivent être imprimés
ou autrement reproduits sans l'autorisation écrite de l'auteur.

DATED/DATE Nov 25/82 SIGNED/SIGNÉ Mark Campbell

PERMANENT ADDRESS/RÉSIDENTIE FIXE 95 Jones St
OTTAWA Ontario

THE ESTIMATION AND ANALYSIS OF ENERGY
CONSUMPTION IN URBAN TRANSPORTATION

by

© MARK R. CAMPBELL

B.Sc. (Civil Engineering, Loyola of Montreal)

A thesis submitted to the Faculty of
Graduate Studies in partial fulfillment
of the requirements for the degree of
Masters of Engineering

Faculty of Engineering
Carleton University

Ottawa, Canada

August, 1980

The undersigned recommend to the faculty of Graduate Studies and Research acceptance of the thesis, "The Estimation and Analysis of Energy Consumption in Urban Transportation", submitted by Mark R. Campbell, B.Sc. (Civil Engineering), in partial fulfillment of the requirements for the degree of Masters of Engineering.

Ata M. Khan

Thesis Supervisor

John R. Gulvan

Chairman
Department of Civil Engineering

ABSTRACT

In this research, a technique was developed for estimating energy consumption of urban transportation systems. The technique was devised to give estimates of the direct energy consumed to propel vehicles and the indirect energy used for producing and maintaining the vehicle and infrastructure and the indirect energy required to produce the direct energy. These energy items were estimated for both the private and public transportation systems.

Annual energy estimates were developed for the years 1977 and 1990. A study was made to establish the effects on future energy consumption due to advancements in vehicle technology. From this study, a private and public vehicle fleet considered most likely to exist by 1990 was selected and used to estimate the change in energy consumption between 1977 and 1990. Furthermore, by developing two behavioural modal split models it was possible to study the effects of changing petroleum prices on the behaviour of travellers and ultimately energy consumption.

ACKNOWLEDGEMENTS

The research reported in this thesis was carried out under the supervision of Professor A.M. Khan, whose encouragement and guidance was greatly appreciated.

The author wishes to express special thanks to Dr. L. Shallal, Chief Systems Planning Engineer, Regional Municipality of Ottawa-Carleton, for his encouragement, interest and guidance during this research.

The author wishes to extend his thanks to Mr. P. Ranniste, R. Rehbein and R. Claude of the Systems Planning Branch, to Mr. D.M. Beere, G. Scale, R. Godding and E. Barter of the Transit Planning Branch and to Mr. E. Blaszyński of the Transportation Planning Branch, at the Regional Municipality of Ottawa-Carleton for their assistance in providing data and guidance throughout this research.

The author wishes to extend his thanks to Mr. D. Saunders of N.D. Lea and Associates Ltd., for his assistance in developing the behavioural modal splits models; to Mr. F.G. Johnson, Department of Industry, Trade and Commerce for his assistance regarding electrically propelled automobiles and to Mr. C. Ditchfield, Urban Transportation Development Corporation Ltd. for his assistance regarding the light rail vehicle.

The author wishes to express special thanks to the Natural Sciences and Engineering Research Council of Canada,

and Transport Canada's University Programs for their generous financial support. Special thanks is extended to the Regional Municipality of Ottawa-Carleton for allowing the author access and use to their computer facilities.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	iii
Acknowledgements	iv
List of Figures	xi
List of Tables	xii
Chapter I - Introduction	1
1.1 Problem Definition	1
1.2 Research Objectives and Scope of Investigation	2
1.3 Organization of the Thesis	4
Chapter II - Energy Consumption in Urban Transportation - A State of the Art Review	6
2.1 Introduction	6
2.2 Requirements for Estimating Direct Energy Consumption	6
2.2.1 Energy Content of Fuels	7
2.2.2 Fuel Consumption	7
2.2.2.1 Fuel Consumption Rates of Vehicles	8
2.2.2.2 Fuel Consumption Rates for the Private Vehicle Fleet	14
2.2.2.3 Fuel Consumption Rates for the Public Vehicle Fleet	19
2.2.2.4 Vehicle Usage	20
2.3 Requirements for Estimating Indirect Energy	22
2.3.1 "Unit" Indirect Energy Requirements..	23

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
2.3.2 Transportation Life Output.....	25
2.3.3 Indirect Energy Intensities	26
2.3.4 Transportation Output	27
2.4 Techniques for Estimating Energy Consumption	27
2.5 Analysis of Energy Consumption	35
2.6 Energy Analysis Issues	37
2.7 Concluding Comments	38
Chapter III - A Framework for Estimating and Analyzing Energy Consumption in Urban Transportation- A Case Study for the Ottawa-Hull Area.....	39
3.1 Introduction	39
3.2 Fundamental Concepts of the Technique	39
3.2.1 Energy Consumed by the Private Transportation System	41
3.2.2 Energy Consumed by the Public Transportation System	43
3.3 Technique Application to the Ottawa-Hull Area	44
3.3.1 Methodology to Model Modal Split ...	47
3.3.2 Establishment of Petroleum Prices and Vehicle Fleets	49
3.3.3 Transportation Output and Fuel Consumption for the Private Transportation System.....	55
3.3.4 Transportation Output and Fuel Consumption for the Public Transportation System.....	56
3.3.5 Methodology to Estimate Energy Consumption.....	57
3.3.6 Analysis	58
3.4 Concluding Comments	59

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
Chapter IV - The Theory and Development of the Behavioural Modal Split Models	61
4.1 Introduction	61
4.2 Theoretical Concept of Behavioural Models..	63
4.3 Data Preparation	68
4.4 Calibration	77
4.5 Selection of the "Home Based Work Trip" Model	79
4.6 Selection of the "All Other Trips" Model ..	85
4.7 Sensitivity Analysis	86
4.8 Aggregation	92
4.9 Validation	95
4.10 Concluding Comments	99
Chapter V - Estimation of Transportation Output and Fuel Consumption	101
5.1 Introduction	101
5.2 Transportation Output for 1977	102
5.2.1 P.M. Peak Hour Mode Split	102
5.2.2 Average P.M. Peak Hour Trip Characteristics	104
5.2.3 Annual Transportation Output of the Private Transportation System	106
5.2.4 Annual Transportation Output of the Public Transportation System	108
5.3 Fuel Consumption for 1977.....	113
5.3.1 The Average EPA Gasoline Consumption Rate	113
5.3.2 Annual Fuel Consumed by the Private Transportation System.....	115
5.3.3 Annual Fuel Consumed by the Public Transportation System	118
5.4 Transportation Output for 1990	118
5.4.1 Average P.M. Peak Hour Trip Characteristics and Mode Split	118
5.4.2 Annual Transportation Output for the Private Transportation System...	122
5.4.3 Annual Transportation Output for the Public Transportation System....	128

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
5.5 Fuel Consumption for 1990	130
5.5.1 The Average EPA Gasoline Consumption Rate	130
5.5.2 Annual Fuel Consumption of the Private Transportation Fleets	132
5.5.3 Annual Fuel Consumption of the Public Transportation Fleets	133
5.6 Concluding Comments	133
 Chapter VI - Estimation and Analysis of Annual Energy Consumption	 134
6.1 Introduction	134
6.2 Estimation of Annual Energy Consumption ...	134
6.2.1 Energy Intensity of Fuels	134
6.2.2 Energy Intensities for Producing and Maintaining Vehicles	134
6.2.3 Energy Requirements for Infra- structure	140
6.2.4 Annual Energy Consumption for 1977 and 1990	143
6.3 Analysis of Energy Consumption	147
6.3.1 Selection of the 1990 Private Vehicle Fleet	147
6.3.2 Selection of the 1990 Public Vehicle Fleet	148
6.3.3 Comparison of Total Energy Consumption between 1977 and 1990 ..	149
6.3.4 Effects of Petroleum Prices on Energy Consumption for 1999	150
6.3.5 Energy Efficiency of the Urban Transportation Systems.....	155
6.3.6 The Effects of Modal Attributes on Total Energy Consumption	157
6.4 Concluding Remarks	161

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
Chapter VII - Summary, Conclusions and Recommendations ..	162
7.1 Summary	162
7.2 Conclusions	164
7.3 Recommendations	170
References	172
Appendices	
A - A1 - Description of the UTPS Programs	178
B - B1 - The 1.4% Home Interview Survey Questionnaire and Key Records	194
B2 - Description of the Road and Transit Networks	198
B3 - Description of the Independent Variables used in the Behavioural Modal Split Models	201
B4 - Establishing the Petroleum Cost for BC 1990	205
C - C1 - Establishing Average Trip Distances Made by the Private Vehicle Fleet	207
C2 - Estimation of the independent Variables for 1990 Modal Split	208
C3 - Fuel Consumption Rates for Electric Vehicles	212
D - D1 - Energy Content of Fuels and Conversion Factors	215
D2 - Establishing the Maintenance Energy Intensity of Electric Private Vehicles	216
D3 - Establishing Production Energy Intensities of the Private and Public Vehicles	217

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
2.1	Factors Affecting Fuel Consumption in Urban Transportation.....	9
2.2	Stopping Frequency Effect on Average Trip Speed.....	11
2.3	Influence of Driving Patterns on Fuel Consumption Rates.....	13
2.4	Warm-Up Effect on Fuel Consumption Rates.....	15
2.5	Trends in Private Vehicle Design.....	18
2.6	Framework to Estimate Fuel Consumption Using the Link-by-Link Techniques.....	31
2.7	Framework of Janson Technique to Estimate Direct Energy Consumption.....	33
3.1	A Framework for Estimating Direct and Indirect Energy Consumption.....	40
3.2	The Urban Ottawa-Hull Area.....	45
3.3	The Rural Ottawa-Hull Area.....	46
3.4	Application of the UTPS Computer Package in the Modal Split Task.....	50
4.1	Development of the Behavioural Modal Split Models.....	62
4.2	The Sigmoid Curve for Binary Mode Choice.....	66
4.3	The Effect of Petroleum Prices on Mode Choice.....	91
4.4	Location of the Transitway for 1990.....	96
4.5	Method for Correcting Aggregation Error.....	98
5.1	Hourly Variation of P.M. Peak Hour Buses in Operation During the Week.....	112
5.2	Method of Adjusting EPA Rates for Cold Start, 1977.....	116
5.3	The Adjusted EPA Curve for the 1977 Private Vehicle Fleet.....	117
5.4	Method of Estimating Modal Split for 1990.....	123
5.5	The Adjusted EPA Curve for the 1990 Private Vehicle Fleet.....	131
6.1	Effects of 1990 Petroleum Prices on Total Energy Consumption.....	154

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
4.1	Number of Records Contained in the Samples.....	72
4.2	Calibrated "Home Based Work Trip" Models.....	80
4.3	Work Trip Models for Other Urban Areas.....	82
4.4	Calibrated "All Other Trips" Models.....	86
4.5	Calibrated "All Other Trips" Models for Other Cities.....	87
4.6	Point Elasticities for the "Home Based Work Trip" Model.....	89
4.7	Point Elasticities for the "All Other Trips" Model.....	90
5.1	P.M. Peak Hour Modal Split for BC 1990 T1.....	103
5.2	Annual Transportation Output of the Private Vehicle Fleets.....	109
5.3	P.M. Peak Hour Data for the Ottawa Public Transportation System, BC 1977 T1.....	111
5.4	Annual Transportation Output and Fleet Size of Public Transportation Systems.....	114
5.5	Annual Fuel Consumption of the Private Vehicle Fleets..	119
5.6	Operational Characteristics and Fuel Consumption Rates for Public Transportation Vehicles.....	120
5.7	Annual Fuel Consumption of the Public Transportation Fleets.....	121
5.8	P.M. Peak Hour Modal Split for 1990.....	124
5.9	P.M. Peak Hour Data for Ottawa Public Transportation System , BC 1990 T1.....	129
6.1	Production and Maintenance Energy Intensities for the Private Vehicles.....	141
6.2	Production and Maintenance Energy Intensities for the Public Vehicles.....	142

<u>Table</u>	<u>Title</u>	<u>Page</u>
6.3	Infrastructure Maintenance and Construction Energies..	141
6.4	Annual Energy Consumption for the Private Transportation Systems.....	145
6.5	Annual Energy Consumption for the Public Transportation Systems.....	146
6.6	Annual Energy Consumption in 1990 Under Various Petroleum Prices.....	152
6.7	Energy Efficiency of the Urban Transportation Systems..	156
6.8	Methods to Reduce Public Transportation Energy Consumption.....	158
6.9	Methods to Reduce Private Transportation Energy Consumption.....	159
6.10	Summary of Energy Computations.....	160

CHAPTER 1

INTRODUCTION

1.1 Problem Definition

For many years the western industrialized countries have enjoyed the benefits of unlimited and inexpensive energy resources. As a result, the technology which developed during this time lent itself to fulfilling the ever increasing demands for goods and services without regard to energy cost or energy supply.

In the early 1970's the middle eastern countries gained greater control over the cost and supply of their petroleum exports. Concurrently, because of the avaricious desire of the western world to consume greater quantities of petroleum, domestic petroleum resource were being depleted. As a result, these industrialized countries are faced with an energy dilemma encompassing the cost and supply of petroleum and the effects they have on the western economy and lifestyle.

For Canada, the economic effects of the energy dilemma due to the devastating price increases of imported petroleum from \$2.20 per barrel in 1973 to over \$30.00 per barrel in 1980, has precipitated high rates of inflation, unemployment, and a decrease in the Gross National Product. In an attempt to lessen the impact, the Federal Government has proposed several policies to reduce the rate of energy

consumption and increase the production of Canadian petroleum resources, thereby reducing Canadian reliance on imported petroleum.

In 1978, over 50 percent of the petroleum consumed in Canada was for transportation. Furthermore, over 40 percent of this petroleum was used for urban travel. When the additional petroleum and other energy resources used to produce and maintain transportation vehicles and infrastructure are included, transportation is one of the largest consumers of energy. Therefore, it was considered advantageous to conduct research in this area by studying the inter-relationships between energy consumption and urban transportation to determine where reductions in energy consumption can be attained.

1.2 Research Objectives and Scope of Investigation

The objectives of this research are; (i) to develop a technique for estimating energy consumption in urban transportation, (ii) to develop a number of behavioural modal split models, (iii) to apply the technique and modal split models in order to determine the effects of human travel behaviour, petroleum prices and travel demand on energy consumption; and (iv) to analyze the effects of advancements in vehicle technology on future energy consumption.

The technique is designed to give separate estimates of energy consumed by the private transportation system, comprised of automobiles and their infrastructures; and the

public transportation system, including the public transit vehicles and their infrastructure. Energy consumption estimates for these systems encompasses both direct energy (the energy used to propel vehicles) and indirect energy (the energy used for producing and maintaining the vehicles and their infrastructures plus the energy used to produce the direct energy), thereby giving total energy consumption.

Behavioural modal split models are used to predict travel demand for the two systems. They are capable of estimating the shift in travel demand due to changes in modal level of service variables (travel time, perceived trip costs and number of transit transfers). In turn, the perceived trip cost variable is used to determine the effects of future petroleum prices on energy consumption.

The energy analysis technique and modal split models are used to estimate annual energy consumption for the years 1977 and 1990 in the Ottawa-Hull area. An energy analysis is conducted to determine the changes in 1990 energy consumption if gasoline, diesel and electric automobiles and the bicycle composed the private vehicle fleet. A similar analysis is made for various transit vehicles including the standard diesel bus, the articulated diesel bus, the articulated electric bus and the light rail vehicle. The author selected a private and public vehicle fleet which are considered most likely to exist by 1990.

An analysis is conducted to compare the change in energy consumption between 1977 and 1900 and to predict the effects of changing petroleum costs on future energy consumption. Conclusions are drawn regarding the effects of modal attributes and modal shifts on energy consumption.

1.3 Organization of the Thesis

In Chapter two, a state-of-the-art review is presented on the estimation and analysis of energy consumption. Based in part on these findings Chapter three outlines the energy analysis technique developed for estimating energy consumption for this research. A description is presented of how the technique was applied to the Ottawa-Hull area.

The fourth Chapter presents the fundamental theoretical concepts of behavioural modal split models. Furthermore, a description is presented of how the models were developed. Sensitivity analysis is performed to rationalize those petroleum prices within the predictive capabilities of the models and at the same time are representative of those prices which may exist by 1990.

In the fifth Chapter, the modal split models and the technique developed in Chapter three are used to estimate the annual amounts of fuels consumed to propel vehicles and annual kilometres travelled by the vehicles in the private and public vehicle fleets.

The sixth chapter is used to convert the amounts of fuels consumed and kilometres travelled in order to obtain direct and indirect energy consumption. With these energy figures, the energy analysis is concluded.

Chapter seven presents the summary, conclusions and recommendations drawn by performing the research.

CHAPTER II

ENERGY CONSUMPTION IN URBAN TRANSPORTATION -A STATE OF THE ART REVIEW

2.1 Introduction

In the past, urban transportation systems were analyzed on financial, economic, social and system performance criteria. However, now that energy has become an important issue, attempts are being made to include it in the analysis.

The first studies related to the estimation and analysis of energy consumption dealt exclusively with quantifying the amount of petroleum consumed to propel vehicles. Later, attempts were made to include electrical power used to propel electric transit vehicles. But to analyze energy consumption in its proper context requires both the direct and indirect energy consumed by the transportation systems. Only by considering direct and indirect energy can analyses establish the energy consumed by various transportation alterations or determine the energy impact caused by changes in travel demand. The planner is then able to alter transportation systems in a realistic manner which will lead to energy efficient improvements in urban transportation.

2.2 Requirements for Estimating Direct Energy Consumption

The two requirements for estimating direct energy consumption are the energy content of fuels and the quantities of each consumed. Their product gives the direct energy.

2.2.1 Energy Content of Fuels

The fossil fuels used exclusively in transportation are gasoline and diesel oil. Each has a different energy content (Mega Joules per litre, MJ/L) which is related to their chemical composition. The energy content of a fuel is expressed as the amount of energy produced when burned.

Electricity is another form of energy used in urban transportation. The energy content of electricity is also measured in MJ from the heat produced by a kilowatt (kW) of electricity. The energy content of electricity is expressed as the quantity of MJ produced per kilowatt hour (MJ/kWh).

2.2.2 Fuel Consumption

To quantify the amounts of fuels consumed by urban transportation systems, the following criteria are required:

1. Establishing those characteristics of a vehicle's design and operation which effects the rate of fuel consumption.
2. Establishing fuel consumption rates which are representative for all private vehicles using the roadway system.
3. Establishing fuel consumption rates which are representative of the public vehicles.
4. Establishing the usage of the private and public fleets over a specified period of time.

To estimate fuel consumption, vehicle usage (expressed in various units including vehicle-km travelled) is multiplied by a fuel consumption rate (L/vehicle-km). Some of the factors which affect fuel consumption estimation are illustrated in Figure 2.1.

The remainder of section 2.2 will examine the above four criteria while the following section will deal with indirect energy.

2.2.2.1 Fuel Consumption Rates of Vehicles

The amount of fuel consumed by a vehicle over a distance travelled is referred to as the vehicle fuel consumption rate. For vehicles consuming petroleum fuels the rate is measured in litres per 100 kilometres (L/100 km) while kilowatt hours per 100 kilometres (kWh/100 km) is used for electrically propelled vehicles.

A substantial amount of research has been conducted into the factors which effect fuel consumption rates. Based on this research, the United States Environmental Protection Agency (EPA)¹ summarized the research findings and concluded that the rates are primarily dependant on vehicle design, average trip speed and trip distance.

1. Vehicle Design

The main features of a vehicle design effecting fuel consumption rates are engine displacement, vehicle weight, body shape and size, drive train design (motor, transmission and drive shaft) and the number of accessories

1 - Fuel Consumption Rate of Vehicle

a) Vehicle Characteristics	b) Vehicle Operation Pattern
- Engine Power Load	- Private Vehicle
- Vehicle Weight	- Trip Speed
- Aerodynamic Load	- Trip Distance
- Drive Train Losses	- Ambient Temperature
- Rolling Friction	- Stopping Frequency
- Accessories	
- Engine Efficiency	- Public Vehicles
- Propulsion Fuel Used	- Speed
- Engine Speed	- Stopping Frequency
- Engine Load Factor	- Ambient Temperature

2 - Vehicle Fleet Composition

a) Average Age of Vehicles in Fleet	b) Proportion of Each Type of Vehicle in the Fleet

3 - Demand For Vehicle Use

a) Demand for Travel	b) Mode Choice	- Level of Service Definitions
- Socio-Economic and Land Use Criteria		
- Vehicle Load Factors	- Number of Seats	
	- Vehicle Occupancy	

FIGURE 2.1

FACTORS AFFECTING FUEL CONSUMPTION IN URBAN TRANSPORTATION

such as power steering, power brakes and air conditioning. Increases in engine displacement and vehicle weight will increase fuel consumption rates. An increase in vehicle body length or frontal area can increase the aerodynamic drag, vehicle weight and the rate of fuel consumption. Increases in the number of vehicle accessories and the use of automatic rather than standard transmissions in the drive train will increase a vehicle fuel consumption rate.

It is the basic features of a vehicle which determine to a large extent the rate of fuel consumption.

2. Average Trip Speed

Average trip speed is obtained by dividing the trip distance travelled by the time spent in the vehicle. The average trip speed of a long urban trip is usually greater than that for short urban trips. This occurs since long urban trips are driven partly on highways where stops per kilometre are low while short trips are driven mostly on arterial and secondary roads where stops per kilometre are high. The relationship of average trip speed to stopping frequency is illustrated in Figure 2.2.

When a vehicle is being driven at a constant speed, referred to as cruising operation, fuel is consumed to overcome aerodynamic drag, rolling friction, drive train losses and accessory losses. However, most urban trips are not driven at constant speeds but rather under cyclic operation involving frequent speed changes and/or stops throughout the

(1) G.M. stands for General Motors

FIGURE 2.2

STOPPING FREQUENCY EFFECT ON AVERAGE TRIP SPEED

Source: Reference 1

trip. For cyclic operation additional fuel is consumed to overcome inertial forces and to keep the motor running while the vehicle is stopped.

The fuel consumption rates for vehicles operating under cruising and cyclic operation are illustrated in Figure 2.3. A comparison of the two curves indicates that fuel consumption rates under cyclic operation are much higher than those for cruising operation at low average trip speeds. At higher average trip speeds, the rates for cyclic operation approach those under cruising operation, but still remain higher. The two curves are closer together at higher speeds since urban trips made at these speeds are long in length and have fewer stops per kilometre as previously discussed. Due to the effects of vehicle operation on fuel consumption rates, the minimum rate for cyclic operation occurs at a higher average trip speed than the minimum rate for cruising operation.

The roadway level of service is another feature which effects average trip speed and fuel consumption rates. During peak periods, the roadway level of service decreases as traffic volumes increase. The increased congestion reduces the average trip speeds and in turn alters fuel consumption rates. The reverse concept occurs when traffic volumes decrease. For most urban trips, the average trip speed is less than the speed where the minimum fuel consumption rate occurs for cyclic operation. This implies that a reduction in average trip speed in an urban area increases the fuel consumption rate.

(1) Curves represent a 1975 compact vehicle
Source: Reference 1

FIGURE 2.3

3. Trip Distance

As Figure 2.4 illustrates, the fuel consumption rate decreases as trip distance increases due to the warm-up effect. The principle reasons why this occurs are:

- a) A reduction in the rolling friction as the tires warm-up and the inflation pressure rises.
- b) A reduction in the engine and transmission friction as the lubricants warm-up.
- c) A reduction in both the carburetor choke and the heat loss to the combustion chamber walls and coolant as the engine approaches optimum operating temperature.

2.2.2.2. Fuel Consumption Rates for the Private Vehicle Fleet

The aforementioned relationships of vehicle design, average trip speed and trip distance on the rate of fuel consumption brings forth the complexities involved at estimating a fuel consumption rate. With the increasing need of a standard measurement for automobile rates, standard tests were developed. Of particular interest are the tests developed by Claffey,² the United States Federal Highway Administration,³ and EPA¹.

Claffey's² work was based on extensive in-traffic tests of several new 1975 automobiles. An in-line fuel meter was used to measure fuel consumption. The effects of stop cycles, slow cycles, gradients, traffic volume, pavement surface texture, highway curvature, side parking, idling, speed, and automobile trailer weight were measured.

- (1) The curves illustrate the increase in an automobile fuel consumption rate for a cold start relative to the fuel consumption rate of a vehicle operating at an ambient temperature of 38°C and operating with a hot start.

FIGURE 2.4

WARM-UP EFFECT ON FUEL CONSUMPTION RATES

Source: Reference 41

The Federal Highway Administration³ test used twelve 1970 or later model year automobiles, each equipped with an in-line fuel meter which were operated over a prescribed steady speed route. Though the data appeared fairly consistent, the number of test replications, the drive train warm-up procedures, if any, and a general assessment of the precision of the test were not reported. However, great care was taken to accurately measure fuel consumption and speed. In general, the tests results were consistent with Claffey's test.

Both Claffey and the Federal Highway Administration test results give estimates of fuel consumption rates for vehicles produced prior to 1976. The tests are not repeated every year to account for different rates of new vehicles. To apply their test results to future years, assumptions are required to account for the rates of new vehicles.

The most frequently used standard measurement of fuel consumption rates are based on two EPA tests¹. The first test represents those rates obtained for urban cyclic operation while the second represents cyclic highway operation rates. The urban test is a 12.08 km stop-and-go driving cycle with a speed range from 0 to 92 km/h and an average speed of 32.3 km/h. The trip begins with a cold start (the engine is started after the vehicle has been parked overnight at an ambient temperature of 21°C), takes 23 minutes and has 18 stops. Eighteen percent of the trip time is spent idling during these stops. The first 8 minute segment of the trip is then repeated

from a hot start (engine is started while it is still hot) and test data are combined to represent a realistic mixture of hot and cold start urban driving.

The EPA highway cyclic test is a 16.1 km non-stop trip with an average speed of 77.3 km/h. The trip begins with a hot start (ambient temperature 21°C) and lasts 13 minutes. Except for starting and stopping at a standstill, the speed range is 45 to 97 km/h.

Both of the EPA tests are performed indoors on a chassis dynamometer. The tests are only carried out for the new vehicles produced each year. Results of the EPA tests as compared to "over the road" rates when the vehicle is actually travelling over the roadway were found to be lower. Adjustment factors are used to increase EPA rates to compensate for this error.⁴

The automobile fleet using a roadway is composed of many sizes and ages of automobiles with different fuel consumption rates. To simplify the estimation of a fleet rate, automobiles are usually classified into the following four class sizes: subcompact, compact, intermediate and standard. An average EPA rate can be found for each class size of new automobiles produced during a specified year. As Figure 2.5 illustrates, vehicle designs have changed significantly over the years. This implies that the average fuel consumption rate for any vehicle class size may differ in any given year.

FIGURE 2.5
TRENDS IN PRIVATE VEHICLE DESIGN

Source: Reference 1

To obtain an automobile fleet EPA rate, Chumak⁵ suggests using new automobile EPA rates for those vehicles produced five years prior to the year under study. This implies that the useful life of a vehicle is ten years and that the mean age is five. A fleet proportion of each class size is found by establishing the year and class size of new vehicles purchased and older vehicles retired during a ten-year period. The EPA rate for the fleet is obtained by using a sales weighted average. This is obtained by multiplying the EPA rates for each class size by their class proportion of the fleet. The sum of these products gives the desired fleet EPA rate.

The fleet EPA rate is obtained for both highway and urban cyclic operation. EPA used these two rates to develop a curve illustrating the relationship of fuel consumption rates versus average trip speed under cyclic operation. An example of the curve for a new 1975 compact automobile was illustrated in Figure 2.3.

2.2.2.3 Fuel Consumption Rates for the Public Vehicle Fleet

No standard tests are in practice to measure the fuel consumption rates of transit vehicles. However, most cities do know the fuel consumption rates of their transit vehicles for both regular and limited stop operation. This classification of operation is so called because of the effect stopping frequency has on the rate of fuel consumption. In regular operation, the vehicle is stopping frequently to pick up and drop off passengers for the entire transit route. The

average speed is low and fuel consumption rates are high.

