Optimization of Integrated Multimodal Urban Transportation Corridors

by

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"Optimization of Integrated Multimodal Urban Transportation Corridors"

Submitted by

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Abstract

Achieving effective use of existing and planned transportation systems for travel time, enhancing energy efficiency and reducing emissions is a major challenge for transportation planners. Within the framework of transportation strategies for major urban travel corridors or entire urban regions, consisting of modal and intermodal infrastructure and technologies, demand management measures have to be defined. These offer the potential to optimize travel in integrated multimodal corridors.

The purpose of this research was to study the optimization of integrated multimodal urban corridors, based on minimizing travel time, energy consumption and emissions per pass-km. A methodology and constituent models were developed for studying the optimal use of the corridor through the interaction of demand and supply. For given corridor system options and demand management policies, travel simulation models were required to estimate trips. A four-step travel forecasting methodology based on equilibrium modelling technique was used. The EMME/2 software was used as a framework for model development and application.

A direct search optimization method was formulated for the minimization of objective functions. The optimization variables chosen include freeway tolls, parking charges in the central area and public transit fare. The choice of these variables for use in travel simulations (in association with infrastructure strategies) reflects the philosophy of how to influence travel decisions for the achievement of travel service quality, energy and environmental quality objectives.

A macroscopic simulation model was developed for the Transitway. A method was developed for the estimation of bus fuel consumption, based on ARFCOM model and

actual fuel consumption data. Fuel consumption for automobile travel was estimated by using existing model. For the calculation of HC, CO and NO_x emissions, a model was used based on MOBILE5c model. CO_2 emission estimates were obtained from fuel consumption and emission factor information.

The developed methodology is generally applicable to any urban transportation corridor. To illustrate the specific application of the developed methodology in this research, a corridor case study in the Regional Municipality of Ottawa-Carleton was implemented for 2011 conditions. The results achieved on optimal values of policy variables are logical. The methodology as well as results achieved are contended to be of much value to urban regions.

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AFMS	Advanced Fleet Management Systems
AMSS	Advanced Mobile Support Systems
APC	Automatic Passenger Counting
ARFCOM	ARRB Road Fuel Consumption Model
ARRB	Australian Road Research Board
ATIS	Advanced Traveller Information Systems
ATMS	Advanced Traffic Management Systems
AVCS	Advanced Vehicle Control Systems
AVI	Automatic Vehicle Identification
CAA	Canadian Automobile Association
CBD	Central Business District
EPA	Environmental Protection Agency
ETC	Electronic Toll Collection
ETTM	Electronic Toll and Traffic Management
FTP	Federal Test Procedure
HBW	Home-Based Work
HDDV	Heavy-Duty Diesel Vehicles
HOV	High Occupancy Vehicles
IC	Integrated Circuit
ITS	Intelligent Transportation Systems

LDGV	Light-Duty Gasoline Vehicles
LOS	Level of Service
MOE	Measures of Effectiveness
OC Transpo	Ottawa-Carleton Regional Transit Commission
O-D	Origin-Destination
RF	Radio Frequency
RMOC	Regional Municipality Ottawa-Carleton
SPSS	Statistical Package for Social Science
TDM	Transportation Demand Management
TRNSIM	Transitway Simulation Model
TSM	Transportation System Management
UTMS	Urban Transportation Modelling System
VKT	Vehicle Kilometer of Travel

CHAPTER 1

RESEARCH OBJECTIVES AND SCOPE

1.1 Background

Traffic congestion is an everyday occurrence in most metropolitan areas, particularly in commuting corridors. The delay, unreliability of travel time, increased fuel consumption and air pollution emissions that accompany congestion translate into significant economic and social problems in developed as well as developing countries [1,2]. In response to the growing recognition of these problems, efforts are underway to find solutions. For example, the Transportation Association of Canada published a briefing entitled "A New Vision for Urban Transportation" which calls for enhancing our knowledge base and taking action in thirteen subject areas [3]. Other literature sources also highlight the importance of public policy that encourages commuters to use public transit rather than private vehicles [4] and recommend priority research focussed on solutions to urban congestion, energy conservation and environmental problems [5].

Transportation of passengers and goods consumes a large fraction of the petroleum-based fuels used in Canada. Twenty-four percent of total energy consumption occurs in Ontario and almost 55% of Ontario's total energy use is expended in transportation. Sixty percent of the energy used by the transportation sector is consumed by the movement of passengers. Automobiles account for about half of this total.

Transportation produces 42% of all hydrocarbon and 63% of all nitrogen oxides emissions. Since automobiles generate considerable carbon monoxide and carbon dioxide, increasing automobile traffic is of great concern in local urban air-quality problems and consequently, in global environmental problems [6].

Due to increasing traffic congestion, inefficient use of energy and continuing air quality problems, there is a need to define strategies for improving the efficiency of transportation systems based on traffic and demand management and to investigate the effects of these strategies on traffic flow, the utilization of high occupancy vehicles (i.e., public transit, carpool, etc.), air quality and energy efficiency [7].

Research in congestion management (the management of both supply and demand to minimize congestion) has provided useful information on problems as well as prospects for improvement [8]. The supply side of transportation is becoming constrained by economic, social, and environment-related barriers [9]. Given the difficulties of expanding roadway capacity in urban areas, most efforts to relieve congestion during the past decade have centred on improving system usage through traffic control and on demand-side strategies. Fortunately, it is possible to make better use of existing facilities by changing the level and/or profile of demand for travel. Therefore, over the past twenty years, Transportation Demand Management (TDM) has become increasingly important to transportation experts for addressing a broad range of concerns including traffic congestion, air quality, energy efficiency, parking shortages, personal mobility, etc. [10].

The growing national problem of urban freeway and arterial congestion is receiving attention from transportation engineers, planners, researchers, policy makers, etc. Both demand-side measures (e.g., tolls) and supply-side innovations (e.g., public rapid transit, high occupancy vehicle lanes on freeway, and arterial and freeway traffic management) are being applied to this problem [11]. New technologies, such as the Electronic Toll and Traffic Management (ETTM) system , have the potential to relieve traffic congestion, reduce pollution, and increase vehicle safety [12].

The purpose of providing separate facilities and other incentives to public transit and

high occupancy vehicle users is to help maximize the person movement capacity of facilities at acceptable levels-of-service. This is accomplished by system design, operation and management initiatives. Public transit, carpools and vanpools are provided a travel time reduction, improved travel time reliability and predictability to encourage motorists to shift away from single occupant vehicles. The same objective can be achieved by freeway tolls and parking charge policies in the Central Business District (CBD).

Urban transportation modes need to be integrated to achieve better utilization of transportation facilities. Auto/bus integration has great potential to create broader social benefits by reducing congestion [13]. This, in turn, can produce other benefits such as reducing energy consumption and emissions. Figure 1.1 shows schematic sketch of an example for an urban transportation corridor which includes freeway, arterial and public rapid transit facilities serving travellers from their origins to destinations in an urban area by auto and bus. Finding the best use of an integrated multimodal corridor will improve utilization of transportation facilities, enhance mobility and resource conservation.

Road pricing and land use measures have been highly effective travel demand management strategies in reducing auto use and thus congestion, fuel consumption and air pollution emissions [14]. Demand management measures for the urban corridors to change the commuter's travel behaviour can include tolls for freeways, parking fees in areas of high demand (i.e., Central Business District) and fares for public transit. Parking charges, of course, reflect the parking supply situation. Congestion pricing is one of the important solutions that can reduce automobile use in urban areas [9]. Pricing policies can influence decision-making of the corridor's users in terms of mode and route choice [14].

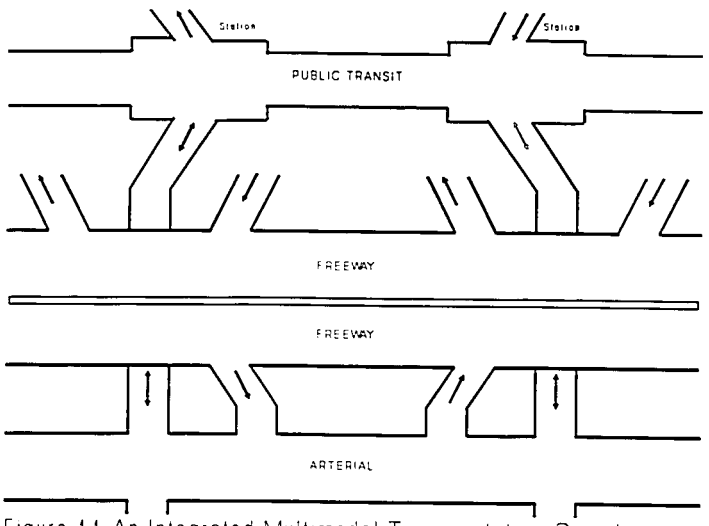


Figure 1.1-An Integrated Multimodal Transportation Corridor

Electronic Toll Collection (ETC) systems which monitor a vehicle's use of toll road electronically and automatically charge the user without the need for traffic-halting toll booths are operating around the world. Since ETC systems do not require the user of a freeway to stop or slow down for the payment of toll, road pricing policies are technically feasible [15].

Optimizing the use of existing (or planned) transportation facilities has been recommended as a policy goal by the Urban Transportation Council of the Transportation Association of Canada [3]. Corridor studies can be approached through a series of

analytic activities. These activities include the definition of study goals, the identification of problems and opportunities in the corridor, and the selection of alternative Transportation Management (TSM) actions. A review of literature indicates there is no prior study on the optimization of integrated multimodal urban corridors using demand management measures (i.e., tolls on freeway, parking charges in central area, public transit fare, etc.). Existing research work has largely been focused on integrated analysis and optimization of freeway and arterial system in major travel corridors. There is a need for a methodology that can lead to the optimal design and use of integrated multimodal urban corridors. Optimization can be achieved in terms of well-defined objective functions of travel time, fuel consumption and emissions. Such a methodology based on the principles of supply-demand interaction can provide a strong tool for planning optimally multimodal urban travel corridors.

Although specific objectives of this research are defined in Section 1.2, it is relevant to note major goals that can be achieved through this research:

- Management of travel demand and serving the resulting travel pattern in a most efficient manner, (e.g., reducing travel time)
- Increasing transportation system productivity, (e.g., increasing person throughput while maintaining an acceptable level of service)
- Reducing energy consumption (i.e., gasoline and diesel)
- Reducing air pollution emissions (i.e., NO_x, CO, HC and CO_2)

Some measures-of-effectiveness for the above goals and objectives are shown in the Table 1.1.

Table 1.1-Measures of effectiveness for various categories [16]

Category	MOE	Unit
Transportation system efficiency	changes in travel time*	minutes per person-km
	changes in speed*	kms per hour
	changes in delay*	seconds per person-km
	changes in cost of transportation**	dollars per person-km
Transportation system productivity	changes in VKT	vehicle kilometres per day
	changes in vehicle occupancy	occupants per vehicle
	changes person throughput	person volumes per hour
Energy	changes in fuel consumption	litres per person-km
Air quality	changes in HC,NO_x,CO and CO_2	kilograms per thousand person-kms

* These characterize level of service.
** For discussion purposes only. This MOE is not quantified in this research.

1.2 Research Objectives and Scope

The objectives of this research are to:

1. define the problem of optimizing major transportation corridors by using objective functions of interest (e.g., travel time, energy and emissions) and control variables drawn from current knowledge of demand management,
2. develop a methodology for corridor travel optimization, consisting of the overall framework and constituent components including demand, simulation, fuel consumption and optimization models,
3. apply the methodology to a major urban multi-modal corridor, and
4. draw conclusions and recommendation for use by policy analysts, planners and researchers.

The focus of this research is on the optimization of integrated multimodal travel corridors. One case study in the Regional Municipality of Ottawa-Carleton is implemented to demonstrate the application of the developed methodology. The control variables are based on demand management and advanced technology for electronic toll collection.

In the case study, pricing policy such as tolls are studied as a solution to freeway traffic congestion. It is assumed that there is no ramp metering (due to the assumption of tolls) for the freeway. The conventional concept of establishing the level of congestion toll is to estimate the marginal cost and the average variable cost during peak travel conditions. The difference between marginal and average variable cost of travel on a road network is regarded as the "congestion toll". In this research, the level of toll is to be established on the basis of optimizing the use of the integrated multimodal corridor.

While arterials can be controlled by available traffic control means, an ETC system for the freeway in the case study was assumed. The methodology of this research is based on implementation of ETC technologies [17].

It is expected that in response to carefully researched levels of toll for the use of freeway, parking charges in the central area and public transit fares, the following objectives of urban transportation can be achieved:

1. To improve average travel time and speed for urban travel corridors consisting of various supply alternatives (i.e., freeways, public rapid transit, etc.).
2. To reduce fuel consumption.
3. To reduce air pollution emissions (HC, NO_x, CO and CO_2).

In this research, in-vehicle travel time and total travel time (door-to-door) are both estimated. In-vehicle travel time is an important level of service variable that commuters

expect to be minimized. This objective can be responsive to planning and policy strategies and it reflects improvement in traffic conditions. On the other hand, total travel time includes out-of-vehicle time components, most of which cannot responsive to policy and planning actions. Thus, in this research, in-vehicle travel time was selected as an objective function and total travel time is estimated as an output for other application purpose. In this research, for obtaining effect of demand-side strategies on the objective functions, the supply side was assumed for transportation systems.

Although the scope of this research does not permit the incorporation of a land use model, the methodology has been designed so that it can be used in conjunction with any land use and socio-economic framework that can specify population, employment and car ownership for various zones/districts in an urbanized region.

1.3 Research Approach And Methodology

1.3.1 General Methodological Considerations

This research called for the development of a methodological framework for studying the optimal use of the corridor through the interaction of demand and supply. Figure 1.2 shows the major methodological steps. For given corridor system and origin-destination (O-D) demand, travel simulation models are required to estimate trips by each mode and route. For this purpose, trip generation, trip distribution, modal split and route split models were developed. Models were also required for the estimation of travel time, fuel consumption and emissions. An optimization methodology had to be developed to find the best combination of values of travel demand management variables, namely public transit fare, freeway toll, and parking charge.

System simulation is selected as an appropriate technique for solving problems which

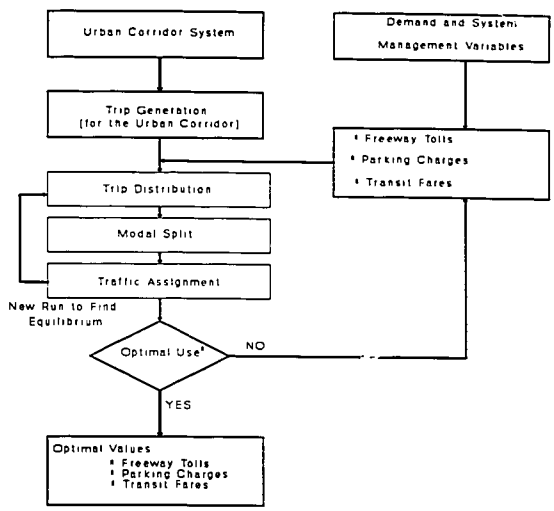


Figure 1.2-The Major Methodological Steps

require the study of results of changes over time. Simulation of vehicular traffic on roadways has been a natural application of computer modelling since the early stages of digital computation. By using computer simulation, a number of strategies can be tested and evaluated at low cost. The traffic environment is complex and stochastic in nature. Traffic simulation models are computer programs that are designed to represent realistically the behaviour of the physical system.

Thus, one of the most important analytical tools in transportation is computer simulation. If a traffic system is simulated on a computer by means of a simulation model, it is possible to predict the effect of planning and operational strategies on the system's performance [18]. The measures of effectiveness (MOE) can be studied and

related to the strategies. Simulation models can be classified as either microscopic or macroscopic in design. Microscopic models describe the detailed, time-varying trajectories of individual vehicles in the traffic stream. Macroscopic models represent the traffic stream in an aggregate form. Macroscopic analysis of traffic stream flow requires estimation of three basic variables (i.e., density, speed and flow rate) on every point of the roadway at all times during the analysis period. From these variables the measures of effectiveness (e.g., travel time, delay, etc.) can be derived. Inputs to models include known attributes of the system such as the geometric features of each link (i.e., length and number of lanes). In this research, macroscopic approach was selected. This approach is most appropriate to study steady-state phenomenon of flow and therefore best describes the overall operational efficiency of the system [19]. These output values are measures of effectiveness (MOE) that describe the operational performance of traffic on each link (i.e., freeways, arterials and Transitway) of the analysis network. Representative MOEs include vehicle kilometres, vehicle hours, speed, delay, density, fuel consumption and vehicle emissions.

1.3.2 Methodological Framework

Figure 1.3 shows the overall research methodologies. Major methodological steps of this research include:

- Definition of corridor system options and their characteristics
- Determination of travel cost variables
- Initial estimation of level of service variables (e.g., travel time)
- Study of O-D demand for peak period travel condition and developing models for the estimation of travel demand

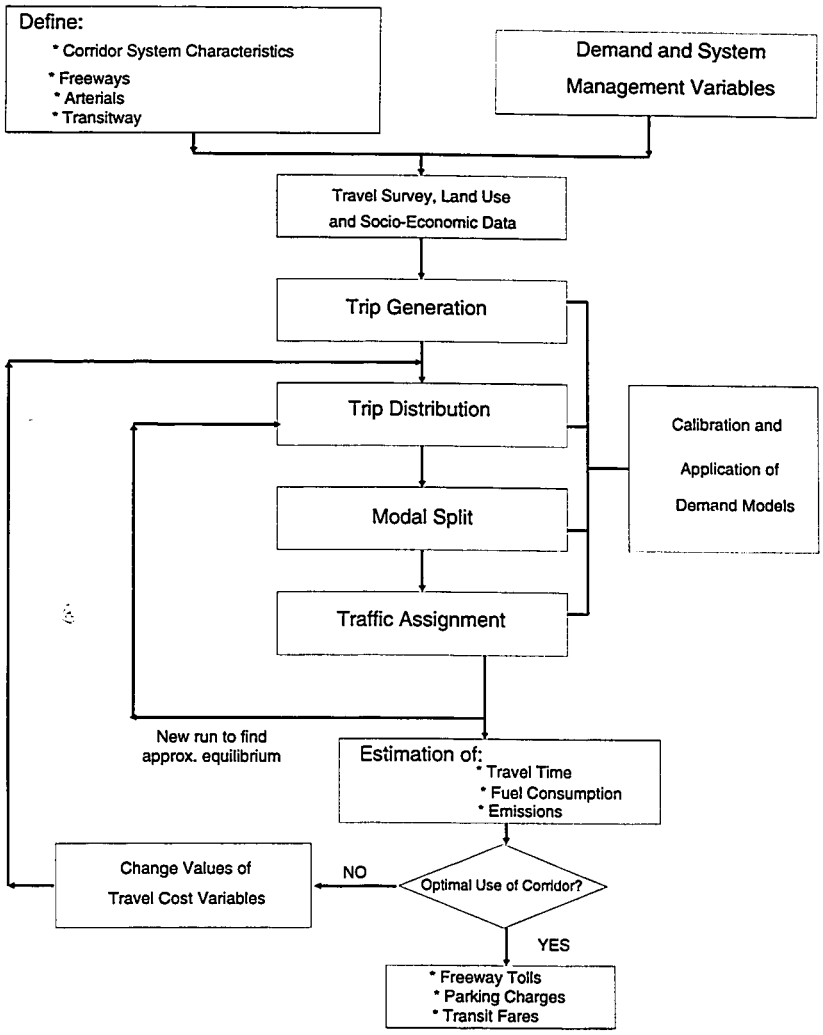


Figure 1.3-The Overall Research Methodology

- Development of a modal split model and its application for the estimation of travel by various modes (i.e., automobile and public transit)
- Traffic assignment based on calibrated road and transit networks to estimate level of service variables
- Re-estimation of modal demand by using new simulated level of service variables (e.g., travel time) in order to find equilibrium
- Estimation of (a) travel time, (b) fuel consumption and (c) emissions
- Development of an optimization methodology and application of the optimization methodology for the establishment of the best values for freeway tolls, parking charges and transit fares in an urban corridor

For expressing both system supply and demand in terms of the same optimization variables (i.e., freeway tolls, parking charge in central area and public transit fare), the other system performance measures are computed in such a way that they automatically adjust to the travel demand for the system. These computed values of the system performance measures are then fed back again into the travel demand models, thus allowing more interaction between the demand and system performance. This feedback process continues until approximate equilibrium between supply and demand is achieved.