For limited stop operation, the transit vehicles make several stops at the beginning of the route to pick up passengers and then travel directly to the end of the route to let passengers off. For this type of operation the speeds are high, few stops are made and fuel consumption rates are lower than those for regular operation.

A third type of transit operation is deadheading which includes those kilometres travelled by the transit vehicles to get to or from the storage garage to the location where regular and limited stop operation begins or ends. The fuel consumption rate for deadheading is different than those obtained for the other forms of operation. Most urban areas do not know this fuel consumption rate.

2.2.2.4 Vehicle Usage

To establish the amount of fuel consumed by fleets it is necessary to know how many kilometres the vehicles travelled over a defined interval of time. This usage will be termed transportation output. Transportation output is expressed in either vehicle-km, seat-km or passenger-km.

Transportation output is a function of the travel demand generated by socio-economic and land use factors of an urban area. Travel demand is interrelated to transportation output through such variables as the temporal and spatial distribution of travel, modal level of service definitions and major tradeoffs among alternative land use/transportation options.^{6,7}

Travel demand models are used to simulate in abstract terms existing transportation systems and to provide a simple and effective method for simulating future transportation systems. Over the years, a variety of travel demand models have been developed which usually encompass four tasks.⁸

1. Trip generation. This task is used to obtain the total number of trips produced and attracted by a zone.
2. Trip distribution. This task is used to distribute the trips estimated in the previous task among the origin-destination pairs.
3. Modal split. This task is used to split the trips between the origin-destination pairs among the available modes.
4. Trip assignment. In this task, trips among the various modes are assigned to their networks.

The selection of a time period to base the travel demand models is an important and fundamental decision. It dictates to a large extent the scope and complexity of the modelling procedure. The choices available to the planner are few but distinct. The models may be based, in general on one or more of the following time periods:⁹

1. 24 hours.
2. A.M. peak hour or peak period.
3. P.M. peak hour or peak period.
4. off-peak hour or off-peak period.

The main criterion in the selection of the time period is the objective for which the models are being developed. Other considerations include: the data base, whether they are used to predict travel in an existing year or one in the future and the availability of time and resources.

Through the application of the models, the number of interzonal and intrazonal trips are estimated. The minimum distance between zones can be found using minimum path algorithms. When the minimum distance and trip frequency are multiplied the product is the total kilometres travelled between those zones. Vehicle occupancy factors can be used to estimate the number of kilometres travelled by the vehicles in both the private and public transportation systems. When this is done for all zonal pairs the total transportation output for the urban area is obtained. Factors can then be applied to obtain another total transportation output for other time periods such as weekly or annual periods.

2.3 Requirements for Estimating Indirect Energy

The previous section dealt with the requirements for estimating fuel consumption and the energy content of fuels which establishes direct energy consumption. This section examines the four requirements to obtain indirect energy consumption which are:

1. Establishing the "unit" indirect energy required to produce and maintain each type of vehicle and their infrastructure plus the energy required to produce a unit of direct energy.

2. Establishing the transportation output each vehicle and their infrastructure can provide over their lifetime.
3. Establishing indirect energy intensities.
4. Establishing transportation output.

Various methods are available to estimate the above energy related items. A review of these methods and their limitations are given next.

2.3.1 "Unit" Indirect Energy Requirements

Process analysis and Input-Output analysis are two methods used to estimate "unit" indirect energy requirements.¹⁰ Process analysis involves tracing the processes used in producing a good and examines the energy inputs into each step of the processes. For the production of an automobile, this involves estimating the energy used in the manufacturing process of the vehicle. It also requires estimating the energy used by all other processes leading to the input materials (glass, iron, etc.) required to build the vehicle. These energy estimates are then summed to obtain the "unit" indirect energy. Due to the many processes and joint use of the facilities for many products (trucks, buses, cars, etc.) the process analysis method can become extremely complex.

The energy input-output analysis uses the energy input/output tables developed by Statistics Canada. These tables are used to compute the total energy input per unit

of output for any industry. The input-output analysis can have conceptual limitations due to its aggregated nature.

The IBI Group¹¹ developed a hybrid method based in part on Process analysis and Input-output analysis. The method used to estimate the energy used to produce a vehicle is obtained by separating the energy required to produce the materials and the energy consumed to transform these materials into the finished vehicle. For each of the materials input the energy requirement per kilogram is obtained using Statistics Canada's input/output energy data relating to the particular industry producing the product. To estimate the energy input to transform these materials into a vehicle one must determine the energy requirement for various manufacturing processes involved to produce the vehicle.

The indirect energy required to maintain a vehicle is obtained by establishing the cost of vehicle maintenance, on a per kilometre basis, and the energy requirement of the vehicle maintenance process.

The indirect energy requirements to construct, operate and maintain infrastructure are evaluated in a different manner. For all the infrastructure elements, the energy required for construction are obtained by using the monetary value of the infrastructure component directly, separating it into types of construction such as elevated, surface or underground and applying the estimated energy requirements.

The energy requirements of infrastructure operation, maintenance and the production of direct energy are estimated by analyses of the various processes and inputs required.

2.3.2 Transportation Life Output

The transportation output which a vehicle or its infrastructures will provide over their useful life is termed their transportation life output. If this output is expressed in vehicle-km, the method adopted by Fels¹² and the IBI group¹¹ can be used for estimating this output. Their method of estimating the transportation life output of vehicles combines the number of years the vehicle will function with the kilometres travelled per year.

Estimates of this transportation output are more reliable for private vehicles than for public vehicles. The IBI Group¹¹ have estimated annual kilometres travelled for transit vehicles. However, the IBI Group state that there are no standards as to the number of years a transit vehicle will function. Many vehicles which are twenty years old are still in service while others are scrapped much earlier.

If the transportation life output of vehicles is to be measured in passenger-km, assumptions are required regarding vehicle occupancy.^{11,12} Particular care must be used when using the average private vehicle occupancy since it changes for different types of trips. For transit vehicles, the average vehicle occupancy is more difficult to obtain. The

occupancy changes for different size vehicles, different types of service, and differs between peak and off-peak periods.

Seat-km can also be used to measure transportation output. The average number of seats in the vehicle is determined and combined with the annual kilometres travelled by the vehicle.

The selection of either vehicle-km, passenger-km, or seat-km to measure transportation life output of vehicles is dependant on the requirements of the energy analysis.

The transportation life output used for infrastructure is passenger car unit kilometres, (PCU-km).¹¹ A PCU is a concept sometimes used for traffic analysis to express the amount of road capacity used by one automobile. Transit vehicles use a multiple of this unit.

To estimate the transportation life output for infrastructure, life and usage assumptions are required. The life of infrastructure is dependant upon whether it consists of a rail system or a paved roadway. The road usage assumptions are the expected total amount of vehicular traffic in an average year.

2.3.3 Indirect Energy Intensities

Indirect energy intensities are obtained by dividing a "unit" indirect energy requirement by its transportation life output. These intensities give the amount of indirect energy in MJ used per unit of transportation output.

The indirect energy intensity of fuels is obtained by estimating the indirect energy required to produce a unit of fuel. For gasoline and diesel oil the unit of fuel is a litre while kilowatt hours is used for electricity.

2.3.4 Transportation Output

As previously stated, estimates of transportation output for a specified time period are obtained using travel demand models. The models are used to estimate the total kilometres travelled for a specified time period. The kilometres are then proportioned among the available modes and infrastructure in the private and public transportation systems. Occupancy factors or vehicle seat factors are used to obtain the transportation output in vehicle-km, passenger-km or seat-km.

Total indirect energy is obtained by multiplying the indirect energy intensity by the transportation output during the time period.¹¹ If separate estimates of indirect energy usage are required for the private and public transportation systems, the total transportation output for infrastructure must be proportioned according to the share of usage between automobiles and transit vehicles.

2.4 Techniques for Estimating Energy Consumption

No "state-of-the-art" technique exists for estimating total energy consumption for urban transportation systems.

The primary research conducted in Canada was performed by the IBI Group¹¹ who developed the aforementioned indirect energy intensities. The IBI Group did not devise a technique to estimate fuel consumption and the transportation output upon which the energy intensities could be applied to obtain total energy consumption. There is no evidence of any Canadian city where transportation planners have attempted to estimate total energy consumption.

Research within the United States has also been limited. Fels¹² developed some energy intensity figures using process analysis. However, she did not develop a technique to estimate fuel consumption or transportation output for an urban area.

In 1974, a study was conducted through The Pennsylvania Transportation Institute¹³ to develop a technique for measuring the fuel consumed by automobiles and diesel buses. Later in 1979, Janson¹⁴ developed a technique for calculating direct energy. No attempts were made to extend the techniques to include indirect energy. However, both techniques contain some interesting concepts for estimating fuel consumption.

1 - The Pennsylvania Transportation Institute Technique

The technique was designed to estimate fuel consumption in a manner compatible with existing travel demand models using their data sets. The models were used to estimate the kilometres travelled by automobiles and diesel buses for each

link in an urban network. Combined with each link was data pertaining to traffic volumes, average speed, length, level of service and the roadway type (such as arterial or expressway). Fuel consumption rates were developed for every link in the urban area. This method of estimating fuel consumption rates will be referred to as the link-by-link approach.

The automobile fuel consumption rates were based on the two EPA tests. The rates were then increased to account for EPA underestimation of "over the road" rates. The rates were again increased to account for the warm-up effect by taking the American national average trip length of 15.1 km and increasing the rate by 3.45%. The rates were then used to develop the EPA fuel consumption rate curve for the fleet. The curve was used to estimate the fuel consumption rate for each link, based on link speed. Another fuel consumption rate was estimated to account for stops per kilometre more than those occurring in the EPA urban test. This rate was estimated by multiplying the number of these additional stops per link by the fuel consumed to stop, idle for thirty seconds and accelerate up to 44 km/h and dividing this product by the link length. The fuel consumption rates for speed and stops per kilometre were added and modified to account for roadway level of service.

For diesel buses, the fuel consumption rates were based on estimates provided by a transit department for regular and

limited stop operation. The kilometres travelled for both types of operation on each link were estimated.

An estimate of the quantity of fuel consumed for a link was computed as follows:

$$\left[(L/100\text{km}) \times (\text{Vehicle-km}) \right]_{\text{auto}} + \left[(L/100\text{km}) \times (\text{Vehicle-km}) \right]_{\text{transit}} = C_1$$

where

$(L/100 \text{ km})$ is the fuel consumption rate for the automobile and transit fleets as they operate over the link,

vehicle-km is vehicle kilometres of travel on the link for a specified time period,

C_1 is the fuel consumption for that link.

The summation of C_1 values over all links represents the total petroleum consumed in the urban area. The technique is illustrated in Figure 2.6.

Although this technique can be used to accurately estimate petroleum consumption, it would require two fundamental alterations to estimate direct and indirect energy consumption:

- a) Separate estimates of the fuel consumed by the automobile and transit systems are required rather than a combined total. This is necessary to measure the different types of fuels consumed for various vehicles in the systems.

FIGURE 2.6

FRAMEWORK TO ESTIMATE FUEL CONSUMPTION USING THE LINK-BY-LINK TECHNIQUE

- b) Separate estimates are required for the kilometres travelled by the different private and public vehicles. This is necessary for determining the different direct and indirect energies consumed for each type of vehicle.

2 - Janson Technique

The Janson technique was also based on the link-by-link approach. Figure 2.7 illustrates the method used to estimate direct energy consumption for the private and public vehicle fleets.

The automobile fuel consumption rates were obtained by using the speed on each link. The rates were based on data from The Federal Highway Administration³ and a test done by Chang¹⁵ which was similar to Claffey's test². An equation devised using this data was applied to a 1975 automobile fleet. No attempt was made to account for fleets after 1975. The equation gave the fleet fuel consumption rate under hot start conditions and was applied to estimate fuel consumption for each link. The fuel consumption between each origin-destination pair was estimated and then an extra quantity of fuel was added, based on trip length, to account for the warm-up effect. This gave zone-to-zone fuel consumption per average automobile trip. The automobile trip table (a matrix giving the number of trips between each origin-destination pair) was multiplied

FIGURE 2.7

FRAMEWORK OF JANSON TECHNIQUE TO ESTIMATE DIRECT ENERGY CONSUMPTION

by the fuel consumed per automobile trip between each origin-destination pair. The sum of the fuel used for each interchange gave total fuel consumption. The energy content of gasoline was used to obtain direct energy consumption.

Transit energy consumption was obtained by first calculating the vehicle kilometres per person trip for each transit link. This was done by dividing the link length multiplied by the number of vehicles by the volume of passengers. A computer program was run to sum both distance and vehicle kilometres of travel per person trip. Three separate transit trip tables were prepared, one for transit users only, a second for transit riders who access rail transit by driving an automobile to the station and a third for those riders who access rail transit as an automobile passenger. Multiplying these trip tables by the appropriate vehicle kilometres per passenger gave zone-to-zone vehicle kilometres for all trips. The energy content of fuels and fuel consumption rates of the transit vehicles for regular and limited stop operation were obtained from the Chicago transit department and multiplied by the appropriate vehicle zone-to-zone vehicle kilometre to obtain direct energy consumption.

The Janson technique could be used to estimate total energy consumption. The technique is more refined than the previous technique since it does separate the types of fuels consumed by the transit fleet. However, it does not include the energy consumed while in deadheading operation.

2.5 Analysis of Energy Consumption

There are several methods which can be used to analyze energy consumption depending on the problem being examined. Of particular interest are the engineering method, the statistical area wide method, and the statistical geographic area method.

1. The Engineering Method

This method is independent of the transportation output in an urban area. Energy content of fuels and indirect energy intensities are applied to obtain the energy consumed for one unit of transportation output. The passenger-km output is useful for this kind of analysis providing reliable vehicle occupancies are available. Seat-km can also be used if vehicle occupancies are not available. This form of analysis was carried out by Fels¹². The effects on energy consumption due to different vehicle occupancy or the introduction of more fuel efficient vehicles can be analyzed. However, this analysis gives no indication regarding total energy consumption during a time period in an urban area.

2. Statistical Area Wide Method

This method is a more useful form of energy analysis. It utilizes travel demand models to estimate transportation output during a time period. The transportation output for the vehicles and infrastructure in each system are estimated and energy intensities applied giving total energy consumption.

For this form of analysis, transportation output would be measured in vehicle-km. An analysis could be performed to determine the energy used by each system for various changes in vehicle occupancies and vehicle usage. Another analysis could be conducted regarding changes in energy consumption for various land use policies.

If the modal split task is performed using models sensitive to petroleum prices, an analysis could be implemented for estimating the effects petroleum prices could have on energy usage. The same method could be applied to study the effects automobile ownership, travel time and other modal level of service characteristics may have on total energy consumption.

Another form of analysis could deal with the selection of transit vehicles for future years. The energy consumed by various transit systems which may use different vehicle technologies as articulated buses or light rail vehicles could be estimated. The energy usage of each system could then be used as an evaluation criterion for selecting a future transit system.

3. The Statistical Geographic Area Method

This method uses the link-by-link approach to estimate energy usage for each link. A ring analysis could be used to establish energy consumption contours or establish the energy consumption intensity for various geographic areas.

This form of analysis could aid the transportation planner in selecting the location of transit park and ride stations and where extra road space should be located.

2.6 Energy Analysis Issues

There is some controversy as to what energy should be included into the analysis of energy consumption. The major issues are briefly discussed below.

1. Treatment of Imports

In Canada, a significant portion of the automobiles and transit vehicles are imported either whole or in part. The energy used to manufacture these vehicles was consumed in a foreign country. Similarly, the energy consumed to produce imported petroleum may be considered as energy not being consumed solely within Canada. If it was decided that it was necessary to distinguish between the energy consumed within Canada or outside Canada, then energy intensities for the transportation vehicles, infrastructures and fuel production could not be considered constant and would have to be re-estimated for each urban area. Contrarily, energy consumption could be treated in a global rather than domestic fashion.¹¹ This would give greater general applicability to the results.

2. Treatment of Energy as a Function of Time

The analysis of total energy consumption can be based on either a historical or marginal approach.¹¹ The

historical approach examines the total energy that has been invested in a transportation system and divides it by the total transportation output to get the average energy consumed per unit of output.

In the marginal approach, the marginal energy which would be required to increase transportation output is included. This implies that infrastructure which was built prior to the time period under study is not considered while the energy used to construct infrastructure within an existing or future time period is included.

2.7 Concluding Comments

It has been established that estimates of both direct and indirect energy consumption are required to effectively analyze energy usage by urban transportation systems. Estimation of these energies involves developing a technique to obtain transportation outputs and fuel consumption rates which are then combined with the energy content of fuels and indirect energy intensities giving total energy consumption. Major considerations which influence the methods used to obtain the desired results include the types of demand models available, the availability of data and computer facilities and the energy analysis methodology.

Based on the literature reviewed in this chapter, the following chapter presents a framework for estimating and analyzing energy consumption to meet the requirements of this research.

CHAPTER III

A FRAMEWORK FOR ESTIMATING AND ANALYZING
ENERGY CONSUMPTION IN URBAN TRANSPORTATION
- A CASE STUDY FOR THE OTTAWA-HULL AREA3.1 Introduction

This chapter presents the fundamental concepts of a technique developed to estimate total energy consumption. A description is presented of how the technique was applied to the Ottawa-Hull area.

3.2 Fundamental Concepts of the Technique

The approach used to estimate total energy consumption begins with establishing transportation output and fuel consumption for the private transportation system using the interzonal and intrazonal travel interchange as the analysis unit rather than the link. For the public transportation system the transit corridor (i.e. designated route of the public vehicle) is used as the analysis unit. The principle advantage of this approach is the ease which energy estimates are obtained using a minimum amount of repetitious calculations. However, this limits the energy analysis to a statistical methodology focusing on the energy consumed either area wide, by interchange or by transit corridors, but not by geographic areas. An outline of the steps used to attain total energy consumption for both transportation systems is illustrated in Figure 3.1.

FIGURE 3.1

A FRAMEWORK FOR ESTIMATING DIRECT AND INDIRECT ENERGY CONSUMPTION

3.2.1 Energy Consumed by the Private Transportation System

The method used to estimate transportation output is accomplished by predicting the number of person trips using the private system for each interchange. A vehicle occupancy factor is used to convert from person trips to vehicle trips. Using a road network, the average distance for each interchange is obtained and then multiplied by the number of vehicle trips for that interchange. The sum of these products for all interchanges gives total vehicle-km travelled during the time period under study. This total transportation output is used to estimate the transportation output for vehicles in the private fleet by proportioning the total output among each vehicle type according to their proportion of the private fleet composition.

Fuel consumption is estimated by establishing one EPA gasoline consumption rate which is representative of an average trip made in the urban area by a fleet which is assumed to consist entirely of gasoline vehicles. Estimates of the various fuels consumed are found by multiplying the EPA gasoline consumption rate by the transportation output in vehicle-km and applying an appropriate fuel type factor and an over the road factor when applicable. Fuel type factors are used to account for the different fuel consumption rates of a diesel or other types of vehicle versus a similar gasoline vehicle.

The EPA gasoline consumption rate for an urban area is obtained as follows:

- a) The average vehicle travel time for each interchange is found using the road network. Each interchange time is multiplied by the corresponding number of interchange vehicle trips. The sum of these products gives total vehicle travel time.
- b) The average trip travel time is found by dividing the total vehicle travel time by the total number of private vehicle trips. The same concepts are used to obtain average trip distance.
- c) The average trip speed in the urban area is found by dividing the average trip distance by the average trip travel time.
- d) By using the EPA curve of average trip speed versus the fleet fuel consumption rate an average EPA fuel consumption rate is obtained for the urban area. The EPA curve must be adjusted to account for the hot start in the highway cyclic test, the cold start in the urban cyclic test, the difference between the ambient temperature used in the tests and in the study area, and the average number of stops. The "over the road" adjustment factor can be applied to modify the curve or later to modify the urban area EPA rate. As

it will be shown when the technique is applied to the Ottawa-Hull area it is also possible to account for roadway level of service.

Using the estimates of transportation output, fuel consumption rates, fuel contents and indirect energy intensities for the various vehicles composing the fleet, direct and indirect energy consumption are obtained.

3.2.2 Energy Consumed by the Public Transportation System

Transportation output for the public transportation system is obtained by using the transit network to establish the ridership demand and length of each corridor. Assumptions are made regarding vehicle load factors, headway and average corridor speed from which the number of vehicle-km travelled are obtained for each type of vehicle and for each of regular, limited stop and deadheading operations. The sum of each type of transportation output over all corridors gives the desired transportation outputs for each type of transit vehicle.

Estimates of fuel consumption are obtained by applying the fuel consumption rates of each vehicle to the corresponding transportation output under regular, limited stop and deadheading operations. The energy content of fuels and the indirect energy intensities are used to estimate direct and indirect energy consumption.

3.3 Technique Application to the Ottawa-Hull Area

The Ottawa-Hull urban area was selected as the study area to apply the energy estimation technique. The area is displayed in Figures 3.2 and 3.3.

Most of the travel demand models developed for this area are based on the P.M. peak hour time period defined by the trip in motion concept.⁹ However, no modal split models were available for analyzing the effects which petroleum prices may have on energy consumption. Therefore, before the energy estimation technique was applied to the study area, modal split models were developed. The models were then used in conjunction with trip distribution data made available from the transportation branch at the Regional Municipality of Ottawa-Carleton (RMOC) to estimate travel demand.

Estimates of energy consumption were for a one year period. This provided an energy analysis which was independent of the fluxuations in energy use by the hours and days in a week. It also accounts for those days in the year when holidays fall on weekdays. However, the use of a one year period made it necessary to develop a method to transform the P.M. peak hour data to an annual amount.

The energy estimates were made for two one year periods, 1977 and 1990. These years were selected due to the availability of travel demand data. Furthermore, 1990

FIGURE 3.2

THE URBAN OTTAWA-HULL AREA

FIGURE 3.3

THE RURAL OTTAWA-HULL AREA

was considered far enough into the future to analyze the effects which changing petroleum prices and the development of new private and public vehicle technologies could have on future energy use.

3.3.1 Methodology to Model Modal Split

For the Ottawa-Hull area, behavioural modal split models were selected to predict mode choice. They are based on the economic theory of consumer behaviour and the psychology of choice behaviour.¹⁶ These models were used for analyzing the effects petroleum prices could have on total energy consumption by including a perceived cost of travel variable in the models.

Behavioural models can be either disaggregate or aggregate in form.¹⁷ A disaggregate model is used to model the response of one traveller while an aggregate model is used to simulate the response for a group of travellers. In most cases disaggregate models are developed and then transformed into aggregate models by applying an aggregation technique to the former models. It is necessary to use aggregate behavioural models in the demand modelling process since the process is aggregate in form.

Two disaggregate models were developed to simulate mode choice response in the Ottawa-Hull area during the P.M. peak hour. One model was used to simulate mode choice for the "home based work trip" and another for "all other trips".

The "home based work trip" model was used for those trips made for the trip purposes of going from home to work, or from work to home. The "all other trips" model was used for all the remaining trip purposes (e.g. home to shopping, work to recreation, etc.).

For the "home based work trip" model, three modes were simulated; auto driver, auto pooler and transit. The auto driver mode consisted of those who used the automobile and were alone in the vehicle. The auto pooler mode comprised of those who used the automobile when more than one person was in the vehicle. The transit mode consisted of those people who used the public transportation system.

For the "all other trips" model, two modes were simulated, auto user and transit. The auto user mode consisted of those who used the automobile to make a trip, while the transit mode was composed of those who used the public transportation system.

There were two principle advantages of modelling modal split using the manner outlined. First, only two models are required to predict modal split for many trip purposes. Secondly, the behaviour of a traveller for selecting a mode in each of the two models are distinguishable which is a requirement for developing models of this type.

Once the disaggregate models were developed, they were aggregated and the model split task was performed using the

computer programs developed for the Urban Mass Transportation Administration, commonly referred to as the UTPS package.¹⁸

Figure 3.4 illustrates the UTPS programs used to prepare input data and perform the modal split task. The name of the program is in heavy print while its function is contained in brackets. A more detailed description of the programs are contained in Appendix A1.

The methodology used to predict travel demand was not capable of changing the total demand for travel during the P.M. peak hour. This implies that any changes in modal attributes within the modal split models could neither increase nor decrease total travel demand but only effect the portion of total demand between modes.

3.3.2 Establishment of Petroleum Prices and Vehicle Fleets

The energy consumed by the Ottawa-Hull transportation systems by 1990 will be dependent upon many changes which will occur during the 1980's. Of particular interest are those which will effect petroleum prices and the private and public vehicle fleets.

1. Petroleum Prices

Since the Arab oil embargo, the cost of imported petroleum has continued to rise rapidly during the 1970's and has forced the Canadian Government to increase domestic petroleum prices in an attempt to reduce both foreign debt

and petroleum demand. Due to the energy dilemma it is expected that the domestic petroleum price will continue to rise during the 1980's. The Federal Government is now saying that a 3.1 to 3.3 cents per litre (in constant 1977 dollars) increase per year from 1980 to 1985 may occur. It is possible that these increases may continue up to 1990.

The petroleum prices analyzed for 1977 and 1990 were the following:

- (a) BC 1977. This is referred to as the Base Case (BC) for 1977. The petroleum price (\$/L) is that which existed in 1977.
- (b) BC 1990. This is referred to as the Base Case (BC) for 1990. This is the petroleum price for 1990 which keeps the cost of fuel per kilometre travelled (\$/km) equal to the cost in BC 1977.
- (c) PPD 1990. This is referred to as the petroleum price decrease (PPD) for 1990. It represents a petroleum price which keeps the cost of fuel per kilometre less than the cost in BC 1990. This condition may occur if the petroleum price increase is not enough to offset the lower quantity of fuel consumed (causing a reduction in the petroleum cost per trip) by the more efficient automobiles in 1990.
- (d) PPI 1990. This is referred to as the petroleum price increase (PPI) for 1990. The petroleum

price was chosen to be high enough to increase the cost of fuel per kilometre above the cost analyzed in BC 1990.

The actual petroleum prices for BC 1990, PPD 1990 and PPI 1990 are presented in Chapter 4.

2. Private Vehicle Fleets

The energy dilemma of the 1970's has greatly influenced the design of automobiles. A significant criterion which has effected their design was the mandate regarding fuel consumption standards placed on the American automobile industry by the United States Government. The mandate has forced the automobile manufacturers to reduce the EPA urban cyclic test rate of fuel consumption from 16.18 L/100 km in 1975 to 9.1 L/100 km by 1985 as the average rate of their automobile production fleet.

The automobile manufacturers have attempted to meet these standards by reducing the size and weight of the vehicles and reducing engine displacement. Another approach has been to use diesel rather than gasoline engines. Furthermore there has been a growing interest to produce vehicles propelled by electric, hydrogen, and other energy sources aimed at reducing the quantity of petroleum consumed.

It is clear that significant changes will occur to the design of private vehicles during the 1980's. To this end, this research has examined several types of automobiles and the

10 speed bicycle as private vehicle alternatives by 1990.

The private vehicle fleets examined were:

- a) A1 - This fleet is composed of automobiles propelled by gasoline motors. This is the first fleet examined for both 1977 and 1990.
- b) A2 - This is the second fleet examined for 1990. It consists of vehicles propelled by gasoline and diesel motors.
- c) A3 - This is the third fleet examined for 1990 and consists of gasoline, diesel and electric vehicles.
- d) A4 - This is the last fleet examined for 1990 which consists of gasoline, diesel and electric vehicles. Furthermore, a bicycle is included as a part of the fleet.

3. Public Transit Systems

Over the years, many forms of transit vehicles have developed. For the most part, these developments have occurred in Europe and include light rail vehicles, heavy rail vehicles, standard buses and articulated buses. These vehicles have been produced for the most part by Europeans in an attempt to provide an integrated transit system which is energy efficient, cost effective, and maintains an attractive level of service.

Within the last several years, there has been a change in the Canadian attitude toward public transit by the government,

city planners and the public. With the recent objectives of reducing petroleum demand and eventually obtaining energy self-sufficiency, attempts are being made to bring the Canadian urban transit systems up to the standard of the successful state-of-the-art European systems.

Due to the changing roll of public transit in Canada, this research analyzed a variety of public transit systems for the Ottawa-Hull area. The proposed systems are considered feasible alternatives for providing an integrated public transportation system with the ridership demand expected by the year 1990. A description of the systems examined for 1977 and 1990 are given below:

- a) T1 - This is the first public transit system examined for 1977 and 1990. It consists of the standard diesel bus fleet which existed in the study area during 1977.
- b) T2 - This is the second fleet analyzed for 1990 and consists of both standard and articulated diesel buses using both transitway and non-transitway corridors.
- c) T3 - The third transit system examined for 1990 is composed of standard and articulated diesel buses for the non-transitway and articulated electric buses on the transitway.
- d) T4 - The fourth transit system for 1990 comprises of standard diesel buses and articulated diesel

buses for the non-transitway system and light rail vehicles on the transitway.

3.3.3 Transportation Output and Fuel Consumption for the Private Transportation System

The framework used to estimate transportation output and fuel consumption began with the application of the fundamental concepts of the energy estimation technique to P.M. peak hour. The number of vehicle trips during the P.M. peak hours were obtained from the modal split models while the average distance and the average travel time for each interchange were based on a P.M. peak hour road network.

The average EPA gasoline fuel consumption rate for the private vehicle fleet was found using the average P.M. peak hour trip speed. This rate was not modified to account for actual stopping frequency. It was assumed that the EPA curve took this into account adequately for the Ottawa-Hull area. Furthermore, the rate corresponds to a roadway level of service between D and E (this level of service is based on RMOC data). No other road factors were applied to the rate at this stage.

Modifications were made to the average P.M. peak hour trip characteristics of distance and the EPA gasoline fuel consumption rate to obtain averages for the weekday off-peaks, Saturday and Sunday. The modifications included finding a new average trip distance for the weekday off-peaks, Saturday and Sunday and using an average level of service between B

and C which exists for the roadways. A level of service factor was used to reduce the EPA rate to account for higher trip speed and reduced stopping frequency.

The number of vehicle trips for each day in the week were found, multiplied by their average trip distance and EPA average gasoline fuel consumption rate to obtain fuel consumption for the five day work week and the weekend. Annual estimates were obtained by multiplying by the number of five day work weeks and weekends in a year and assuming that the fuel consumed during national and provincial holidays were similar to that encountered on weekends. An annual EPA gasoline consumption rate for the area was found by dividing annual gasoline consumption by total transportation output. The rate was then used to estimate the amounts of various fuels consumed using fuel consumption rates and transportation outputs. Estimates of direct and indirect energy were then estimated as was illustrated in Figure 3.1.

3.3.4 Transportation Output and Fuel Consumption for the Public Transportation System

The framework used to estimate transportation output and fuels consumed by the transit system were based on the number of P.M. peak hour transit trips and the P.M. peak hour transit network. By loading the transit network with the number of person transit trips for each interchange it was possible to obtain the kilometres travelled by the vehicles in the P.M. peak hour for regular, limited stop and deadheading operations.

The transportation output for the remaining weekday peak period, weekday off-peak, Saturday and Sunday were based on P.M. peak hour kilometres of travel in regular and limited stop operation and the hourly and daily variation of buses in operation. Deadheading kilometres travelled was obtained by using an average deadheading distance and applying the frequency in which buses start and end revenue operation throughout the week.

Annual estimates of transportation output were obtained by estimating the transportation output for the five day work week and the weekend and multiplying by the number of each in a year. Fuel consumption rates for each vehicle and each type of vehicle operation were obtained and combined with transportation output to give fuel consumption.

3.3.5 Methodology to Estimate Energy Consumption

The methodology for estimating energy intensities were based on the IBI study.¹¹ For each type of private and public vehicle analyzed, the "unit" indirect energy requirement was found for production and maintenance. The transportation life output of vehicles was based on data from the municipal transit department, the IBI study¹¹ and Fels¹².

In this research the estimates of energy requirements were based on the global concept. Furthermore, 1977 infrastructure construction energy was based on the marginal approach by establishing the infrastructure constructed during 1977 and for the 1990 analysis from 1977 to 1990.

For the infrastructure constructed, the total construction energy was divided by its useful life expectancy in years, giving a construction energy intensity ($\text{JMx}10^6/\text{year}$). The number of years the infrastructure was in use within the time periods analyzed (1977, 1977-1990) was multiplied by the construction energy intensity, giving construction energy use.

3.3.6 Analysis

The methodology for analyzing energy consumption was as follows:

1. The energy consumed by the private vehicle fleet A1 and the transit fleet T1 for the petroleum price which existed in 1977 (BC 1977) was obtained for 1977.
2. The energy consumed for all the private and public vehicle fleets for 1990 were obtained using the BC 1990 petroleum cost. An analysis was conducted to determine the effects which different types of vehicles have on energy consumption and the possible energy savings which are attainable if the vehicles are used. From the analysis the author selected a private and public vehicle fleet which was most likely to exist by 1990 in an energy conservative society.
3. The energy consumed for the years 1977 and 1990 using the private and public fleets which existed

in 1977 and those selected in step two for 1990 were compared. The cost of petroleum per kilometre used was that which existed in 1977 (i.e. BC 1977 and BC 1990).

4. The energy consumed in 1990 using the selected fleets was obtained for PPD 1990 and PPI 1990. An analysis was conducted to establish the changes in the energy consumed by the private and public fleets under changing petroleum prices.

3.4 Concluding Comments

This chapter presented a detailed description of the technique developed to estimate energy consumption and how it was applied to the Ottawa-Hull area. As it was implied in the description, the first phase of the technique calls for estimating travel demand from which transportation output is obtained. A pair of behavioural modal split models had to be developed to estimate travel demand. The following chapter presents the theory and the method used to develop these models.

The fifth chapter applies the models within the demand modelling process to obtain travel demand and then transportation output. Furthermore, estimates are attained of the amounts of fuels consumed to propel both the private and public vehicle fleets.

In chapter six the characteristics of the various vehicles in the private and public fleets of 1990 are determined and used to establish indirect energy intensities. Estimates of total energy consumption are obtained and the analysis is performed. As it was mentioned in chapter one, the final chapter presents a summary and draws conclusions and recommendations from the research.

CHAPTER IV

THE THEORY AND DEVELOPMENT OF THE BEHAVIOURAL MODAL SPLIT MODELS

4.1 Introduction

As shown in the previous chapter, the modal split models selected for this research were behavioural in form and attempt to estimate mode choice based on economic and psychological principles. A clear understanding of the theoretical concepts of these models is essential for applying them in the most effective manner. To this end, the first part of this chapter presents their theoretical concepts and the technique used for calibration.

The remainder of this chapter describes the method and results obtained by developing the models using the method illustrated in figure 4.1. The method encompassed the following four tasks; (i) data preparation, (ii) calibration, (iii) aggregation, (iv) validation. A great deal of effort, data, and skill is required to develop behavioural modal split models which predict modal split accurately.

Initially in the data preparation task, samples were prepared by the author for developing the models. However, due to inaccurate estimates of several transit attributes obtained from a transit network, it was not possible to use these samples for calibrating the models.

FIGURE 4.1

Other samples were then prepared in conjunction with the consulting firm N.D. Lea and Associates Limited. The consultant was retained by the staff at RMOC to develop similar behavioural models for their modelling requirements.¹⁹ With these samples, the author was able to obtain successful calibrations.

4.2 Theoretical Concept of Behavioural Models

Disaggregate behavioural modal split models are theoretically based on the economics of consumer behaviour and the psychology of choice behaviour. The behavioural assumptions for these models are as follows:²⁰

1. The traveller will behave in a rational manner.
2. The economic resources available to the traveller are limited.
3. The traveller knows the characteristics of all modes available to him.
4. The choice of a given mode by a traveller implies that he has considered the characteristics of the modes available relative to his own and his trip characteristics, and has reached a decision that one mode is preferable.

These assumptions imply that the traveller will logically select a mode from those available to him so as to maximize his benefits. In modal split models, this implies that the traveller will select a mode which he perceives as having the least travel impedance, or "disutility". The

disutility of a mode can be expressed by a linear function. The function is a vector of independent variables measuring the level of service characteristics of each alternative mode and the socio-economic characteristics possessed by the traveller. The form of the disutility function is

$$U_{ij} = a_{i1} x_{ij1} + a_{i2} x_{ij2} + \dots + a_{in} x_{ijn} + b_{ij} \quad \dots \quad (4.1)$$

where

- U_{ij} = the disutility function of alternative j for individual i ,
- x_{ijn} = the level of magnitude of attribute n of alternative j for individual i .
- a_{in} = a perception coefficient which reflects the weight placed by individual i on travel attribute n ,
- b_{ij} = a constant reflecting the disutilities associated with alternative j for individual i which are not directly quantified,
- n = the number of the quantifiable alternative attributes used.

The disutility function contains those attributes which can be observed and measured. The function indirectly represents the unmeasurable attributes primarily through the value obtained for the constant b_{ij} .

The individual's behaviour when selecting one mode from those available can be represented by a sigmoid curve such as the one illustrated in Figure 4.2. The curve displays consumer choice well. That is, it is behaviourally reasonable to postulate that a travel cost difference between two modes from 90 to 100 cents is perceived by the individual as less than a difference of 5 to 15 cents. The curve also illustrates the behaviour of captive mode users who will keep choosing the same mode no matter what the difference in cost is, providing he will still decide to make the trip.

Both the probit and logit functions have successively been used to explain in a mathematical form this sigmoid curve choice behaviour. Within the range of most data both techniques provide almost equal probability figures.²¹ However, the logit technique is computationally more convenient and therefore was selected for this research.

The mathematical equation of the multinomial mode choice in logit form is expressed as:

$$P_{ij} = \frac{e^{-U_{ij}}}{\sum_{r=1}^M e^{-U_{ir}}} \quad j \in r \quad \dots \quad (4.2)$$

where P_{ij} is the probability of individual i choosing a particular mode j out of M available alternatives.

The statistical estimation of the multinomial choice model's coefficients can be carried out by using either the maximum likelihood estimation technique, or the simultaneous multiple linear regression technique. It has been shown that the coefficients obtained by the two techniques are not

FIGURE 4.2
THE SIGMOID CURVE FOR BINARY MODE CHOICE

significantly different.²² However, the maximum likelihood technique requires far less data to calibrate a multinomial model and therefore this technique was selected for this research. The maximum likelihood technique can be explained as follows:²³

Assume that out of N individuals who belong to the same user group (all the i 's) and who are observed travelling between a given origin-destination pair, n_1 choose to travel by alternative 1, n_2 choose to travel by alternative 2, ..., and n_m choose to travel by alternative M , where M alternatives are available. The likelihood L of such a sample is then:

$$L = \left[\frac{N!}{n_1! n_2! \dots n_M!} \right] P_1^{n_1} \cdot P_2^{n_2} \cdot \dots P_M^{n_M} \dots \quad (4.3)$$

where

P_j = the probability of choosing travel alternative j

($j = 1, 2, \dots, M$) as given by equation (4.2)

and

$$\sum_{j=1}^M P_j = 1.0, \text{ and } \sum_{j=1}^M n_j = N$$

the likelihood function L is thus a function of the unknown coefficients (a 's and b 's).

Ignoring the constant term contained between brackets in equation (4.3) as it does not affect the maximization of L with respect to the coefficients, the logarithm of the sample likelihood may be written as:

$$\text{Log } L = \sum_{j=1}^M n_j \cdot \log P_j \quad \dots \quad (4.4)$$

Considering a sample that covers all the user groups and all the travel links, equation (4.4) would then be:

$$\text{Log } L = \sum_{j=1}^M \sum_{l=1}^R \sum_{k=1}^S n_{ljk} \cdot \log P_{ljk} \quad \dots \quad (4.5)$$

where

n_{ljk} = the number of travellers in user group k travelling along link l by alternative j ,

P_{ljk} = the probability that an individual belonging to user group k who is travelling along link l will choose alternative j ,

M = the number of travel alternatives available

S = the number of user groups, and

R = the number of travel links sampled.

Maximization of the logarithm of the likelihood function given by equation (4.5) with respect to the unknown logit coefficients yields their maximum likelihood estimate.

4.3 Data Preparation

The primary source of data used to develop the two modal split models was a 1.4% home interview telephone survey conducted by RMOC in the Fall of 1977. Approximately 1.4% of the households residing in the Ottawa-Hull area were contacted by mail and interviewed by telephone. From each

household, data was obtained regarding the trips made during the day by each individual, together with their socio-economic characteristics. Further data was obtained pertaining to the household itself. Appendix B1 contains both the survey questionnaire and a key record outlining the survey data which was available for the development of the models.

The data preparation task began with selecting the appropriate telephone survey data, contained on computer tape. The following data were selected:

1. The record number; this was used to attain the original survey questionnaire and obtain the address of the trip's origin and destination.
2. The traveller's perceived travel time for the mode used.
3. The number of people in the automobile, if the traveller made the trip in an automobile.
4. The parking cost incurred, if any.
5. The trip purpose.
6. Socio-economic and household data pertaining to the traveller.

This data was then used to generate additional data for each traveller. This was necessary since the telephone survey did not provide data describing many of the attributes of the mode used and in fact no data regarding the attributes of the other modes available to the traveller.

Five steps were required to transform the telephone survey data into a format from which the models could be calibrated. This consisted of developing two samples, one to calibrate each of the modal split models. The sample used to develop the "home based work trip" model was called the "home based work trip" sample while the other was called the "all other trips" sample.

The five steps performed were:

1. The removal of the following records from the 21,912 original telephone survey records. (A record is the data contained on computer tape which has all the information pertaining to the individual surveyed. There is one record for each individual.)
 - a) Records which were incomplete.
 - b) Records where no trip was made.
 - c) Records which had intrazonal trips.
 - d) Records which had the trip beginning or ending in a zone where no transit service was provided.
 - e) Records where modes other than those being modelled were used.
 - f) Records containing trips not made during the P.M. peak hour.
2. With the remaining 2,616 records, a computer printout was obtained. Using this printout, the records were

sorted manually to obtain those trips which were "home based work" and "all other". A systematic sample of records was then taken from each of the record groups. Once this was accomplished, two samples of records were obtained; one for the "home based work trip", and another for the "all other trips".

From each record, the record number was used to obtain the original telephone survey questionnaire form. If the questionnaire was incomplete, the record was removed from the sample.

Each record was then examined for coding errors. Any record containing an error was removed from the sample. The "home based work trip" sample now contained 236 records and the "all other" sample contained 252 records. The mode choice of the samples and the number of records for each mode is illustrated in Table 4.1. The number of records illustrated in the table for each mode is adequate to describe the variance of individual behaviour regarding mode choice. Therefore, the number of records now prepared were used in the calibration step to develop the desired modal split models.

The two samples were then placed into separate SPSS²⁵ files.

3. For each of the records in the two samples, additional travel data was prepared. To estimate the automobile

TABLE 4.1
OBSERVED MODE CHOICE IN OTTAWA-HULL

Trip Purpose	Mode	Number of Records	Modal Split in Percent
Home Based Work	Auto Driver	71	30
	Auto Pooler	58	25
	Transit	107	45
	Total	236	100
All Other Trips	Auto User	159	63
	Transit	93	37
	Total	252	100

travel data a road network was developed. A description of this network is presented in Appendix B2. The variables developed were:

a) In-vehicle Travel Time

This was the time, in minutes, spent inside the vehicle. The variable was obtained for automobile travel from the road network.

For transit, the time was estimated manually using transit schedules and the address of the origin and destination for each trip.

b) Number of Transfers

This was the number of times an individual switched from one transit vehicle to another while making the transit trip. The variable was obtained manually using transit schedules.

c) Transfer Time

This was the time, in minutes, spent transferring from one transit vehicle to another. This was obtained manually.

d) Access Distance

This was the distance, in hundreds of feet, required to get from the trip origin to where the individual began waiting for the first transit vehicle. This was obtained manually.

e) Transit Fare

This was the cost, in cents, to take the transit mode. This was obtained manually.

f) Trip Distance

This was the distance, in kilometres, travelled by the modes in order to get from the trip origin to the destination. The distances were obtained from the road network for automobile trips and manually for the transit modes.

g) Parking Cost

This was the cost, in cents, incurred for parking an automobile. This variable was estimated, for the most part, manually.

Appendix B3 describes in greater detail the method and data used for developing each variable. Once the variables were estimated, they were coded and punched onto computer cards, so that they could be added to the appropriate record.

4. Using the data from each record, the following additional variables were generated using the SPSS software;

a) Automobile Perceived Costs

This was the cost, in cents, perceived by the automobile user to operate his vehicle. Stopper¹⁶ suggests that this cost should include the cost of petroleum consumed for making the trip and any parking costs incurred. The perceived cost can be substantially less than the actual cost an automobile owner

actually pays for making the trip. This is due to the unperceived trip costs including portions of the initial investment for purchasing the vehicle and other costs including insurance, financing, licence, maintenance and repairs to the vehicle. For new vehicles the actual cost for making a trip may be twice the perceived cost while for those who purchase used vehicles the perceived cost can be slightly lower than the actual cost.

For this research, the automobile perceived cost included the cost of petroleum consumed and the parking cost incurred.

b) Vehicles per Household

This was the number of vehicles owned or rented by household members, divided by the number of individuals in the household.

c) Vehicles per Household/Dwellers Over 5 Years Old

This was the number of vehicles owned or rented in the household, divided by the number of individuals in the household over five years old.

d) CBD Flag

This variable was used to distinguish between a central business district trip (CBD) whose origin and/or destination began in zones 1-6. All other trips were considered non-CBD.

Each record now contained the original data obtained from the 1.4% telephone survey and the data

for each variable developed for the modes available to the traveller.

5. The two samples were then taken out of the SPSS file and placed into another file as input into the UTPS program UMODEL. UMODEL was then run to transform the two samples onto a format which could be used as input into ULOGIT. This program used the maximum likelihood technique to estimate the coefficients in the two models.

As it was mentioned in the introduction of this chapter, the author initially developed other "home based work trip" and "all other trips" samples. The principle difference between the two data preparation tasks was the data source used to estimate transit attributes. The procedure just outlined used transit schedules and the actual address of the trip origin and destination. This method produced highly accurate estimates of trip time, access distance, and number of transfers. However, the method was extremely time consuming and therefore limited the number of samples which could be prepared.

The samples prepared by the author used estimates of transit trip time and number of transfers obtained from a transit network. A description of the network prepared by the author is presented in Appendix B.2. By using the transit network data, it was possible to obtain a greater number of records for each sample in a shorter period of time. The author's opinion was that the larger number of observations and therefore the greater diver-

sity of travel behaviour could offset part of the problems associated with the inaccuracies of the estimated transit variables obtained from the transit network.

Unfortunately, due to the large size of error at estimating these transit variables, it was not possible to obtain successful model calibrations using these samples.

4.4 Calibration

As stated previously, the UTPS program ULOGIT was used to estimate the coefficients in the models. Due to ULOGIT limitations and the characteristics of the maximum likelihood technique, the following three restrictions were imposed on formulating each model.

1. The independent variable could not be used in every disutility function. This would create a degree of freedom for changing the coefficients without affecting the mode choice probabilities. The same problem could occur if every disutility function contained a constant or if two constants were placed in the same disutility function.
2. The disutility functions were required to have at least one, but not more than ten independent variables.
3. The number of coefficients being used in all the disutility functions at any given time was limited to twenty.

The selection of independent variables used for each disutility function was based on the following criteria:

1. Whether the models were to be used in a predictive or explanatory manner. A predictive model is used to predict modal split at a future time period (as in year 1990). The model can only contain independent variables which can be estimated for this future time period. Explanatory models use independent variables which can be measured for either a present or past time period.
2. The ability of the independent variable to describe the mode's level of service or the traveller's socio-economic characteristics.
3. The independent variables' ability to relate energy consumption to modal split.
4. The correlation between each independent variable. When variables were correlated, the more appropriate one was used in the disutility function. Furthermore, independent variables which showed very high correlation with the dependant variable were excluded.
5. The accuracy of the independent variable's values estimated through the data preparation procedure.
6. Whether the independent variable was describing a common modal attribute (such as perceived cost and in vehicle travel time but not transfer time) which could be contained in the other disutility functions.

A formulation of the disutility functions where each has a common attribute in each function was required to effectively analyze the effect that the independent variable can have on mode split.

7. The results of previous calibration attempts. These can provide valuable insight regarding the significance of variables and how different combinations of independent variables in the disutility functions inter-relate with one another.
8. The possible problems which can occur when the variable is being aggregated. Variables which are difficult or cannot be aggregated accurately should be excluded from the model.

Based on the criteria just described, independent variables were selected for the disutility functions in the models. Each model formulation was then input into ULOGIT and calibrated, using the appropriate "home based work trip" sample or the "all other trip" sample.

4.5 Selection of the "Home Based Work Trip" Model

The two "home based work trip" model formulations calibrated are illustrated in Table 4.2. The formulation of the two models were relatively similar. The only difference between them was that the second formulation contained number of transfers rather than transfer time. An analysis was conducted to determine which of the two formulation best suited

TABLE 4.2

CALIBRATED "HOME BASED WORK TRIP" MODELS

Mode	Independent Variables	Formulation Number	
		1	2 (1)
AUTO DRIVER	In-Vehicle Travel Time (min)	-0.031 ⁽²⁾ (-1.71) ⁽³⁾	-0.0245 (-1.33)
	Perceived Auto Cost (cents)	-0.008 (-1.54)	-0.0071 (-1.37)
	Vehicles per Household	1.278 (5.14)	1.2861 (5.16)
	Auto Driver Bias	-2.652 (-5.73)	-2.741 (-5.84)
AUTO POOLER	In-Vehicle Travel Time (min)	-0.030 (-1.71)	-0.0245 (-1.33)
	Perceived Auto Cost (cents)	-0.008 (-1.54)	-0.007 (-1.37)
	Sex	-1.087 (-3.49)	-1.1058 (-3.54)
	Auto Passenger Bias	-0.834 (-2.63)	-0.8849 (-2.73)
TRANSIT	In-Vehicle Travel Time (min)	-0.030 (-1.71)	-0.0245 (-1.33)
	Fare (cents)	-0.008 (-1.54)	-0.0071 (-1.37)
	Access Distance (100 ft.)	-0.220 (-2.71)	-0.0934 (-2.73)
	Number of Transfers	-	-1.1114 (-3.53)
	Transfer Time (min)	-0.178 (-3.14)	

(1) Selected formulation

(2) The estimated value of the coefficient

(3) The t-statistic of the coefficient

the needs of this research. The criteria upon which this decision was based were:

1. The Sign of the Coefficient

This criterion was used to determine whether each independent variable was perceived correctly as either a disutility (such as travel times and perceived costs) which must have a negative coefficient or as a utility (vehicles per household) which must have a positive coefficient. Both formulations had all the coefficient signs correct.

2. The Significance of the Independent Variable

The t-statistic for each coefficient must be greater than or equal to 2.0 in order to be confident (at a 95 percent level) that the value of the coefficient is reliable. However, Atherton²⁶ suggests that the failure of a coefficient to meet this criterion may indicate that either the "true" value of the coefficient is significantly different from its estimated value and/or that a larger sample size is required. Atherton's analysis was based on the models presented in Table 4.3.

Several coefficients had t-statistics below 2.0 in the two "home based work trip" models illustrated in Table 4.2. However, since these models were calibrated using a small sample size, it is possible that the coefficients were significant and that the t-statistics were small primarily due to the sample size.

TABLE 4.3

82

WORK TRIP MODELS FOR OTHER URBAN AREAS

Independent Variables (1)	Washington (Sample Size=1114)	Los Angeles (Sample Size=879)	New Bedford (Sample Size=453)
D_a	-3.24 (1) (-6.86) (2)	-2.746 (-4.85)	-2.198 (-2.648)
D_p	-2.24 (-5.60)	-1.830 (-3.95)	-1.535 (-1.535)
OPTC	-0.0048 (-2.26)	-0.0049 (-2.07)	-0.0194 (-1.576)
IVTT	-0.0308 (-2.67)	-0.0398 (-0.49)	-0.0398 (-0.490)
OVTT	-0.040 (-4.08)	-0.041 (-2.90)	-0.1014 (-2.900)
AALD _a	3.99 (10.08)	3.741 (3.67)	2.541 (3.903)
AALD _p	1.62 (5.31)	0.6093 (1.58)	0.4499 (0.8478)
BW _a	0.890 (4.79)	0.8101 (3.28)	1.026 (3.769)
GW _p	0.287 (1.78)	-	-
DCITY _a	-0.854 (-2.75)	-	-
DCITY _p	-0.404 (-1.36)	-	-
DINC _{a,p}	0.00007 (3.46)	0.000083 (2.31)	0.000072 (1.279)
NWORK _p	0.0983 (1.03)	0.081 (0.46)	0.1874 (1.249)
DTECA _p	0.00063 (1.34)	0.00027 (2.23)	0.00060 (0.7665)

(1) Variable Definition

- D_a 1, for Auto Driver, 0 Otherwise
 D_p 1, for Auto Pooler, 0 Otherwise
 OPTC One Way Out-of-Pocket Travel Cost (cents)
 IVTT One Way In-Vehicle Travel Time (minutes)
 OVTT One Way Out-of-Vehicle Travel Time (minutes)
 AALD_a Number of Automobiles/Licensed Drivers, for Auto Driver, 0 Otherwise
 AALD_p Number of Automobiles/Licensed Drivers, for Auto Pooler, 0 Otherwise
 BW_a 1, if Worker is Head of Household, for Auto Driver, 0 Otherwise
 GW_p 1, if Worker is Head of Household, for Auto Driver, 0 Otherwise
 DCITY_a 1, if Work Place is in CBD for Auto Driver, 0 Otherwise
 DCITY_p 1, if Work Place is in CBD for Auto Pooler, 0 Otherwise
 DINC_{a,p} Household Annual Income
 NWORK_p Number of Workers in the Household for Auto Pooler, 0 Otherwise
 DTECA_p Employment Density at the Work Zone for Auto Pooler, 0 Otherwise

(2) Value of Coefficient

(3) Value of t-statistic

2

3. The Similarity of the Coefficients in Other Models

The coefficients for three American cities are in Table 4.3. These coefficients were compared to the "home based work trip" coefficients illustrated in Table 4.2. Of particular interest were the in-vehicle travel time and the perceived trip cost coefficients.

The in-vehicle travel time coefficients for Ottawa-Hull were slightly lower than those of the American cities. The first Ottawa-Hull formulation has a coefficient which appears more similar to those of the American models.

The perceived cost coefficients of the three American models ranged from -0.0048 to -0.0194. A comparison of the perceived cost coefficients from other urban areas indicates that a range between -0.05 to -0.01 is more common. This suggests that both Ottawa-Hull formulations have acceptable perceived cost coefficients.

4. The Ease and Accuracy Which the Model Could Be Aggregated

The second formulation satisfied this criteria. This is due to the greater accuracy which the number of transfers can be aggregated compared to transfer time.

5. The Goodness-of-fit Statistic, ρ^2

This statistic provides a single measure to rank the goodness-of-fit of the model to the samples. However, it is rarely used as a model selection criteria. This is due to its abstract measure which make it difficult to grasp what differences in ρ^2 actually mean in terms of model performance.

In this research the model's performance was dependant on several criterion including the usefulness of the variables included in the formulation and the ability of the model to predict mode split well once it is aggregated.

Atherton²⁶ suggests that a better procedure for measuring the goodness-of-fit is to compare the observed mode split of the sample with that predicted by the model.

Of the two formulations, the first predicted 65 per cent of the observed choice between automobile and transit as was recorded on the records in the sample while the second formulation predicted 69 per cent correctly. Therefore, it appears that the second formulation may predict mode choice better.

Based on the five criteria just presented, the second formulation was selected for this research. This decision was primarily based on the aggregation criteria and its better ability to predict mode choice.

4.6 Selection of the "All Other Trips" Model

The two "all other trips" formulations are illustrated in Table 4.4. The first formulation differs from the second since it contains an additional variable, the CBD flag. The selection between the two formulations was again based on the five criteria used to select the better "home based work trip" model. The coefficients of similar models developed for other cities are illustrated in Table 4.5. A comparison could only be made for the perceived cost coefficient. The coefficients in the two Ottawa-Hull formulations fall within the range of those obtained in the other urban areas, and therefore appear acceptable.