In this research, the Urban Transportation Modelling System (UTMS) was used to predict interzonal trips. For developing the urban travel models, EMME/2 (i.e., a computer program) was used to provide an acceptable framework for implementation of many different modelling procedures [20,21].

Investigation of the Transitway was one of the important parts of the case study in this research. There are a number of factors which affect the operation of the Transitway. A macroscopic simulation model was developed for this purpose to investigate changes

of in-vehicle travel time, energy and emissions on the Transitway.

For estimation of fuel consumption by road vehicles in urban networks (e.g., automobile), INRO Consultants developed an EMME/2 macro [22,23].

A review of literature did not reveal suitable analytical methods or results of specific test for the estimation of fuel consumption of buses on the Transitway. A number of heavy vehicle (i.e., various trucks) fuel consumption models have been developed. One of these models used is ARFCOM (ARRB Road Fuel Consumption Model) for the estimation of fuel consumption [24]. In this research, the ARFCOM was modified to include the bus fuel consumption estimation capability for each of the four modes of driving, namely acceleration, cruise, deceleration and idle in order to estimate fuel consumption on the Transitway.

Therefore, by using the INRO model and the modified ARFCOM for bus operation on the Transitway (developed in this research), fuel consumption was estimated for the integrated multimodal corridors.

INRO Consultants developed an EMME/2 macro based on MOBILE5c which is used for the estimation of emissions. This macro calculates emissions for the three regulated pollutants, namely hydrocarbon (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x) for various types of vehicles. This macro was used to estimate HC, CO and NO_x emissions [22,23]. Carbon dioxide (CO_2) emissions were estimated from fuel consumption and emission factor information [26]. For the estimation of in-vehicle travel time, fuel consumption and emissions per pass-km, a methodology was required which can integrate results of models for Transitway simulation, fuel consumption, and emissions in EMME/2 framework.

Many demand and traffic management strategies affect the mode and route choice of

trip makers. For investigating such strategies, trip distribution, modal split and route choice models had to be defined and calibrated for an urban travel corridor encompassing Transitway, freeway and arterial.

There was a need to develop a methodology for optimizing the use of the corridor, based on travel time, fuel efficiency and emissions in response to change in tolls on the freeway, parking charges and transit fares. The optimization methodology involves modelling in terms of the variables of demand management (i.e., public transit fare, parking fee and freeway toll). The choice of an optimization criterion is important since it reflects policy considerations. The objective functions used include minimizing in-vehicle travel time, fuel consumption and emissions (HC, CO, NO_x and CO_2) per pass-km. The optimization methodology, which can be applied to identify the optimal system, is the direct search method that finds the optimal value of the optimization variables for minimization of the objective function.

Thus, the basic approach of this research was to develop a set of methods which, when working together and in conjunction with available transportation analysis techniques, enabled the optimization of integrated multimodal urban travel corridors.

1.4 Highlights of Methodological Requirements

A review of literature indicates the absence of research in the optimal use of integrated multimodal urban transportation corridors. Existing research work has largely been focused on integrated analysis and optimization of freeways and arterials in corridors. Even for such analysis and optimization works, the important objectives of minimization of fuel consumption and emissions were not attempted.

Methodological innovations are required in this research:

- an optimization methodology for establishing the best combination of control variables for minimizing a selected objective function
- a supply-demand interaction methodology to investigate the effect of combination of values of pricing policy variables (i.e., toll, parking charge for auto and fare for public transit) in an urban travel corridor
- a demand modelling framework for the estimation of modal demand based on changing values of pricing policy variables
- macroscopic simulation models including the Transitway simulation model
- model for the estimation of fuel consumption
- models for the estimation of emissions

Although available models and techniques were incorporated in the overall methodological framework, new models are to be developed as well. A description of the original contributions of this research is presented as a part of conclusions (Chapter 9).

1.5 Thesis Organization

Chapters 2 to 8 follow this description of research objectives and scope. Chapter 2 explains the approach to urban travel demand modelling and how to develop and use the models. Chapter 3 represents the components of the Transitway and the development of a simulation model. Chapter 4 discusses the estimation of fuel consumption for the system and explains the modification of a method to estimate fuel consumption for buses. Chapter 5 contains a description of how to estimate air pollution emissions in this research. Chapter 6 covers an optimization methodology for a transport system serving an urban corridor. Chapter 7 presents a case study which demonstrates the application

of the methodological framework. Conclusions and recommendations can be found in Chapter 8, followed by references and appendices. Appendix A contains results of the demand model calibration. Appendix B includes the simulation model computer program and some results of this model. Finally, Appendix C contains more details and results of the modified model for the estimation of bus fuel consumption.

CHAPTER 2

THE URBAN CORRIDOR TRAVEL DEMAND MODELLING

2.1 Modelling Requirements

Demand forecasting is an essential part in the analysis of transportation systems [27]. Depending on the objectives for the modelling system, the demand forecast framework may be required to provide different levels of detail about resources and other transportation variables. For example, forecasting demand for the long term planning of land-use transportation systems requires macro-level estimates of travel [28]. On the other hand, the modelling of air quality requires detailed simulation of the transportation systems [29].

Since this research combines congestion management, energy and environmental factors, the demand models have to satisfy the following requirements that go beyond air quality studies:

1. Multimodal models are required to treat the private and public modes of travel. Car (auto driver), carpool (auto passenger) and bus transit (transit passenger) have to be modelled in an interactive fashion.
2. For multimodal travel, the models should incorporate necessary variables in order to test the influence of policy, system, or exogenous factors on travel behaviour. For instance, in the absence of price and service variables, the model cannot be used to test the influence of effects of transit fares, parking charges, congestion and tolls on changes in multimodal travel.
3. The models should be based on behavioral theories of travel demand. That is, to

the extent feasible, the models should have the power to explain the response of the modal and intermodal travel markets to system and pricing policy changes. The model structure and detailed specifications in terms of variables and functions should have policy relevance and reflect traveller behaviour in travel decision-making.

4. The models should be unbiased. That is, in addition to a strong behavioral theory base, the models should be based on econometric principles in terms of their specification and calibration. In practical terms, inaccurately measured input data and multi-collinearity of independent variables should be avoided.

The practical implications of the above requirements can be dealt with in the following forms:

- Subject to the availability of data, the demand for travel should be modelled for a number of adjacent periods, and inter-period elasticities should be investigated. The travel demand models should be calibrated with actual origin-destination data based on behavioral factors.
- Following successful calibration, the models should yield detailed link-route level demand by mode. For service quality, energy and emission studies, operating speed of vehicles at the link/route level should be obtained through appropriate models.
- The service variables for auto travel should reflect the level of congestion on arterials and freeways since the level of congestion influences mode and route choice decisions. In order to meet this requirement, detailed simulation models have to be used to study travel times. Only through such detailed and accurate input information, can the calibrated models provide realistic estimates of travel on a link/route level.

- The service variables for bus rapid transit should be modelled so that there is sensitivity to passenger and bus activity. This can be achieved if a simulation model is used to estimate performance of the bus transit system rather than relying on the use of average values.

Research studies on policy development and modelling have identified areas of improvement in modelling travel demand [29,30]. According to a review of literature, the direct demand models are complex mathematical formulations and have not received broad acceptance among transportation planners and engineers. Many transportation planners believe that direct demand models are difficult to develop and apply successfully [31].

Most transportation planning studies use the Urban Transportation Modelling System (UTMS) for predicting interzonal trips. The UTMS in its conventional four-step form was used for demand forecasting in the analysis of transportation system in this research. For developing the urban travel demand models, EMME/2 was used for providing an acceptable framework for implementation of many different modelling procedures [20,21].

In the following sections, the process of specifying demand model structure and calibration is described.

2.2 The Urban Transportation Modelling System

A model incorporating transport system and socio-economic variables can be used to predict travel demand. In the demand estimation study, the starting point is the D^p_{ij}, travel demand for purpose p between zones i and j. For a base year, the D^p_{ij} data are obtained from an origin-destination survey. Future forecasts of D^p_{ij} can be obtained through the use of a calibrated demand model. In such a case, D^p_{ijt} is the number of trips during a given period (e.g., peak period) of time t for purpose p, from origin i to

destination j. The demand can be expressed in terms of person-trips per hour.

The Urban Transportation Modelling System (UTMS) is a system of models to predict the number of interzonal trips generated and distributed within an urban area by type of modes on various roads during a specific period of time. The UTMS is composed of four major steps including trip generation, trip distribution, modal split and trip assignment. Figure 2.1 shows the UTMS framework [32]. The steps are described below [32,33]:

- Trip generation: This stage estimates the number of trips which are produced by and attracted to each zone based on land use characteristics of each zone.
- Trip distribution: This step distributes trips generated in each zone among various destination zones.
- Modal split: This step estimates the percentage of the origin-destination flows for each available mode of travel (e.g., auto, transit, etc.).
- Traffic assignment: This stage predicts the origin-destination flows for various modes on routes.

For calibration and implementation of urban transportation models, it is necessary to use a computerized modelling framework such as EMME/2 and QRS II due to time consuming and iterative nature of computations. EMME/2 is one these programs which is used by most transportation planners for travel analysis and forecasting purposes. It consists of a set of approaches that permits transportation planners to develop and apply urban travel models. As a framework, it can support different modelling approaches. For this work, EMME/2 provides an acceptable framework for travel demand forecasting [20,21].

For developing the demand models, results of the latest available comprehensive origin-destination survey (1986) were obtained from the Regional Municipality of Ottawa-

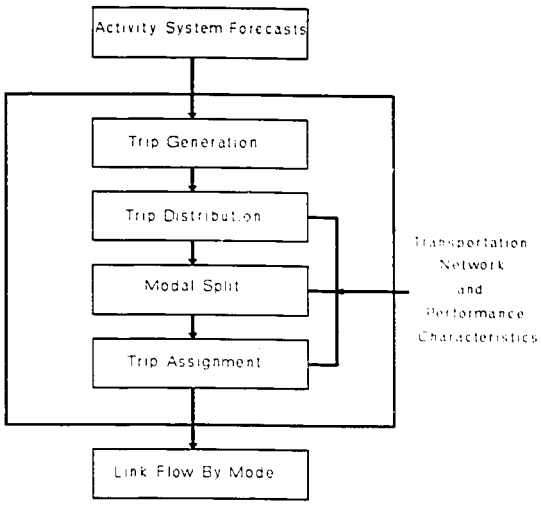


Figure 2.1- Urban Transportation Modelling System Framework

Carleton (RMOC). Although, the result of 1995/96 origin-destination survey was available in July 1996, these data did not include travel cost components (e.g., parking cost, fare) for 258 zones system at that time. Thus, it cannot be used in model calibration.

2.2.1 Trip Generation

The first step of the travel demand forecasting predicts the number of trips produced by origin zones and attracted to destination zones. This step is for establishing a relationship between land use, socio-economic and travel characteristics of an area

[32,33]. Trip generation usually relates to land use activities such as population and employment. There are two types of trip-generation analyses which include trip productions and trip attractions.

For calibration of trip generation equations, results of the 1986 O-D survey were used. The transportation planning division of the RMOC uses a 258-traffic zone system which covers the entire urbanized region.

Trip generation is usually based on daily or peak-period basis [32]. In this research, for developing trip generation equations, results of O-D survey for p.m. peak period were used instead of the 24 hour period. Using peak period rates permitted the observed data to be analyzed directly. For instance, the work-to-home trips in the p.m. peak period are separated from the home-to-work trips in the a.m. peak period. In comparison, if 24 hour trip generation rates are used the derivation of a directional factor for the peak period will be required. The use of peak period rates allows a more direct representation of the effect of demand management measures on level of service of transportation facilities. Also, the transit and road networks can be tested by peak period distribution instead of 24-hour distribution. For some urban areas, recent O-D surveys were limited to peak period travel [34].

For the reasons noted, this study deals only with trips made in the afternoon peak period which would be defined adequately by a 2.5 hour duration [34]. Thus, all the necessary input data for analyses such as observed origin-destination person-trips, travel time, etc. correspond to that period of time. Due to limitation of origin-destination data, it was not possible to study demand on the basis of sub-periods within the peak period.

Two types of trips were defined in this research. The first type is home-based work (HBW) trips (i.e., trips that have one end at home and the other one at work). From the central area, most trips are home-based work trips during p.m. peak period. The second

type is non-work trips including home-based non-work and non-home-based trips.

Regression analysis was used for developing trip generation equations [34]. The Statistical Package for Social Science (SPSS), a statistical software package under Unix, was used for the estimation of the unknown coefficients [35].

Land use and socio-economic data for 1986 were provided by the RMOC according to the 258-zone system:

- Population (total, 0-4 years, 5-14 years, 15-24 years, 25-44 years, 45-64 years, 65 and more)
- Dwelling Units
- Employment (total, retail, other)
- School Enrollment (secondary, post-secondary)
- Shopping Center Gross Leasable Area (GLA)
- Average Zonal Vehicles/Household
- Hospital Beds

The trip generation model includes trip production and trip attraction equations. For work and non-work trips, several equations were developed for p.m. peak period. It should be noted that the relationship between trip generation and independent variables (e.g., population, employment, etc.) must be causal and logical. For instance, employment is an important variable used for a.m. attractions and p.m. productions of work trips during peak period [34]. Regression equations for predicting non-work and work trip productions and attractions during p.m. peak period are as shown next (Appendix A for more details):

- Non-work trips (p.m. peak period)

$$P_{i_{pm}} = 0.1346\ pop + 0.2897\ emp + 0.0043\ GLA + 209 \quad (R^2=0.76) \tag{2.1}$$

$$A_{j_{pm}} = 0.0888\ emp + 0.6204\ DWEL + 0.0045\ GLA + 221 \quad (R^2=0.80) \tag{2.2}$$

- Work trips (p.m. peak period)

$$P_{i_{pm}} = 0.4572\ emp - 138 \quad (R^2=0.87) \tag{2.3}$$

$$A_{j_{pm}} = 0.1848\ pop + 9 \quad (R^2=0.90) \tag{2.4}$$

where

P : Production

A : Attraction

pop : Total Population

emp : Total Employment

GLA : Shopping Center Gross Leasable Area (ft^2)

DWEL: Dwelling Units

As mentioned earlier, non-work trips include home-based non-work and non-home-based trips. There are common variables between two type of non-work trip equations which were selected taking into consideration previous studies in the Regional Municipality Ottawa-Carleton [34].

According to the above equations, changes to the network are assumed to have no effects on trip productions and attractions. For solving this problem, some transportation

planners have tried to incorporate a measure of accessibility into trip generation equations. The following equation can represent typical accessibility measures in general form [36]:

$$Acc_i = \sum_j^n f\,(\,E_j\,,\,c_{ij}\,) \tag{2.5}$$

where

Acc_i : accessibility of zone i

E_j : a measure of attraction of zone j

c_{ij} : the generalized cost of travel between zones i and j

Most times, this procedure has not produced the expected results because the estimated parameters of the accessibility variable have been non-significant or contained wrong sign [36].

An accessibility measure was tested after calibration of trip distribution model for developing trip production equations in this study. The following equation was used for the estimation of Acc_i for use in the work trip generation (i.e., production) model.

$$Acc_i = \sum_j^n [\exp(-\beta_a\,T_a\,) + \exp(-\beta_t\,T_t\,)]_{ij}\,A_j \tag{2.6}$$

where

β_a,β_t : calibrated parameters from the gravity model, 0.110 and 0.041, respectively

T_a,T_t : auto and transit travel times, respectively

A_j : trip attraction

Table 2.1- The conversion of 258 traffic zones to 23 districts

District	Traffic Zones
1	1-3 , 11-21
2	4-10 , 22-25 , 201
3	90-98 , 100
4	68-89
5	99 , 101-109
6	26-45 , 57 , 58
7	59-67
8	46-56
9	120-124
10	135-138 , 221-226
11	110 , 142-143 , 202 , 204 , 234-237 , 246-247
12	144-145 , 203 , 238-244
13	139 , 141 , 230-231 , 245
14	111-119 , 140 , 205 , 227-229 , 232-233
15	125-128
16	156 , 157 , 162 , 165-181 , 185 , 248-253
17	125-128
18	146-155 , 158-161 , 163-164 , 182-184 , 186-187 , 254-258
19	129-131 , 206-220
20	188-189
21	190-191 , 193-194
22	192 , 195-197 , 200
23	198-199

The result obtained following the use of the new variable shows that the estimated parameter (i.e., accessibility) has a negative sign. This is an illogical (i.e., wrong) sign for this variable in trip production equation. Therefore, it was decided that trip generation

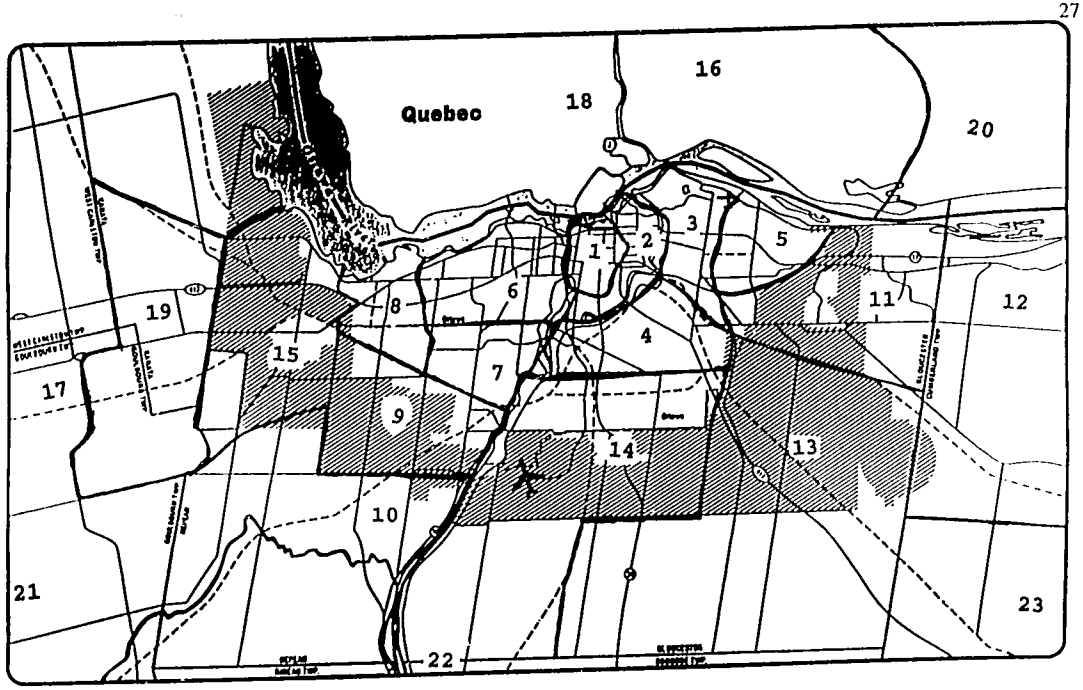


Figure 2.2- District Systems

equations should remain as a function of land use variables in this research and no network impedance variable should be included in regression equations.