An examination of the t-statistics of the two Ottawa-Hull formulations indicate that the removal of the CBD flag improved the statistical performance. This tends to indicate that the second formulation was a better model. An analysis of the predictive capability of the two formulations indicated that the second formulation was superior.

Based upon the five criteria, the analysis indicated that the second "all other trips" formulation was the better model and therefore was used for this research.

4.7 Sensitivity Analysis

To effectively use the behavioural modal split models, it was necessary to determine the sensitivity of the independent variables relative to their effects upon modal split. This

TABLE 4.4

CALIBRATED "ALL OTHER TRIPS" MODELS

<u>Mode</u>	Independent Variables	Formulation Number	
		1	2 (1)
Auto User	In-Vehicle Travel Time (min)	-0.0157 ⁽²⁾ (-0.93) ⁽³⁾	-0.0205 (-1.03)
	Perceived Cost (cents)	-0.0288 (-3.09)	-0.0295 (-3.21)
	Total Vehicle/Persons Over 5 Years Old in Household	3.8927 (5.06)	3.92 (5.11)
	CBD Flag	-0.1734 (-0.49)	
	Auto User Bias	-1.1551 (-2.29)	-1.2686 (-2.86)
Transit	In-Vehicle Travel Time (min)	-0.0192 (-0.93)	-0.0205 (-1.03)
	Fare (cents)	-0.285 (-3.09)	-0.0295 (-3.21)
	Number of Transfers	-0.2511 (-0.76)	-0.2741 (-0.84)

(1) Selected Formulation

(2) The estimated Value of the Coefficient

(3) The t-statistic of the Coefficient

TABLE 4.5
CALIBRATED "ALL OTHER TRIPS" MODELS FOR OTHER CITIES

Independent Variable	Shopping Trips		Social/Recreational Trips	
	Washington	San Francisco Bay Area	Washington	San Francisco Bay Area
Out of Vehicle Travel Time (minutes)	-1.00 (0.0296) (1) (2)		-0.207 (0.0430)	
ln (In Vehicle Travel Time plus Out of Vehicle Travel Time)	-2.24 (0.189)	-1.418 (0.0861)	-1.94 (0.232)	-0.768 (0.0524)
Perceived Trip Cost (cents)	-0.0242 (0.00575)	-0.0856 (0.0077) (3) -0.282 (0.060) (4)	-0.004 (0.007)	0.0896 (0.0043) (3) -0.1323 (0.0455) (4)
Auto Bias	0.557 (0.0993)			0.3368 (0.2738)

Notes: (1) The estimated value of the coefficient
(2) The standard error
(3) Auto Coefficient
(4) Transit Coefficient

information can be obtained using point elasticities and arc elasticities. Point elasticities are used to study the effects that small changes to an independant variable can have on modal split. Arc elasticities are used to study the effects that large changes to an independant variable can have on modal split.²⁷

The point elasticities of the independant variables are illustrated in Tables 4.6 and 4.7. These elasticities were used as an aid for determining which independant variables would require particular attention during the aggregation task. A large point elasticity (i.e., where an elasticity is one or more) indicates that even a small estimation error would significantly increase the error at predicting modal split. This indicated that particular effort should be allocated to those variables with higher elasticities during the aggregation task.

Arc elasticities were used to examine the effects that large changes in petroleum costs may have on modal split. This was accomplished by using the "home based work trip" and "all other trips" samples to obtain an average perceived cost for auto driver, auto pooler and auto user. These costs were then used to estimate the average petroleum costs by deducting from the perceived cost the average parking cost. Estimates of mode split were then obtained for a variety of petroleum prices while the other independant variables remained unchanged. The curves, illustrated in Figure 4.3, were developed to display the changes in modal split for changing petroleum prices. Each curve displays the percentage change in the average petroleum costs from -60 to 100 percent. This

TABLE 4.6

POINT ELASTICITIES FOR THE "HOME BASED WORK TRIP" MODEL

Variable	Auto Driver	Auto Pooler	Transit
Auto Driver In Vehicle Travel Time (min.)	D -0.231 ⁽¹⁾	C 0.145 ⁽²⁾	C 0.145
Auto Driver Perceived Travel Cost (cents)	D -0.210	C 0.132	C 0.132
Total Vehicles Per Household	D 1.040	C -0.650	C -0.650
Auto Pooler In Vehicle Travel Time (min.)	C 0.125	D -0.313	C 0.125
Auto Pooler Perceived Travel Cost (cents)	C 0.040	D -0.102	C 0.040
Sex	C 0.173	D -0.434	C 0.173
Transit Fare (cents)	C 0.087	C 0.087	D -0.177
Transit In-Vehicle Travel Time (min.)	C 0.200	C 0.200	D -0.409
Access Distance (100 ft.)	C 0.170	C 0.170	D -0.347
Number of Transfers	C 0.178	C 0.178	D -0.362

- (1) D = Direct Elasticity: A direct elasticity can be defined as the percentage change in the probability of choosing a mode resultant on a change in one of the level of service characteristics of the mode.
- (2) C = Cross Elasticity: A cross elasticity refers to the effect on the choice probability of a given mode due to a change in one of the level of service characteristics of another mode.

TABLE 4.7

POINT ELASTICITIES OF THE "ALL OTHER TRIPS" MODEL

Variable	Point Elasticity	
	Auto User	Transit
Total vehicles/ persons over 5 years old in household	D 0.369 ⁽¹⁾	C -1.87 ⁽²⁾
Auto user preceived travel cost (cents)	D -0.111	C 0.560
Auto in vehicle travel time (minutes)	D -0.0459	C 0.232
Transit Fare (cents)	C 0.158	D -0.801
Transit in vehicle travel time (minutes)	C 0.0841	D -0.426
Number of transfers	C 0.0223	D -0.113

(1) D = Direct Elasticity

(2) C = Cross Elasticity

(1) The petroleum price changes were assumed to effect the cost of travel by automobile but not transit.

FIGURE 4.3

THE EFFECT OF PETROLEUM PRICES ON MODE CHOICE

range of costs is within the predictive capabilities of the modal split models since they were calibrated using records containing perceived costs within this range.

From an analysis of the curves, the following 1990 prices per litre of fuel for automobile were selected:

- 1) BC 1990. The price per litre was chosen to be 37.1¢/L, which was 87 percent greater than the cost in 1977 of 19.84¢/L. This price would keep the cost per kilometre the same for BC 1990 as it was for BC 1977, as illustrated in Appendix B.4.
- 2) PPD 1990. The cost of petroleum selected was equal to the cost of 19.84 cents per litre which existed in 1977.
- 3) PPI 1990. This cost of petroleum was 49.6¢/L, which represented a 150 percent increase in petroleum costs per litre over 1977. This cost represents a 60 percent increase in the cost per kilometre travelled over the 1977 cost.

Transit fare was assumed to be unaffected by increasing petroleum prices above 19.84 ¢/L for the reasons presented in section 6.3.4.

4.8 Aggregation

As previously stated, aggregated modal split models were used in the demand modelling process. Therefore, an aggregation methodology was required to transform the disaggregate models into an aggregate form. A theoretically consistent methodology would use the disaggregate formulations

to estimate the choice probability for each traveller making a trip in the P.M. peak hour. These choice probabilities could then be averaged to obtain the expected share choosing each alternative. The extreme data requirements of this procedure has motivated the development of other methodologies.

Koppelman¹⁷ has analyzed several methodologies which use the disaggregate formulation. Of particular interest is the Naive method which uses the disaggregate formulation and assumes that the mode choice behaviour of one traveller for a particular trip can be used to describe a group of travellers making a similar trip. The Naive methodology was adopted for this research.

To apply the Naive methodology, the average socio-economic and average modal attributes for all those travelling within an interchange were considered equal. These averages were then used in the disaggregate formulations to perform the aggregated modal split task. The procedures used to obtain the aggregated socio-economic values for 1977 is now described:

1. For each socio-economic variable, an average zonal value was found for each zone. Since the 1.4% Telephone Survey did not contain enough records of P.M. peak hour travellers for each zone, the zonal average was based on all those who lived in a zone whether or not they made a P.M. peak hour trip.

2. For "home based work trips", the socio-economic zonal average was that of the destination zone. This was done since most work trips made during the P.M. peak hour are from work to home and therefore it is the zonal average at the destination (home) and not the origin which describe the travellers socio-economic characteristics.
3. For the "all other trips", the zonal average was based on the average of the origin and destination zones. This attempted to account for those who were travelling either to or from home. It was not possible to account for the socio-economic characteristics of those travellers who were making a trip which neither began or ended at home.

The average socio-economic values used in 1990 were assumed to be equal to those of 1977.

Average modal attributes for 1977 were based on inter-zonal estimates obtained from the road and transit networks described in Appendix B.2. As it was previously mentioned, the transit attributes obtained from the transit network were not considered highly reliable. However, these estimates were used since it was not feasible to estimate them manually.

A problem was encountered when estimating the auto driver and auto pooler perceived costs. For those interchanges

where a parking cost was incurred, the perceived cost consisted of a parking cost which was one-third of the average parking cost. In actuality, it was one-third of these travellers who should have paid the average parking cost.

The road network used to obtain 1977 interchange attributes was also used to estimate 1990 attributes. No changes were made to account for the several new roadways to be constructed by 1990. It was felt that the extra time and resources used to re-run the road network programs was unnecessary since the addition of the new roadways was not expected to significantly alter the average P.M. peak hour trip characteristics or mode choice.

A modified 1977 transit network was used to obtain transit attributes for 1990. The modified network included a new transitway corridor as illustrated in Figure 4.4. Several corridors located near the new transitway in the 1977 network were not included for 1990 so that transit trips would be diverted to the new transitway. The location of several other 1977 corridors were altered for 1990 to account for expected changes in travel demand and also to connect the corridors to the transitway.

4.9 Validation

Through the validation task, an attempt is made to correct for any biases which occur when the modal split models are aggregated and implemented into the demand modelling process.

A validation method used by the Twin Cities²⁸ applied the aggregation methodology to a pair of samples obtained from home interview surveys. One of these samples was for the base year from which their modal split models were calibrated while the other sample was representative of a past year. The predicted results were then compared with the actual modal split and other characteristics as average trip distance and average trip time to determine any biases which occurred during aggregation. They attempted to correct for the biases by including a set of correction factors which became an integral part of their modelling process.

The Twin Cities validation method corrects for aggregation biases well, but is tedious and time-consuming to implement. Therefore, another method was devised for this research. The method attempted to estimate the biases, which will be referred to as aggregation errors, by comparing the predicted modal split and average trip characteristics obtained from the demand modelling process to those observed in the "home based work trip" and "all other trips" samples. The procedure is illustrated in Figure 4.5. The method does not use any correction factors within the modelling process, but instead a manual selection process is used to obtain the more reliable modal split and average trip characteristics. An important assumption using this method is that the samples are considered representative of the Ottawa-Hull area and that any biases which occur in the samples must be found and considered during the selection process.

FIGURE 4.5
METHOD FOR CORRECTING AGGREGATION ERROR

4.10 Concluding Comments

It was found that the fundamental requirement for the successful calibration of behavioural modal split models was the development of record samples which were accurate and contained adequate variance of travel behavior. It was found that the transit network could not estimate transit attributes with sufficient accuracy. This shortcoming not only influenced the procedure used in the data preparation task, but also the aggregation task which ultimately effected the quality of the entire demand modelling process.

The development of a transit network which is both accurate and detailed to the extent that accurate estimates of access distance, number of transfers, and travel times are obtained is an extremely time-consuming and difficult task. However, if the successful application of the behavioural modal split models in the demand modelling process is desired, then the development of such a network is essential.

The selection of the independent variables used to describe modal attributes and the socio-economic characteristics of a traveller depends upon many factors including whether the models were to be used as predictive or explanatory in nature. In this research, it was necessary to use prediction models which included variables describing perceived cost of travel. This variable was difficult to aggregate since it included a petroleum cost and a parking cost for the auto driver and auto pooler modes.

The results of the sensitivity analysis indicated that the most influential variable which determines modal split was automobile ownership. It was found that automobile users place greater emphasis on in-vehicle travel time than perceived trip cost. A transit user making a home based work trip placed greater importance on in-vehicle travel time than number of transfers. Furthermore, the number of transfers was considered more important than access distance and less important than transit fare. Those transit users making "all other trips" considered transit fare most important followed by in-vehicle travel time and then number of transfers.

The Naive aggregation methodology was selected to transform the disaggregate models into an integral part of the aggregate demand modelling process.

A method was developed to validate the aggregated results obtained from the demand modelling process. The method attempts to correct for aggregation errors by comparing the predicted estimates with those observed in the "home based work trip" sample and the "all other trips" samples.

The following chapter will use the modal split models to estimate travel demand which will then be used to estimate the energy consumed for transportation in the Ottawa-Hull area.

CHAPTER V

ESTIMATION OF TRANSPORTATION OUTPUT
AND FUEL CONSUMPTION5.1 Introduction

In the previous chapter a validation methodology was devised to determine if aggregation errors arose during the modal split task. In order to correct for these errors it was necessary to obtain two estimates of modal split and average P.M. peak hour trip characteristics. From these, the more reliable estimates were used to calculate transportation output of the A1 and T1 fleets for BC 1977.

As it was pointed out in Chapter three, peak hour transportation output was used to estimate annual transportation output. This task involves many steps and the application of several conversion factors which were made available through the Systems Planning Branch at RMOC.

The estimation of fuel consumption by the private and public fleets for BC 1977 was obtained by using fuel consumption rates which were combined with annual transportation outputs giving annual fuel consumption for BC 1977.

The methodology used to estimate transportation output and fuel consumption for 1990 was more difficult. The principle procedures used remained basically the same as for BC 1977, but additional tasks were required, including:

1. Modifying the methodology used to estimate aggregation error.

2. Estimating annual transportation output for three different petroleum prices.
3. Establishing the proportion of new vehicles in the private and public fleets.
4. Estimating fuel consumption rates for vehicles not in use during the 1970's.

Due to these additional tasks, it was decided to estimate transportation output and fuel consumption for 1977 first and then 1990.

5.2 Transportation Output for 1977

5.2.1 P.M. Peak Hour Modal Split

Two estimates of P.M. peak hour mode choice were obtained using the methodology outlined in Figure 4.5 and are illustrated in Table 5.1. A comparison of the two estimates for "home based work trips" shows that the aggregated model predicted substantially more transit trips. This large difference between the two estimates indicates that there were aggregation errors. The author feels that much of the errors were attributable to an underestimation of the aggregated vehicles per household variable. As it was shown in Chapter Four, this variable was elastic and therefore even a slightly lower estimate of the variable would cause a significant increase in transit use. From the onset it was known that the aggregated transit attributes

TABLE 5.1

P.M. PEAK HOUR MODAL SPLIT FOR BC 1977 T1

Trip Purpose	Mode	Results from the Aggregated Modal Split Models		Results Using the Samples and Disaggregated Formulation ⁽¹⁾	
		In Percent	Person Trips	In Percent	Person Trips
Home Based Work Trips	Auto Driver	22.44	21,667	38.60	37,270
	Auto Pooler	20.43	19,726	28.60	27,615
	Transit	57.13	55,162	32.80	31,670
	Total	100.00	96,555	100.00	96,555
All Other Trips	Auto	88.06	51,434	85.90	50,172
	Transit	11.94	6,974	14.10	8,236
	Total	100.00	58,408	100.00	58,408

(1) The mean values of the independent variables obtained from the samples were:

"HOME BASED WORK TRIPS"

- Auto Driver - In-Vehicle Trip Time - 15.32 min.
- Perceived Trip Cost - 47.89 cents
- Vehicles/Household - 1.31
- Auto Pooler - In-Vehicle Trip Time - 17.87 min.
- Perceived Travel Cost - 19.96 cents
- Sex - .55
- Transit - In-Vehicle Trip Time - 24.82 min.
- Fare - 37.02 cents
- Access Distance (100') - 5.54
- Transfers - .49

"ALL OTHER TRIPS"

- Auto User - In-Vehicle Trip Time - 13.48 min.
- Perceived Trip Cost - 22.71 cents
- Automobile Ownership - .57
- Transit - In-Vehicle Trip Time - 29.82 min.
- Fare - 32.46 cents
- Transfers - .49

were overestimated and would cause a decrease in transit modal split. However, the low transit point elasticities combined with the overestimation of the transit variables did not effect modal split to the extent as that of the aggregation error of the vehicles per household variable.

A comparison of the two mode choice estimates for the "all other trips" indicates that the aggregated model predicted less transit trips. For these models the transit attribute variables had much higher point elasticities than the automobile ownership variable. Therefore, the opposite effect occurred with the "all other trips" model than with the "home based work trip" model causing the aggregation error of the transit variables to surpass the effects of underestimating automobile ownership.

It was felt that the modal split obtained from the disaggregate formulations and the samples was the most reliable. They compare favourably with RMO's modal split estimates. RMO estimated that 38 percent of the "home based work trips" were made by transit and 62 percent by automobile while 25 percent of the "all other trips" were made by transit and 75 percent by automobiles.

5.2.2 Average P.M. Peak Hour Trip Characteristics

The methodology used to obtain average trip time and distance from the aggregated models was presented in Chapter three. The methodology used to obtain the average trip

characteristics from the two samples was accomplished by estimating the average trip time from the in-vehicle trip time variables and average trip distance from the perceived trip cost variables. The trip characteristics obtained from the aggregated models were: average trip distance of 9.4 km, average trip time of 15.9 minutes and average trip speed of 35.5 km/h, while those obtained from the disaggregate formulations and samples were: average trip distance of 9.32 km, average trip time of 17.05 minutes and an average trip speed of 32.8 km/h.

As the above figures show, the two sets of trip characteristics are almost identical which tends to indicate that the aggregation error did not affect the average trip characteristics to the same extent as modal split. If the aggregated automobile ownership variables were underestimated for most of the trip inter-changes, then it is possible that the average trip characteristics would only slightly change while substantial changes would be observed in the estimated modal split.

The quality of the trip characteristics obtained from the two samples are now examined. As it was mentioned in Section 4.3, the samples did not contain any intrazonal trips which have short trip distances. Furthermore, those trips where the traveller did not have access to the transit system were excluded from the samples. Most trips where the

transit system was not available to the traveller were long in length with either the trip origin or trip destination located within the outskirts of the urban area.

It is possible that the combined affect of excluding the intrazonal trips and the trips where transit facilities were not available would not have effected the average trip characteristics much if they were included in the samples since the proportion of these trips are small compared to all trips made in the urban area. Based on the facts presented, the average trip characteristics obtained from the aggregated models where all intrazonal and interzonal trips were included plus those trips made by private vehicles where transit was not available were used in this research.'

5.2.3 Annual Transportation Output of the Private Transportation System

The methodology for estimating annual transportation output began with expanding P.M. peak-hour vehicle trips and average trip distance to weekday and weekend amounts in the manner outlined in Section 3.3.3. The P.M. peak hour person trips were factored to represent those made on Wednesday as follows:

$$\begin{aligned} &[(\text{Auto driver P.M. peak hour person trips} + \text{auto} \\ &\quad \text{pooler P.M. peak hour person trips}) * 6.5418 + \\ &\quad \text{auto user P.M. peak hour person trips} * 16.018] * \\ &\quad (1/1.4 \text{ vehicles per person}) = \text{number of private} \\ &\quad \text{vehicle trips for Wednesday.} \end{aligned}$$

The factors of 6.5418 and 16.018 were obtained from RMOC staff.

The private vehicle trips for the remaining days of the week were found by multiplying Wednesday trips by a percentage of average daily traffic of 0.94 for Monday, 0.95 for Tuesday, 1.0 for Wednesday, 1.02 for Thursday, 1.08 for Friday; 1.05 for Saturday and 0.60 for Sunday. These percentages were obtained from RMOC staff.

The number of vehicle trips per day were divided into those made on weekday peak periods between 6:30 AM to 9:00 AM and 3:00 PM to 5:30 PM and off-peak trips made during the remaining hours of the weekday. All trips made on Saturday and Sunday were considered as off-peak trips.

According to Reference 24, 37.7 percent of the weekday vehicle trips are made in the peak periods and the remaining 62.3 percent are made in the off-peak period. Therefore, to obtain a weekday peak period transportation output, the total number of vehicle trips made for that day was multiplied by .377 and then by the average P.M. peak hour trip length. In a similar manner, off-peak transportation output was obtained using an average off-peak trip length of 9.1 km for weekdays, 8.89 km for Saturday and 10.86 km for Sunday. See Appendix C1 for the method used to obtain the off-peak distances. The peak and off-peak transportation outputs were found for Monday to Friday and multiplied by 50.2 while weekend transportation output was multiplied by 57. The sum of these products gave annual transportation output for BC 1977 A1.

This output was then proportioned among the four private vehicle class sizes in the fleet. Reference 4 suggests that the 1977 Ontario fleet consisted of 16.88 percent sub-compact, 24.49 percent compact, 20.20 percent intermediate and 38.43 percent standard sized private vehicles. These transportation outputs for BC 1977 A1 are illustrated in Table 5.2:

5.2.4 Annual Transportation Output of the Public Transportation System

The annual transportation output of the Ottawa public transportation system was calculated by first assigning P.M. peak hour transit trips to the transit network, finding the maximum ridership per corridor and adjusting this ridership to account for aggregation errors in the manner illustrated in Figure 4.5. To each transit corridor one of two bus design capacities was used to estimate the number of vehicles and peak hour transportation output per corridor under defined level of service criteria. A design capacity of 40 passengers per standard bus was used where the maximum link volume in the corridor fell outside the CBD area, designated as zones 1-6 in Figure 3.2. The other design capacity used was 54 passengers per bus when the maximum link volume was located within zones 1-6. These design capacities reflect the policy in the Ottawa area of providing frequent bus service in outer urban areas in an attempt to make the transit mode more

n

TABLE 5.2
ANNUAL TRANSPORTATION OUTPUT OF THE PRIVATE VEHICLE FLEETS

Vehicle Propul- sion Fuel	Private Class Size	BC 1977 A1		BC 1990 A1		BC 1990 A2		BC 1990 A3		BC 1990 A4	
		Percent of Fleet	Annual Trans- portation Out- put in Vehicle km*10 ⁶	Percent of Fleet	Annual Trans- portation Out- put in Vehicle km*10 ⁶	Percent of Fleet	Annual Trans- portation Out- put in Vehicle km*10 ⁶	Percent of Fleet	Annual Trans- portation Out- put in Vehicle km*10 ⁶	Percent of Fleet	Annual Trans- portation Out- put in Vehicle km*10 ⁶
Gas- oline	Subcompact	16.88	475.35	30.00	1,264.67	25.50	1,074.97	21.60	910.56	21.15	891.50
	Compact	24.49	689.65	35.00	1,475.45	29.75	1,254.13	25.15	1,060.22	24.62	1,038.02
	Intermediate	20.20	568.84	20.00	841.11	17.00	716.65	17.00	716.65	16.64	701.64
	Standard	88.43	1,082.20	15.00	632.34	12.75	537.48	12.75	537.48	12.48	526.23
	Sales Weighted Average	100.00	2,816.04	100.00	4,215.57	85.00	3,583.23	76.50	3,224.91	74.90	3,157.39
Diesel	Subcompact					4.50	189.70	3.80	160.19	3.72	160.19
	Compact					5.25	221.32	4.45	187.59	4.36	183.67
	Intermediate					3.00	126.47	3.00	126.47	2.94	123.87
	Standard					2.25	94.85	2.25	94.85	2.20	92.86
	Sales Weighted Average					15.00	632.34	13.50	569.10	13.22	557.19
Elec- tric	Subcompact							4.60	193.92	4.50	189.86
	Compact							5.40	227.64	5.29	222.87
	Intermediate										
	Standard										
	Sales Weighted Average							10.00	421.56	9.79	412.73
Manual	Bicycle									2.09	
	Sales Weighted Average									2.09	88.26

attractive. The total number of P.M. peak hour standard buses in use and P.M. peak hour transportation output for the Ottawa area are illustrated in Table 5.3.

To establish weekly transportation output, Figure 5.1 was used to estimate the percentage of the P.M. peak hour standard bus fleet in regular and limited stop operation for each hour of the week. Using this data it was possible to find the number of buses in use per corridor throughout the week, which was then combined with corridor vehicle speed to give transportation output during regular and limited stop operation. The transportation output attributed to deadheading was calculated by multiplying the number of times a vehicle began and ended regular operation by 8.21 km or by 15 km for the number of times it began and ended limited stop operation.

The estimation of fleet size and transportation output for the Hull transit system was based directly on the Ottawa data just outlined. It was not possible to obtain a direct simulation of the Hull transit system due to the size of zones used in the Hull area. Many of these transit trips were intrazonal and could not be assigned to the transit network. To overcome this problem, the statistics regarding Hull's transit fleet size and annual kilometres of travel for 1977 were obtained from the Hull Transit 1977 annual report.³¹

The kilometres travelled by the Hull fleet were then proportioned between regular, limited stop and deadheading

TABLE 5.3

P.M. PEAK HOUR DATA FOR OTTAWA PUBLIC TRANSPORTATION SYSTEM, BC 1977 T1

Corridor	Maximum Link Volume	Vehicle Design Capacity	Corridor Length Kilometers	Vehicle Speeds (2) (km/h)	% Buses Required Per Corridor	Regular and Limited Stop Transportation Output (Vehicle-km)
1	811	40	17.1	19.0	39	679.3
2	600	54	19.2	19.2	24	422.4
3	1013	40	19.4	19.9	53	966.8
4	3149	54	10.9	20.9	67	1237.0
5	437	40	10.4	22.4	11	221.8
6	588	54	12.5	19.7	19	343.1
7	720	54	13.7	19.9	22	401.3
8	936	54	14.9	18.9	31	527.3
9	1223	54	24.5	20.9	51	977.0
10	771	40	28.6	23.1	44	931.7
11	968	40	25.2	19.8	56	1016.4
12	668	40	28.7	20.3	40	744.3
13	795	40	19.3	18.4	43	725.3
14	505	54	18.8	20.4	17	318.0
15	740	40	26.3	22.5	40	825.0
16	677	54	22.9	19.8	29	526.4
17	181	54	24.2	31.6	4	115.9
18	394	54	26.3	30.0	8	220.0
19	139	54	26.5	30.0	3	82.5
20	49	54	30.1	33.0	1	30.1
21	621	54	31.1	31.0	12	341.0
22	556	54	28.2	29.0	11	292.4
23	282	54	12.5	30.1	3	82.8
24	200	54	26.8	33.0	4	121.0
Total	N/A	N/A	N/A	N/A	632	12148.8

(1) A locational description of each corridor is available at the Systems Planning Branch at RMOC. Corridors numbered 1 to 16 were under regular operation while corridors 17 - 24 were under limited stop service.

(2) The vehicle speed represents the average speed travelled while the vehicle is moving. There is a 5 to 8 minute period of time when the bus driver rests at the end of a run. Therefore, when calculating transportation output, the time when the vehicle is not moving must be taken into account.

N/A Not Applicable

Notes: All of Base Service and Additional Day Service were supplied using buses under regular operation within corridors 1 to 16.

For the weekday A.M. and P.M. peak service, corridors numbered 1 to 16 were under regular operation while corridors numbered 17 to 24 were under limited stop operation.

FIGURE 5.1

HOURLY VARIATION OF P.M. PEAK HOUR BUSES IN OPERATION DURING THE WEEK

operation in the same proportions as those obtained from the simulation of the Ottawa transit system.

The annual transportation output for BC 1977 T1 is presented in Table 5.4. The results compare favourably with the statistics presented in the 1977 OC Transpo Annual Report.³² The report states that 695 regular buses were in the Ottawa fleet as of December 1977, and that 35,507,000 km were travelled by the whole transit system (including dial-a-bus, sightseeing and chartered buses).