For comparison the observed data and the results of the trip generation model, the 258-zone system is aggregated into a 23-district system (Table 2.1 and Figure 2.2). Districts 20-23 are external to the coverage area for the National Capital Region. In this research, District 1 is considered as the central area.

Table 2.2 shows a comparison between observed and simulated trip productions and attractions for total trips during afternoon peak period. With regard to different types of equations for trip generation (i.e., trip productions and trip attractions), it is not expected that the estimated total trip productions are equal to the total trip attractions. Therefore, it is necessary to balance trip attractions against trip productions in the model's result by holding trip productions constant and adjusting trip attractions.

2.2.2 Trip Distribution

The trip distribution model is for the distribution of total trips produced by and attracted to each zone in the area of study. Trip distribution matrices have to satisfy the following constraint equations [33]:

- The trip production constraint

$$P_i = \sum_{j=1}^{n} t_{ij} \qquad (2.7.1)$$

- The trip attraction constraint

Table 2.2-The simulated versus observed person trips (p.m. peak period)

district	Observed		Simulated	
	Production	Attraction	Production	Attraction
1	76341	30450	80440	36278
2	45658	27492	37162	26357
3	27917	30105	28460	33148
4	47357	41195	44857	37356
5	13742	18255	13566	17466
6	54284	48711	50475	47310
7	22594	24491	21718	21036
8	17100	28444	21101	29294
9	9969	13879	9811	11410
10	7315	13499	8414	13859
11	15357	27418	14421	22890
12	5046	11912	6546	13203
13	3447	6928	5924	7293
14	13311	20806	21132	24327
15	12857	10167	12101	8944
16	29923	44351	38171	53961
17	4028	9340	5676	9832
18	55141	51812	54992	57946
19	14600	19074	15377	18833
20	539	288	418	357
21	1938	833	836	713
22	827	392	1045	891
23	1137	586	418	357
Total	480428	480428	493061	493061

$$A_j = \sum_{i=1}^{n} t_{ij} \tag{2.7.2}$$

where

P_i : the number of trips produced in zone i based on land use allocation

A_j : the number of trips attracted to zone j

t_{ij} : the number of trips produced in zone i and attracted to zone j

Several trip distribution model types can be developed, such as the Frater method, the opportunities model and the gravity model [19]. Here, the gravity model approach is used.

The gravity model is based on the assumption that the number of trips between a pair of zones is directly related to activities in the zones, and inversely related to impedance (e.g., travel time, distance, etc.) between zones [32,33]. It is the most common model used for achieving the trip distribution. A typical formulation of the gravity model which is used in transportation planning is as follows [32]:

$$T_{ij} = \alpha\, P_i\, A_j\, f\,(c_{ij}) \quad ; \alpha = 1/\sum_{j=1}^{n} A_j\, f\,(c_{ij}) \tag{2.8}$$

where

P_i : total number of trips produced in zone i

A_j : total number of trips attracted to zone j

$f(c_{ij})$: friction factor

The friction factor between zones i and j is an inverse of cost function such as travel time, distance, etc. In the gravity model, travel time is usually used as a friction factor

which can take several forms, such as [36]:

$$f_{ij} = c_{ij}^{-\beta} \tag{2.9.1}$$

$$f_{ij} = \exp\ (-\beta c_{ij}) \tag{2.9.2}$$

$$f_{ij} = c_{ij}^{\beta} \exp(-\beta c_{ij}) \tag{2.9.3}$$

The purpose of the calibration procedure is to express the relationship between f_{ij} and c_{ij} and the determination of value of parameter β which enables the model to best fit observed data for area of the study.

Although, the gravity model does not provide a strong theoretical explanation of travel behaviour, it is the most common model among trip distribution models [19,34]. It has been stated already that EMME/2 was selected as a framework in this research. EMME/2 can use the gravity model for the estimation of trip interchanges between each pair of zones.

For satisfaction of the constrain equations (Equations 2.7.1-2.7.2), two set of balancing factors (i.e., doubly constrained) α_i and β_j are used as follows:

$$T_{ij} = \alpha_i\ P_i\ \beta_j\ A_j\ f(c_{ij}) \tag{2.10}$$

where

$$\alpha_i = \frac{1}{\sum_j \beta_j A_j f(c_{ij})}$$

$$\beta_j = \frac{1}{\sum_i \alpha_i P_i f(c_{ij})}$$

The balancing factors are not independent, this means that the estimation of one set needs the values of the other set.

A review of previous studies, indicates that the impedance functions used in the previous gravity models in the region, were an exponential function of impedance (i.e., travel time). The following equation, consisting of exponential functions of auto and transit times, was suggested in the literature [34].

$$e^{-\beta_a T_a} + e^{-\beta_t T_t} \qquad (2.11)$$

Where T_a and T_t are travel times for auto and transit, respectively. This function shows that in addition to automobile travel time, transit travel time can be incorporated explicitly in the travel demand modelling as well as auto travel time. A previous study suggests different values of β_a and β_t for different part of the region in the case of work trips [34]. Thus, it was decided to calibrate new gravity models for two type of trips (i.e., work and non-work trips) in this research.

The impedance functions of the gravity model were calibrated by using EMME/2 software through an iterative process. The observed distribution of trip length frequency was compared with the gravity model simulated frequency. Also, the shape and position of both curves (i.e., the observed and simulated trip-length-frequency distributions) and the difference between the average trip lengths were studied according to the standard

practice [33,36].

Initial parameters (β_a and β_t) were assumed and EMME/2 was run in order to find the average trip lengths. The model was calibrated in terms of different value of β_a and β_t until the simulated and observed trip-length frequency distributions were as close as possible. The final results are shown below:

$$e^{(-0.110\ T_a)} + e^{(-0.041\ T_t)} \qquad \textit{for work trips} \tag{2.12}$$

$$e^{(-0.159\ T_a)} + e^{(-0.048\ T_t)} \qquad \textit{for non-work trips} \tag{2.13}$$

Where T_a and T_t are travel times for auto and transit, respectively. Figures 2.3-2.8 illustrate the observed and simulated results for trip length distributions. These are plotted as a function of impedance, auto travel time and transit travel time, respectively for work and non-work trips. The results of models show that the mean trip lengths were close together.

Table 2.3 shows the zonal aggregations at the screenlines between the observed O-D and simulated trips. These results indicate a good agreement for work trips. This result is important for this research since most trips are home-based-work trips leaving the central district during p.m. peak period. Due to a small number of non-work trips, their result is acceptable. Given the importance of trips from central district as major employment center during p.m. peak period, the observed total trips from Ottawa and Hull central area (District 1) to other residential areas (Figure 2.2) were compared with the

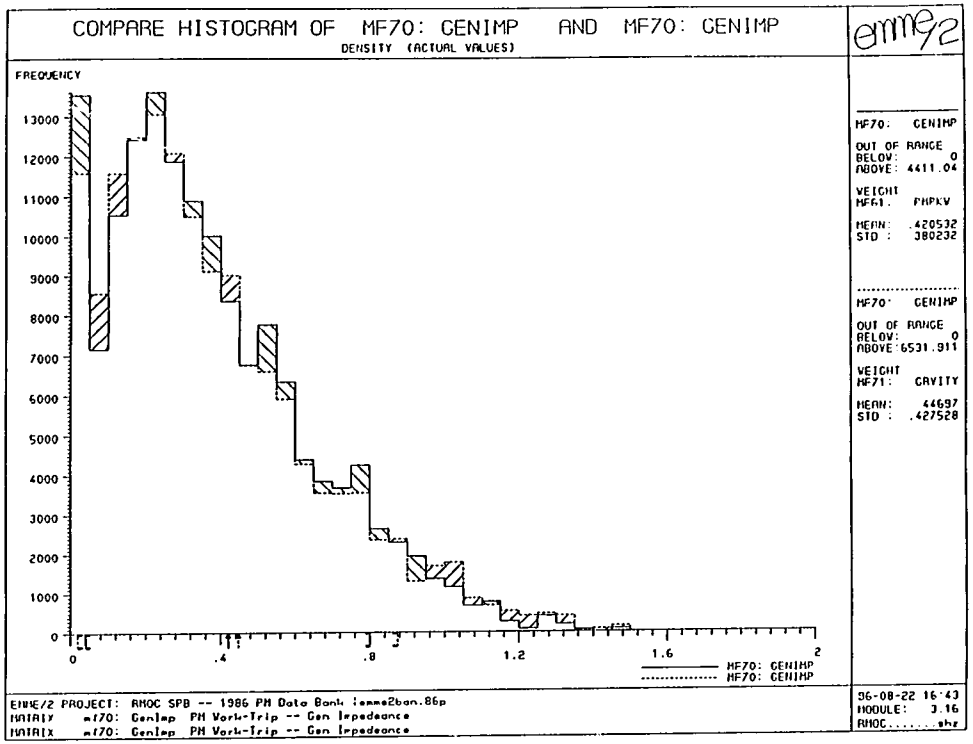


Figure 2.3- Work Trip Length Distribution (Impedances)

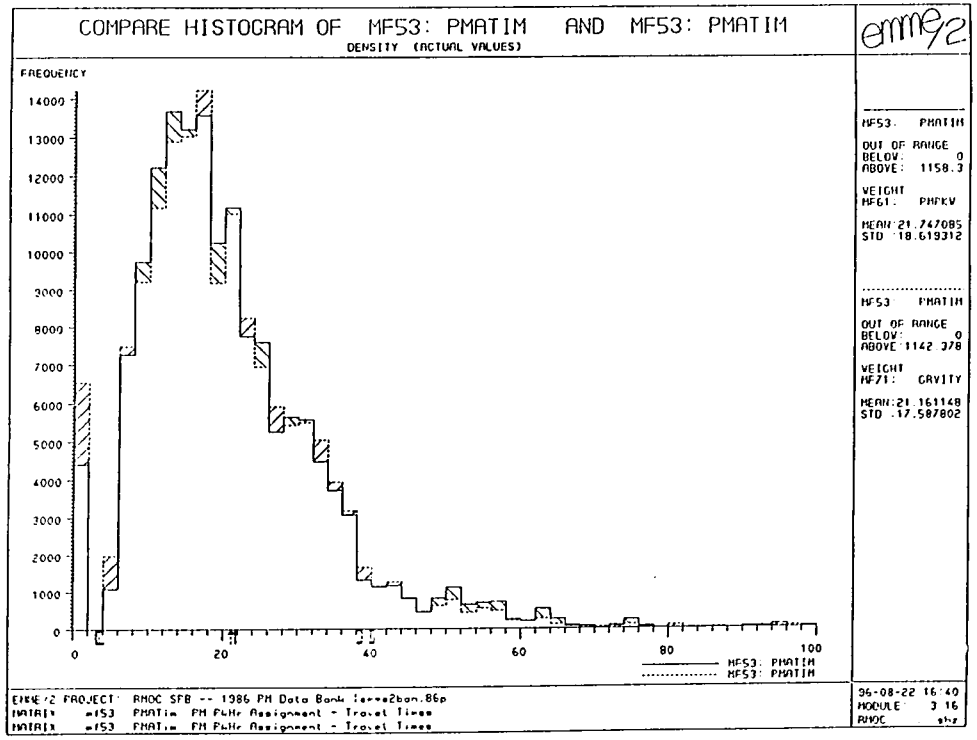


Figure 2.4- Work Trip Length Distribution (Auto Travel time)

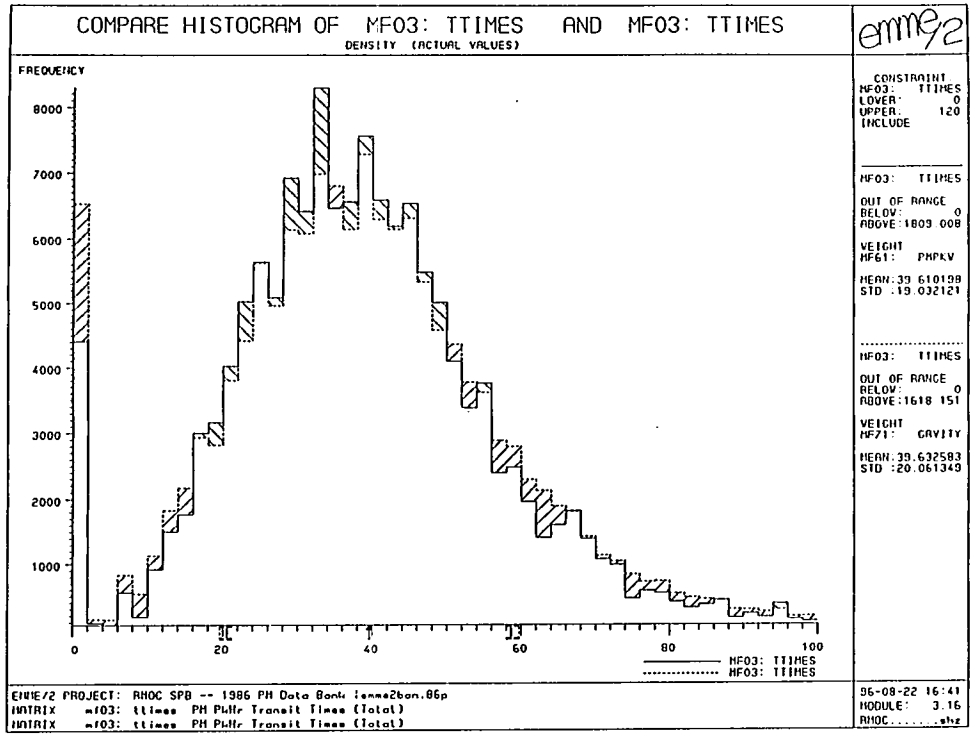


Figure 2.5- Work Trip Length Distribution (Bus Travel time)

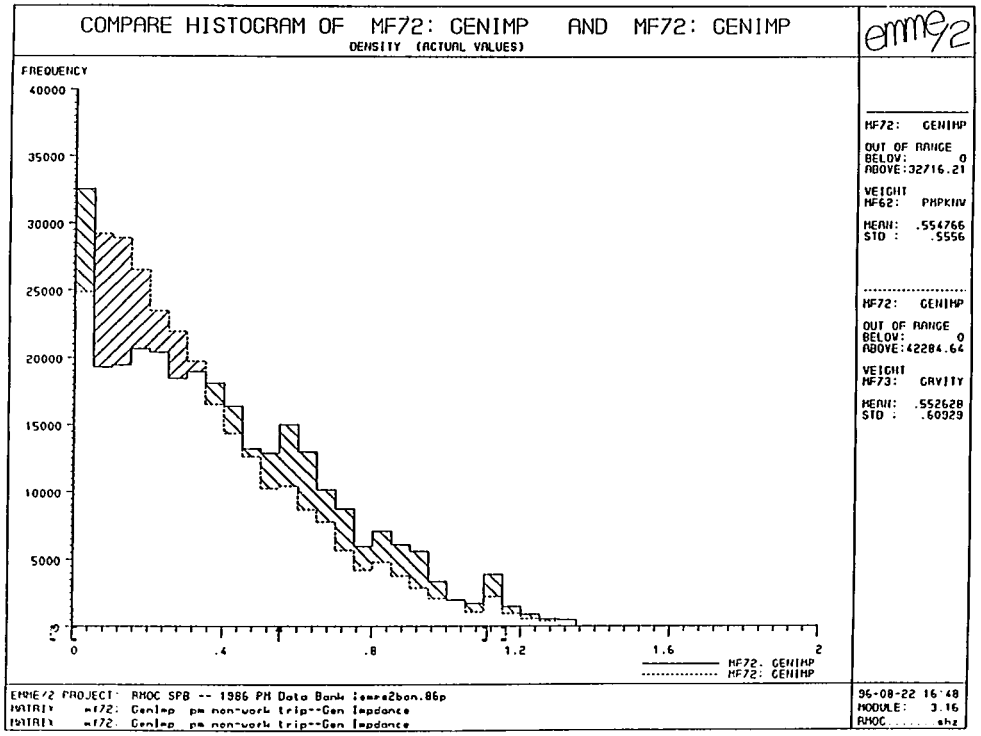


Figure 2.6- Non-Work Trip Length Distribution (Impedances)

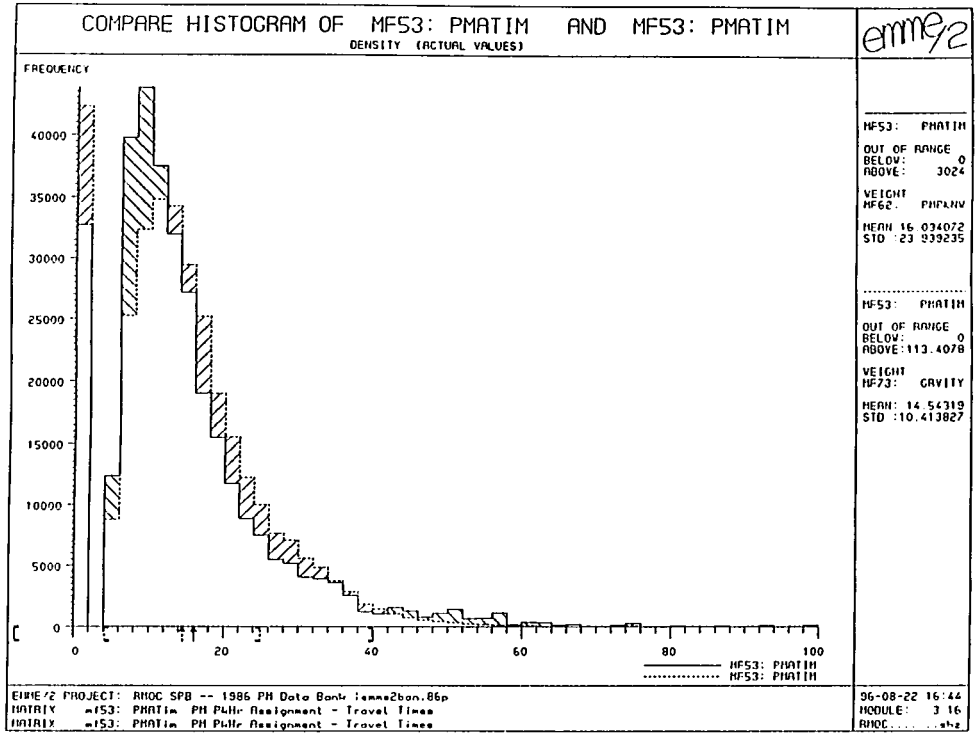


Figure 2.7- Non-Work Trip Length Distribution (Auto Travel time)

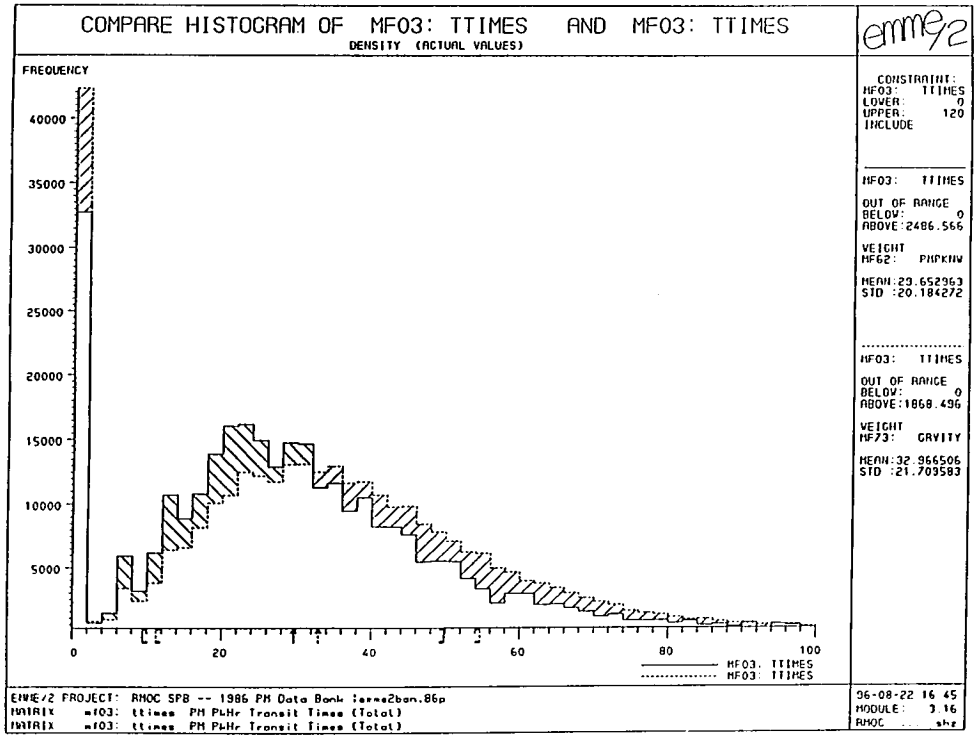


Figure 2.8- Non-Work Trip Length Distribution (Bus Travel time)

Table 2.3-Trip distribution results for the screenlines

Screenline	Work Trips		Non-Work Trips	
	Observed	Simulated	Observed	Simulated
Rideau River - IB	14934	14603	34462	40050
Rideau River - OB	39250	37722	42565	48358
CPR / Rideau River - IB	14719	14403	24344	32727
CPR / Rideau River - OB	30129	30471	33384	41419
Gatineau River - IB	2672	2246	7335	7312
Gatineau River - OB	11843	12637	11517	12270

simulated trips. There are 3% and 4% differences between the observed and simulated trips for work and non-work trips, respectively. However, the results suggest the general acceptability of goodness-of-fit of the distribution model.

2.2.3 Modal Split

The mode choice model predicts the person trips for various available travel modes. In this research, for work trips, a logit modal split formulation was employed that includes car (auto driver), carpool (auto passenger), and bus (transit passenger). The modal split model is based on individual level data (i.e., 3105 records based on interviews). Recently, the RMOC developed diversion curves to predict modal split for non-work trips during the afternoon peak period at three times the in-vehicle time. In this study, these equations were used for the estimation of mode choice for non-work trips which are based on the ratio of travel times of auto and transit.

2.2.3.1 Work Trip Modal Spilt Model

Travel behaviour analyses suggests that a deterministic model of mode choice may be limited in its replication of real life situations. Experience with travel demand modelling suggests that a stochastic model of mode choice is more suitable for explaining mode choice behaviour [37]. The assumptions and theoretical basis of such models are covered in the literature [27,36]. On the basis of theory and estimation considerations, the logit model is widely used by planners and researchers.

In order to justify the choice of the logit model, a brief introduction to model split model is in order. Modal split models can be developed using the aggregate approach (zonal level) or disaggregate behavioral approach (household/individual level). Each of these approaches may be further classified into several categories, as shown in Figure 2.9. The aggregate approach relies on statistical summaries (means, variance, etc.) of the attributes which are specified in terms of some aggregate characteristics of the socio-economics and transportation system [38,39]. The disaggregate approaches avoid the use of data represented at the zonal level and work at the basic level of the decision-maker. The disaggregate models are complex in terms of calibration and require special calibration procedures. Methods for developing disaggregate models include least square regression, diversion curves and probabilistic techniques.

Today probabilistic methods are used more than other methods for the calibration of disaggregate models. These models are developed by using probabilistic concepts in the sense that they assign a probability to each possible travel decision for a specific traveller and indicate a likelihood of certain events following as a result of certain causes.

There are various types of mathematical techniques which can be used to develop this type of model. These techniques consist of probit, discriminant and logit analyses. Discriminant analysis is not as satisfactory as others because it is both conceptually less

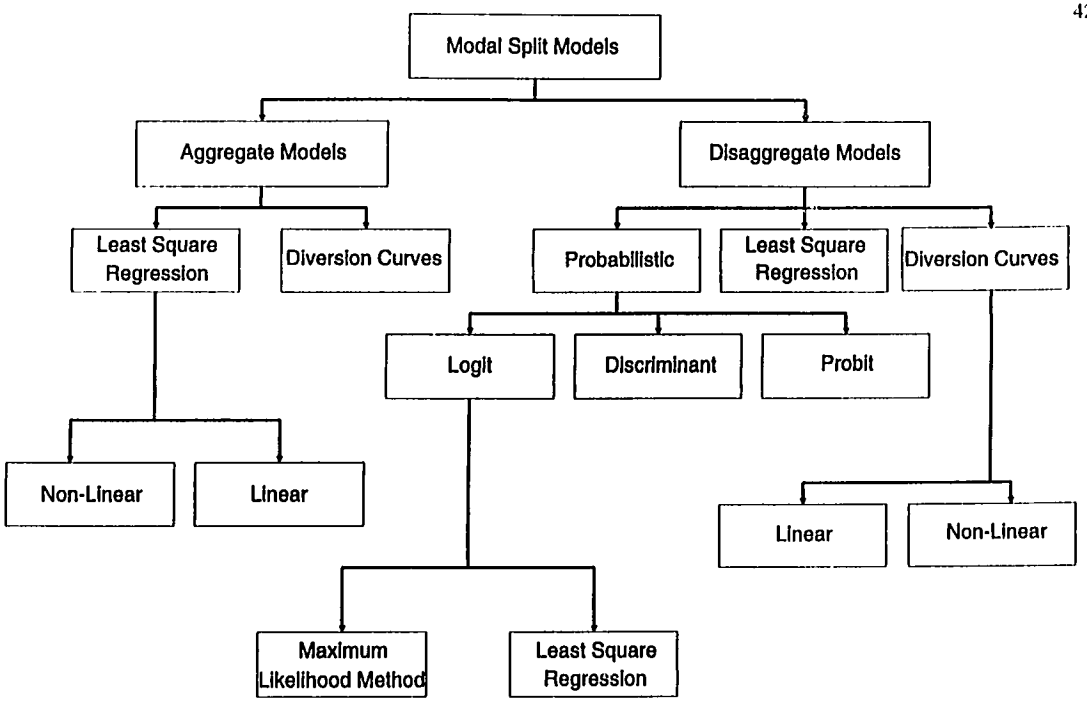


Figure 2.9- Classification of Modal Split Models

suitable and more restrictive in the case of logistic function. The probit and logit analyses are much more accurate for producing predictions. In general, the logit model is preferred, as it is an easier function to work with and the results are easier to interpret. In particular, the multinominal logit model is the most common form currently used. Based on the literature review, it can be observed that in comparison with the logit model, the probit and discriminant models do not appear to be attractive for building behavioral choice models [38,39,40]. Thus, the logit model has been chosen, as an appropriate tool, in this research for the development of modal split model.

A mode choice model can be calibrated for the prediction of mode, given an origin-destination pair. A multinominal logit model calculates the proportion of travellers that will select a specific mode according to the following relationship [37]:

$$p(m) = \frac{e^{U_m}}{\sum_{k=1}^{n} e^{U_{mk}}} \tag{2.14}$$

where p(m) is the probability that a traveller will use mode m and U_m and U_{mk} are the utility of modes m and mk to the traveller, respectively, and n is number of modes in consideration.

The logit model has several properties which can be suitable for the simulation of mode choice decisions such as [34]:

- the probability of choosing one mode depends on its utility relative to the utilities of other available modes
- the probability of choosing a mode increases with an increase in that models utility

- the probability of choosing one mode increases, when the utility of any other mode decreases, and vice-versa
- logit models are able to simulate decisions covering any number of modes

As noted earlier, due to data limitations, three modes are represented in the logit modal split model: car, carpool and bus.

The utility functions used in the logit model are defined as the linear weighted sum of the independent variables or their transformation. That is (omitting the error term) [18]:

$$U = \lambda + \delta_1 Y_1 + \delta_2 Y_2 + \ldots + \delta_n Y_n \qquad (2.15)$$

Where U is the utility derived from a choice defined by the magnitudes of the attributes Y that are represented in that choice and that are weighted by the model constant parameters λ and δ_1, δ_2, ..., etc.

The utility function for each mode involves a linear combination of the explanatory variables that represent socio-economic and transportation system characteristics. For a given traveller, mode choice decisions are known to be affected by travel cost and time [41]. In most real-world decisions, there are many attributes of relevance to each decision maker, and it is very rare to find an alternative that is dominant over all attributes [40]. A number of other factors such as comfort, privacy, etc. may play a role in mode selection due to the fact that either these variables cannot be treated as policy and planning factors or there is a lack of data. Here, travel time, travel cost and car ownership are used for model calibration.

Each mode can be represented by its attributes, such as travel time, travel cost, etc. Travel cost, an important factor, is usually broken down into two components. One is

vehicle cost, and the other is out-of-vehicle cost. Vehicle cost refers to the fare paid on a public transportation mode and the perceived vehicle operating cost for private automobile. The out-of-vehicle cost would include other costs associated with the use of mode, such as automobile parking charges. According to another definition, out-of pocket costs can be defined as monies actually spent during the journey and paid directly as opposed to costs that may be perceived but not paid directly during the journey. According to the literature, the out-of-pocket costs are perceived differently by trip makers than other costs.

In this research, fare is regarded as a user cost variable for bus users. The travel cost for auto user includes operating cost (i.e., fuel) and variable cost such as parking fees and tolls (if applicable). Therefore, travel cost for automobile can be expressed in terms of operating cost, parking charge and toll charge.

In this research, transit bus and auto (including car and carpool) serve travel demand in the corridor. Buses use local, collector and arterial roads for collection-distribution and the Transitway for line haul functions. Autos can use the freeway or arterial roads. The performance of routes under traffic loads has to be estimated in a detailed fashion since this information is fed back to trip distribution, modal split and route split models. Although in this research, a bus rapid transit is used, in theory, other modes (i.e., Light Rail Transit (LRT)) can also be included to carry people from their origin to destination in an urban corridor. For each mode, there is a need for a model to estimate performance, which is necessary for analyzing an urban corridor (i.e., travel time).

The calibration process of choice models consists of estimating the parameter values and evaluating the statistical significance of the estimates. These steps are usually carried out simultaneously as a statistical process of estimation.

For the logit modal split model calibration, computer-based model estimation software

developed by Professor Eric J. Miller, University of Toronto, was used. This software includes two computer programs (SETUP.F and LOGIT.F). The programs are written in Fortran 77 and operate on a Unix Workstation. "The LOGIT.F program (Version 5.1, last revised: September 1994) uses the multi-dimensional Newton-Raphson method to find the roots of the system of equations formed by the first-order conditions for maximizing the log-likelihood function associated with a given multinominal logit model and a particular sample of data" [42]. The program assumes a linear utility function for each alternative (mode).

Another component of this software is SETUP.F (Version 7.4, last revised : January 1994) which must be run prior to executing LOGIT.F, in order to prepare the input for LOGIT.F for the particular model to be estimated. The process of evaluation of the obtained results of this software is very important. Some of the measures for the evaluation are described next:

- The signs of the parameters have to be correct. If the sign is not correct, the variable associated with that parameter should not be in the utility function. For example, if the sign of the travel cost term in a utility function is positive, but should have a negative impact, the utility function should be revised.
- T-statistics (ratio of maximum likelihood estimate and standard error of estimate) are very important in the model evaluation process. High t-statistics are desirable. Their significance can be tested and the results can form the basis of removing variables from the equation.
- The software provides a table of correlations between each pair of independent variables specified in the model. Low values for correlation between a pair of variables can show reasonable values for coefficient of independent variables in logit model.

- At the end, using the results of log-likelihood ratio, adjusted rho-square and expected percent right, models can be compared and the best one chosen. The expected percent right is calculated as the average predicted probability for chosen alternatives (modes). The expected percent right can be regarded as an appropriate measure of goodness-of-fit, since the values of this statistic can be associated with correct models.

Model variables include the following:

- Travel cost factors: car and carpool parking and operating costs, and also bus fare.
- Travel time factors: in-vehicle and out-of-vehicle travel times.
- Car ownership: The car ownership variable has an important effect on modal choice decisions [27]. High car ownership may result in lower bus ridership. The higher the total vehicles per household, the more likely an individual will be to travel by automobile. This variable can be regarded as a socio-economic variable that characterizes the users of transportation.

For developing the modal utility functions, appropriate combinations of variables were investigated in order to find the set that best explains modal choice. Some of the explanatory variables are included as dummy variables while others are entered as real variables. Public transit fare and travel time for the bus mode characterize the bus mode. Travel cost, travel time and car ownership as a socio-economic attribute variable characterize the auto mode. It is recognized that available variables cannot capture the full decision-making characteristics of travellers, thus the role for the stochastic error term. The final modal utility equations calibrated for p.m. peak period are shown as follows:

$$U_{car} = \underset{(t=10.4)}{1.47} - \underset{(t=-18.5)}{0.542}\ tcostc - \underset{(t=-3.5)}{1.99*10^{-2}}\ carint + \underset{(t=9.2)}{0.611}\ numveh \quad (2.16.1)$$

$$U_{carpool} = - \underset{(t=-18.5)}{0.542}\ tcostp - \underset{(t=-3.5)}{1.99*10^{-2}}\ cptime + \underset{(t=3.7)}{0.289}\ numveh \quad (2.16.2)$$

$$U_{bus} = \underset{(t=10.6)}{1.55} - \underset{(t=-18.5)}{0.542}\ farcos - \underset{(t=-2.7)}{1.13*10^{-2}}\ busint - \underset{(t=-3.5)}{1.99*10^{-2}}\ busovt \quad (2.16.3)$$

where

U_{car} : the utility function for car
$U_{carpool}$: the utility function for carpool
U_{bus} : the utility function for bus
tcostc : car parking cost at destination (1986$) plus car operating cost of $0.06 (per km) * distance (km) between origins and destinations (1986$). This variable could include toll charges, but for 1986 toll charges are zero.
carint : car travel time (min)
numveh : number of vehicles per household (car ownership)
tcostp : carpool parking cost at destination (1986$) plus carpool operating cost including cost of $0.06 (per km) * distance (km) between origins and destinations (1986$)
cptime : total travel time for carpool (min)
farcos : bus fare (1986$)
busint : bus in-vehicle travel time (min)
busovt : combined average walking and waiting time for bus (min)

According to the logit model calibration methodology, the constant in the carpool utility equation is set equal to zero and other variables are scaled in relative terms. The equal coefficients for common variables reflect their generic treatment in model calibration.

The car and carpool are independent options due to substantial differences in level of service, cost and convenience attributes. Therefore, the multinomial logit (MNL) model structure is better suited to this research than a hierarchical (nested) logit model.

The results show significant and reasonable values of the coefficients. The following observations can be presented on the inputs and models: (a) The $0.06 per kilometre as automobile operating cost (without toll charges) given by the Canadian Automobile Association (CAA) for 1986 was used for model development [34]. (b) In the case of carpool, the passenger's share is 50% of the cost. (c) 5 minutes out-of-vehicle time is used for auto mode in order to account for parking and walking time from the office (location of the work place). (d) For a carpool, a 5 minutes waiting time penalty is applied [34]. (e) The constants in the car and bus utility equations represent the effect of decision-making factors which are not included in the equations. The utilities of car and carpool are based on total travel time, total cost and car ownership. The utility of bus is based on fare, in-vehicle and out-of- vehicle travel times. The utility function of bus has shown that out-of vehicle time is valued at greater than 1.75 times the in-vehicle time. In many pervious studies have shown that this ratio is greater than two.

Equations 2.16.1-2.16.3 show that all coefficients have correct signs. The t-statistics for all variable coefficients in each of the utility equation, have an absolute value greater than 1.65, (t-statistic with 95 percent confidence level). The results show that travel cost plays a major role in choosing modes (see Appendix A for elasticities). There are some explanations for a higher importance of travel cost than travel time. These are short commuting distances and generally low congestion levels in the urban area as represented by the 1986 O-D data [34].

Table 2.4 shows the correlation matrix for the variables used. There is low correlation between independent variable coefficients which are used in the utility

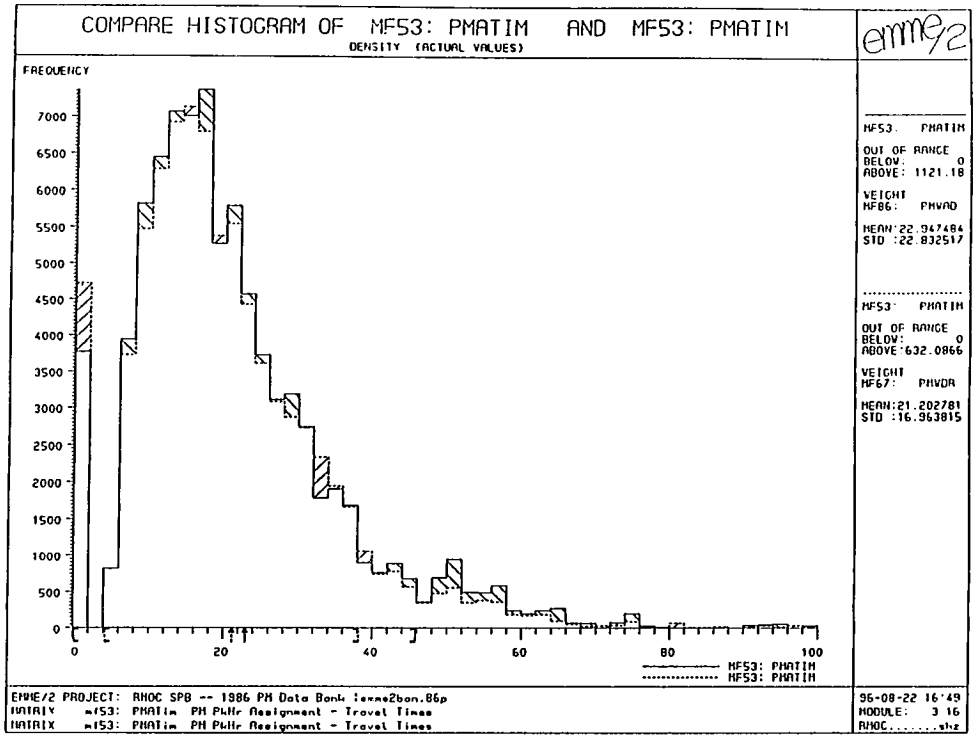


Figure 2.10- Work Trip Modal Split Results For Car (Auto Driver)

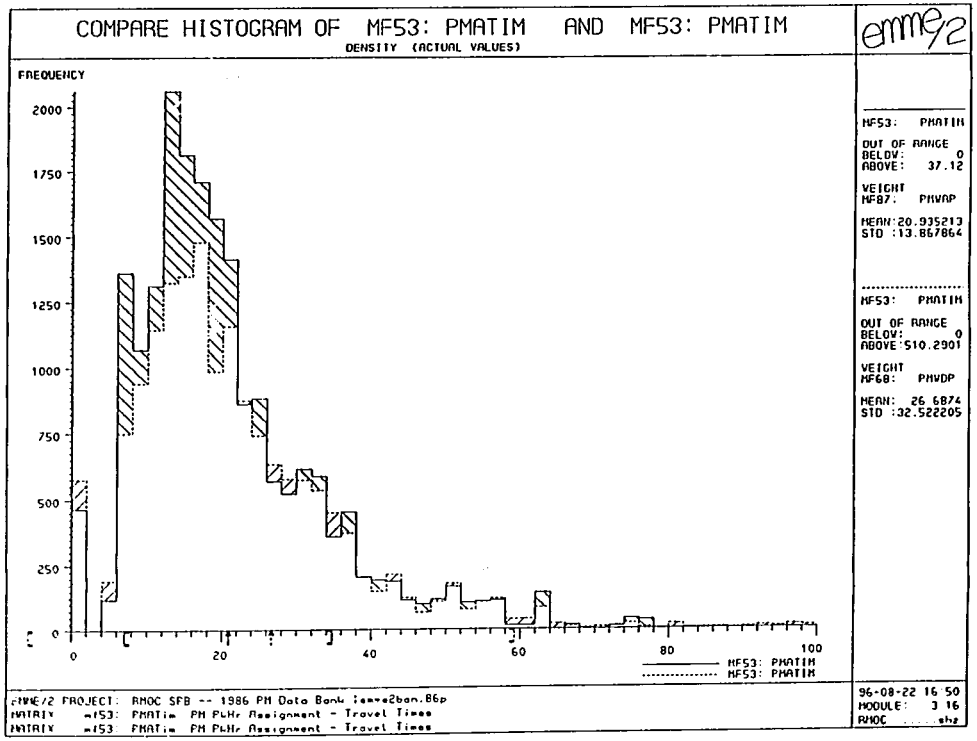


Figure 2.11- Work Trip Modal Split Results For Carpool (Auto Passenger)