5.3 Fuel Consumption for 1977

5.3.1 The Average EPA Gasoline Consumption Rate

The average EPA gasoline consumption rate was based on the average P.M. peak hour trip time, distance and speed obtained from the aggregated modal split task. The rate was estimated as follows:

1. The average age of an automobile using the roadways in 1977 was assumed to be two years. Therefore, the EPA rates were based on the 1975 new car fleet. A two year average vehicle age was used rather than five due to the availability of literature for 1975 new vehicles and since the characteristics of 1975 and 1972 vehicles were relatively similar.
2. The fuel consumption rates were obtained for the urban cyclic test and the highway cyclic test for the 1977 vehicle fleet. The urban cyclic test rate was increased by 4 percent

TABLE 5.4

ANNUAL TRANSPORTATION OUTPUT AND FLEET SIZE OF PUBLIC TRANSPORTATION SYSTEMS

Case	Vehicle Type (1)	Ottawa Transit					Hull Transit					Ottawa and Hull	
		Vehicles in PM Operation	Inactive Vehicles	Transportation Output in Vehicle-km*10 ⁶			Vehicles in PM Operation	Inactive Vehicles	Transportation Output in Vehicle-km*10 ⁶			Total Vehicles	Total Transportation Output in Vehicle-km*10 ⁶
				Regular Operation	Limited Stop Operation	Dead-heading			Regular Operation	Limited Stop Operation	Dead-heading		
BC 1977 T1	DSTD-NT	632	63 (2)	24.461	4.329	6.025	100	10	3.921	0.694	0.966	805	40.396
BC 1990 T1	DSTD-NT	629	63	25.504	2.409	5.635	121	12	4.483	0.793	1.104	825	39.928
	DSTD-T	137	14	4.483	0.793	1.104						151	6.380
	Σ			29.987	3.202	6.739			4.483	0.793	1.104		46.308
	DSTD-NT	340	34	13.395	1.298	2.957	121	12	4.483	0.793	1.104	507	24.030
BC 1990 T2	DART-NT	154	15	6.044	0.593	1.343						169	7.980
	DSTD-T	9	1	0.095	0.378	0.016						10	0.489
	DART-T	67	7	0.639	2.556	0.114						74	3.309
	Σ			20.173	4.825	4.430			4.483	0.793	1.104		35.808
BC 1990 T3	DSTD-NT	357	36	14.065	1.362	3.105	121	12	4.483	0.793	1.104	526	24.913
	DART-NT	162	16	6.346	0.623	1.410						178	8.379
	EART-T	72	7	0.607	2.599	0.125						79	3.331
	Σ			21.018	4.584	4.640			4.483	0.793	1.104		36.622
BC 1990 T4	DSTD-NT	357	36	14.064	1.392	3.105	121	12	4.483	0.793	1.104	526	24.912
	DART-NT	162	16	6.346	0.623	1.410						178	8.379
	ELRT-T	63	6	0.604	2.418	0.110						69	3.161
	Σ			21.014	4.433	4.625			4.483	0.793	1.104		36.452

- (1) DSTD = Diesel Standard Bus
 DART = Diesel Articulated Bus
 EART = Electric Articulated Bus
 ELRT = Electric Light Rail Transit Vehicle
 NT = Non-Transitway
 T = Transitway
- (2) Since a transit fleet cannot consist only of those vehicles in Active service, an additional 10 percent of vehicles were added to the fleet to account for those on reserve and in maintenance.

(illustrated in Figure 5.2 as $\Delta 1$) while the highway cyclic test rate was increased by 3 percent (illustrated in Figure 5.2 as $\Delta 2$) to account for the 12°C ambient temperature in Ottawa-Hull as opposed to the ambient temperature of 21°C used in the tests. The urban rate was then decreased by 6 percent (illustrated in Figure 5.2 as $\Delta 3$) to give a hot start rate. The adjusted EPA curve of fuel consumption rates versus average trip speed for a hot start is illustrated in Figure 5.3.

3. The average EPA gasoline consumption rate for the Ottawa-Hull area was found for the average trip speed by finding the rate which corresponded to the speed in Figure 5.3 and then increasing the rate by 10 percent (illustrated in Figure 5.2 as $\Delta 4$) to account for the warm-up effect for the average P.M. peak hour trip length. The rate was found to be 17.0 L/100 km.

5.3.2 Annual Fuel Consumed by the Private Transportation System

The gasoline consumed during the weekday peak period was found by multiplying the fuel consumption rate by peak period transportation output. The gasoline consumption rate

Note: A description of $\Delta 1$, $\Delta 2$, $\Delta 3$, and $\Delta 4$ are contained in section 5.3.1 .

FIGURE 5.2

METHOD OF ADJUSTING EPA RATES FOR COLD START, 1977

FIGURE 5.3

THE ADJUSTED EPA CURVE FOR THE 1977 PRIVATE VEHICLE FLEET

(1), (2) The unadjusted EPA fuel consumption rates for the 1977 Private Vehicle Fleet were obtained as follows:

Class Size	% of Fleet	EPA Fuel Consumption Rates, L/100 km	
		Urban Cyclic Test	Highway Cyclic Test
Subcompact	16.88	10.4	8.6
Compact	24.49	12.8	9.6
Intermediate	20.20	16.2	12.3
Standard	38.43	20.8	14.7
Sales Weighted Fleet Average	100.00	16.2	11.9

Where: The percentage of each class size in the fleet was obtained from Reference 4 while the fuel consumption rates for each class size was obtained from Reference 10

- (3) The curve illustrates the initial EPA curve corresponding to the cold start urban cyclic test, and hot start highway cyclic test performed at an ambient temperature of 21°C.
- (4) The curve illustrates the adjusted hot start EPA curve for the Ottawa-Hull area with an ambient temperature of 12°C.

for the weekday and weekend off-peak periods was found by decreasing the peak period rate by four percent¹³ to account for the change in roadway level of service. The off-peak rate was multiplied by the off-peak transportation outputs. Daily amounts of gasoline consumption were converted to an annual amount in the same manner as daily transportation output was used to estimate annual transportation output. Since this amount of gasoline was based on EPA estimates, it was multiplied by the fleet "over the road" correction factor giving the annual total for BC 1977 A1 illustrated in Table 5.5.

5.3.3 Annual Fuel Consumed by the Public Transportation System

The fuel consumption rates for regular and limited stop operation of the standard diesel bus were based on a report from the Ottawa-Carleton Rapid Transit Development program³⁰ and are illustrated in Table 5.6. The deadheading rate was assumed to be midway between the rates for regular and limited stop operations. The three rates were combined with the corresponding transportation output thereby producing fuel consumption for BC 1977 T1 as illustrated in Table 5.7.

5.4 Transportation Output for 1990

5.4.1 Average P.M. Peak Hour Trip Characteristics and Mode Split

The average speed for a 1990 P.M. peak hour trip was estimated to be 37.5 km/h and the average trip distance was

TABLE 5.5

ANNUAL FUEL CONSUMPTION OF THE PRIVATE VEHICLE FLEETS

Vehicle Propul- sion Fuel	Class Size	BC 1977 A1			BC 1990 A1			BC 1990 A2			BC 1990			BC 1990 A4		
		Percent of Fleet	Over the Road Factor	Annual Fuel Consumption L-10 ⁶ (1)	Percent of Fleet	Over the Road Factor	Annual Fuel Consumption L-10 ⁶ (1)	Percent of Fleet	Over the Road Factor	Annual Fuel Consumption L-10 ⁶ (1)	Percent of Fleet	Over the Road Factor	Annual Fuel Consumption L-10 ⁶ (1)	Percent of Fleet	Over the Road Factor	Annual Fuel Consumption L-10 ⁶ (1)
Gasoline	Subcompact	16.88	1.140		30.00	1.140		25.50	1.140		21.60	1.140		21.15	1.140	
	Compact	24.49	1.080		35.00	1.080		29.50	1.080		25.15	1.080		24.62	1.080	
	Inter- mediate	20.20	1.030		20.00	1.030		17.00	1.030		17.00	1.030		16.64	1.030	
	Standard	38.43	1.160		15.00	1.160		12.75	1.160		12.75	1.160		12.48	1.160	
Diesel	Sales weighted Fleet Average	100.00	1.111	513.48	100.00	1.100	408.42	85.00	1.100	367.56	76.50	1.099	330.80	74.90	1.099	323.04
	Subcompact							4.50	1.140		3.80	1.140		3.72	1.140	
	Compact							5.25	1.080		4.25	1.080		4.36	1.080	
	Inter- mediate Standard							3.00	1.030		3.00	1.030		2.94	1.030	
Electric	Sales weighted Fleet Average							13.00	1.100	40.86	13.50	1.099	36.74	13.22	1.099	35.97
	Subcompact										4.60			4.50		
	Compact										5.40			5.29		
	Sales weighted Fleet Average										10.00			9.79		
Manual Bicycle																241.70

(1) For any of the fleets, the amount of fuel consumed can be divided by its transportation output to give the over the road fuel consumption rate for the Ottawa-Hull area.

TABLE 5.6

OPERATIONAL CHARACTERISTICS AND FUEL CONSUMPTION RATES FOR PUBLIC TRANSPORTATION VEHICLES

Propulation Fuel	Public Transportation Vehicle	Design Load Factors of Public Transportation Vehicles (1)		Deadheading One-Way Distance in km (2)		Fuel Consumption Rates, L/100 km for diesel fuel (3) and kWh/100 km for elect.		
		Inside CBD Area	Outside CBD Area	Regular	Limited Stop	Regular	Limited Stop	Dead-heading
Diesel Oil	Standard Bus	54	40	8.20	15.0	51.3	37.6	44.5
Diesel Oil	Articulated Bus	102	90	8.20	15.0	74.3	54.3	64.3
Electricity	Articulated Bus	102	N/A	2.0	N/A	341.6	249.6	295.6
Electricity	Light Rail Vehicle	117	N/A	2.0	N/A	243.0	243.0	243.0

N/A - Not Applicable

(1) : Reference 32

(2) Deadheading distances for the standard diesel bus and the articulated diesel bus were obtained from the Transit Planning Branch at RMOC. It was assumed that a 2 km distance would apply to the vehicles propelled by electricity.

(3) The regular and limited stop rates for the standard diesel bus and articulated diesel bus were obtained from Reference 32. The deadheading rate was assumed midway between the rates for regular and limited stop service. The rate for the articulated electric bus was based on Toronto Transit Rates for standard electric buses which were then increased in proportion to the difference between the diesel fuel consumption rates for standard diesel buses and articulated diesel buses. The rate for the light rail vehicle was based on Reference 33.

TABLE 5.7

ANNUAL FUEL CONSUMPTION OF THE PUBLIC TRANSPORTATION FLEETS

Propulsion Fuel	Public Transportation Vehicle	Annual Fuel Consumption for Ottawa-Hull				
		BC 1977 T1 L*106	BC 1990 T1 L*106	BC 1990 T2 L*106	BC 1990 T3 L*106, kWh*106	BC 1990 T4 L*106, kW*106
Diesel Oil	DSTD - NT	19.560	19.586	11.854	12.200	12.200
Diesel Oil	DSTD - T		3.089	.198		
Diesel Oil	DART - NT			5.676	5.960	5.960
Diesel Oil	DART - T			1.936		
Electricity	EART - NT					
Electricity	EART - T				8.933	
Electricity	ELRT - T					7.611
Total Fuel Consumed		19.56	22.68	19.664	18.160	18.160
					8.933	7.611

10.86 km. These averages were obtained from the aggregated modal split results using the method outlined in Section 3.3.3.

The modal splits for 1990 were obtained by estimating new average values for the independent variables and then inputting them into the disaggregate formulations. This method, illustrated in Figure 5.4, attempted to adjust 1977 travel times, perceived trip costs and transit fare to those expected in 1990. All the remaining independent variables were assumed to remain the same for 1977 and 1990. Appendix C2 contains the calculations performed to obtain the 1990 independent variables.

The modal splits for PPD 1990 and PPI 1990 were obtained by using the same values for the independent variables except perceived trip cost. The modal split task was not performed for either PPD 1990 or PPI 1990. Therefore, no changes in trip characteristics which may have occurred due to the different perceived travel costs was taken into account. The modal split estimates are illustrated in Table 5.8.

5.4.2 Annual Transportation Output for the Private Transportation System

The method used to estimate transportation output for 1990 was the same as that previously outlined for 1977. The same average daily traffic and percentages of vehicle trips occurring in the peak and off-peak periods were used. The average weekday trip lengths for weekday peaks was 10.86 km, weekday off-peaks 10.51 km, Saturday off-peak 10.25 km and Sunday off-peak 12.55 km.

FIGURE 5.4

TABLE 5.8

P.M. PEAK HOUR MODAL SPLIT FOR 1990

Trip Purpose	Mode	Modal Split (1)					
		BC 1990		PPI 1990		PPD 1990	
		%	Person Trips	%	Person Trips	%	Person Trips
"Home Based Work Trips"	Auto Driver	39.15	53,468	37.28	50,914	41.88	57,197
	Auto Pooler	29.47	40,248	29.72	40,590	29.00	39,606
	Transit	31.38	42,857	33.00	45,069	29.12	39,770
	Σ	100.00	136,573	100.00	136,573	100.00	136,573
All Other Trips	Auto	85.53	61,079	82.00	58,558	89.45	63,878
	Transit	14.47	10,333	18.00	12,854	10.55	7,534
	Σ	100.00	71,412	100.00	71,412	100.00	71,412

(1) The mean values of the independent variables used to estimate modal split for 1990 are derived in Appendix C2 and are illustrated below.

"HOME BASED WORK TRIPS"FOR BC 1990

- Auto Driver - In-Vehicle Trip Time - 16.77 min.
- Perceived Trip Cost - 53.55 cents
- Vehicles/Household - 1.31
- Auto Pooler - In-Vehicle Trip Time - 19.56 min.
- Perceived Trip Cost - 22.32 cents
- Sex - .55
- Transit - In-Vehicle Trip Time - 28.66 min.
- Fare - 42.80 cents
- Access Distance(100') - 5.54
- Transfers - .49

FOR PPD 1990

The BC 1990 mean values were used for PPD 1990 with the exception of:

- Auto Driver - Perceived Trip Cost - 33.81 cents
- Auto Pooler - Perceived Trip Cost - 14.09 cents

FOR PPI 1990

The BC 1990 mean values were used for PPI 1990 with the exception of:

- Auto Driver - Perceived Trip Cost - 67.85 cents
- Auto Pooler - Perceived Trip Cost - 28.27 cents

"ALL OTHER TRIPS"FOR BC 1990

- Auto User - In-Vehicle Trip Time - 14.75 min.
- Perceived Trip Cost - 26.24 cents
- Automobile Ownership - .57
- Transit - In-Vehicle Trip Time - 34.45 min.
- Fare - 37.50 cents
- Transfers - .49

The perceived trip cost used for PPD 1990 was 14.03 cents while 35.03 cents was used for PPI 1990.

Since a variety of private vehicles were analyzed for 1990, it was necessary to proportion the annual transportation output among each type of vehicle in fleets A2, A3 and A4 for BC 1990. The highlights from the literature review used to establish these proportions are presented below:

1. BC 1990 A2. Studies ^{34,35} have suggested that diesel vehicles could consist of more than 12 percent of the 1990 automobile fleet. Therefore, for the A2 fleet it was assumed that diesel vehicles consisted of 15 percent of the fleet and the remaining 85 percent were gasoline vehicles.
2. BC 1990 A3. The demand for electrically propelled private vehicles did not penetrate the private vehicle market during the 1970's, but is expected to do so within the next 10 years. Two characteristics of these vehicles will influence what portion of the petroleum propelled vehicle market they will absorb.
 - (a) The electric vehicles with present battery technology can approximately travel 50 km between battery charges. This limits the electric vehicles to trips of short length and few in number.³⁶
 - (b) The electric vehicle motor is designed to produce maximum torque at low speeds while the

torque drops as speed increases.³⁶ This feature forces the vehicle to have low top speeds of approximately 50 km/h which is not adequate for intercity travel but is acceptable for short urban trips.

These characteristics of the electric vehicle appear appropriate for introducing a new breed of private vehicles in the 1980's. Bevilacqua³⁷ suggests that electric vehicles could be used as the second family automobile. The families would use a gasoline or diesel vehicle for trips which are long in length and require high trip speeds. The electric automobile could be used for the urban trips which are short in length and have a low average top speed. Bevilacqua suggests that the market potential of the electric vehicles will be in the subcompact and compact size automobiles.

A study by the Road and Transportation Association of Canada³⁸ suggests that if an electric vehicle can be produced with better battery systems (lighter, less expensive, more efficient), they could comprise 20 percent or more of the automobile fleet by the year 2000. However, Train³⁴ stated that even if battery improvements are made, the electric vehicles will only capture 8.2 percent of the automobile market

by the year 2000. In this research, it was assumed that the electric vehicles would account for 10 percent of the A3 fleet while the remaining 90 percent would consist of 85 percent gasoline and 15 percent diesel vehicles. Furthermore, the electric vehicles would be either subcompact or compact in class size.

3. BC 1990 A4. The use of the bicycle as a means of urban transportation continues to increase in Canada due to low travel costs, the door-to-door service, physical health benefits and its high energy efficiency. Ohrn³⁹ did a study to establish the potential share of trips which may be shifted from the automobile to the bicycle. He estimated that two percent of work trips and eleven percent of non-work trips could be made by bicycles in the Minneapolis and St. Paul cities in Minnesota.

The potential transportation output for the bicycle in Ottawa-Hull was based on Ohrn's estimated percentage of work and non-work trips. The number of daily work and non-work person trips were estimated for BC 1990 and then multiplied by the potential bicycle share of trips and the average bicycle trip length of 6.6 km⁴⁰ in the Ottawa-Hull area. Assuming the bicycle is used five months of

the year, and that sixty percent of these trips were made by those who used to drive an automobile, the bicycle transportation output was 88.26×10^6 km. The annual bicycle transportation output was subtracted from the BC 1990 A3 total. The remaining BC 1990 transportation output was proportioned among the other vehicles according to the proportions used for BC 1990 A3.

No attempt was made to adjust any of the transit transportation outputs to account for their reduction in ridership due to the introduction of the bicycle.

Table 5.2 illustrates the estimated transportation outputs for each type of vehicle contained in the A1, A2, A3 and A4 fleets for BC 1990.

5.4.3 Annual Transportation Output For the Public Transportation System

The P.M. peak hour transit data for BC 1990 T1 is illustrated in Table 5.9. Annual transportation output was obtained in the same manner as described for BC 1977 T1. The hourly variation of the transit fleet in service was assumed to remain unchanged between 1977 and 1990.

The transportation output for transit fleets T2, T3 and T4 were based on the transportation output for BC 1990 T1 which was modified to account for different vehicle load factors and average deadheading distances as illustrated in

TABLE 5.9

P.M. PEAK HOUR DATA FOR OTTAWA PUBLIC TRANSPORTATION SYSTEM, BC 1990 T1

Corridor	Maximum Link Volume	Vehicle Design Capacity	Corridor Length Kilometers	Vehicle Speed (km/h) (2)	Buses Required per Corridor	Regular and Limited Stop Transportation Output (Vehicle-km)
1	1126	40	17.1	19.0	54	940.5
2	770	54	19.2	19.2	30	528.0
3	1292	40	19.4	19.9	67	1222.2
4	4349	54	10.9	20.9	92	1698.5
5	553	54	10.4	22.4	10	197.9
6	658	40	12.5	19.7	24	425.5
7	728	54	13.7	19.9	21	383.1
8	1113	54	14.9	18.9	37	641.0
9	1457	54	24.5	20.9	60	1149.5
10	815	54	28.5	23.1	34	720.0
14	1076	40	18.8	20.4	49	916.3
15	1534	40	26.3	17.1	96	1504.8
16	560	54	22.9	22.3	22	450.5
23	1338	54	12.5	30.0	3	82.5
24	412	54	26.8	33.5	18	552.8
25	93	40	10.9	24.0	3	66.0
26	936	40	4.5	25.0	5	114.6
27	414	40	7.7	22.6	4	82.9
28	3430	54	24.6	22.3	137	2800.5
Total	N/A	N/A	N/A	N/A	N/A	14477.1

(1) A locational description of these corridors is available at the Systems Planning Branch at the RMOC. Corridors numbered 1 to 16 are for regular service while the remaining corridors are for limited stop service. Corridor 28 is the transitway.

(2) The vehicle speed represents the average speed travelled while the vehicle is moving. There is a 5 to 8 minute period of time when the transit vehicle does not move in the corridor. This time the bus driver rests at the end of a run. Therefore, when calculating transportation output, the time when the vehicle is not moving must be taken into account.

N/A Not Applicable

Table 5.6. The proportion of articulated buses and light rail vehicles to standard buses for transitway and non-transitway operation were based on a study done for RMOC by the Deleuw-Dillion-IBI Group.³⁷

Additional transit vehicles and transportation output were required to provide a feeder system when the light rail vehicle and electric articulated bus were used on the transitway. This was necessary since the electrically propelled vehicles are unable to get off the transitway and continue travelling on the non-transitway segment of a corridor. To account for the feeder system, the transportation output and number of vehicles utilized on the non-transitway were increased by five percent. This was assumed adequate according to the Transit Planning Branch at RMOC.

The fleet composition and transportation output for the transit systems in 1990 are illustrated in Table 5.4.

5.5 Fuel Consumption for 1990

5.5.1 The Average EPA Gasoline Consumption Rate

The average age of a private vehicle in 1990 was assumed to be five years old. Therefore, the 1985 mandatory EPA rates for the urban and highway tests were used and modified in the manner outlined in Section 5.3.1. The modified EPA curve is illustrated in Figure 5.5. The rate corresponding to an average trip speed of 37.5 km/h and an average trip length of 10.86 km was found to be 9.07 L/100 km.

FIGURE 5.5

131

THE ADJUSTED EPA CURVE FOR THE 1990 PRIVATE VEHICLE FLEET

(1), (2) The unadjusted EPA fuel consumption rates for the 1990 private vehicle fleet were obtained as follows:

Class Size	% of Fleet	EPA Fuel Consumption Rates, L/100 km	
		Urban Cyclic Test	Highway Cyclic Test
Subcompact	30.00	N/A	N/A
Compact	35.00	N/A	N/A
Intermediate	20.00	N/A	N/A
Standard	15.00	N/A	N/A
Sales Weighted Fleet Average	100.00	9.12	7.85

Where: The percentage of each class size in the fleet was obtained from Reference 41 based on slow economic growth and continued long term supply of petroleum. The sales weighted fleet average EPA rates were obtained from Reference 10.

(3) The curve illustrates the initial EPA curve corresponding to the cold start urban cyclic test and hot start highway cyclic test performed at an ambient temperature of 21°C.

(4) The curve illustrates the adjusted hot start EPA curve for the Ottawa-Hull area with an ambient temperature of 12°C.

5.5.2 Annual Fuel Consumption for the Private Transportation System

The modified EPA gasoline consumption rate was used to obtain annual gasoline consumption for BC 1990 A1 in the same manner as it was for BC 1977 A1.

The fuel consumption rate for the A2 fleet was the same as that obtained above for the fleet A1, 9.07 L/100 km. This was done to account for the mandatory fuel consumption rate since it is the entire production line of vehicles which has to meet the standards, diesel and gasoline vehicles combined. However, due to the different characteristics of the diesel and gasoline engines, it was necessary to estimate the corresponding fuel consumption rates for both which, when weighted by their fleet proportions, gives a fleet rate of 9.07L/100 km.

An analysis was conducted to estimate the difference between the fuel consumption rate for diesel versus gasoline engines. A comparison was made of the EPA gasoline and diesel fuel consumption rates^{42,43} for various Mercedes Benz, Volkswagen and General Motors automobiles where the same model of automobile (such as the Volkswagen Rabbit) had either a gasoline or diesel drive unit. It was found that a diesel propelled vehicle consumes on an average 37 percent less litres of fuel per 100 kilometres in the urban cyclic test than an identical vehicle propelled by a gasoline motor. Therefore, it was found that the diesel fuel consumption.

rate was 6.05 L/100 km and 9.60 L/100 km for the gasoline vehicles, giving the A2 fleet an overall rate of 9.07 L/100km. This implies that the A1 and A2 fleets consumed the same amount of litres of fuel in 1990.

The fuel consumption rates for the electric vehicles were based on electric vehicles in use during the late 1970's.^{36,47} The calculations performed to obtain these rates are presented in Appendix C3.

Table 5.5 illustrates the amounts of fuels consumed for BC 1990 private vehicle fleets of A1, A2, A3, and A4.

5.5.3 Annual Fuel Consumption for the Public Transportation System

The fuel consumption rates for the transit vehicles were illustrated in Table 5.6. Each rate was multiplied by a transportation output to give the amount of fuels consumed in Table 5.7.

5.6 Concluding Comments

This chapter was used to estimate transportation output and fuel consumption for 1977 and 1990 using the framework presented in Chapter three. These estimates were obtained in a specific manner so that the energy content of fuels and indirect energy intensities could easily be applied in the following chapter to estimate direct and indirect energy consumption.

CHAPTER VI

ESTIMATION AND ANALYSIS OF ENERGY CONSUMPTION

6.1 Introduction

In this chapter, indirect energy intensities are developed and used to estimate the energy consumed by the private and public transportation systems. Using these energy estimates, the analysis was carried out to fulfill the objectives of this research which were outlined in Chapter 1.

6.2 Estimation of Annual Energy Consumption6.2.1 Energy Intensity of Fuels

The energy content for fuels are: 35 MJ/L for gasoline, 39 MJ/L for diesel oil, and 3.6 MJ/kWh for electricity.¹⁰ The indirect energy intensities to produce fuels are 6.825 MJ/L for gasoline,¹⁰ 4.9 MJ/L for diesel oil¹⁰ and 2.10 MJ/kWh for electricity in 1990.⁴⁴ These energy contents and several conversion factors are presented in Appendix D1.

6.2.2 Energy Intensities for Producing and Maintaining Vehicles

A literature search and in some cases an analysis was conducted to establish energy requirement for producing and maintaining vehicles per unit of transportation output. The results from this task follow.

1. Gasoline Propelled Automobiles

The production energy intensities (MJ/vehicle-km) for automobiles produced in 1975 were available from Reference

11. These intensities were used to estimate similar energy intensities for 1985 automobiles by first establishing the weight of the material inputs. Estimates of these weights were based on the following:

- a) The 1985 vehicles are to be lighter than 1975 vehicles due to the reduction in vehicle size and the use of lighter materials.
- b) It has been established that due to the smaller size of the 1985 vehicles, they will be lighter than the 1975 vehicles by 5 percent for the subcompact, 9 percent for the compact, 10 percent for the intermediate and 15 percent for the standard size vehicle.²⁹
- c) The energy requirement to produce 1985 vehicles were assumed to be unaffected by weight savings due to the use of lighter materials. It was felt that the energy required to produce the lighter materials which are more energy intensive would provide no energy savings through their replacement for the heavier, less energy intensive materials. Therefore, the production energy requirement for 1985 vehicles was based on the energy intensities of the less energy intense heavier materials composing the 1975 vehicles.

- d) Using the weights of the 1975 vehicles, modified by the percent decrease in weights due to reduction in vehicle size, the weight of the 1985 vehicles was obtained.
- e) A ratio of the 1985 to the 1975 vehicle weight was multiplied by the inputs material of the 1975 vehicles, giving material input weights for 1985 vehicles. Each of these material weights were multiplied by the material energy intensity. The sum of this product for all input materials gave the energy input due to materials. Additional energy was included to account for the energy to transform the input materials into the finished vehicle, to move the vehicle from the factory to the market and to store and prepare the vehicle for sale. This gave the vehicle production energy.
- f) The vehicle production energy was divided by 161,000 km, the transportation life output of the vehicle, giving production energy intensity.

The maintenance energy intensities (MJ/vehicle-km) for the 1975 vehicles were obtained from Reference 11. It was assumed that the same intensities were valid for 1985 vehicles.

2. Diesel Propelled Automobiles

It was assumed that the energy intensities to

produce the 1985 diesel vehicles would be the same as those for the 1985 gasoline vehicles.