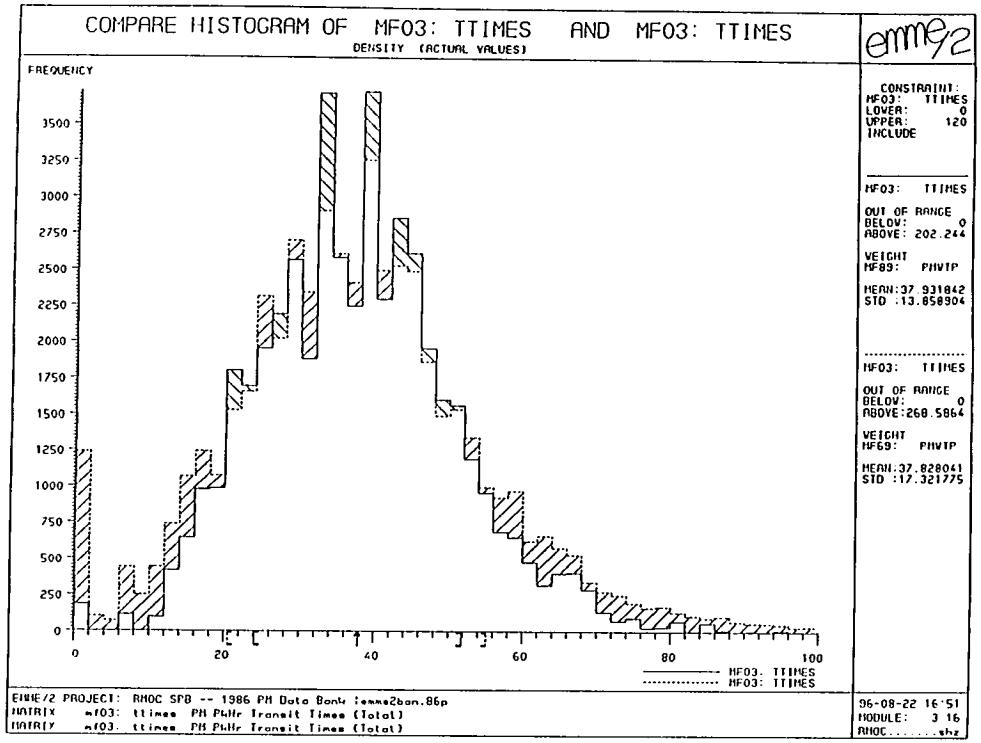


Figure 2.12- Work Trip Modal Split Results For Bus (Transit Passenger)

function of modes. The low correlation between independent variables is a desirable feature of calibration results.

"The expected percent right" for the calibrated model is 55.6, which reflects the estimated proportion of observed (or survey) choices which would be reproduced by the specified model. This value is acceptable for models of this type [34,36].

Figures 2.10-2.12 compare the observed and simulated trip length distribution for the p.m. peak period of various modes for work trips.

The figures show that the transit passenger (bus) and auto driver (car) compare well, in terms of trip length distribution. The auto passenger (carpool) mean trip length is about 20% greater than the observed mean. Since auto passenger trips are about 13% of the total p.m. work trip matrix, this result can be regarded as reasonable.

Table 2.5 shows the total simulated travel demand (i.e., using gravity model for

Table 2.4-Parameter first-order correlation coefficients of utility functions

PAR	a'	b'	c'	d'	e'
Car	tcostc	0	carint	numveh	0
Carpool	tcostp	0	cptime	0	numveh
Bus	farcos	busint	busovt	0	0
	a'	b'	c'	d'	e'
a'	1.000				
b'	-0.1291	1.000			
c'	-0.5116	0.5073	1.000		
d'	-0.0632	0.0477	-0.0168	1.000	
e'	-0.0309	0.0600	-0.0421	0.4354	1.000

* For example, "a'" expresses coefficient of "tcostc" (total cost for car), "tcostp" (total cost for carpool) and "farcos" (fare for bus) in the utility equations

prediction of trips) and observed travel demand for various modes based on logit model application to p.m. peak period work trips. The simulated total trips is quite close to the observed total trips.

Table 2.5- Simulated versus observed work trips for various modes

Mode	Observed Total O-D		Simulated Total O-D		% Difference
	person-trips	% total	person-trips	%total	
Car	85468	56	82874	55	3%
Carpool	19448	13	16827	11	13%
Bus	47029	31	51928	34	10%
Total	151945	100	151629	100	0.5%

2.2.3.2 Non-Work Trip Modal Spilt Model

A review of studies shown that recently, the transportation planning division of the RMOC developed new diversion curves modal split for p.m. non-work trips based on 1986 O-D survey [43]. These equations were developed as a function of travel time. The relationships were based on the ratio of auto and transit travel times. These new equations update the non-work modal split model developed by the consultants a few years ago [34]. The reason for modifying the equations is reported next.

The previous model is of diversion curve type, based on the ratio of auto travel time and transit travel time. The curves give a good fit to the observed data for travel time ratios between 0 and 0.5. Based on 1986 O-D data, it was found that 17% of the p.m. non-work trips had a time ratio greater than 0.5. The new equations use three sets of diversion curves for short trips under 10 minutes for auto travel time, medium trips

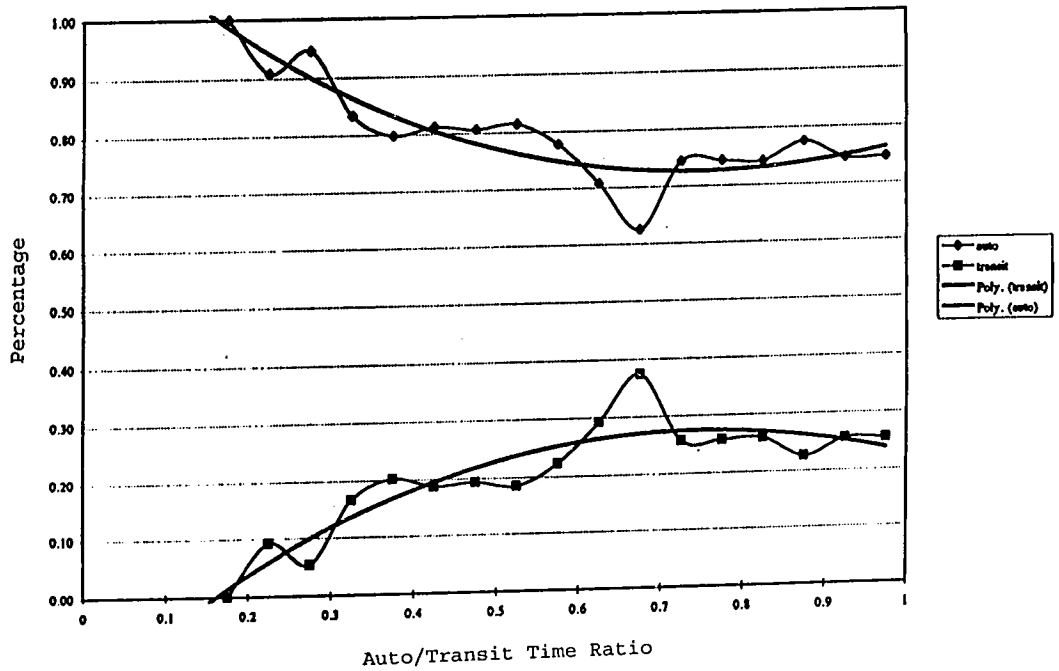


Figure 2.13- Non-Work Trip Modal Split-Auto Travel Time Interval 0-10 Minutes

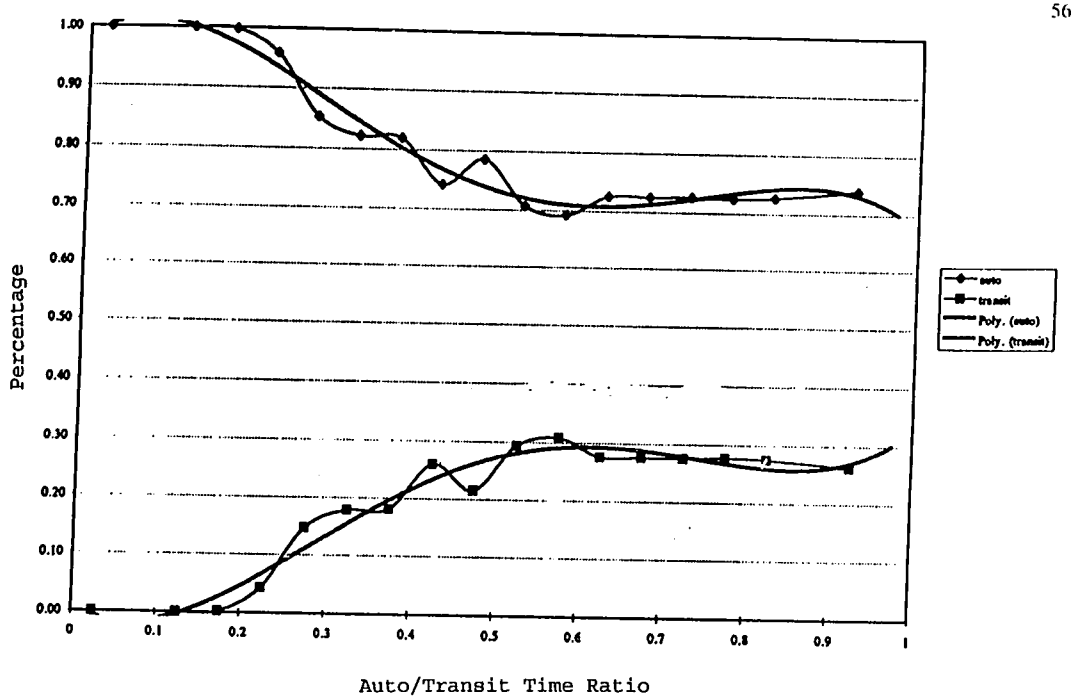


Figure 2.14- Non-Work Trip Modal Split-Auto Travel Time Interval 10-20 Minutes

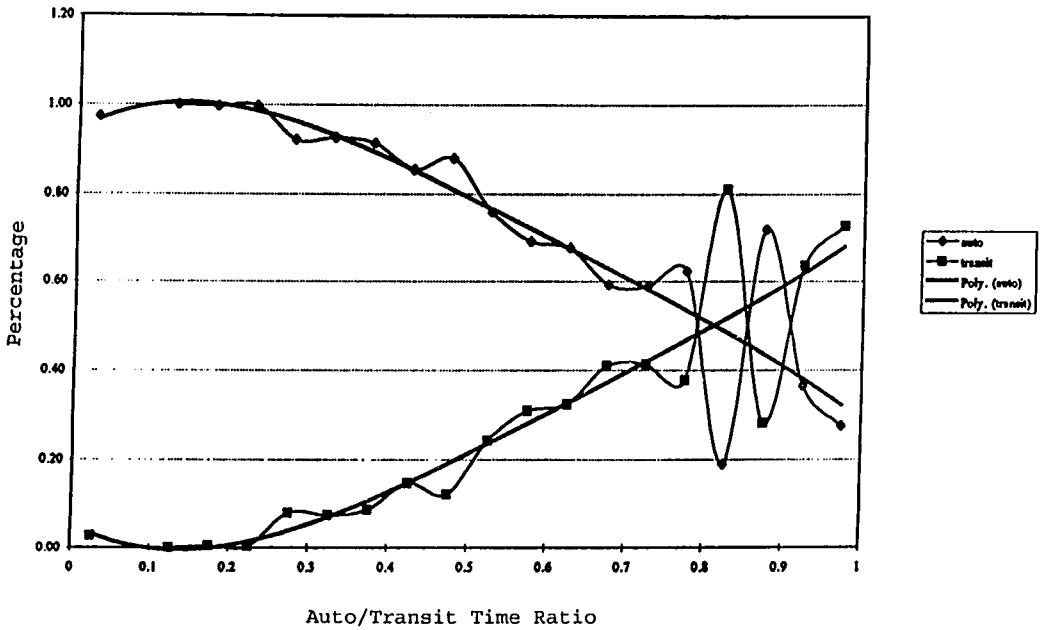


Figure 2.15- Non-Work Trip Modal Split-Auto Travel Time Interval Over 20 Minutes

between 10 and 20 minutes and long trips of more than 20 minutes duration by consideration of the data. These diversion curves also are based on the ratio of travel times for auto and transit. These new equations enable a more precise analysis of changes to level of service [43].

In this research, these sets of diversion curves (Equations 2.17-2.22) based on auto travel time intervals 0-10, 10-20, 20+ minutes, were used for estimation of travel demand for various modes for non-work trips during p.m. peak period (Figures 2.13-2.15) [43].

- Auto travel time interval 0-10 minutes

$$\textbf{\textit{Car (Auto)}} = -0.14R_T^3 + 1.0353R_T^2 - 1.3093R_T + 1.1851 \quad (2.17)$$

$$\textbf{\textit{Bus (Transit)}} = 0.14R_T^3 - 1.0353R_T^2 + 1.3093R_T - 0.1851 \quad (2.18)$$

- Auto travel time interval 10-20 minutes

$$\textbf{\textit{Car (Auto)}} = -5.5783R_T^4 + 11.445R_T^3 - 6.9913R_T^2 + 0.8093R_T + 0.9898 \quad (2.19)$$

$$\textbf{\textit{Bus (Transit)}} = 5.5783R_T^4 - 11.445R_T^3 + 6.9913R_T^2 - 0.8093R_T + 0.0102 \quad (2.20)$$

- Auto travel time interval over 20 minutes

$$\textbf{\textit{Car (Auto)}} = -1.8104R_T^4 + 4.5691R_T^3 - 4.3647R_T^2 + 0.9509R_T + 0.9452 \quad (2.21)$$

$$\textbf{\textit{Bus (Transit)}} = 1.8104R_T^4 - 4.5691R_T^3 + 4.3647R_T^2 - 0.9509R_T + 0.0548 \quad (2.22)$$

where R_T is ratio of car and bus travel times. For carpool (auto passenger), the following equation was developed based on auto travel time (Figure 2.16) [43].

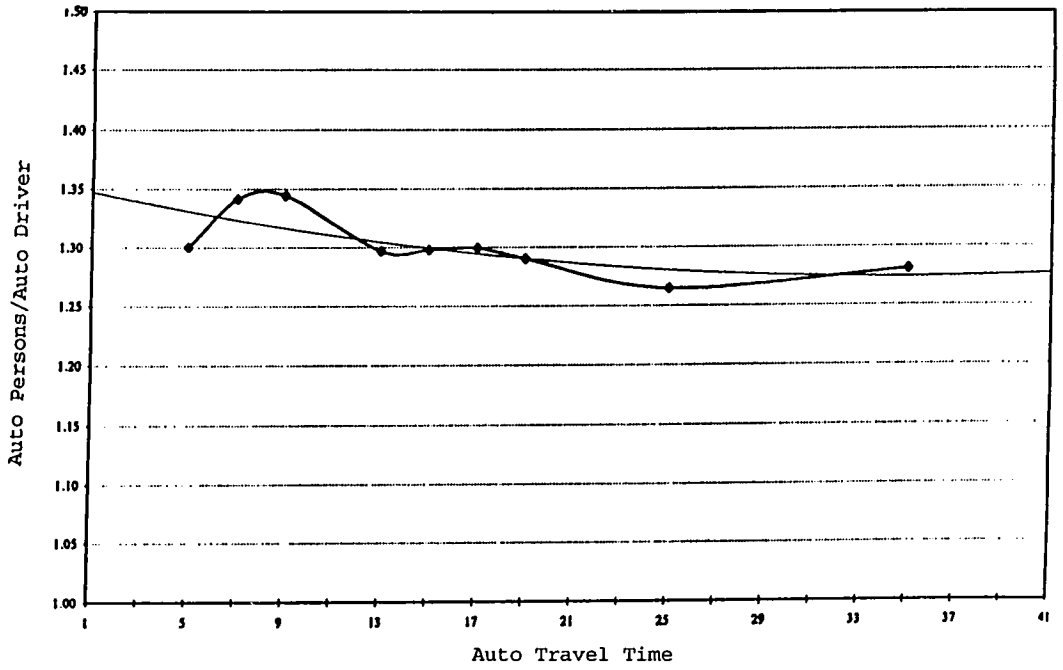


Figure 2.16- Non-Work Trip Modal Split-Carpool (Auto Passenger)

$$\textit{Carpool (Auto passenger)} = 6E\text{-}05\ T_a^{\ 2} - 0.0045\ T_a + 1.3518 \quad (2.23)$$

where T_a is auto travel time.

Table 2.6- Simulated versus observed non-work trips for various modes

Mode	Observed Total O-D		Simulated Total O-D		% Difference
	person-trips	% total	person-trips	%total	
Car	202442	62	208447	63	3%
Carpool	69945	21	63837	20	9%
Bus	56435	17	56512	17	-
Total	328822	100	328796	100	-

Table 2.6 shows the total simulated travel demand (i.e., using gravity model for prediction of trips) and observed travel demand for various modes for non-work trips during p.m. peak period. The simulated total trips are quite close to the observed total trips.

2.2.4 Traffic Assignment

The final step of the travel demand model is traffic assignment analysis. This stage is for developing a procedure that simulates the way in which trips by various modes (e.g., car, bus, etc.) between an origin zone and a destination zone distribute to network links [33].

The volume-delay functions for network in EMME/2 framework were obtained from RMOC. This network can vary broadly in terms of level of detail. Volume-delay

functions were specified for all links of the network that reflect the relationship between travel time and assigned volume [34].

There are several techniques that are used in traffic assignment. Some of these are noted below:

- The all-or-nothing assignment techniques are based on the assumption that travellers attempt to minimize travel time (or other route impedance) between an origin zone and a destination zone. In this technique, all trips between a given origin and destination are assigned to the minimum path tree without consideration of the traffic capacities of the links that make up the minimum path tree [19,33].
- The capacity restraint techniques are based on achieving compatibility between the volume of traffic and the travel time on road links. For this technique, the relationship between travel time and the volume should be specified for each link. This method attempts to balance the assignment volume, the capacity of the road and the related speed [19,33].
- The multipath assignment techniques, assign the trip interchanges among the routes between origin and destination zones based on route characteristics [33].

In this research, by using EMME/2, the equilibrium assignment (i.e., capacity restraint technique) was used to assign auto vehicle trips to the network during p.m. peak period. Equilibrium road assignment is based on use of volume-delay functions. Using volume-delay functions makes it possible to achieve equilibrium route split where the traveller is not able to minimize his/her travel time by choosing different routes [21]. With regard to other vehicles (e.g., commercial vehicles), a peak hour factor of 0.5 was used to convert from peak-period to peak-hour trips [34].