From the published literature reviewed, it was not possible to estimate the differences in maintenance energy intensities between the diesel and gasoline vehicles. Therefore, the author interviewed several automobile dealers in the Ottawa-Hull area who carry vehicles which have either diesel or gasoline drive units. It was found that a vehicle with a diesel drive unit costs an average of 35 percent less to maintain than the same vehicle with a gasoline drive unit. Since the IBI Group¹¹ based their estimates of maintenance energy intensities on maintenance costs, it was assumed that the maintenance energy intensities of diesel vehicles were 35 percent less than a similar gasoline vehicle.

3. Electrically Propelled Automobiles

The production energy intensities (MJ/vehicle-km) for these vehicles were based on 1985 gasoline vehicles with a battery system and an electric motor replacing the gasoline engine, transmission, radiator and exhaust system. The battery system was adequate to propel the vehicle for approximately 50 kilometres between charges.

The energy intensities (MJ/vehicle-km) for maintaining these vehicles were based on the energy required to replace the battery and to maintain the motor and other vehicle parts. The assumptions made to obtain these maintenance energy intensities are contained in Appendix D2.

4. The Bicycle

The maintenance and production energy intensities (MJ/bicycle-km) to produce and maintain a bicycle was based on Fels¹² research.

5. The Standard Diesel Bus

The energy used to produce a standard bus was obtained from Reference 11. This energy was divided by 16, the life expectancy of buses in the Ottawa-Hull area, to give the proportion of a bus production energy per annum, (MJ/vehicle-year). It was felt that the use of vehicle-year rather than vehicle-km as the unit of transportation output would provide a more reliable energy estimate since the number of buses and their useful life expectancy are known.

The energy intensity (MJ/vehicle-km) to maintain the bus was obtained from Reference 11.

6. The Articulated Diesel Bus

To obtain this production energy intensity (MJ/vehicle-year), a ratio of the articulated bus weight⁴⁵ to the standard bus weight was calculated. The ratio was used to estimate the vehicle production energy and then the energy intensity (based on a 16 year useful life output) in the same manner as the production energy intensity of 1985 gasoline automobiles was found by using 1975 automobiles.

No information was found regarding maintenance energy intensities. Since articulated vehicles have larger

engines, a greater number of wheels, more doors and other parts than a standard bus, it can be assumed that the energy intensity for the articulated bus would be more than a standard bus. To account for this, it was decided to multiply the maintenance energy intensity of the standard bus by the vehicle weight ratio described above to obtain the energy intensity for the articulated bus.

7. The Articulated Electric Bus

It was assumed that the production energy intensity of the articulated electric bus was the same as the articulated diesel bus.

In the literature search done for this research, no information was found regarding maintenance requirements of articulated electric buses. However, the Proceedings of the 47th International Union of Public Transport (UITP)⁴⁶ suggests that the maintenance costs of a standard electric trolley bus is the same as a standard diesel bus. Therefore, it was assumed that the maintenance cost of an articulated electric bus would be the same as the articulated diesel bus and that their maintenance energy intensities would also be equal.

8. The Light Rail Vehicle

This production energy intensity (MJ/vehicle-year) was based on the energy requirement to manufacture a Montreal subway vehicle and the material contents of the Urban Transportation Development Corporation (UTDC) light rail

vehicle. The information regarding the material contents of the vehicle was based on a discussion with Mr. C. Ditchfield of UTDC.

The maintenance energy intensity (MJ/vehicle-km) was also based on a discussion with Mr. C. Ditchfield.

The energy intensities for the private vehicles are illustrated in Table 6.1 while those for the public vehicles are presented in Table 6.2. Appendix D3 contains the calculations performed to establish the production energy intensities.

5.2.3 Energy Requirements for Infrastructure

The energy intensities to maintain urban roads and freeways were available from Reference 11. To obtain infrastructure maintenance energy, these intensities were multiplied by the amounts of roadways in the Ottawa-Hull area. This procedure resulted in the estimates of total infrastructure maintenance energy.

The infrastructure maintenance energy was proportioned among the private and public transportation systems by multiplying the transportation output of each system by a vehicle PCU, taking their sum and multiplying the sum by each former product.

Those kilometres travelled by transit vehicles on the transitway were not included when establishing either the roadway maintenance energy or share of roadway usage. Separate

TABLE 6.1

PRODUCTION AND MAINTENANCE ENERGY INTENSITIES FOR THE PRIVATE VEHICLES

[illegible]

TABLE 6.2

PRODUCTION AND MAINTENANCE ENERGY INTENSITIES FOR THE PUBLIC VEHICLES

Vehicle Propulsion Fuel	Type of Vehicle	Production Energy Intensity MJ*10 ⁶ /vehicle-Yr.	Maintenance Energy Intensity MJ*10 ⁶ /vehicle-Yr.
Diesel	Standard Bus	0.0927	2.202
Diesel	Articulated Bus	0.1841	3.473
Diesel	Articulated Bus	0.1841	3.473
Electric	Light Rail Transit	0.1866	1.145

calculations were performed to establish maintenance energy for the transitway.

As previously stated, roadway construction energy was based on the infrastructure constructed in 1977 for the 1977 analysis and for the 1990 analysis, from 1977 to 1990. For each type of infrastructure constructed, an energy intensity (MJ/year) was obtained. This intensity was multiplied by the number of years that particular piece of infrastructure was expected to be in use for the time periods under study. Table 6.3 illustrates the infrastructure maintenance and construction energies.

6.2.4 Annual Energy Consumption for 1977 and 1990

The energy content of fuels and the indirect energy intensities to produce the fuels were multiplied by the amounts of fuels consumed to transform fuel consumption into energy. The annual energies required to produce and maintain private vehicles were obtained by multiplying the transportation outputs by the energy intensities. In a similar manner annual maintenance energies were found for transit vehicles while transit vehicle production energies were the energy intensities themselves.

Annual energy consumption for the 1977 and 1990 private vehicle fleets are illustrated in Table 6.4 while Table 6.5 illustrates energy consumption for the transit fleets.

TABLE 6.3

**INFRASTRUCTURE MAINTENANCE AND CONSTRUCTION
ENERGIES**

Case	Roadway Usage Percent	Roadway Maintenance (1) MJ*10 ⁶	Transitway Maintenance (2) MJ*10 ⁶	Roadway Construction (3) MJ*10 ⁶	Transitway Construction (4) MJ*10 ⁶
BC 1977 A1	95.87	936.53	-	13.00	-
BC 1977 T1	4.13	40.35	-	0.56	-
BC 1990 A1,A2, A3,A4	97.24	1022.44	-	113.71	-
BC 1990 T1	2.76	28.48	48.00	3.23	191.88
BC 1990 A1,A2, A3,A4	97.77	1027.48	-	114.33	-
BC 1990 T2	2.23	23.44	48.00	2.61	191.88
BC 1990 A1,A2, A3,A4	97.69	1026.64	-	114.24	-
BC 1990 T3	2.31	24.28	54.00	2.70	191.88
BC 1990 A1,A2, A3,A4	97.69	1026.64	-	114.24	-
BC 1990 T4	2.31	24.28	54.00	2.70	138.41

(1) Maintenance energy per kilometre of roadway per year is:

- For a 2 lane roadway: 495,360.0 MJ
- For a 4 lane roadway: 990,720.0 MJ
- For a 6 lane freeway: 1,557,000.0 MJ

(2) Maintenance energy per kilometre of transitway per year is:

- For a 2 lane paved busway, 1,960,000.0 MJ
- For a 2 track ground level guideway, 2,210,000.0 MJ
- For a 2 track elevated guideway, 2,210,000.0 MJ

*For the T3 and T4 fleets using a catenary system in the transitway, an additional 13 percent more energy was used to operate and maintain it than the transitway without a catenary system. This assumption was based on reference 30 which illustrated that maintenance and operating costs for a transitway using a catenary is 13 percent more costly to maintain and operate than a transitway without such a system.

(3) Construction energy per kilometre of roadway per year is:

- For a 2 lane roadway 1,612,800.0 MJ
- For a 4 lane roadway 3,225,600.0 MJ
- For a 6 lane freeway 10,890,000.0 MJ

These construction energies includes the combustion energy as asphalt cement.

(4) Construction energy per kilometre of transitway per year is:

- For a 2 lane busway - 7,800,000.0 MJ
- For a 2 track ground level guideway - 5,520,000.0 MJ
- For a 2 track elevated guideway - 7,680,000.0 MJ

The construction energy of the busway includes the combustion energy of asphalt cement.

TABLE 6.4

145

ANNUAL ENERGY CONSUMPTION FOR THE PRIVATE TRANSPORTATION SYSTEMS

Type of Energy Use	Annual Energy Consumption MJ*10 ⁶				
	BC 1977 A1	BC 1990 A1	BC 1990 A2	BC 1990 A3	BC 1990 A4
Direct Energy		(1)	(1)		
- Gasoline Veh.	17,971.88	14,294.70	12,864.60	11,578.00	11,335.80
- Diesel Veh.			1,593.40	1,432.86	1,402.83
- Electric Veh.				803.91	787.07
- Bicycles					
I	17,971.88	14,294.70	14,458.14	13,814.77	13,525.70
Fuel Production Energy					
- Gasoline Veh.	3,504.51	2,787.47	2,508.60	2,257.75	2,210.48
- Diesel Veh.			200.77	180.54	176.76
- Electric Veh.				466.46	456.50
- Bicycles					
I	3,504.51	2,787.47	2,709.37	2,904.75	2,843.74
Vehicle Production Energy					
- Gasoline Veh.	3,067.79	3,869.72	3,289.26	2,999.17	2,936.37
- Diesel Veh.			580.46	529.26	518.19
- Electric Veh.				365.49	357.84
- Bicycles					8.29
I	3,067.79	3,869.72	3,869.72	3,893.92	3,820.69
Vehicle Maintenance Energy					
- Gasoline Veh.	1,646.54	2,324.55	1,975.86	1,778.28	1,741.05
- Diesel Veh.			226.63	203.97	199.70
- Electric Veh.				355.38	347.93
- Bicycles					3.07
I	1,646.54	2,324.55	2,202.49	2,337.63	2,291.75
Infrastructure					
- Maintenance	936.53	1,026.64	1,026.64	1,026.64	1,026.64
- Construction	13.00	114.24	114.24	114.24	114.24
I	949.53	1,140.88	1,140.88	1,140.88	1,140.88
Total Energy Requirement	27,140.25	24,417.32	24,380.60	24,091.95	23,622.76

(1) Estimating Direct Energy Consumption for:

BC 1990 A1

From table 5.5, litres of gasoline consumed is 408.42×10^6 Direct Energy = $(408.42 \times 10^6) \times (35 \text{ MJ/L}) = 14,294.7 \text{ MJ} \times 10^6$

BC 1990 A2

From table 5.5, litres of gasoline consumed is 367.56×10^6 L
litres of diesel oil consumed 40.86×10^6 L
I 408.42×10^6 LDirect Energy of gasoline is $367.56 \times 10^6 \text{ L} \times 35 \text{ MJ/L} = 12,864.6 \times 10^6 \text{ MJ}$ Direct Energy of diesel oil $40.86 \times 10^6 \text{ L} \times 39 \text{ MJ/L} = 1,593.4 \times 10^6 \text{ MJ}$
I $14,458.14 \times 10^6 \text{ MJ}$

Notice that the direct energy for BC 1990 A2 is more than that of BC 1990 A1. This is due to the assumption that both the A1 and A2 fleets will have an equal fleet rate of fuel consumption and therefore both must consume the same amount of litres. The same approach was used to estimate direct energy for the A3 and A4 fleet.

TABLE 6.5

146

ANNUAL ENERGY CONSUMPTION FOR THE PUBLIC TRANSPORTATION SYSTEMS

Type of Energy Use	Annual Energy Consumption MJ*10 ⁶				
	BC 1977 T1	BC 1990 T1	BC 1990 T2	BC 1990 T3	BC 1990 T4
Direct Energy					
- DSTD	762.840	884.520	470.030	475.800	475.800
- DART			296.870	232.440	232.440
- EART				31.190	
- ELRT					27.410
Σ	762.840	884.520	766.896	740.399	735.640
Fuel Production Energy					
- DSTD	96.118	111.450	59.224	53.932	59.951
- DART			37.406	26.109	29.287
- EART				18.091	
- ELRT					15.895
Σ	96.118	111.450	96.630	107.329	105.133
Vehicle Production Energy					
- DSTD	74.632	90.210	47.931	48.765	48.765
- DART			44.736	32.770	32.770
- EART				14.544	
- ELRT					12.875
Σ	74.632	90.210	92.667	96.079	94.410
Vehicle Maintenance Energy					
- DSTD	88.952	101.970	53.989	54.854	54.854
- DART			39.204	29.100	29.100
- EART				10.882	
- ELRT					3.592
Σ	88.952	101.970	93.193	94.836	87.546
Infrastructure					
- Maintenance					
. Transitway		48.00	48.00	54.00	54.00
. Non-Transitway	40.35	28.48	23.44	24.28	24.28
- Construction					
. Transitway		191.88	191.88	191.88	138.41
. Non-Transitway	0.56	3.23	2.61	2.70	2.70
Σ	40.91	271.59	265.93	272.86	219.39
Total Energy Requirement	1,063.45	1,459.74	1,315.32	1,311.50	1,242.12

6.3 Analysis of Energy Consumption

6.3.1 Selection of the 1990 Private Vehicle Fleet

As table 6.4 illustrated, the A1 fleet consumed the most energy followed by A2 and A3 while the A4 fleet consumed the least energy.

A comparison between the A1 and A2 fleets illustrates that the A2 fleet consumed more direct energy than the A1 fleet. This is due to the assumption that both the A1 and A2 fleets would consume the same annual amount of 408.42×10^6 litres of fuel. Since the energy content of diesel oil is over 11 percent greater than that of gasoline, the A2 fleet consumed more direct energy. However, the A2 fleet had lower fuel production energy than the A1 fleet. When all the direct and indirect energy consumed by the two fleets were added, it was found that the A1 fleet consumed slightly more energy than the A2 fleet. Since automobile producers intend to use diesel vehicles with their lower fuel consumption rates to offset the higher rated gasoline vehicle in order to meet the 1985 mandatory fuel consumption rates for their production line of vehicles, it was felt that the A2 fleet would more likely be in existence by 1990 than the A1 fleet.

The use of electric vehicles in fleet A3 decreased energy consumption by 1.2 percent over that of the A2 fleet. The author feels that this estimate is conservative and that developments in battery technology will occur in the future reducing both energy consumption and the large maintenance

energy (the high energy use for replacing the batteries). These developments will also make the electric vehicle more attractive to own. Another benefit of electric vehicles is that their batteries can be charged over night during the off-peak hours of electric utility supplier so that few changes would be required to provide this additional power.

The author feels that although the A3 fleet consumes less energy than the A2 fleet, the A2 fleet will more likely be in use for 1990. It is questionable whether the electric vehicle will absorb 10 percent of the 1990 fleet unless large scale production begins very soon.

An analysis of the A4 fleet shows that the bicycle and the electric vehicle dropped energy consumption 3.2 percent below that of the A2 fleet. Of this percentage, over 2 percent is due to the addition of the bicycle. This suggests that it would be advantageous to encourage bicycle use by supplying attractive but not extravagant facilities. However, since the A4 fleet included the electric vehicle, it was felt that the A2 fleet was more likely to exist by 1990 and therefore was selected as the 1990 private vehicle fleet.

6.3.2 Selection of the 1990 Public Vehicle Fleet

As the figures indicate in Table 6.5, the energy consumed by the T1 fleet consumed the most energy. By using articulated buses in the T2 fleet, a 9.9 percent drop in energy use was obtained, primarily due to the reduction in

direct energy and the energy to produce the fuels. It was felt that the T2 fleet would more likely be in use by 1990 than the T1 fleet. The T2 fleet not only consumes less energy but also is a more cost effective system.⁴⁵

The energy consumed by the T3 fleet was almost identical to the T2 fleet. However, if electric articulated buses could be made to operate off the transitway, either on battery power or by using an auxillary diesel motor, there would be no need for the bus feeder system. This would make the T3 fleet more attractive than the T2 fleet. However, the use of electric buses which have an overhead catenary system pose operational constraints when buses pass each other travelling in the same direction. It was felt that the T2 fleet would more likely be used in 1990 than the T3 fleet since the fleet is easier to operate on the transitway and no feeder system is required.

The energy consumed by the T4 fleet is 5.6 percent less than that used by the T2 fleet. The T4 fleet not only consumes the least energy of the four fleets but also the least petroleum for propelling the vehicles. Therefore, for this research, the T4 transit fleet was considered most likely to be in use by 1990.

6.3.3 Comparison of Total Energy Consumption Between 1977 and 1990

A comparison of energy usage between the private and public transportation systems indicates that the private system consumed 96 percent of the transportation energy in

1977 and 95 percent in 1990.

By adding the energy consumption for the private and public fleets, the total energy consumption for the transportation systems was $28,203.70 \times 10^6$ MJ for BC 1977 and $25,622.72 \times 10^6$ MJ for BC 1990. The figures illustrate that annual energy usage in 1990 will be 9.1 percent less than in 1977.

Of particular interest was the 19.5 percent drop in direct energy consumption by private vehicles in 1990 over that of 1977. This implies that the effects on energy consumption due to the mandatory fuel consumption rates will be so extensive that a reduction in energy use will occur in 1990 despite a 29.6 percent increase in annual private vehicle trips and an increase in annual private vehicle kilometres travelled of 49.7 percent over those of 1977.

The energy consumed by the transit fleet in 1990 was 17 percent greater than that of 1977. A large portion of this additional energy was attributed to the annual energy required for constructing and maintaining the transitway. Slight increases to indirect energy occur over 1977 for transit vehicle production and maintenance, while direct energy consumption was lower in 1990.

6.3.4 Effects of Petroleum Prices on Energy Consumption for 1990

In Chapter V, no estimates of transportation output or fuel consumption were established for PPD 1990 and PPI 1990 since the private and public vehicle fleets had not been

selected for 1990. Therefore, using the same methodologies as used to estimate both transportation output and fuel consumption for BC 1990 A2 and BC 1990 T4, estimates were obtained for PPD 1990 and PPI 1990 and transformed into direct and indirect energy consumption for the A2 and T4 fleets. The results are presented together with those of BC 1990 in Table 6.6.

As previously mentioned, the BC 1990 petroleum price per litre was estimated to be 87 percent greater than that for BC 1977. This was done to keep cost of fuel per kilometre travelled (\$/km) by automobile equal to that of BC 1977. The PPD 1990 represents the same cost of petroleum for 1990 as existed in 1977, while PPI 1990 was a 150 percent increase in the petroleum price for BC 1977.

In this research, the transit fare per kilometre of travel for BC 1990, PPI 1990, and PPD 1990 were based on the price of petroleum which existed in 1977. It was assumed that petroleum price increases would not effect transit fare. The two reasons for making this assumption were:

1. It was assumed that if the government wants to reduce petroleum consumption then it should subsidize increases in transit operating costs due to increases in petroleum costs (in 1977 the cost of petroleum consumed accounted for 7.0 percent of transit operating costs). Therefore, as petroleum prices increases making the perceived travel cost by

TABLE 6.6

152

**ANNUAL ENERGY CONSUMPTION IN
1990 UNDER VARIOUS PETROLEUM PRICES**

Transportation System	Type of Energy Use	Annual Energy Consumption MJ*10 ⁶		
		BC 1990 A2,T4	PPD 1990 A2,T4	PPI 1990 A2,T4
Private	Direct Energy	14,458.14	15,045.82	13,932.86
	Fuel Production Energy	2,709.37	2,819.49	2,610.91
	Vehicle Production Energy	3,869.72	4,028.76	3,730.82
	Vehicle Maintenance Energy	2,202.49	2,293.00	2,123.44
	Infrastructure			
	Maintenance	114.23	115.02	112.95
	Construction	1,026.64	1,030.91	1,023.63
	Σ	24,380.60	25,333.00	23,534.61
Public	Direct Energy	735.64	638.68	819.54
	Fuel Production Energy	105.13	91.27	117.12
	Vehicle Production Energy	94.41	82.08	105.24
	Vehicle Maintenance Energy	87.54	76.02	97.55
	Infrastructure			
	Maintenance	78.28	77.49	79.56
	Construction	141.11	136.69	143.96
	Σ	1,242.12	1,102.23	1,362.97
Public and Private	Total Energy Requirement	25,622.72	26,435.23	24,897.58

automobile higher and keeping transit fares fixed, more people will shift from using the automobile to transit, thereby reducing petroleum consumption.

2. As the perceived cost of travel by automobile increases while transit fares remain constant, some people who would normally have used the automobile for making a trip will switch to transit, especially for "all other trips". This will cause transit ridership to increase particularly in the off-peak periods when "all other trips" predominate. This increased ridership will increase revenue obtained through fares and increase the vehicle load factor in off-peak periods without substantially effecting operating costs other than those incurred due to changing petroleum costs.

The results in Table 6.6 illustrate that as petroleum prices increase, direct energy usage for the private fleet drops while the direct energy consumption for transit increases, but at a slower rate. Indirect energy consumption also follows the same trend for both the private and public vehicles. As Figure 6.1 illustrates, the net effect is that as petroleum prices rise above the BC 1990 price, energy consumption drops by 0.5 percent for a 10 percent increase in price. For a 10 percent decrease in petroleum prices, below BC 1990, a 0.4 percent decrease in energy consumption occurs. This suggests that petroleum prices have little effect on energy consumption in urban transportation.

(1) The petroleum price changes were assumed to effect the cost of travel by automobile but not transit fare.

FIGURE 6.1

EFFECTS OF 1990 PETROLEUM PRICES ON TOTAL ENERGY CONSUMPTION

6.3.5 Energy Efficiency of the Urban Transportation Systems

The energy efficiency (MJ/passenger-km) of the private and public fleets in 1977 and 1990 are illustrated in Table

6.7. A comparison of these efficiencies indicate that for BC 1977 it takes 4.41 times as much energy to move a traveller by a private vehicle than by a public vehicle. Similarly, for BC 1990, PPD 1990 and PPI 1990 it takes 3.53, 3.24 and 3.70 times more energy to travel by a private vehicle than a public vehicle.

In the three 1990 cases, it is clear that slight changes in efficiency occur for changes in petroleum prices. The effects of petroleum prices are as follows:

1. If petroleum price in 1990 is the same as it was in 1977, (i.e. PPD 1990) that is 19.84¢/L in constant dollars of 1977, then the 1990 transportation system would be 38.2 percent more efficient than the 1977 system.
2. If the 1990 petroleum price is 37.1 ¢/L (i.e. BC 1990) in constant dollars of 1977, then the 1990 system would be 39.7 percent more efficient as it was in 1977.
3. If the 1990 petroleum price is 49.6¢/L (i.e. PPI 1990) in constant dollars of 1977, then the 1990 system would be 41.0 percent more efficient than it was in 1977.

TABLE 6.7

ENERGY EFFICIENCY OF THE URBAN TRANSPORTATION SYSTEMS

Transportation System	Energy Efficiency - MJ/Passenger-km ⁽¹⁾ , (2)			
	BC 1977 A1,T1	BC 1990 A2,T4	PPD 1990 A2,T4	PPI 1990 A2,T4
Private	6.88	4.13	4.12	4.14
Public	1.56	1.17	1.23	1.12
Private and Public	6.07	3.66	3.75	3.58

(1) Load factor for automobiles was 1.4 persons per vehicle

The load factor for the 1977 T1 fleet was 19 while the 1990 T4 fleet load factor was 26.0.

(2) For this research, the load factors of the transit vehicles were assumed to remain constant for BC 1990, PPD 1990 and PPI 1990. This assumption was required in order that the same level of service was provided in each of the three cases. In actuality, it would be expected that transit vehicle load factors would increase for PPI 1990 primarily due to increases in off-peak ridership. This implies that the energy efficiency of the transit fleet under PPI 1990 could be higher than that shown in this table.

4. As petroleum prices increase, transit ridership and vehicle-kilometres travelled increases more in the off-peak than in the peak periods. This will cause the vehicle load factor for transit to increase and in turn increase the energy efficiency of the transit system. Furthermore since only a small amount of the increase in ridership will occur in the peak periods (which establishes the fleet size requirements) only small increases in the requirements of additional vehicles will occur.

6.3.6 The Effects of Modal Attributes on Total Energy Consumption

Any change in transit attributes which increases the transit level of service and causes a modal shift from private to public vehicles will reduce energy consumption. However, if the average private vehicle occupancy is greater than 3.24 to 3.70 (depending on the cost of petroleum) then the automobile mode becomes a more energy efficient mode than transit, especially for longer trips where the warm-up effect is minimal.

It is difficult to predict what will happen to the energy efficiency of the transportation system if the automobile attributes become more attractive causing a shift from transit to automobile. If the average trip speed were to increase, the average fuel consumption rate for the private vehicles would decrease. If the savings in fuel due to

TABLE 6.8
METHODS TO REDUCE PUBLIC TRANSPORTATION ENERGY CONSUMPTION

Mode	Variables	Reduces Energy Consumption When	Reason for Decrease in Energy Consumption	Comments
Transit (both for Work and Non-Work Trips)	In-Vehicle Travel Time	Decreased	Increases mode split for transit	In general it is difficult to implement. Addition of limited stop routes is advantageous.
	Fare	Decreased	Increases transit share of mode split	Lower fares can make transit more attractive. However, large reductions in revenue can reduce the overall transit level of service causing an eventual reduction in transit patronage.
	Access Distance	Decreased	Increases transit share of mode split	The extra kilometre of bus routes required to decrease the access distance may offset energy savings caused by increased transit patronage in some cases.
	Number of Transfers	Decreased	Increases transit share of mode split. Further energy savings could occur if the methodology used to reduce transfers involves less transfer locations, less stops, and thus greater average speed.	The use of more limited stop bus routes could reduce the number of transfers. This requires better matching of origin-destination demand and service pattern.

TABLE 6.9
METHODS TO REDUCE PRIVATE TRANSPORTATION ENERGY CONSUMPTION

Mode	Variables	Reduces Energy Consumption When	Reason for Decrease in Energy Consumption	Comments
Auto Driver, Auto Pooler and Auto User (non-work travel)	In-Vehicle Travel Time	Decreased	The fuel consumption rate for the automobile fleet will decrease if stops per kilometre are reduced	The shift in modal split from transit to automobiles may offset the energy savings due to decreased fuel consumption rates for the automobile.
Auto Driver and Auto Pooler	Parking Cost	Increased	Increases transit share of mode split, where most of this new ridership is from auto driver mode, and little from auto pooler	May tend to increase the auto pooler incentive.
Auto Driver, Auto Pooler and Auto User (non-work travel)	Petroleum Costs	Increased	Shifts auto users and auto drivers to transit. Little shift of pool users to transit	Elasticity may be greater than expected for large increases due to reductions in disposable personal income.
Auto Driver and Auto User (non-work travel)	Number of Vehicles per Household	Decreased	Increases transit share of mode split. Small reduction in automobile ownership will significantly increase transit portion of mode split.	Policies which decreases the number of vehicles per household will be an effective method to increase the energy efficiency of the Transportation System even if autos are becoming very efficient.

TABLE 6.10

SUMMARY OF ENERGY COMPUTATIONS

Item		BC 1977 A1,T1	BC 1990 A2,T4	PPD 1990 A2,T4	PPI 1990 A2,T4
Travel Demand	Annual Person Trips				
	- Private	423.15*10 ⁶	548.32*10 ⁶	570.86*10 ⁶	528.64*10 ⁶
	- Public	76.51*10 ⁶	102.81*10 ⁶	84.23*10 ⁶	118.23*10 ⁶
	Annual Transportation Output (Vehicle-km)				
	- Private	2,816.04*10 ⁶	4,215.57*10 ⁶	4,388.82*10 ⁶	4,064.26*10 ⁶
	- Public	40.40*10 ⁶	36.62*10 ⁶	32.19*10 ⁶	41.30*10 ⁶
Annual Trip Characteristics	Fuel Consumption Rate (L/100km)				
	- Private	18.11	9.69	9.69	9.69
	Vehicle Load Factor				
	- Private	1.40	1.40	1.40	1.40
	- Public	19.00	26.00	26.00	26.00
	Trip Distance(km)				
	- Private	9.32	10.76	10.76	10.76
Annual Energy Consumption	Private and Public Systems Combined (MJ*10 ⁶)				
	- Direct Energy	18,734.72	15,193.78	15,684.50	14,752.40
	- Fuel Production	3,600.64	2,814.50	2,910.76	2,728.03
	- Remaining				
	- Indirect Energy	5,868.35	7,614.44	7,839.97	7,417.15
	- Total Energy Requirement	28,203.70	25,622.72	26,435.23	24,897.58
Energy Efficiency	Private and Public Systems Combined (MJ/Passenger-km)				
	- Direct Energy	4.83	2.59	2.66	2.53
	- Plus Fuel Production Energy				
	- Remaining Indirect Energy	1.24	1.07	1.09	1.05
	- Total Energy	6.07	3.66	3.75	3.58

reductions in the fuel consumption rates could offset the additional energy consumed by the shift from transit to automobiles, then this could be one way to reduce energy consumption. Tables 6.8 and 6.9 illustrate some areas where energy savings can be made by altering modal attributes and socio-economic characteristics.