A multi-modal assignment is used in EMME/2 for accounting transit vehicles in the calculation of the link capacity. In this approach, the transit vehicles can be defined in

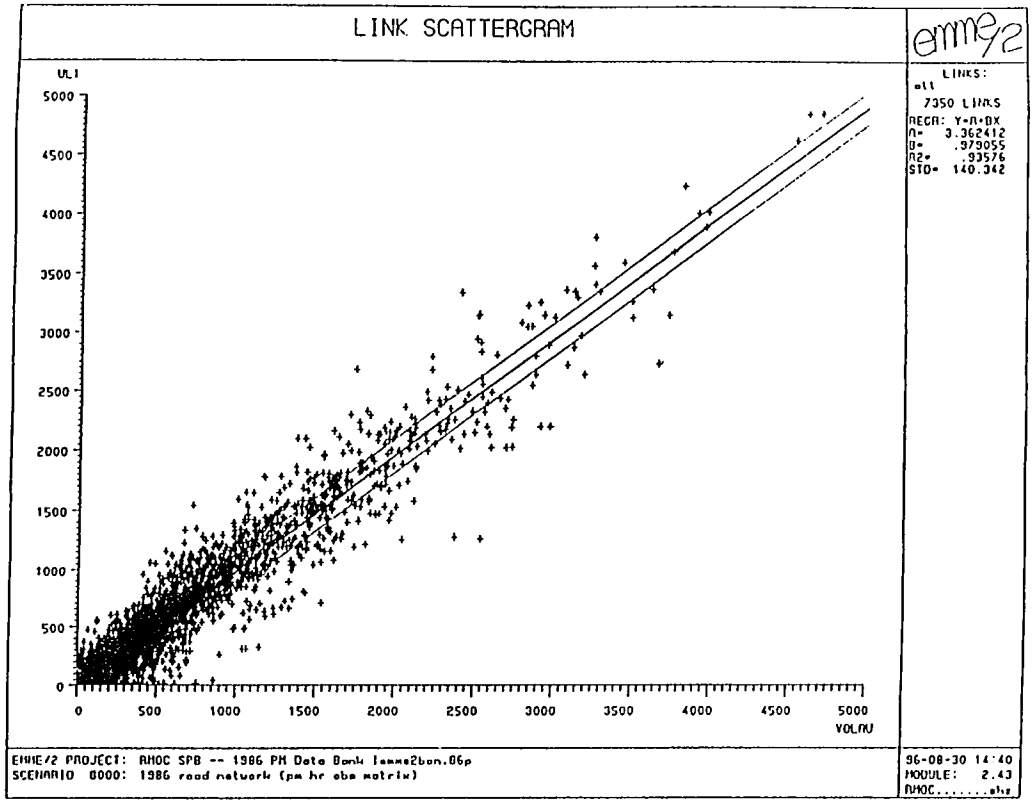


Figure 2.17- Link Volumes of Four-Step Model Versus the Observed Data

terms of auto equivalent units for the estimation of the available link capacity. This approach was used for auto assignment in this study. For transit bus, a multi-path transit assignment technique was used to allocate transit person trip O-D matrices to the transit network. "Multipath transit assignment is based on the concept of optimal strategy" [20]. This is for the minimization of total travel time which is a weighted sum of in-vehicle travel time, boarding time, auxiliary transit time and waiting time [44]. A peak hour factor of 0.45 was used to convert from peak-period transit person trips to peak-hour transit person trips [34].

It is logical to compare the simulated results of four-step transportation demand model and the observed data. Figure 2.17 shows a scattergram which compares auto link volumes obtained through the assignment of the observed data (volau) and the simulated model volumes (ul1). The scattergram shows a R-square of 0.93, which indicates a highly acceptable degree of agreement between EMME/2 runs using the volumes obtained from the four-step model and the observed assigned volumes.

In this research, travel costs are expressed in 1986 dollars. Actual cost for any future years (e.g., 2011) can be obtained by using the following formula [45]:

$$\textit{Travel cost of } 2011 = \textit{Travel cost of } 1986 * (1 + f)^{(2011-1986)} \qquad (2.24)$$

where f is the average inflation rate between 1986 and 2011. Estimates of inflation rates are obtainable from appropriate agencies. This equation was not used in this research.

In summary, in this research, the travel demand models were developed for the estimation of number of trips between origins and destinations by various modes on different routes.

Next chapter presents the components of a macroscopic simulation model. This model was developed for the estimation of travel time, energy consumption and emissions for bus operation on the Transitway.

CHAPTER 3

A SIMULATION MODEL OF THE TRANSITWAY (TRNSIM)

In this research, since the Transitway is an essential part of the case study urban transportation corridor, it became necessary to develop a Transitway simulation model. Given the increasing acceptance of bus rapid transit around the world, such a model can be applied elsewhere as well. The simulation model can be used to investigate changes to in-vehicle travel time, energy and emissions on the Transitway for various demand levels. The model was calibrated for Ottawa-Carleton Transitway by using realistic input data.

3.1 Overview

High Occupancy Vehicles (HOV) are vehicles which carry a minimum pre-defined number of people making the same trip. Thus, HOVs exclude vehicles with a single occupant. The ideal HOV priority treatment will provide an incentive to encourage people to share vehicles, leading to reduced vehicle volume and vehicle-kms. HOV lanes can be designated for carpools, vanpool and/or transit vehicles. Provision of exclusive facilities for HOVs, either in separate rights-of-way (e.g., Transitway) or within freeway (or arterial) is a TSM strategy which encourages people to use high occupancy vehicles. In this research, the Transitway is used only for buses.

A review of the literature indicated that a suitable macro simulation model for the Transitway could not be located. McBrayer developed a microscopic simulation model for the Karachi Mass Transit study [47]. The Regional Municipality of Ottawa-Carleton developed a site-specific simulation model for the Transitway that presents the flow of

articulated buses from the Campus station to the Lebreton station with four intermediate stations. This simulation model was written in Fortran and can be run for the 4071 meter maximum value of length of the Transitway (the end of the sixth station). Average speed, average travel time in the system, load factor, passenger wait time and passenger queue length are the outputs of this model [48]. Another simulation model was developed for OC Transpo. The objectives of the OC Transpo's model are (a) to serve as a tool for the testing and evaluation of various service strategies, and (b) to serve as a training simulator for current and new service control staff. The simulation model was designed to replicate the movement of buses and passenger activities on any one route. The model can simulate up to 50 (i.e., 40' and 60') buses scheduled or assigned on a single route. At this time, only bus route 95 data specifications are provided with the model. The outputs of this model can include bus-stop performance and activity, such as queue length on arrival, load on departure, headway performance, schedule performance, etc. [49].

For the following reasons, a new flexible comprehensive macroscopic simulation model of the Transitway is required for this research. First, given the macroscopic analysis orientation of this research, there is a need to develop a macroscopic simulation model for the Transitway. Second, details of the McBrayer's micro simulation model have not been published and his model has not been available to other researchers. Third, the RMOC simulation model was developed for 60-foot articulated buses operating on a specific length of the Ottawa-Carleton Transitway. Fourth, the OC Transpo simulation model is used to represent the bus operation and passenger activities on a specific route.

By definition, a Transitway is an exclusive grade-separated facility, constructed at, above or below ground level. In analyzing rapid transit capacity and service, its characteristics must be taken into account. The hourly capacity of a single rapid transit lane is determined by the number of vehicles that can pass a given point during one hour.

On the basis of the number of passengers carried in each vehicle, capacity can be expressed in terms of passengers/hour. At the stations, stopping lanes are extended in both directions to provide for storage and for deceleration/acceleration functions. Buses which are not required to stop at a particular station can therefore proceed through the station area relatively unimpeded.

Simulation is a numerical technique for conducting experiments on a digital computer. It may include stochastic characteristics, which could be microscopic or macroscopic in nature. Simulation techniques incorporate mathematical models that describe the behaviour of a transportation system over extended periods of time. The simulation model can represent operating conditions in vehicular operations analysis [18].

The macroscopic simulation model for buses operating on the Transitway developed in this research can calculate travel time, speed, energy consumption and emissions for bus operation on the Transitway.

The computer language of the model is Fortran 77 which is widely used for scientific computing and is highly transferable between computer facilities (Appendix B). The details of this model are provided next.

3.2 The Structure of the Simulation Model

The Transitway system is designed as a grade-separated access-controlled rapid bus transit facility. Access is restricted to buses and emergency or maintenance vehicles on the Ottawa-Carleton Transitway.

The roadway for buses which connects the collection and distribution portions of the urban transit system is the line haul facility (Transitway). To carry a reasonably high volume of passengers and to provide a high level of service (LOS), a grade-separated

two-way guideway is necessary. The geometry and facility type varies, depending on the specific needs of the urban area. The Ottawa-Carleton Transitway is a two-way exclusive facility. It is grade separated and constructed on or below the surface.

For the Transitway to be successful, it has to offer a reasonably high travel speed and a reliable travel time. Design speeds within the Transitway system are shown as follows [50].

Table 3.1-The design speed for various locations on the Transitway

Location	Design Speed (km/h)
Transitway Main Busway	90 *
Station Areas	60
Ramps & Access Routes	40

* Max. bus speed is limited to 80 km/h for the Ottawa-Carleton Transitway.

Stations are an important component of the Transitway. In most cases, Transitway stations incorporate a local route interface. The design of stations allows through buses to bypass loading/unloading buses. Stopping lanes are extended in both directions to provide for storage and for deceleration/acceleration functions. The maximum speed of buses on the Ottawa-Carleton Transitway is limited to 80 km/h between stations on the busway and restricted to 50 km/h through stations. Entrances can be at the platform ends or at any point along their length. The acceleration lane length is 150 m, based on 50 km/h operating speed in the station area. The deceleration lane length is 75 m, based on 50 km/h approach speed and assuming deceleration on the taper lane covers 35 m. The ratio of boarding to alighting passengers is also important. When the proportion boarding is high, bus dwell times at stops increases and thus, the Transitway flow may decrease

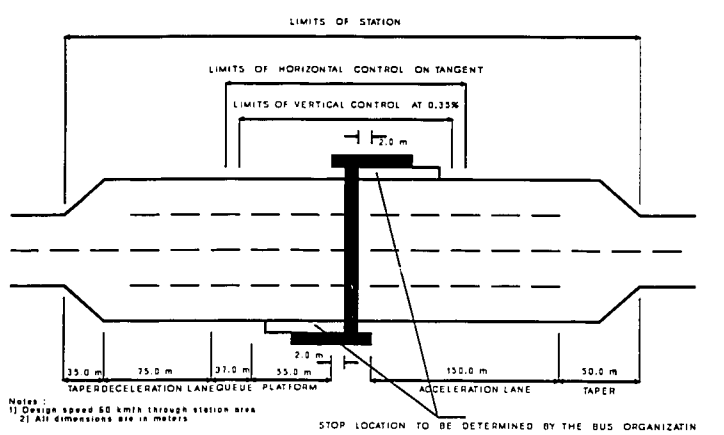
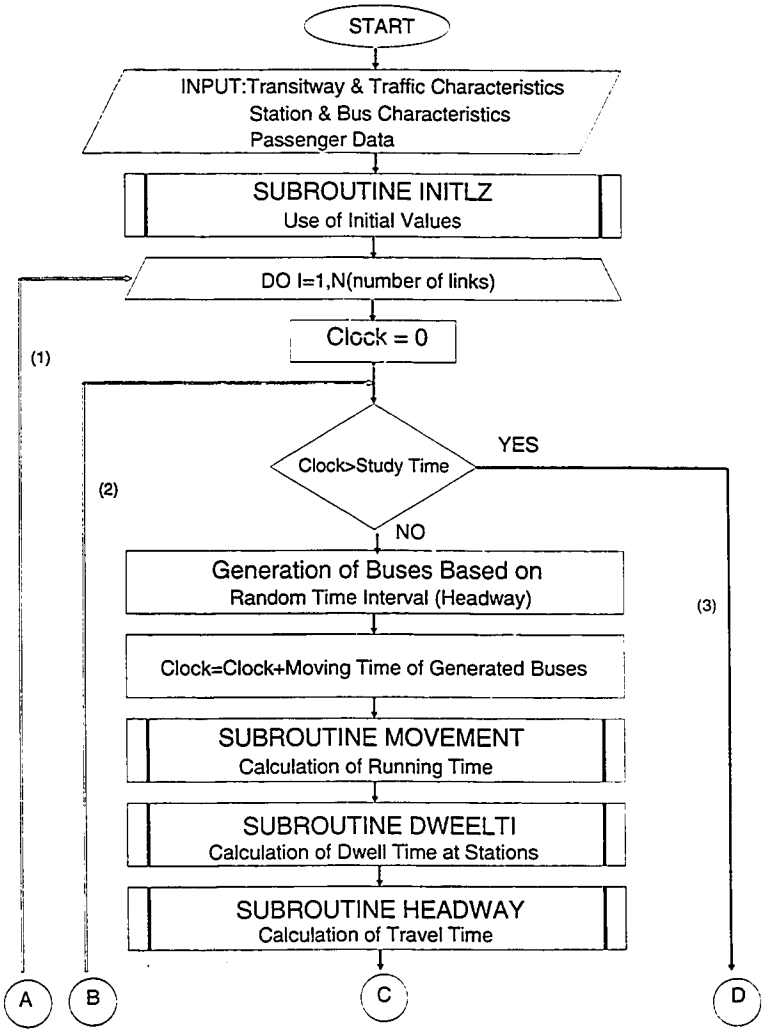


Figure 3.1-Station Area Lane Arrangements

due to station capacity [51]. Figure 3.1 shows the station area lane arrangements [50].

As a part of this research, a simulation model was developed for bus operation on the Transitway. The simulation model can represent all phases of vehicular operation with a reasonable degree of accuracy. For analyzing traffic stream flow, the model requires the estimation of three variables (i.e., flow rate, speed and density) on every point on the Transitway at all times during the analysis period. This model includes stochastic characteristics which will be described in the following sections. Figure 3.2 shows a macroscopic flow chart of the computer program for this model. The outputs of the model include: average travel time (including times for loading and unloading of passengers), average speed, average dwell time, total boarding and alighting passengers, vehicle-kms, average pass/bus, total passenger movement, fuel consumption and air pollution emissions estimates including CO, HC, NO_x and CO_2.


START
INPUT:Transitway & Traffic Characteristics
Station & Bus Characteristics
Passenger Data
SUBROUTINE INITLZ
Use of Initial Values
DO I=1,N(number of links)
Clock = 0
(1)
(2)
Clock>Study Time
YES
NO
Generation of Buses Based on
Random Time Interval (Headway)
(3)
Clock=Clock+Moving Time of Generated Buses
SUBROUTINE MOVEMENT
Calculation of Running Time
SUBROUTINE DWEELTI
Calculation of Dwell Time at Stations
SUBROUTINE HEADWAY
Calculation of Travel Time
A
B
C
D

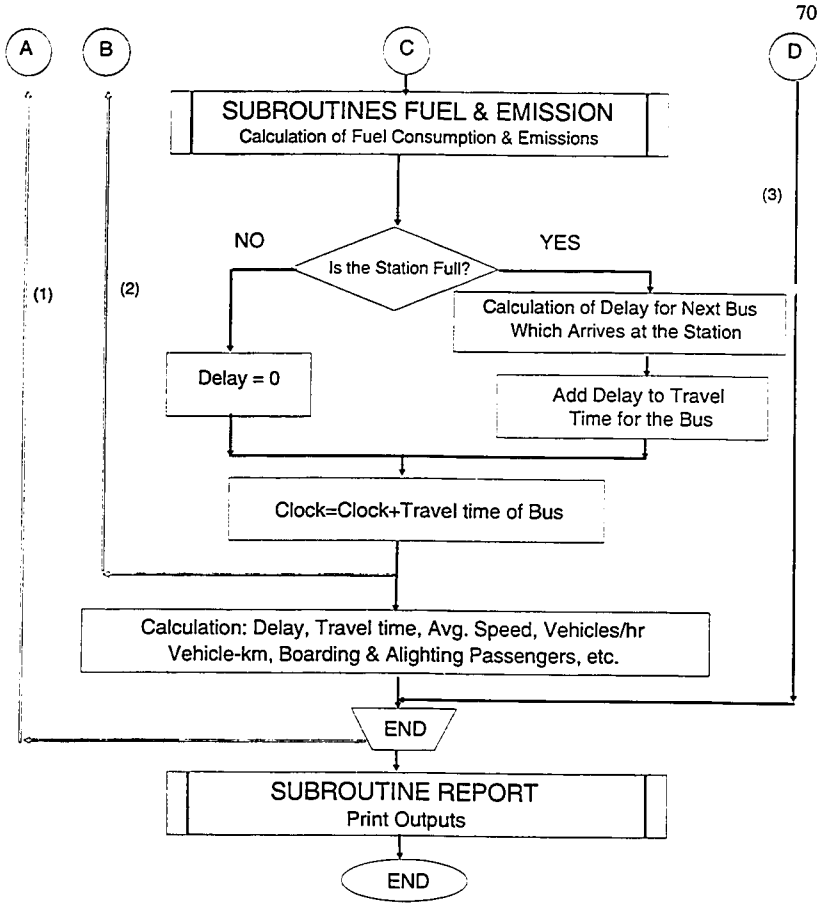


Figure 3.2: Flow Chart of the Simulation Model

3.3 Simulation Model Design: Probabilistic Elements

One of the most important features of simulating traffic is the ability to generate random events. Such generation takes place in two steps. First, a random number following a uniform distribution is generated. Second, this random number is handled as a probability to substitute into an appropriate distribution function in order to solve for the associated event. Therefore, simulation is the process of replicating the real world events based on a set of assumptions and models. It may be performed theoretically or experimentally. In practice, theoretical simulation is usually performed numerically using computer. As with experimental methods, numerical simulation may be used to produce (simulated) data about the real-world [18,52].

An important step of the application of simulation is the generation of the appropriate values of the random variables (i.e., random number) for agreement with the determined probability distributions as noted above. This can be done systematically for each variable by first generating a uniformly distributed random number between 0 and 1.0, and then it should be transformed to correspond to a random number with the specified probability distribution. Thus, random values can be generated [18,52]. The application of this methodology to the Transitway is described next.

The normal distribution is commonly used for speed, travel time and delay, etc. This is the most common continuous distribution because any process that is the sum of many parts tends to be normally distributed. Also, it is close in shape to many other distributions and in many cases cannot be distinguished statistically. Certain processes are in fact normal. For the generation of the average number of boarding and alighting passengers at various stations on the Transitway, data provided by Automatic Passengers Counting (APC) system of the OC Transpo were used. These data were compared with

random numbers generated with a normal distribution based on the average number of boarding and alighting passengers. A comparison between the observed data and generated random numbers showed that a normal distribution provides a good fit to the average distribution of boarding and alighting passengers at the Transitway's station. An r^2 greater than 0.60 was obtained by a regression analysis between the OC Transpo data and the random values from a normal distribution. Also, in the simulation model random numbers from a normal distribution are used to generate the load for buses when they arrive at the Transitway.

The poisson distribution is also used in the simulation model [53].

A poisson random variable, N, with mean $\lambda > 0$, can be obtained as follows:

$$P(n) = p(N=n) = \frac{\lambda^n e^{-\lambda}}{n!} \qquad n = 0,1,2,3,... \qquad (3.1)$$

where n is a positive integer. N (accepted n) can be interpreted as the number of arrivals from a poisson arrival process in one unit of time. The procedure for generating a poisson random variate, N, is given by the following steps:

Step 1: set n=0 and p=1

Step 2: generate a random number R_{n+1} and replace p by p x R_{n+1}

Step 3: if $p < e^{-\lambda}$, then accept N=n. If $p \geq e^{-\lambda}$ reject the current n, increase n by one, and return to step 2 [52].

In the simulation model, the number of vehicles that arrive at the station are assumed to be random, based on a poisson probability distribution. For this purpose, the chi-square (χ^2), goodness-of-fit test was used. The test procedure begins with arranging the n observation into a set of k class interval. The test statistic is shown by following the

equation [52]:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \qquad (3.2)$$

where

X^2 : the chi-square distribution value
O_i : observed frequency in class interval i
E_i : expected frequency in class interval i

The X^2 follows the chi-square distribution with k-s-1 degrees of freedom, where s is the number of parameters of the hypothesized distribution estimated by the sample statistics. The critical value $X^2_{\alpha,k-s-1}$ is estimated from the data. Here, α, is the level of significance, is obtained from the table and is compared with the calculated X^2. If the calculated X^2 is less than the critical one, then the distribution is accepted. In this research, the chi-square (X^2) test was performed for poisson distribution for four stations of the Ottawa-Carleton Transitway including Baseline, Lebreton, Campus and Lees stations. The data were used from OC Transpo for off-peak (10:00 - 11:00) and peak (16:00 - 17:00) hours in September 1993 weekday (Appendix B for details). The X^2 value was calculated for each station. The critical value $X^2_{\alpha,k-s-1}$ was found from the chi-square table [52]. A summary of the analysis result for the stations is shown in Tables 3.2.1-3.2.4 at level of significance 5 percent (α = 0.05). The results show that the calculated values in the peak hour for all stations and in the off-peak hour for two stations, were less than the critical values at level of significance α = 0.05.

Therefore, according to the results, the poisson distribution could be used to generate random numbers for bus arrival at the stations. Also, to determine the number of boarding and alighting passengers at a station, a poisson distribution can be used to create

random variables [54]. "For large mean (λ>15), the poisson distribution may be approximated by the normal distribution with mean (λ-½) and standard deviation ($\sqrt{\lambda}$). Therefore, in such a case, to generate a value for a poisson distributed random variable, a value may first be generated from the normal distribution. Random variable of poisson distribution could assume values of zero and positive values. The random variable could be the nearest integer to the values" [52].

3.4 Flow Stream Models (Vehicular Flow Models)

A traffic stream may be described macroscopically by three parameters: volume, density and speed. Volume or flow can be computed from speed and density. When vehicles follow each other on a long roadway, a relationship between spacing, speed, and deceleration can be obtained as follows [18].

$$S = V\delta + \frac{V^2}{2D_F} - \frac{V^2}{2D_L} + L + S_0 \qquad (3.3)$$

where

S : spacing between two vehicles (m)
V : initial speed of the two vehicles (m/s)
D_L: deceleration rate of the leading vehicle (m/s^2)
D_F: deceleration rate of the following vehicle (m/s^2)
δ : perception-reaction time of the following vehicle (s)
S_0: safety margin after stop (m)
L : length of vehicle (m)

Table 3.2.1-Summary of the chi-square analysis for Baseline station

Category	Bus Arrival at the Station (per min)	Off-Peak Hour			Peak Hour		
		O	E	$(O-E)^2/E$	O	E	$(O-E)^2/E$
1	0	47	48	0.02	30	33	0.27
2	1	13	10	0.9	25	20	1.25
3	2	0	2	2	4	6	0.67
4	3				1	1	0
5	4				0	0	0
		Σ		2.92	Σ		2.19
		Critical Value of X^2 *		3.84	Critical Value of X^2 **		7.81

* with level of significance α=0.05 for 1 degree of freedom
** with level of significance α=0.05 for 3 degrees of freedom

Table 3.2.2-Summary of the chi-square analysis for Lebreton station

Category	Bus Arrival at the Station (per min)	Off-Peak Hour			Peak Hour		
		O	E	$(O-E)^2/E$	O	E	$(O-E)^2/E$
1	0	44	40	0.4	5	9	1.78
2	1	8	16	4	18	18	0
3	2	8	3	8.33	23	16	3.06
4	3	0	1	1	9	10	0.1
5	4				5	5	0
6	5				0	1	1
		Σ		13.73	Σ		5.94
		Critical Value of X^2 *		5.99	Critical Value of X^2 **		9.49

* with level of significance α=0.05 for 2 degrees of freedom
** with level of significance α=0.05 for 4 degrees of freedom

Table 3.2.3-Summary of the chi-square analysis for Campus station

Category	Bus Arrival at the Station (per min)	Off-Peak Hour			Peak Hour		
		O	E	$(O-E)^2/E$	O	E	$(O-E)^2/E$
1	0	28	33	0.76	3	5	0.8
2	1	28	20	3.2	16	13	0.69
3	2	4	6	0.67	15	16	0.06
4	3	0	1	1	13	13	0
5	4				6	8	0.5
6	5				4	4	0
7	6				3	1	4
8	7				0	0	0
		Σ		5.63	Σ		6.05
		Critical Value of X^2 *		5.99	Critical Value of X^2 **		12.6

* with level of significance α=0.05 for 2 degrees of freedom
** with level of significance α=0.05 for 6 degrees of freedom

Table 3.2.4-Summary of the chi-square analysis for Lees station

Category	Bus Arrival at the Station (per min)	Off-Peak Hour			Peak Hour		
		O	E	$(O-E)^2/E$	O	E	$(O-E)^2/E$
1	0	36	32	0.5	3	5	0.8
2	1	11	20	4.05	11	12	0.08
3	2	13	6	8.17	16	15	0.07
4	3	0	2	2	16	13	0.69
5	4				10	8	0.5
6	5				1	4	2.25
7	6				3	2	0.5
8	7				0	1	1
		Σ		14.72	Σ		5.89
		Critical Value of X^2 *		5.99	Critical Value of X^2 **		12.6

* with level of significance α=0.05 for 2 degrees of freedom
** with level of significance α=0.05 for 6 degrees of freedom

There are different values of deceleration in terms of the safety level of operation, where

D_n: normal or comfortable deceleration

D_e: emergency deceleration

The combinations of leading and following vehicle decelerations designate various safety regimes a, b and c. For regimes a, b and c, deceleration of the leading vehicle is defined as ∞, D_e and ∞, respectively. Deceleration of following vehicle for regimes a, b and c are specified as D_n, D_n and D_e, respectively [18].

The relationship between spacing (or average spacing when not constant) and density is:

$$S = \frac{1}{K} \tag{3.4}$$

where K is density (veh/km) which is the number of vehicles per length of roadway. The relationship between headway and flow is:

$$H = \frac{1}{Q} \tag{3.5}$$

Where Q is the number of vehicles that pass a point on a roadway or a lane, during a specified time.

If two vehicles are travelling at spacing S and speed V, the headway between them can be H=S/V. By substituting the previous equations, the following relation is found which is the fundamental equation of a traffic stream [18].

$$Q = \frac{1}{H} = \frac{1}{S}.V = K.V \tag{3.6}$$

Therefore, the following relationship between flow and speed can be defined (from Equations 3.3 and 3.6) [18].

$$Q = \frac{V}{[\ V\delta + (\frac{V^2}{2D_F}) - (\frac{V^2}{2D_L}) + L + S_0\ ]} \qquad (3.7)$$

This equation can be calibrated for a transit lane or Transitway between the two successive stations.

Here, δ is perception-reaction time. It is the total time taken for perception, identification, decision and reaction of any event such as brake application of the leading vehicle which in turn results in braking of the following vehicle.

Actual perception-reaction times vary from individual to individual. This parameter ranges from 0.3 to 2.0 seconds, with a median value of 0.66 seconds [55]. The American Association of State Highway and Transportation Officials (AASHTO) recommends a value of 2.5 seconds for stopping sight distance [56]. Therefore, it can be assumed to have a value of 1 second for perception reaction time to calibrate the formula.

L; length of vehicle is another parameter which affects the formula. This is based on vehicle characteristics (i.e., 18 m for articulated bus, 12 m for standard bus, etc.).

$\mathbf{D_F}$ and $\mathbf{D_L}$; deceleration rate of following and leading vehicles are important. Based on acceleration test by OC Transpo and according to the Manual of Transitway Design, normal deceleration rate (D_n) could be calculated.

The Highway Capacity Manual shows that the capacity of an exclusive bus lane (within freeway) with uninterrupted flow, can be calculated by applying the 1.5 car equivalency factor to the calculated capacity in passenger car per hour [57]. According to 90 km/h design speed at level of service E (capacity), "the capacity of 1300 buses per lane per hour can be achieved on exclusive bus roadways with uninterrupted flow and no stops for passengers. These capacities can be compared with some 700 to 750 buses per hour moving through the Lincoln-Tunel-the highest bus flows found in the U.S." [57].

Average speed can be found by the following equations [56].

$$V_{avg} = \frac{D}{T_{avg}} \qquad (3.8)$$

where

V_{avg} : average speed (m/s)
D : distance between two successive stations (m)
T_{avg} : average travel time between two successive stations (s)

The components of transit travel time include: bus-stop (idle) time, acceleration time, cruise time and deceleration time.

An acceleration test was performed by OC Transpo [for 0 to 50 ft (15.24 m), 0 to 100 ft (30.48 m), 0 to 200 ft (60.96 m) and 0 to 60 km/h] at Hurdman station (Ottawa-Carleton Transitway). By using these data collected and regression analysis technique, a formula for V_{avg} as a function of acceleration time was found (Figure 3.3):

$$V_{avg} = 9.518\ T^{1/2} + 0.327\ T \qquad (3.9)$$

where

V_{avg} : average speed (km/h)
T : acceleration time (sec.)

From this, it was found:

$$\frac{\partial V_{avg}}{\partial T} = a \quad \Rightarrow \quad a = 0.327 + \frac{9.518}{2\ T^{1/2}} \qquad (3.10)$$

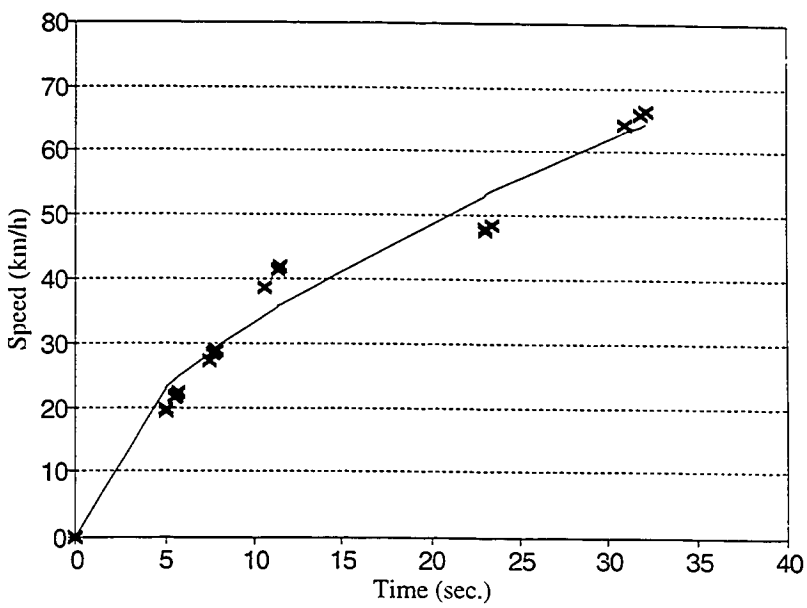


Figure 3.3-Speed-Time Bus Acceleration Test Result

where

a : acceleration rate (km/h/sec; 1 km/h/sec = 0.2778 m/s^2)

The R^2 of the above formula was found to be 0.99. According to this test, the average acceleration rate was 0.96 m/s^2.

The deceleration lane length of 75 m is based on deceleration rate of 3.2 km/h/sec from 50 km/h, and assuming deceleration on the taper lane of 35 m. In the absence of any deceleration rate test data available from OC Transpo and other available sources, the information contained in the Transitway Design Manual and acceleration test of the OC Transpo, can be used to obtain the following relationship between acceleration and deceleration functions for buses on the Transitway:

$$D_a = \frac{1}{2a_{avg}} V^2 \qquad (3.11)$$

$$D_d = \frac{1}{2d_{avg}} V^2 \qquad (3.12)$$

where

a_{avg} : average acceleration rate
d_{avg} : average deceleration rate
D_a : acceleration length
D_d : deceleration length
V : cruise speed

By using the maximum values for acceleration and deceleration lengths and constant speed for both of the above equations, a value for deceleration rate can be obtained in terms of acceleration rate.

$$\frac{D_a}{D_d} = \frac{d_{avg}}{a_{avg}} \Rightarrow d_{avg} = \frac{150+50}{75+35} a_{avg} = 1.81 a_{avg} \qquad (3.13)$$

where D_a is sum of 150 m and 50 m and also D_d is sum of 75 m and 35 m, can be used. By substituting the average rate of acceleration in the above formula, average deceleration rate can be obtained.

The values of deceleration for leading and following vehicles are found for three different safety regime definitions according to the operation's safety level. For the characteristics of typical transit system, average normal deceleration rate is 1.4 m/s² [55]. But in the model, 1.72 m/s² was assumed (according to the mentioned calculation). For emergency deceleration, a rate (D_e) could be 4 m/s². Safety regimes a, b and c are defined in Table 3.3. It is suggested that the regime c be used for buses [18]. This regime is based on ∞ deceleration of leading vehicle and emergency deceleration of following vehicle.

S_0: safety margin after stop was assumed to be 1 m (between buses); according to the experience of the OC Transpo, this value could be an accepted value for safety margin.

Figures 3.4 and 3.5 show graphically the relationship between cruise speed and flow by using given values.

3.5 Effect of Grades and Geometric Design on Transitway

For uninterrupted flow, buses are equivalent to 1.5 passenger car units in the lane where they operate at their maximum flow level under ideal conditions on a lane that is designed for 95-110 km/h. Such a lane has an ideal capacity of 2000 passenger cars per hour per lane. In the Highway Capacity Manual, there is a factor (f_{HV}) which is used to

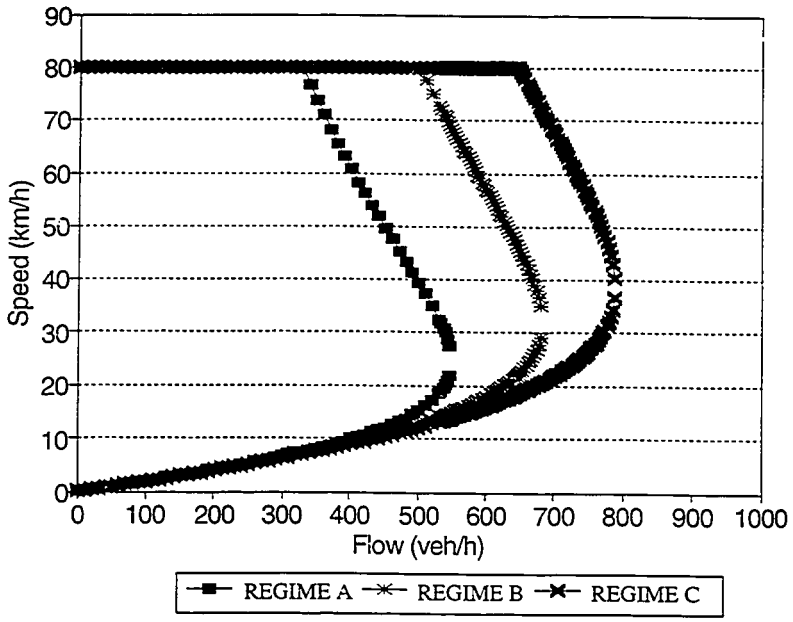


Figure 3.4-Plot of Speed-Flow for Articulated Bus

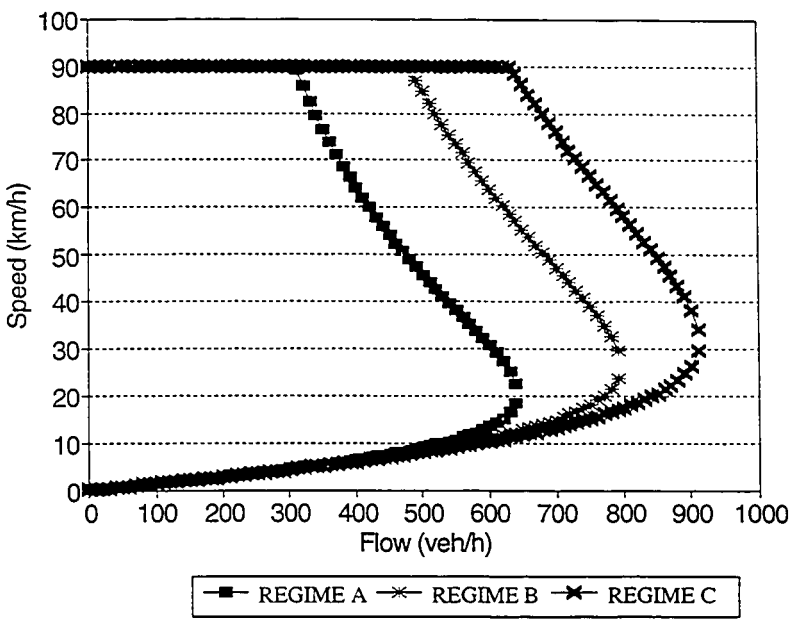


Figure 3.5-Plot of Speed-Flow for Standard Bus

adjust for the effect of heavy vehicles in the traffic stream. If there are only buses on a lane, this factor will be calculated as [57]:

Table 3.3-The speed limit based on flow of buses on Transitway for various safety regimes

Regime	Standard Bus (12 m)	Articulated Bus (18 m)
a	$Q \leq 411$ $V_{CRUISE}=90$ km/h	$Q \leq 400$ $V_{CRUISE}=80$ km/h
	$411<Q\leq 738$ $V_{CRUISE}<90$ km/h	$400<Q\leq 633$ $V_{CRUISE}<80$ km/h
b	$Q \leq 640$ $V_{CRUISE}=90$ km/h	$Q \leq 614$ $V_{CRUISE}=80$ km/h
	$640<Q\leq 918$ $V_{CRUISE}<90$ km/h	$614<Q\leq 794$ $V_{CRUISE}<80$ km/h
c	$Q \leq 775$ $V_{CRUISE}=90$ km/h	$Q \leq 736$ $V_{CRUISE}=80$ km/h
	$775<Q\leq 1054$ $V_{CRUISE}<90$ km/h	$736<Q\leq 881$ $V_{CRUISE}<80$ km/h

$$f_{HV} = \frac{1}{1 + p_B\,(E_B-1)} = \frac{1}{1 + (E_B-1)} \qquad (3.14)$$

where

f_{HV} : the adjustment factor for the effect of buses on the traffic stream
E_B : the passenger-car equivalents for bus
p_B : the proportion of buses, in the traffic stream

If the entire traffic stream consists of buses on lane, p_B will be 1 or 100%. Table 3.4 gives values of passenger-car equivalents for use in capacity analysis. These values are for the up grade condition only [57].

However, any combination of grades and horizontal or vertical alignment reduce operating speed on a lane. Any lane length of more than 1.6 km for grades of less than 3 percent, or 800 m for grades of 3 percent or more is usually considered as a separate segment [57].

These factors could be the same, due to a short distance between stations, for standard

and articulated buses, but capacity of the Transitway and operating speed for them are different.

Table 3.4-Passenger-car equivalent for the up grade condition

Grade(%)	Passenger-Car Equivalent
0	1.5
0 - 3	1.6
4(≥400 m)	1.6
5(≥400 m)	3.0
6(≥400 m)	5.5

From Table 3.4 the effect of grade on capacity of lanes (by using f_{HV}) can be calculated. These changes can be obtained based on grade zero (level). Table 3.5 shows results as a factor, which is 100% for grade zero (level)(i.e., no effect). The results for other grades (g>0), are also shown in Table 3.5 [57].