6.4 Concluding Comments

This chapter attempted to estimate and analyze energy consumption for 1977 and 1990. The highlights of the analysis are illustrated in Table 6.10. Many unexpected events could occur between now and 1990 which could strongly influence energy consumption. Therefore, the estimates presented in this research could vary little or substantially from what will actually occur in 1990.

In the following chapter, a summary, conclusions and extensions are presented regarding energy consumption in urban transportation.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

In this research a technique was developed to estimate the direct and indirect energy consumed by the private and public transportation systems. The technique was applied to the Ottawa-Hull area for the years 1977 and 1990.

Travel demand models based on the P.M. peak hour were applied to estimate travel demand. This involved obtaining trip generation and trip distribution data; building P.M. peak hour road and transit networks, and developing two behavioural modal split models. One was used for estimating travel demand for "home based work trips" and the other for "all other trips". The formulation of the models included a variable to measure the perceived cost of travel for automobile trips. This variable was used to estimate the effects petroleum price changes can have on energy consumption.

A method was devised to estimate the fuel consumed by the private vehicle fleet using the P.M. peak hour average trip characteristics of distance, time, speed, and eventually an EPA fuel consumption rate. These trip characteristics were used to obtain off-peak trip characteristics for the weekdays, Saturday and Sunday. The average distances and fuel consumption rates were combined with the number of weekday and weekend trips to obtain annual transportation output and annual fuel consumption.

The methodology used to obtain annual transportation output and fuel consumption for transit began by assigning the number of P.M. peak hour transit trips in each interchange to the P.M. peak hour transit network to estimate transit fleet size and kilometres travelled while in regular, limited stop and deadheading operation. Using this P.M. peak hour transit data and the hourly variation of the transit fleet in service for all hours of the weekday, Saturday and Sunday, annual transportation output and fuel consumption were obtained.

Energy figures (MJ/km) to propel, produce and maintain the private and public vehicles were developed and combined with annual transportation output to obtain the direct and indirect energy consumed by the vehicles per year. Furthermore, energy required to maintain and construct infrastructure were estimated and proportioned among the private and public transportation systems according to their share of infrastructure usage. The infrastructure energy of each system was added to the other energy items consumed, giving total energy consumed per year by each system.

The private transportation system analyzed for 1977 was that which was in use at that time. For 1990, gasoline, diesel and electric automobiles and the bicycle were examined. An analysis was conducted to establish the energy consumption

of each vehicle type. Furthermore, one combination of these private vehicles was chosen by the author as the private vehicle fleet for 1990 and was used for estimating annual energy consumption.

The public transportation system which was in use during 1977 was used for the 1977 energy analysis. For 1990, four types of vehicles were examined; the standard diesel bus, the articulated diesel bus, the articulated electric bus and the light rail vehicle. Estimates of energy consumed by transit fleets composed of these vehicles were obtained and conclusions drawn regarding which fleet was most likely to be in use by 1990 from an energy conservation view point.

An analysis was conducted to estimate the change in energy consumed by the 1977 and 1990 transportation systems and to establish the effects of changing petroleum prices on every consumption in 1990. Conclusions were drawn regarding the effects which changes to modal attributes may have on energy consumption.

7.2 Conclusions

In the process of analyzing energy consumption through the technique developed, a number of conclusions given below were drawn regarding energy consumption. These center around the following five areas: the behaviour of travellers, the demand for travel, the operation of vehicles, the advancements

in vehicle technologies, and infrastructure. The conclusion regarding each of these areas are as follows:

1) The Behaviour of Travellers:

- (i) Urban travellers who chose the automobile for making a trip show little sensitivity to the cost of petroleum, particularly for trips made from home to work and from work to home.
- (ii) When petroleum prices increase, the change in transit ridership is greater in the off-peak weekdays, Saturday and Sunday, than in the weekday peak periods. This tends to reduce the gap between the transit vehicles used in off-peak and peak periods, which increases the public transportation system operational efficiency.
- (iii) The number of automobiles in a household greatly influences the household traveller's choice between using the automobile or transit system for a trip. As the number of automobiles increases, the more likely the traveller is to select the automobile for making the trip, particularly for "home based work trips".
- (iv) Automobile users place more importance on the time of travel rather than the perceived cost of travel.

- (v) The emphasis placed on transit attributes for home based work trips are, in decreasing order, in-vehicle travel time (most important), number of transfers, access distance, and then transit fare (least important).
- (vi) For transit users making "all other trips", transit fare is the most important attribute, followed by in-vehicle travel time and number of transfers.
- (vii) The number of transit trips was found to increase by 34 percent between 1977 and 1990, assuming that the cost of travel (in constant dollars of 1977) per kilometre by auto and transit does not change. It was found that if a 150 percent increase in the price of petroleum was to occur between 1977 and 1990 that transit ridership would increase by 55 percent in 1990 over that of 1977, assuming transit fare is not influenced by changing petroleum prices.

2) Demand for Travel:

- (i) During the P.M. peak period more "home based work trips" are made than "all other trips". A greater proportion of these trips are made by automobiles, particularly for the "all other trips".
- (ii) During a 24-hour weekday, trips made by automobiles are much more frequent than those made by transit,

particularly for the "all other trips".

- (iii) The number of trips made by the automobile will increase by 30 percent in 1990 over that of 1977, assuming the perceived cost of travel (¢/km) remains the same.
- (iv) The number of annual automobile trips in 1990 were estimated to decrease by approximately 3.7% if the cost of petroleum per kilometre travelled were to increase by 60% over the 1977 cost.
- (v) The number of annual automobile trips in 1990 were estimated to increase by 4.5% if the cost of petroleum per kilometre travelled by auto was to decrease by 87% over the 1977 cost.
- (vi) The change in modal split from automobile trips to transit trips reduces the energy consumed by the urban transportation systems.

3) Operation of Vehicles:

- (i) To decrease the fuel consumed for propelling gasoline and diesel powered automobiles in an urban area, it is necessary to increase or decrease the existing speed limits to 45 km/h. It would also be advantageous to reduce the number of stops per trip by altering traffic lights in off-peak hours to flash red or amber

indicating a warning rather than stopping vehicles. Furthermore, yield signs could replace stop signs in those areas where no significant loss in safety would occur.

- (ii) Reductions in trip distances can be used to reduce energy consumption. This could be accomplished by considering this as an objective in land use planning.

4) Advancements in Vehicle Technologies

- (i) The lighter, smaller, more energy efficient automobiles which will be produced during the 1980's may consume gasoline, diesel oil, electricity and possibly other fuels.
- (ii) Automobiles propelled by diesel drive units consume approximately 37 percent less petroleum under urban cyclic driving conditions. The diesel vehicle will be approximately 35 percent less energy intensive to maintain than a similar gasoline automobile. The diesel vehicle may comprise 15 percent of the automobile fleet by 1990.
- (iii) Diesel fuel contains over 11 percent more energy per litre than gasoline. Therefore, if automobile producers begin substituting the more fuel efficient diesel vehicles for the less fuel efficient gasoline vehicles to obtain a "production fleet" fuel

consumption rate in the future, then this "production fleet" will consume more direct energy than if it was composed only of gasoline automobiles.

- (iv) There is a need for a new form of urban private vehicle. Since urban trips are short in distance and have low average trip speeds, the gasoline and diesel vehicles are operating at a low energy efficiency level. However, an electric automobile powered by batteries developed in the near future may operate substantially more efficiently than either the gasoline or diesel vehicles under urban cyclic driving conditions. It is felt that electric vehicles should be designed for urban travel.
- (v) Energy savings of 1.2 percent may be obtained if electric automobiles comprise 10 percent of the "on the road" automobile fleet, while the greater use of the bicycle could reduce energy consumption by two percent.
- (vi) There is a need for a dual mode bus. Approximately 5 percent of the energy consumed by transit in the study area by 1990 could be saved if an electric articulated bus is used which can operate off the transitway using battery power or a diesel motor.

- (vii) The introduction of the more energy efficient automobiles in 1990 should require 40 percent less energy to move a person than that which was required by the 1977 automobile fleet. Similarly, by using articulated buses and building a transitway for a light rail transit system in 1990, the transit system for 1990 should require 25 percent less energy to move a passenger as that which was required by the 1977 transit system.

5) Infrastructure:

- (i) The energy consumed to maintain and operate the roadway system is small compared to the energy consumed to propel, produce and maintain the vehicles which use the infrastructure.

7.3 Recommendations

More research is required to better understand the relationships of urban transportation and energy consumption. The following should be considered for further study:

- 1) The change in automobile travel demand due to increase in the cost of living. This is expected to influence automobile ownership per household, and the sensitivity of the perceived cost of travel. As disposable income for travel decreases, a higher value will be placed on perceived costs than those experienced in the 1970's.

- 2) The changes in automobile fleet size mix which may occur due to increasing the registration tax on the lesser energy efficient automobiles and reducing the tax for more energy efficient vehicles.
- 3) The extent to which bicycle facilities should be developed to increase the energy efficiency of the urban area's transportation system.
- 4) The energy savings which may occur by applying a higher level of service for transit.
- 5) The energy savings which could be achieved by re-cycling materials used in scrapped vehicles for producing new vehicles.
- 6) Establishing the amounts of each fuel used during the processes of producing and maintaining vehicles and the production of fuels. This would permit the analyst to compare the amounts of each type of fuel consumed both directly and indirectly by transportation systems.
- 7) The IBI Group used PCU units to distinguish the amounts of infrastructure maintenance and construction energy requirements between the private and public transportation systems. Since transit vehicles are much heavier than automobiles and therefore cause much more damage to the infrastructure, then the use of the PCU, a vehicle space measurement on roadways, may not be representative for a vehicle damage measure for infrastructure.

REFERENCES

1. Environmental Protection Agency (EPA), U.S.A., "Factors Affecting Automobile Fuel Economy," September 1975.
2. Claffey, P.J., "Running Costs of Motor Vehicles as Affected by Road Design and Traffic," National Cooperative Highway Research Programs, Report No. 111, 1971.
3. Cope, E.M., "The Effects of Speed on Automobile Gasoline Consumption Rates," Federal Highway Administration, Highway Statistics Division, October 1973.
4. Lea, N.D. and Associates Ltd., "A Study of Measures to Encourage the Adoption of More Energy Efficient Automobiles, Volume 1," 1976.
5. Chumak, A., "Trends in the Use of Energy in Transportation," Working Paper No. 23, Role of the Automobile Study, Strategic Planning, Transport Canada.
6. Stopher, P.R. and Meyburg, H.A., Urban Transportation Modelling and Planning, Lexington Books, 1975.
7. Peat, Marwick, Mitchell and Company, "A Review of Operational Urban Transportation Planning Models," NTIS, U.S. Department of Commerce, April 1973.
8. Ministry of Transportation and Communications of Ontario, "Travel Demand Forecast Models," 1976.

9. Shallal, L., "Peak Hour Ratios Estimation, Applications and Cost-Effectiveness in the Urban Transportation Planning Process," Ph.D. Thesis, Carleton University, April 1979.
10. Khan, A., "Energy Efficiency in Canadian Intercity Passenger Transportation," Carleton University, March, 1978.
11. IBI Group, "Indirect Energy in Transportation," Prepared for the Strategic Studies Branch of Transport Canada, March 1978.
12. Fels, Margret, F., "Comparative Energy Costs of Urban Transportation Systems," Transportation Research, Vol. 9, 1975.
13. Pennsylvania Transportation Institute, "Energy Consumption Through Urban Transportation Planning," NTIS, U.S. Department of Commerce, 1975.
14. Janson, B.N., "Direct Energy Accounts for Urban Transportation Planning," Department of Civil Engineering, University of Illinois at Urbana - Champaign, August 1979.
15. Chang, M., Evans, L., Herman, R. and Wasielewski, P., "Gasoline Consumption in Urban Traffic," Transportation Research Record No. 599, Washington D.C., 1976.
16. Stopher, P.R. and Mayburg, A.H., Behavioural Travel Demand Models, Lexington Books, 1975.

17. Koppelman, F.S., "Guidelines for Aggregate Travel Prediction Using Disaggregate Choice Models," TEB No. 610, Transportation Research Board, 1976.
18. U.S. Department of Transportation, Urban Mass Transportation Administration, Planning Methodology and Technical Support Division, "Urban Mass Transportation Planning System," August 1975, Washington D.C..
19. Regional Municipality of Ottawa-Carleton, "A Model of Individual's Choice of Travel Modes," Transportation Department, July 1979.
20. Edwards, W., "The Theory of Decision-Making," Psychological Bulletin, Volume 51, No. 4, 1954.
21. Stopher, P.R. and Lavender, J.O., "Disaggregate, Behavioural Demand Models: Empirical Tests of three Hypotheses," Transportation Research Forum Proceedings, XIII (1), 1972.
22. Domenick, J.A., Urban Travel Demand, North Holland Publishing Company, 1975.
23. Hamzawi, S.G., "An Optimization Methodology for Design and Evaluation of Intercity Passenger Transport Systems," Ph.D. Thesis, Carleton University, 1977.
24. Regional Municipality of Ottawa-Carleton, "Comparative Analysis of 1963, 1972 and 1977 Travel O-D Surveys," Internal Report, Transportation Department, Sept. 1978.

25. Nie, N.H., et. al., Statistical Package for the Social Sciences, 2nd Edition, McGraw-Hill Book Company, 1975.
26. Atherton, T.J. and M.E. Ben-Akiva, "Transferability and Updating of Disaggregate Travel Demand Models," TRR #610, Transportation Research Board, 1976.
27. Richards, M.G and M.E. Ben Akiva, A Disaggregate Travel Demand Model, Saxon House, 1975.
28. U.S. Department of Transportation, "Development and Calibration of Mode Choice Models for the Twin Cities Area," Federal Highway Administration, February, 1977.
29. National Cooperative Highway Research Program, "Energy Effects, Efficiencies, and Prospects for Various Modes of Transportation," Synthesis of Highway Practice Report #43, Transportation Research Board, 1977.
30. De Leuw-Dillon-IBI Group, "Ottawa-Carleton Rapid Transit Development Program, Technical Memorandum Task 4806," September 1978.
31. Hull Transit Commission, "Hull Transit Annual Report," 1977.
32. Ottawa-Carleton Regional Transit Commission, "O.C. Transpo Annual Report," 1977.

33. Urban Transportation Development Corporation Ltd.,
"Light Rail Transit, the Vehicle," Toronto, 1977.
34. Train, Kenneth, "The Potential Market for Non-Gasoline
Powered Automobiles," Cambridge Systematics Inc.,
Berkeley, CA.
35. Civil Engineering Journal, American Society of Civil
Engineers, December, 1977.
36. Johnson, F.G., "The Energy Efficiency of Electric
Vehicles vs Internal Combustion Vehicles," Department
of Industry, Trade and Commerce, Ottawa, November 1978.
37. Bevilacqua, D.M., "An Assessment of Electric Vehicle
Market Potentials," De Leuw, Cather and Company,
August, 1978.
38. Road and Transportation Association of Canada, News,
May/June 1979.
39. Ohrn, Carl, E., "Predicting the Type and Volume of
Purposeful Bicycle Trips," TRR #570, Transportation
Research Board.
40. Transportation Branch, "Downtown Ottawa Bicycle
Questionnaire - Summary of Findings," Regional Municipality
of Ottawa-Carleton, November 1979.
41. Flannagan, R., "Automobile Technology Assessments and
Projects to the Year 2000," Role of the Automobile Study,
Strategic Planning, Transport Canada, Working Paper #14.

42. Public Affairs Branch, "Edition 2, 1978 Fuel Economy Guide," Transport Canada.
43. Public Affairs Branch, "1979 Fuel Consumption Guide," Transport Canada.
44. The National Research Council, "Energy Equivalents for Current and Prospective Automobile Fuels in Canada," Mechanical Engineering Report MD-53, February 1976.
45. De Leuw-Dillon-IBI Group, "Ottawa-Carleton Rapid Transit Development Program, Volume 1," March 1978.
46. Proceedings of the 42nd UITP International Congress, "Development of the Motorbus and its Integration in Modern Transport Systems," 1977.
47. North American Space Administration (NASA), "Performance of Conventionally Powered Vehicles Tested to an Electric Vehicle Test Procedure", NASA TM 73768, December, 1977

Appendix A

A. 1 Description of the UTPS Programs

Description of the UTPS Programs

THE MAIN UTPS PROGRAMS

Transit Network	1. UNET (inputs coded transit network)
	2. UPATH (finds minimum paths)
	3. UPSUM (produces & reports data of
transit network)
	4. ULOAD (loads trips onto transit network)
	5. UPRAS (produces & reports data regarding
loaded network)
Road Network	1. HR (inputs coded transit network)
	2. UROAD (path finding, skimming, loading
trips onto network)
Demand
Modelling	1. UMODEL (trip generation, distribution,
mode split)
	2. ULOGIT (mode split modelling)
Matrix
Manipulation	1. UMATRIX (preforms mathematical functions
on matrix)

3 3
OF / DE

3. Produces a printed report describing the shortest path and fares from selected origin zones to all other zones,
4. Produces a frequency distribution plot for cumulative zone to zone times and/or fares

Outputs:

1. Transit pathfile
2. Zone to zone fare matrix data set
3. Frequency distribution plots
 - for zone to zone times
 - for zone to zone fares

Uses of Outputs:

1. The reports output can be used to edit network
2. The transit paths file can be input to the minimum path summary program "UPSUM", to the loading program "ULOAD", and the station to station travel program "USTOS"
3. The zone to zone fare matrix can be input to:
 - to "UMODEL" as an interchange variable for mode split forecasting
 - to "UMNIP" to be multiplied by a transit trip table to obtain system revenues

UPATH

Functions:

1. Produces a data set describing the shortest interzonal transit paths
 - the technique for determining the shortest path is the sum of the path's weighted link times, wait times and transfer penalties
 - link times can be weighted differently for each transit or non-transit mode
 - wait and transfer times are automatically calculated as half the combined headway of the lines used, then factored by the weighting factor, and checked against the maximum and minimum wait times, reset to the nearest limit if it doesn't fall within the limits, and if any transfer penalty has been coded, it is then added as the last step
 - the number of transfers allowed can be limited
 - transfers between specified modes may be prohibited
 - transit fare cannot be used in the criterion for selecting the path
2. Produces a matrix of zone to zone fares

3. Produces a printed report describing the shortest path and fares from selected origin zones to all other zones,
4. Produces a frequency distribution plot for cumulative zone to zone times and/or fares

Outputs:

1. Transit pathfile
2. Zone to zone fare matrix data set
3. Frequency distribution plots
 - for zone to zone times
 - for zone to zone fares

Uses of Outputs:

1. The reports output can be used to edit network
2. The transit paths file can be input to the minimum path summary program "UPSUM", to the loading program "ULOAD", and the station to station travel program "USTOS"
3. The zone to zone fare matrix can be input to:
 - to "UMODEL" as an interchange variable for mode split forecasting
 - to "UMNIP" to be multiplied by a transit trip table to obtain system revenues

UPSUM

- Functions:
1. Produces a single, merged matrix data set showing zone to zone unweighted travel time by mode, number of transfers, initial waiting time, transfer time and total weighted time required for each zone to zone trip using the transit network. These elements can be output individually or in additive combinations
 2. Produces a printed report with plots of frequency distributions for each output matrix

- Outputs:
1. Up to 12 zone to zone impedance matrices in a single merged data set
 2. Printed impedance matrices for selected origin zones
 3. A plot of frequency distributions for each output matrix

- Uses of Outputs:
1. The impedance matrices may be input to "UFMTR" to format and print selected zone to zone impedances for analysis or to obtain trip length distribution; or to "UMODEL" as some of the interzonal variables for demand analysis and forecasting

2. The frequency distribution plots are used for network evaluation providing measures of levels of service

ULOAD & UPRAS

- Function:
- 1.. ULOAD - Load trips on network
 2. UPRAS - Report loaded network

Outputs

ULOAD

1. Mode to mode transfer report
2. Loaded legs file for input into sort

UPRAS

1. Line volumes
2. Link volumes
3. Line reports with revised headways
4. Mode and line summaries
5. Matrix of mode to mode movements for
all lines of selected modes

- Uses of Output:
1. Link volumes - used to determine number
of vehicles
 2. System evaluation, etc.

Road Network Programs

HR

- Functions:
1. To edit and build from coded input, a description of the highway network
 2. To update an existing historical record
 3. To insert coordinates into an historical record
 4. To print a description of the historical record

- Outputs:
1. Edits messages
 2. Input listings
 3. Reports of historical records
 4. Binary historical record file

- Uses of Outputs:
1. For path finding, skimming, and assignment
 2. For plotting using UTPS software

UROAD

- Functions:
1. Pathfinding (time, distance, cost)
 - single minimum path
 - all minimum paths
 - stochastic multi path
 2. Path skimming (time, distance, costs)
 3. Loading
 - all or nothing
 - all minimum path
 - Iterative - equilibrium
 - User coded algorithms
 4. Selected link analysis
 - screenline
 - link
 5. Parameterized speed and capacity by area type, facility type, number of lanes
- Outputs:
1. Updated historical record
 2. Impedance skim time, distance, cost and toll revenue matrices
 3. Trip tables of trips using selected links
 4. Reports
 - link data
 - selected tree reports
 - link and turn volumes, congested speeds

- summaries of VMT, congested speeds
and road miles stratified by:
 - i. v/c level
 - ii. facility type
 - iii. geographic location
- 5. Total volume and v/c for link groups
eg. cut lines across major corridors
- 6. Report of parametric speed/capacity tables
- 7. Impact report of emissions, fuel use, etc.

- Uses of Outputs:
- 1. Checking of o/d data or model data
against ground counts
 - 2. Network calibration
 - 3. Network evaluation
 - i. for selected links
 - ii. corridor level (link groups)
 - 4. Facility design using link and turn
volumes
 - 5. Demand modelling through "UMODEL"

Demand Modelling Programs

UMODEL

Functions:

1. To provide a framework for a user specified demand model as
 - trip generation, trip distribution and modal split
 - disaggregate demand forecasting
2. To assist in model calibration
3. To perform general matrix manipulation

Outputs:

1. Any number of matrices
 - modal trip tables
 - to transform survey data into trip matrices
2. Disaggregate data sets
3. Binary calibration file for "ULOGIT"
4. Trip end summaries
5. Statistical data
 - means, variances, correlations
 - summary of residuals
 - summary of residuals (errors, or deviations)
 - i. stratified by curve values
 - ii. stratified by goodness-of-fit

- Uses of Outputs:
1. Input trips to assignment models
 2. Evaluation
 - analyze trip tables with impedance levels
 - i. trip length distributions "VFMTR"
 - ii. revenue calculations "UMNIP"
 - iii. effective speed matrices "UNODEL"
 - perform sensitivity analysis "UMODEL"

ULOGIT

Functions: 1. Assists in the calibration of modal split and other models of the linear logit form. Uses the maximum likelihood fitting technique and allows the constraining of coefficients. Reads a calibration file from "UMODEL"

Outputs: 1. Calibrated coefficients, statistics and printer plots showing goodness-of-fit to input calibration file.

Uses of Outputs: 1. For modifying input formulation to approach a better fitting logit model

Matrix Manipulation Program

UMATRIX

Functions:

1. Output multiple matrices (trips of impedances)
2. Perform operations on or among matrices
 - arithmetic (+, -, *, ÷)
 - functions (log, e^x , $\sqrt{\quad}$, etc)
 - transpose (trip table splitting)
3. Logical selection of the if, then, else type

Outputs

1. The matrices developed for output
2. A report showing selected rows of the output matrix.

Uses of Outputs:

1. Combining trip tables or skims
2. Splitting P/A to O/D trip tables
3. Others

Appendix B

- B. 1 The 1.4% Home Interview Survey Questionnaire and Key Records.
- B. 2 Description of the Road and Transit Networks.
- B. 3 Description of the Independent Variables used in the Behavioural Modals Split Models.
- B. 4 Establishing the Petroleum Price for BC 1990

APPENDIX B. 1

--	--	--	--

Sample Number

The 1.48 Home Interview Survey Questionnaire and Key Record

ADMINISTRATIVE RECORD

Interviewer's Name _____

CONTACTS WITH RESPONDENT

Telephone Calls

	Date	Time
1.	-----	-----
2.	-----	-----
3.	-----	-----
4.	-----	-----

Interviewer's Remarks

REPORT SUBMITTED INCOMPLETE

Date _____

- Reason: 1. Vacant 5. No Such Address
2. Demolished 6. Illness
3. Comm. Structure 7. Vacation
4. Refusal 8. Out of study area on travel day.

Supervisor's Remarks

REPORT SUBMITTED COMPLETE

I certify that the information recorded on this form was obtained from the respondents listed as being interviewed by me at the above address, and that it is true and complete to the best of my knowledge.

DATE _____ SIGNATURE OF INTERVIEWER _____ INTERVIEW CHECKED BY: _____ DATE _____ TELEPHONE _____ INITIALS _____ OTHER _____

CODED BY: _____ INITIALS _____ DATE _____ CODING CHECKED BY: _____ INITIALS _____ DATE _____

[illegible]

ATTITUDINAL QUESTIONS

1. Do you think that more emphasis should be placed on road improvement? or transit improvement?
2. Are you aware that there is a Rapid Transit Study going on in Ottawa-Carleton? Yes No
3. Have you attended any public meetings of this Study? Yes No
4. Would you like to learn more about it? Yes No
5. Do you think rapid transit is a good idea for Ottawa-Carleton? Yes No
6. Do you think that we should proceed on rapid transit in the near future? or should it be left as a long term need?

SAMPLE RECORD FORMAT

42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340	1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373	1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384	1385	1386	1387	1388	1389	1390	1391	1392	1393	1394	1395	1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439	1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	1454	1455	1456	1457	1458	1459	1460	1461	1462	1463	1464	1465	1466	1467	1468	1469	1470	1471	1472	1473	1474	1475	1476	1477	1478	1479	1480	1481	1482	1483	1484	1485	1486	1487	1488	1489	1490	1491	1492	1493	1494	1495	1496	1497	1498	1499	1500	1501	1502	1503	1504	1505	1506	1507	1508	1509	1510	1511	1512	1513	1514	1515	1516</
----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	--------

Appendix B.2

Description of the Road and Transit Networks

The road network developed for this research was used to simulate the roadway system in the Ottawa-Hull area during the weekday P.M. peak hour. The roadways included in the network were the expressways, parkways, and major arterials. The local distribution roadways were for the most part excluded from the network.

The network was coded into a format to be input into the UTPS program HR. This was accomplished by locating nodes in the road network where intersections existed. A link was then used to define the roadway between a pair of nodes. The distance and the average speed travelled on each link was found for each link in the road network.

Once the coded network was input into HR, it was possible to obtain minimum times, distances, and speeds to travel between each pair of zones in the network using the program UROAD. The UTPS users manual¹⁸ contains additional literature describing the procedure used to use HR and UROAD.

The transit networks which were developed for this study were used to simulate the public transit system in the Ottawa-Hull area during a weekday P.M. peak hour for the years 1977 and 1990.

The transit networks consisted of those transit corridors which contained the heavier demands for ridership. Twenty-four corridors were used to simulate the transit system in 1977, while nineteen corridors were used on the 1990 network. The 1990 network altered several locations of the 1977 corridors and added a transitway corridor. Furthermore, several of the 1977 corridors were not used in the 1990 network due to the addition of the transitway.

The transit networks were coded into a format whereby they could be input into the UTPS program UNET. This was accomplished by locating nodes in each transit corridor which served as transfer locations. Links were then used to define each segment of a corridor between a pair of nodes. For each link the following were obtained: (i) length of link; (ii) the speed the transit vehicle travelled on the link; (iii) the headway.

Particular care was required when selecting the location of the nodes. If too few nodes were used, the "in-vehicle travel time" becomes excessively high, while if too many nodes were used, an excessive number of transfers and transfer times occur.

Once this data was coded, UNET was run. The output from UNET was then used as input to UPATH to obtain the shortest path between each pair of zones in the network. This output from UPATH was then input to UPSUM to obtain the minimum in vehicle travel time, number of transfers, and other required transit data for each pair of zones in the network.

The transit trips were "loaded" onto the transit network from a centroid connector link. This link joined the zone centroid (where trips began or ended) to a node on a nearby transit corridor. No more than two centroid connectors were used from any one zone. ULOAD was used to perform this task.

day if they had used the auto driver mode and (\$1.48/2.4) for the auto pooler mode (2.4 was the auto pooler average occupancy. For all other trip purposes, it was assumed that no parking cost would be incurred if a transit user used the automobile vehicle.

Automobile Perceived Cost:

The perceived cost of using the automobile included the cost of parking and the cost of gasoline. The gasoline cost was assumed to be 3.727¢ /km. The cost of gasoline per kilometer was multiplied by the trip length in kilometers. The parking cost was then added to the gasoline cost and then divided by the number of travellers in the automobile. For the "all other trips" mode by automobile, the full cost was placed on the traveller's record since it was believed that most "all other trips" where two or more travellers are in the vehicle do not share the trip cost.

For transit users making a "home based work trip", it was assumed that if they were using the auto pooler mode, a total of 2.4 travellers would absorb the perceived cost.

was a considerable amount of variation in the travel times between any two zones depending up on the actual location of the trip origin and trip destination within the zones. Therefore, the in-vehicle travel time was estimated using the addresses of the origin and destination locations recorded on the telephone survey questionnaire. For each record, the most probable route⁽¹⁾ between the addresses was determined and the in-vehicle travel time for each bus taken was estimated from transit schedules.

Number of Transfers, Access Distance;
Transit Out of Vehicle Travel Time:

These transit variables were estimated using the address of the trip origin and/or trip destination recorded on the telephone survey questionnaire. For each record, the most probable route between addresses was found and the transit variables were then estimated.

Transit Fare:

No data was available from the telephone survey as to the actual fare paid for a transit ride. In the Ottawa-Hull area, several fare options exist such as monthly passes, single tickets, cash, reduced rates for students and senior citizens, and express bus premiums. Therefore it was necessary to develop mean fares by age and transit service type. The mean fares were then applied to the appropriate traveller's record.

(1) Based on the 1977 O.C. Transpo Or Bus Survey results:

Automobile Trip Length:

This variable was developed for the automobile modes. It was the shortest distance which could be travelled between any zone centroid to another zone centroid within the road network.

Parking Cost:

Since most of the automobile trips made during the P.M. peak hour were destined to the traveller's home, no parking cost was recorded for the trip unless the traveller actually paid for parking at home. Since it was believed that a traveller's mode choice, particularly for the work trip, was influenced by the cost of parking at the place of work, it was necessary to return to the survey questionnaires and determine the parking cost incurred.

To estimate what the parking costs of transit users would have been if they had used the automobile, a parking cost analysis was conducted using the telephone survey data. The results of the study indicated that of those automobile users working in the CBD, 33.1 percent incurred some parking cost. The average cost for parking a vehicle for this trip type was \$1.48 per day. Based on this analysis, it was decided that 70 percent⁽¹⁾ of all transit riders who work in the CBD would have incurred a parking cost of \$1.48 per

(1) The value of 70 percent is approximately the mean of 33.1 percent (percent of automobile users incurring a parking cost) and 100 percent (the initial parking cost estimate for transit users).

day if they had used the auto driver mode and (\$1.48/2.4) for the auto pooler mode (2.4 was the auto pooler average occupancy. For all other trip purposes, it was assumed that no parking cost would be incurred if a transit user used the automobile vehicle.

Automobile Perceived Cost:

The perceived cost of using the automobile included the cost of parking and the cost of gasoline. The gasoline cost was assumed to be 3.727¢ /km. The cost of gasoline per kilometer was multiplied by the trip length in kilometers. The parking cost was then added to the gasoline cost and then divided by the number of travellers in the automobile. For the "all other trips" mode by automobile, the full cost was placed on the traveller's record since it was believed that most "all other trips" where two or more travellers are in the vehicle do not share the trip cost.

For transit users making a "home based work trip", it was assumed that if they were using the auto pooler mode, a total of 2.4 travellers would absorb the perceived cost.

Appendix B4

Establishing the Petroleum Price for BC 1990

In section 5.3.2 it was found that the average fuel consumption rate for the private vehicle fleet of 1977 was 17.00 L/100km while in section 5.5.1 the 1990 rate was found to be 9.07 L/100km. This implies the the 1990 fleet will consume 87 percent less fuel per 100km than the 1977 fleet. Therefore, to keep the cost of petroleum per 100 kilometres the same for 1990 as it was for 1977, the 1977 petroleum price per litre must be reduced by 87 percent to obtain the desired 1990 price.

Appendix C

C. 1 Establishing Average Trip Distances Made
by the Private Vehicle Fleet.

C. 2 Fuel Consumption Rates for Electric Vehicles.

APPENDIX C.1
ESTABLISHING AVERAGE TRIP DISTANCES MADE BY THE PRIVATE VEHICLE FLEET

Trip Purpose	USA Urban Trip Data		Ottawa-Hull Urban Trip Data			
	Average Trip Length (1) (km)	% of Trips (1)	% of Trips for Weekday Peaks	% of Trips for Weekday Off Peaks	% of Trips for Saturday	% of Trips for Sunday
Earning a Living						
To and From Work	15.13	32.2	47	22.0	22.0	2
Related Business	25.76	4.4	3.44	5.15	5.15	0
Family Business						
Medical	13.36	1.8	1.41	2.11	2.11	1
Shopping	7.08	15.4	12.04	18.03	28.03	2
Others	10.47	14.2	11.10	16.63	6.63	4
Social and Educational						
Visiting Friends	19.32	9.0	7.03	10.54	10.54	14
Pleasure Rides	31.6	1.4	1.09	1.64	1.64	22
School/Religion	7.57	9.4	7.35	11.01	11.01	40
Others	18.35	12.2	9.54	13.29	13.29	15
Average Trip Length		14.33	14.21	13.80	13.47	16.42

(1) Source Reference 29

For weekday peaks, 1977 average trip length in Ottawa-Hull area is 9.4 km.
Reference overestimates Ottawa-Hull trip length by: $(14.21 - 9.4) / 14.21 = 34\%$

weekday offpeak trip length is $13.80 \times .66 = 9.1$

Saturday trip length is $13.47 \times .66 = 8.89$

Sunday trip length is $16.52 \times .66 = 10.86$

Appendix C2

Estimation of the Independent
Variables for 1990 Modal Split

In-Vehicle Travel Time

Auto Driver: From the aggregation result, the average P.M. peak hour trip time for all automobile trips was 15.9 minutes in 1977. From the samples used to calibrate the models, the average automobile trip time for auto driver was found to be 15.32 minutes in 1977. From the aggregation results performed for 1990, the average in-vehicle travel time for all automobile trips was 17.4 minutes. Therefore, to obtain the desired 1990 in-vehicle travel time the following ratio was used:

$$\frac{\text{Aggregation, 1977}}{\text{Value Used, 1977}} = \frac{\text{Aggregation, 1990}}{\text{Desired Value, 1990}}$$

$$\frac{15.9}{15.32} = \frac{17.4}{x} \quad x = 16.77 \text{ minutes for auto driver in BC 1990}$$

Auto Pooler: Using the same procedure as described for auto driver, one obtains:

$$\frac{15.9}{17.87} = \frac{17.4}{x} \quad x = 19.56 \text{ minutes for auto pooler in BC 1990}$$

Auto User: Using the same procedure as described for auto driver, one gets:

$$\frac{15.9}{13.48} = \frac{17.4}{x} \quad x = 14.75 \text{ minutes for auto user in BC 1990}$$

Transit (Home Based Work Trips): The average trip length for transit in 1977 (according to the samples used to calibrate the models) was:

$$24.82 \text{ minutes} \times \frac{20 \text{ km/h}}{60 \text{ minutes/h}} = 8.27 \text{ km}$$

where 20 km/h was the average speed of a bus in 1977. Assuming the increase in transit trip distance for home-based work trips in 1990 is proportional to the increase in automobile home-based work trips one obtains:

$$\frac{8.27 \text{ km} \times \frac{10.86 \text{ km}}{9.4 \text{ km}}}{\frac{20 \text{ km}}{\text{h}}} \times \frac{60 \text{ minutes}}{\text{h}} = 28.6 \text{ minutes}$$

for transit
home based
work trips
in BC 1990

Transit (All Other Trips): Using the same procedure just outlined one obtains:

$$29.82 \text{ minutes} \times \frac{20 \text{ km/h}}{60 \text{ minutes/h}} = 9.94 \text{ km (1977)}$$

for 1990

$$\frac{9.94 \text{ km} \times \frac{10.86 \text{ km}}{9.4 \text{ km}}}{\frac{20 \text{ km}}{\text{h}}} \times \frac{60 \text{ minutes}}{\text{h}} = 34.45 \text{ minutes}$$

for transit
all other
trips in
BC 1990

Perceived Trip Cost

Auto Driver: From the parking cost analysis outlined in Appndix B.3 it is known that the average parking cost in 1977 was 11.11¢ per home based work trip. From the aggregation step done for 1977 the perceived trip cost would be: (based on an average trip distance of 9.4 km)

$$9.4 \text{ km} * 3.727 \text{ ¢/km} + 11.11\text{¢} = 46.16\text{¢}$$

From the samples, the perceived trip cost is 47.89¢ in 1977 while from the aggregation step done for 1990 the perceived trip cost would be (assuming an average trip length of 10.86 km):

$$10.86 \text{ km} * 3.727 \text{ ¢/km} + 11.11 \text{ ¢/parking} = 51.59\text{¢}$$

therefore:
$$\frac{\text{Aggregation, 1977}}{\text{Value Used, 1977}} = \frac{\text{Aggregation, 1990}}{\text{Desired Value, 1990}}$$

$$\frac{46.14\text{¢}}{47.89\text{¢}} = \frac{51.59\text{¢}}{x} \quad x = .53.55\text{¢ for auto driver in BC 1990}$$

Auto Pooler: Using the same procedure as that outlined in above but now using a load factor of 2.4 persons/vehicle, one obtains:

$$\frac{46.14\text{¢}/2.4 \text{ persons}}{19.96\text{¢/person}} = \frac{51.59\text{¢}/2.4 \text{ persons}}{x \text{ ¢/person}}$$

$$x = 22.32 \text{ ¢/trip for auto pooler in BC 1990}$$

Auto User: Using the same procedure as outlined for auto driver but using a load factor of 1.4 and excluding a parking cost, one obtains:

$$\frac{(9.4 \text{ km} * 3.727 \text{ ¢/km}) / (1.4 \text{ pers/car})}{22.71 \text{ ¢/person}} = \frac{(10.86 \text{ km} * 3.727 \text{ ¢/km}) / (1.4 \text{ pers/km})}{x}$$

$$x = 26.24 \text{ ¢/trip for auto user in BC 1990}$$

Transit (Home Based Work Trips): Cost per kilometre for transit in 1977 was:

$$\frac{37.01 \text{ ¢}}{8.27 \text{ km}} = 4.48 \text{ ¢/km}$$

therefore, trip cost in BC 1990 was:

$$8.27 \text{ km} * \frac{10.86 \text{ km}}{9.4 \text{ km}} * 4.48 \text{ ¢/km} = 42.80 \text{ ¢/trip for transit in BC 1990}$$

Transit (All Other Trips): Using the same procedure presented above, one obtains:

$$9.94 \text{ km} * \frac{10.86 \text{ km}}{9.4 \text{ km}} * \frac{32.46 \text{ ¢/trip}}{9.94 \text{ km}} = 37.5 \text{ ¢/trip for transit in BC 1990}$$

To estimate perceived trip costs for PPD 1990 and PPI 1990, the following procedure was used:

$$(\text{Cost of petroleum per trip for BC 1990}) * \% \text{ change} + \text{parking (if applicable)} = \text{new perceived cost}$$

example: for auto driver PPI 1990

$$(53.55 \text{ ¢/trip} - 11.11 \text{ ¢/parking}) * \frac{49.6 \text{ ¢/L}}{37.1 \text{ ¢/L}} + 11.11 \text{ ¢/parking} = 67.85 \text{ ¢ for PPI 1990 (auto driver)}$$

where 53.55 ¢/trip accounts for a petroleum cost of 37.1 ¢/L while for PPI 1990 it is 49.6 ¢/L

Appendix C3

Fuel Consumption Rates for Electric Vehicles

The rate of electricity consumption of the 1985 electric vehicles was based on a study conducted by NASA entitled "Performance of Conventionally Powered Vehicles Tested to an Electric Vehicle Test Procedure"⁴⁶. Tests were developed to determine gasoline vehicle performance characteristics (the tests were carried out on the Volkswagen Transporter, Renault 5, the American Motor's Pacer and an American Motors General DJ5 delivery Van) and to compare these characteristics to those obtained from the same vehicles altered to run on electric power.

Based on the gasoline consumption rate obtained by the NASA Test, it was found that their rate was 149 percent of that obtained by EPA for the urban cyclic test. The EPA rate for the 1975 subcompact and compact gasoline vehicles were found and multiplied by 1.49 to obtain the NASA gasoline consumption rate. Using these rates and Figure C.1, it was possible to estimate the electricity consumption rates of the subcompact and compact electric vehicles. It was found that the 1985 subcompact electric vehicle rate was 45.0 kWh/100 km, and for the compact vehicle, 57.0 kWh/100 km.

Figure C.1

Gasoline Vs. Electricity Consumption Rates

- (1) the point corresponds to the subcompact electric vehicle used in this research.
- (2) the point corresponds to the compact electric vehicle used in this research.

Appendix D

- D1 Energy Content of Fuels and Conversion Factors
- D2 Establishing the Maintenance Energy Intensity of Electric Private Vehicles
- D3 Establishing Production Energy Intensities of the Private and Public Vehicles

Appendix D1

Energy Content of Fuels and Conversion Factors

Energy Content of Fuels*

<u>Fuel</u>	<u>BTU/l. Gallon</u>	<u>MJ/Litre</u>
Motor gasoline	149,200	35
Aviation gasoline	144,300	34
Aviation turbo fuel	154,700	36
Kerosene	162,200	38
Diesel oil	166,500	39
Light fuel oil	166,500	39
Heavy fuel oil	179,640	42
Electricity (1000 Kilowatt Hrs.)	3.412×10^6 BTU	

*Source: "Detailed Energy Supply and Demand in Canada", Statistics Canada Catalogue 57-207.

Energy Conversions

1 BTU = 1055 Jules
 1 Cal. = 4.187 Jules
 1 BTU = 252 Calories
 = 0.252 K. cal.
 = 2.931×10^{-4} KWHr.

1 KWHr. = 3412 BTU
 1 Jule (J) = 4.18 Cal.

Conversion Factors

1 Imperial Gallon = 277.42 Cubic Inch
 1 U.S. Gallon = 231.000 Cubic Inch
 1 Imperial Gallon = 1.2 U.S. Gallons
 1 U.S. Gallon = 0.833 Imp. Gallons
 1 U.S. Gallon = 3.785 Litre
 1 Imperial Gallon = 4.546

Appendix D2

MAINTENANCE ENERGY INTENSITY OF ELECTRIC
VEHICLES

For the 1990 Sub-Compact

- Assume: 1. Maintenance Cost (in \$1974) to maintain motor is 10.00/year.
- 2. Maintenance Cost to maintain vehicle body is 42.00/year.

Energy equivalent for Maintenance, excluding battery;

$$\left(\frac{52.00\$ \text{ for Electric Vehicle}}{208.00\$ \text{ for Gasoline Vehicle}} \right) * \left(\frac{.4850 \text{ MJ}}{\text{vehicle-km}} \right) = \frac{.121 \text{ MJ}}{\text{vehicle-km}}$$

Annual Replacement Cost of Battery

$$\left(\frac{550 \text{ cycles}}{\text{battery}} \right) * \left(\frac{50 \text{ km}}{\text{cycle}} \right) = \frac{27,500 \text{ km}}{\text{battery}}$$

Portion of Battery used Per Year

$$\frac{10,000 \text{ km/year}}{27,500 \text{ km/battery}} = .364 \text{ or } 36.4\% \text{ of } \frac{\text{battery}}{\text{year}}$$

$$* \left(\frac{18,311 \text{ MJ}}{\text{battery}} \right) * \left(.364 \frac{\text{battery}}{\text{year}} \right) * \left(\frac{\text{year}}{10,000 \text{ km}} \right) = .667 \frac{\text{MJ}}{\text{km}}$$

∴ Maintenance energy intensity for a 1975 subcompact electric vehicle = .667 + .121 = .788 MJ/km.

- For a 1985 subcompact vehicle

$$.788 * \left(\frac{1392 \text{ kg (1985 vehicle)}}{1466 \text{ kg (1975 vehicle)}} \right) = .748 \frac{\text{MJ}}{\text{km}}$$

- For a 1985 compact vehicle

$$.788 * \left(\frac{1783 \text{ kg}}{1466 \text{ kg}} \right) = .958 \frac{\text{MJ}}{\text{km}}$$

Appendix D3

The Energy Required to Produce
A 1975 Sub-compact Automobile - Gasoline

Basic Material	Weight (kg)	Value (1974\$)	Energy Intensity (MJ/kg)	Total Energy Requirement (MJ)
Rolled steel	670	162	36.286	24,312
Pig iron	190	20	13.956	2,652
Aluminum ingots	26	19	130.023	3,381
Other non-ferrous ingots	25	38	94.901	2,373
Solder	2	4	78.154	156
Glass	27	36	110.252	2,977
Rubber	37	25	40.705	1,506
plastic resins	49	51	110.020	5,391
Paint	8	10	81.41	651
Tires	46	56	80.48	3,702
Fluids & lubricants	54	12	53.498	2,889
Total materials	1,134	433		49,990
Delivered price less freight		<u>3,703</u> 43	68.61 MJ/\$	2,950
Retail price less retail margin		<u>3,660</u> 420	37.41 MJ/\$	15,712
Producers price less total basic materials		<u>3,240</u> 433		49,990
Value added		2,807	20.05 MJ/\$	<u>56,280</u>
Total energy requirement				124,932 MJ
Production Energy per kilometre = $\frac{124,932}{161,000} = 0.7760 \frac{\text{MJ}}{\text{km}}$				

The Energy Required to Produce
A 1985 Sub-compact Automobile - Gasoline & Diesel

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials(1)	1,077(1)	411(1)		47,491(1)
Delivered Price		3,678		
Less Freight		<u>43</u>	68.61	2,950
Retail Price		3,635		
Less Retail Margin		417	37.41	15,600
Producers Price		3,218		
Less Total Materials		<u>411</u>		47,491
Value Added		2,807	20.05	<u>56,280</u>
Total Energy				122,321

Production Energy Intensity

$$\text{per Kilometre} \quad \frac{122,321}{161,000} = .75976 \frac{\text{MJ}}{\text{km}}$$

(1) These values were obtained by reducing the values for the 1975 sub-compact automobile by 5%. This reduction was based on data presented in reference 29.

The Energy Required to Produce
A 1975 Sub-compact Automobile - Electric

Material	Weight (kg)	Value (1974\$)	Energy Intensity (MJ/kg)	Total Energy (MJ)
Rolled Steel	568	137	36.286	20,610
Pig Iron	204	21	13.956	2,847
Al Ingots	21	15	130.023	2,730
Other Non- Ferrious Metals	45	68	94.901	4,271
Glass	27	36	110.252	2,977
Plastic resin	49	51	110.020	5,391
Paint	8	10	81.41	651
Rubber	37	25	40.705	1,506
Tires	46	56	80.48	3,702
Batteries	450	204	42.474	18,311
Solder	1	2	78.154	78
Fluid & Lubricants	10	4.5	53.498	535
Total	1,466	630		63,608
Delivered Price	3,622			
Less Freight	56		68.61 MJ/\$	3,842
Retail Price	3,466			
Less retail margin	422		37.41 MJ/\$	15,787
Producers price	3,044			
Less materials	630			63,608
Value added	2,414		20.05 MJ/\$	48,401
				131,771 MJ

Production Energy Intensity
per Kilometre

$$\frac{131,771}{161,000} = .81845 \frac{\text{MJ}}{\text{km}}$$

The Energy Requirement to Produce
A 1985 Sub-compact Automobile - Electric

Materials	Weight (kg)	Value (1974\$)	Energy Intensity (MJ) per Dollar	Total Energy Requirement (MJ)
Total Materials	1,392	599		60,428
Delivered Price		3,487		
Less Freight		<u>56</u>	68.61	3,842
Retail Price		3,431		
Less Retail Margin		<u>418</u>	37.41	15,787
Producers Price		3,013		
Less Total Materials		<u>599</u>		60,428
Value Added		2,414	20.05	<u>48,401</u>
Total Energy				128,458

Production Energy Intensity

Per Kilometre $\frac{128,458}{161,000} = .79788 \frac{\text{MJ}}{\text{km}}$

The Energy Required to Produce
1975 Compact Automobile - Gasoline

Material	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	1,452	557		64,159
Delivered Price		3,955		
Less Freight		55	68.61	3,774
Retail Price		3,900		
Less Retail Margin		465	37.41	17,396
Producers Price		3,435		
Less Total Materials		557		64,159
Value Added		2,878	20.05	57,703
Total Energy				143,032

Production Energy Intensity

Per Kilometre

$$\frac{143,032}{161,000} = .8884 \frac{\text{MJ}}{\text{km}}$$

The Energy Required to Produce
A 1985 Compact Automobile - Gasoline & Diesel

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	1,321 ⁽¹⁾	507 (1)		53,375 ⁽¹⁾
Delivered Price		3,898		
Less Freight		55	68.61	3,776
Retail Price		3,843		
Less Retail Margin		458	37.41	17,134
Producers Price		3,385		
Less Total Materials		<u>507</u>		58,305
Value Added		2,878	20.05	<u>57,703</u>
Total Energy				136,998

Production Energy Intensity

per Kilometre $\frac{136,998}{161,000} = .85092 \frac{\text{MJ}}{\text{km}}$

- (1) These values were obtained by reducing the values for the 1975 compact automobile by 9 percent. This reduction was based on data presented in reference 29.

The Energy Required to Produce
A 1975 Compact Automobile - Electric

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) per Dollar	Total Energy Requirement (MJ)
Total Materials	1,877	807		82,456
Delivered Price		3,786		
Less Freight		<u>71</u>	68.61	4,872
Retail Price		3,715		
Less Retail Margin		<u>443</u>	37.41	16,572
Producers Price		3,272		
Less Total Materials		<u>807</u>		82,456
Value Added		2,465	20.05	<u>49,423</u>
Total Energy				153,323

Production Energy Intensity

per Kilometre $\frac{153,323}{161,000} = .95232 \frac{\text{MJ}}{\text{km}}$

The Energy Required to Produce
A 1985 Compact Automobile - Electric

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) per Dollar	Total Energy Requirement (MJ)
Total Materials	1,783	767		78,333
Delivered Price		3,741		
Less Freight		<u>71</u>	68.61	4,872
Retail Price		3,670		
Less Retail Margin		<u>438</u>	37.41	16,386
Producers Price		3,232		
Less Total Materials		<u>767</u>		78,333
Value Added		2,465	20.05	<u>49,423</u>
Total Energy				149,014

Production Energy Intensity

per Kilometre $\frac{149,014}{161,000} = .92555 \frac{\text{MJ}}{\text{km}}$

The Energy Required to Produce
A 1975 Intermediate Automobile - Gasoline

Material	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	1,826	697		80,573
Delivered Price	4,666			
Less Freight	<u>68</u>		68.61	4,665
Retail Price	4,598			
Less Retail Margin	<u>590</u>		37.41	22,072
Producers Price	4,008			
Less Total Materials	<u>697</u>			80,573
Value Added	3,311		20.05	<u>66,386</u>
Total Energy				173,696

Production Energy Intensity

per Kilometre

$$\frac{173,696}{161,000} = 1.07886 \frac{\text{MJ}}{\text{km}}$$

The Energy Required to Produce
A 1985 Intermediate Automobile - Gasoline & Diesel

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) per Dollar	Total Energy Requirement (MJ)
Total Materials	1,643 ⁽¹⁾	627 ⁽¹⁾		72,516 ⁽¹⁾
Delivered Price		4,586		
Less Freight		<u>68</u>	68.61	4,665
Retail Price		4,518		
Less Retail Margin		<u>580</u>	37.41	21,698
Producers Price		3,938		
Less Total Materials		<u>627</u>		72,516
Value Added		3,311	20.05	<u>63,659</u>
Total Energy				162,538
Production Energy Intensity per Kilometre		$\frac{162,538}{161,000}$	$= 1.00955 \frac{\text{MJ}}{\text{km}}$	

- (1) These values were obtained by reducing the values for the 1975 intermediate automobile by 10 percent. This reduction was based on data presented in reference 29.

The Energy Required to Produce
A 1975 Standard Automobile - Gasoline

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	2,117	810		93,411
Delivered Price		6,154		
Less Freight		<u>79</u>	68.61	5,420
Retail Price		6,075		
Less Retail Margin		<u>845</u>	37.41	31,611
Producers Price		5,230		
Less Total Materials		<u>810</u>		93,411
Value Added		4,420	20.05	<u>88,611</u>
Total Energy				219,063
Production Energy Intensity per Kilometre		$\frac{219,063}{161,000}$	$= 1.36065 \frac{\text{MJ}}{\text{km}}$	

The Energy Required to Produce
A 1985 Standard Automobile - Gasoline & Diesel

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) per Dollar	Total Energy Requirement (MJ)
Total Materials	1,850 ⁽¹⁾	688 ⁽¹⁾		79,400 ⁽¹⁾
Delivered Price		6,012		
Less Freight		<u>79</u>	68.61	5,420
Retail Price		5,933		
Less Retail Margin		<u>825</u>	37.41	30,864
Producers Price		5,108		
Less Total Materials		<u>688</u>		79,400
Value Added		4,420	20.05	<u>88,621</u>
Total Energy				204,305
Production Energy Intensity				
per Kilometre		$\frac{204,305}{161,000}$	$= 1.26898$	$\frac{\text{MJ}}{\text{km}}$

- (1) These values were obtained by reducing the values for the 1975 standard Automobile by 15%. This reduction was based on data presented in reference 29.

The Energy Requirement to Produce
A Regular Diesel Bus 1975, 1990

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	9,695.45	4,077		437,462
Producers Price		62,417		
Less Total Materials		4,077		437,462
Value Added		58,340	17,935	<u>1,046,328</u>
Total Energy				1,483,790

Production Energy Intensity

Per Year $\frac{1,483,790}{16 \text{ Years}} = .0927 \times 10^6 \frac{\text{MJ}}{\text{Year}}$

The Energy Requirement to Produce

A Diesel and Electric Articulated Bus 1975, 1990

Materials	Weight (Kg)	Value (1974\$)	Energy Intensity (MJ) Per Dollar	Total Energy Requirement (MJ)
Total Materials	14,545	6,117		656,355
Producers Price		133,751		
Less Total Materials		6,117		656,355
Value Added		127,634	17,935	<u>2,289,116</u>
Total Energy				2,945,470

Production Energy Intensity

Per Year $\frac{2,945,470}{16 \text{ Years}} = .1841 \times 10^6 \frac{\text{MJ}}{\text{Year}}$

END

30108H84

FIN