The vertical alignment of most lanes results in a continuous series of grades. The average grade is defined as the total rise from the beginning of the composite grade divided by the length of the grade. The horizontal alignment of a lane affects maximum speed for driving, which can be considered within the Transitway system.

3.6 Capacity of Stations

Stopping of buses at a fixed location always increases the minimum headway at which buses can follow each other within a given safety regime. Station headway is usually a function of dwell time and other factors, described later. The dwell time

depends on the passenger boarding and alighting volume and station operating practices.

Headway between successive buses at a station consists of two groups of elements. The first component is the time interval reflecting vehicle motion (i.e., acceleration and deceleration rates of buses). It depends on vehicle dynamics, operating regime and safety

Table 3.5-The effect of grade on capacity of lanes

Grade(%)	E_B	f_{HV}	grade factor affect on capacity
0	1.5	0.667	100
0 - 3	1.6	0.625	94
4(≥400 m)	1.6	0.625	94
5(≥400 m)	3	0.333	50
6(≥400 m)	5	0.200	30

requirements. Dwell time is the second component which consists of door opening, passenger exchange and departure preparation (i.e., door closing). The capacity of a bus berth in station can be calculated by [55].

$$Q_{s\,(max)} = \frac{3600}{H_{s\,(min)}} \qquad (3.15)$$

where

$Q_{s\,(max)}$: capacity at station (veh/h)

$H_{s\,(min)}$: minimum headway at station between buses (sec.)

The passenger service times and dwell times at bus stops are necessary for the estimating bus capacity at stations. The minimum headway of buses at a stop consists of:

- dwell time

- clearance times between buses.

Bus dwell time is taken to be the time for the bus unload and load passengers and leave the bus stop. The minimum headway $H_{s\,(min)}$ can be obtained as follows [57]. If buses have a common door for passenger boarding and alighting, dwell time can be calculated by using the following formula:

$$H_{s\,(min)} = aN_1 + bN_2 + c \qquad (3.16)$$

where

a : average alighting time per passenger in second
b : average boarding time per passenger in second
N_1 : number of alighting passengers
N_2 : number of boarding passengers
c : clearance time (lost time in opening and closing doors, leaving the bus stop or to traffic delays when bus is ready to leave), c is usually between 9 and 20 seconds

For separate doors (different doors for passenger boarding and alighting) the formula can be changed as follows:

$$H_{s\,(min)} = \max\,(\,aN_1\,,\,bN_2\,) + c \qquad (3.17)$$

Bus dwell times strongly influence bus stop performance [51]. According to the Manual of Transitway Design, up to three articulated buses can stop at platforms. Buses that are not required to stop at a particular station can proceed through the station area relatively unimpeded [50].

The passenger capacity of a bus is given by [57]:

$$C = C_1 + \psi C_2 \qquad (3.18)$$

where

C : total passenger capacity per bus
C_1 : bus sitting capacity
C_2 : bus standing capacity
ψ : fraction of C_2 allowed

In the simulation model ψ is assumed to be 100% and other data were assumed according to the OC Transpo information.

The boarding and alighting passenger times depend on many factors such as fare collection system, type of door control, etc. The Highway Capacity Manual suggests for typical operating conditions with single door 1.7-2.0 seconds as alighting passenger time. These values are modified to be 1.5-2.3 seconds for alighting passenger with very little hand baggage and parcels. For typical operating conditions with single door, the boarding passenger time is suggested as between 2.6 and 3.5 seconds. For prepayment condition before entering bus (e.g., bus pass) 1.5-2.5 seconds are suggested. For single coin or token with fare box condition, 2.5-3.0 seconds are suggested by the Highway Capacity Manual. For articulated buses, a time reduction can be applied amounting to 30% (or 0.4 sec per passenger) for boarding passenger time and 27%-80% for alighting passenger time due to the use of the bus rear and center doors [57].

3.7 Estimation of Fuel Consumption and Emissions

For the estimation of fuel consumption, it was decided to modify the heavy vehicle fuel consumption model ARFCOM (ARRB Road Fuel Consumption Model) [24]. A literature review did not reveal suitable analytical method or result of specific test to estimate fuel consumption of buses on Transitway (see Chapter 4 and Appendix C for

details). Thus, the simulation model uses a modification of the ARFCOM which was developed in this research to estimate bus fuel consumption in terms of litres/km for each of the four modes of driving, namely acceleration, cruise, deceleration and idle on the Transitway.

The simulation model can also estimate emissions including HC, CO and NO_x based on MOBILE5c. CO_2 emission is estimated from the fuel consumption and the emission factor.

3.8 General Specification of the Transitway Simulation Model (TRNSIM)

The simulation model's general specifications are briefly noted here.

- Gradient and geometric design of the Transitway affect speed limit of buses and maximum capacity of the Transitway. A user of this model should be able to specify length (m), grade (%) and speed limit (km/h) as input data for each link (between two successive stations). The model can alter the range of accepted speed and capacity on Transitway by using input data.
- The buses are assumed to be 9 m , 12 m and 18 m for small, standard and articulated buses, respectively. This capability of the model reflects the expectation that various sizes of buses would use the Transitway. Uniform acceleration and deceleration rates are used which are based on analysis of available data obtained from OC Transpo and use of the Manual of Transitway Design [50].
- Time intervals between buses are random based on average headway and exponential random generator. The type of buses (i.e., articulated bus, standard bus, etc.) are determined by using a random number generator based on average percentage of buses in operation by type.
- The maximum speed limit between stations was observed to be 80 km/h at

Ottawa-Carleton Transitway. The speed is also restricted by vertical or horizontal curves specified as input, which can be determined by the user of the model. In the model, maximum operating speed for buses was determined, based on general information concerning bus operation [59].

- The arrival of buses at the stations is according to poisson random generator with average specific headway.
- By using theoretical formulation (i.e., vehicle-following logic) the relationship between speed and flow for a specific length of Transitway (i.e., between two successive stations) is defined. This equation was calibrated by using bus characteristics and other Transitway-specific assumptions.
- The simulation model assigns a dwell time of random value to each bus at each stop with respect to the mean and standard deviation of boarding and alighting passengers. These data were obtained from OC Transpo. These values are changed at each station by using normal random variables and average time for each passenger to board and alight buses.
- Based on Ottawa-Carleton public transit condition (i.e., use of bus pass), 2 and 1.5 seconds for boarding and alighting passenger times were assumed, respectively [58]. For articulated buses, these values are decreased by 20% and 35% for boarding and alighting passenger times, respectively [57].
- The Transitway between stations would have only a single lane in each direction, and two lanes at the station area for on-line and off-line operation at the station. In the model, it was assumed that buses on the Transitway can operate at minimum headway of 15 seconds if an off-line station is used [60].

Bus operation at a station is very important because in most cases, the Transitway capacity is limited by capacity of stations. If the station is full, buses which will arrive

at the station must wait until the previous buses leave. A stopping lane at the station can accommodate three or more buses (depending upon input data provided by user). Therefore, during high volume travel condition, travel time is increased due to limitation of station capacity. It is assumed that at stations a bus stopped behind another bus cannot leave the station until the bus ahead departs.

The outputs of this model include: average travel time (including boarding and alighting passenger time), average speed, average dwell time, total loading and unloading passengers, vehicle-km, average pass/bus as well as fuel consumption and air pollution emissions, etc. during a specific time (Appendix B). The length of Transitway between stations, capacity of station, size of buses and volume (veh/h) on Transitway have an important effect on maximum passenger movement.

In order to establish busway capacity and to investigate factors which influence busway performance, Gardner, Cornwell and Cracknell [51] selected eight busways out of about 40 which have been identified in the world. For passenger flow on the busway, they recorded between 15000 and 26000 passengers per hour per direction (p/h/d). The highest recorded passenger flow was 26000 p/h/d in Porto Alegre (Brazil). The highest recorded passenger throughput on a basic 2-lane busway (without special operational measures for serving a corridor with busy bus stations) was 19500 p/h/d in the Abidjan (Cote D'ivore). Bus flows were recorded to be 380 per hour per lane along busway [51]. Similar two lane busways and operating conditions exist in Ankara and Istanbul (Turkey). The highest average bus speed was 30 km.h in Avenida Cristiano Machado busway in Brazil. The Canadian Transit Handbook suggests 180 b/h/d with on-line station and 240 b/h/d with off-line station for busway design flows [60]. For example, for safety regulation, standing passengers on high speed bus system cannot be permitted. In the simulation model, $H_{s(min)}$ corresponds to 240 b/h/d. User of the model may use another

suitable $H_{s(min)}$.

3.9 Statistical Analysis of the Model Output

A simulation model is only an approximation to the actual system. In the case of the simulation model, the general objective of validation is the determination of agreement between model output and observed data [61]. For validation of simulation models, it is common to use the r^2, standard t and F statistical tests in order to compare the observed versus simulated information [62].

The results of the model based on OC Transpo data, show that average capacity of the Ottawa-Carleton Transitway can be about 20000 pass/h (one direction) with average operating speed of 41 km/h. This estimate is based on four bus passenger boarding and alighting platforms (Appendix B). The input data were collected from Blair station to Laurier station and from transit station near Booth St. (intersection of Albert St. and Slater St.; near Bronson Ave.) to Baseline station on the Ottawa-Carleton Transitway. The OC Transpo had a survey for obtaining actual travel time for bus route 95 on the Transitway. The results of this survey show that average observed travel time (i.e., actual) has differences to scheduled travel time for some Transitway segments (links) during p.m. peak period (Figure 3.6). For validation of the model output, it is reasonable to compare the simulated travel time which was calculated by the simulation model with the average observed travel time obtained from OC Transpo test (i.e., actual) from Blair station to Laurier station (links 1-8) and from Transitway station near Booth St. to Baseline station (links 8-14)(Figure 3.7).

An examination of Figure 3.7 shows a reasonable agreement between average observed travel time obtained from OC Transpo test and the simulated travel time

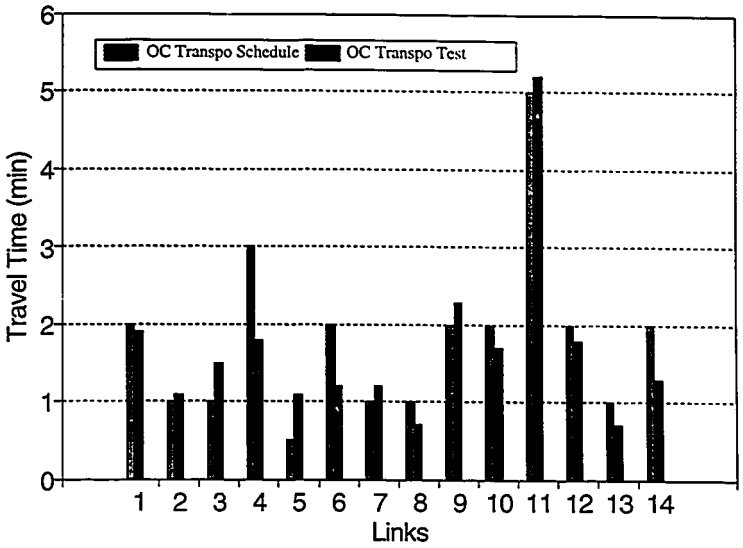


Figure 3.6-Bus Travel Time at Transitway

(OC Transapo Schedule & OC Transpo Test)

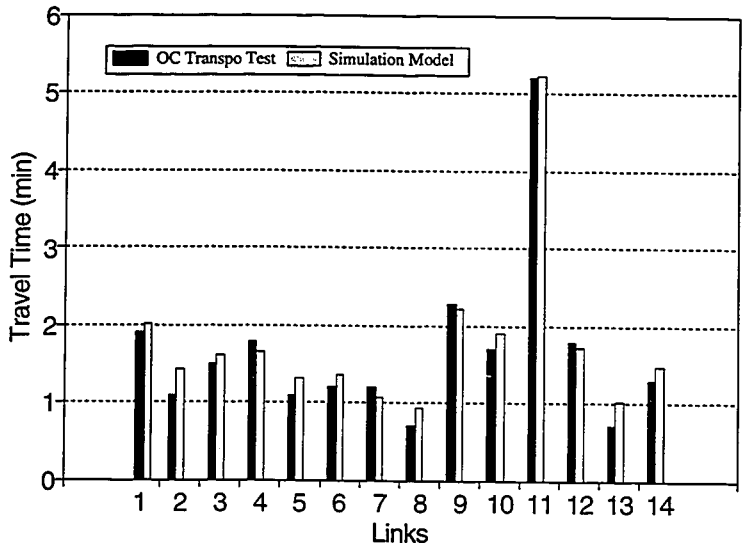


Figure 3.7-Bus Travel Time at Transitway

(OC Tranapo Test & Simulation Model)

between stations at the Transitway. For finding the degree of correlation between the model output and average observed values, a regression analysis test was performed. For this purpose, the statistical package of SPSS was used for linear regression analysis between the simulated and average observed values [35]. Linear regression analysis gave an r^2 of 0.98, which shows that the simulation result is moderately to highly correlated with average observed travel time from OC Transpo test. The results of SPSS package for travel time between the stations at Ottawa-Carleton Transitway, are summarized in Table 3.6 (Appendix B). Also the results show that the t-statistics for estimated regression coefficient has a value grater than 1.65, (t-statistics with 95 percent confidence level).

High t and F values (i.e., t value =24.3 and F value = 590) and also value of r^2 show a good agreement between the average observed data and simulated results. Figure 3.8 illustrates results with a 45 degree line which are obtained from the SPSS Package.

Thus, the simulated travel times are close to actual (test) data.

3.10 Developing Travel Time Functions for the Transitway

Since EMME/2 was selected as a modelling framework in this research, it was necessary to develop travel time functions for buses in the transit network. In EMME/2, travel time of transit lines can be specified by travel time functions. These functions define the travel time on each segment of the line, and are integrated into the transit assignment procedures of the EMME/2 [20].

The Transitway simulation model (TRNSIM) was used to simulate operations under various traffic conditions (i.e., volumes of buses). The location of stations were specified to create realism in simulations. On the basis of inputs and outputs, transit volume-delay

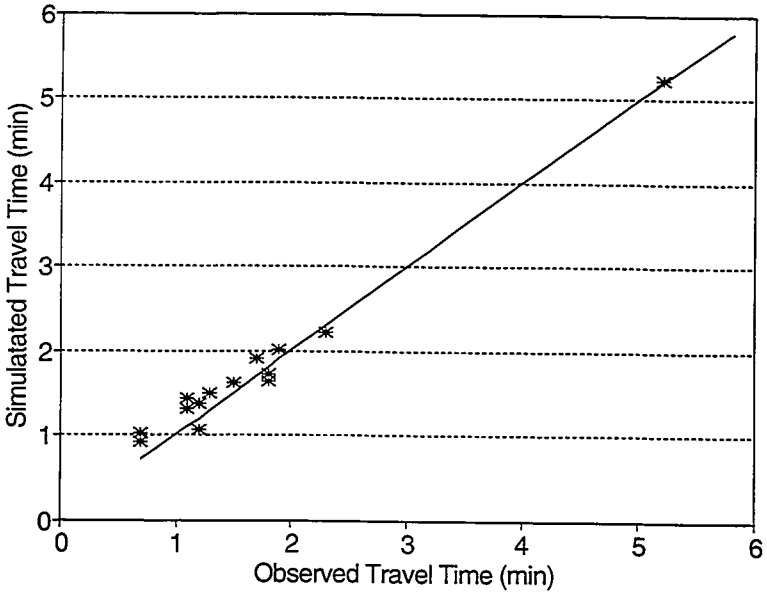


Figure 3.8-The Observed Data vs. Simulation Output

functions were based on buses/h which is an appropriate variable for the estimation of travel time under various traffic conditions by using regression analysis (i.e., log linear form).

$$ft1 = (len/28.8)*(1+0.46*10^{-3}*vol^{1.21})*60 \quad (3.19.1)$$

$$ft2 = (len/24.7)*(1+0.45*10^{-3}*vol^{1.22})*60 \quad (3.19.2)$$

$$ft3 = (len/30.6)*(1+0.45*10^{-3}*vol^{1.22})*60 \quad (3.19.3)$$

$$ft4 = (len/43.7)*(1+0.34*10^{-3}*vol^{1.20})*60 \quad (3.19.4)$$

$$ft5 = (len/33.6)*(1+0.37*10^{-3}*vol^{1.22})*60 \quad (3.19.5)$$

$$ft6 = (len/48.3)*(1+0.26*10^{-3}*vol^{1.22})*60 \quad (3.19.6)$$

$$ft7 = (len/47.0)*(1+0.31*10^{-3}*vol^{1.20})*60 \quad (3.19.7)$$

$$ft8 = (len/40.3)*(1+0.44*10^{-3}*vol^{1.17})*60 \quad (3.19.8)$$

$$ft9 = (len/53.4)*(1+0.27*10^{-3}*vol^{1.19})*60 \quad (3.19.9)$$

$$ft10=(len/64.0)*(1+0.21*10^{-3}*vol^{1.15})*60 \quad (3.19.10)$$

$$ft11=(len/60.1)*(1+0.15*10^{-3}*vol^{1.17})*60 \quad (3.19.11)$$

$$ft12=(len/60.0)*(1+0.29*10^{-3}*vol^{1.15})*60 \quad (3.19.12)$$

$$ft13=(len/63.5)*(1+0.18*10^{-3}*vol^{1.17})*60 \quad (3.19.13)$$

$$ft14=(len/35.3)*(1+0.41*10^{-3}*vol^{1.21})*60 \quad (3.19.14)$$

where

ft : travel time of Transitway segments (i.e., between stations) (min)

len : length of Transitway segments (links) (km)

vol : volume of buses on Transitway segments (per hour)

The regression analysis gave an R^2 of about 0.95, high t and F values for all of the functions. These functions can be used for estimation of travel time on the Transitway in EMME/2 for transit assignment.

The next chapter discuses the estimation of fuel consumption for transportation systems (i.e., consisting of auto and bus). It describes a model for automobile fuel consumption and explains the modification of a method for the estimation of bus fuel consumption.

CHAPTER 4

FUEL CONSUMPTION ESTIMATION

4.1 Overview

To study fuel consumption in transportation, it is useful to separate the contribution made by each of three components: the driver, the vehicle and road/traffic systems. The measurement of vehicle fuel consumption under real road conditions is complicated by the variance introduced by traffic density, road topography, road layout, traffic management controls, traffic content (private and public vehicles), weather (temperature) and visibility. The work may be separated into several broad categories. The first category is concerned primarily with the relationship between fuel consumption and factors that directly relate to vehicle speed profile, such as average speed, journey time, acceleration, number of stops and stopped time. The second category of investigation is the attempt to correlate the fuel consumption and speed-independent factors (such as type of road, road gradient, road profile, climatic conditions and vehicle load). The effect of driver behaviour is particulary important.

Petroleum-based fuels used in transportation are gasoline and diesel oil. To estimate fuel consumption, vehicle usage expressed in various units including vehicle kilometres of travel is multiplied by a fuel consumption rate (liter/vehicle-km). The amount of fuel consumed by a vehicle over a distance travelled is referred to as the vehicle fuel consumption rate.

4.2 Estimation of Automobile Fuel Consumption

INRO Consultants developed an EMME/2 macro for the macroscopic analysis of fuel

consumption (CONSOM.MAC). The macro is a powerful language in EMME/2 for the automation of repetitive and frequently used commands. This macro was not prepared for the public, but its use was authorized in this study. The macro estimates consumed fuel by automobile travel in the network. This estimation is based on traffic variables which are generated by EMME/2 and also automobile characteristics (i.e., weight, engine size). Car fleet of the INRO fuel model is represented by 1600 kg as average weight and 2.5 lit as average engine size. Accuracy of output of INRO fuel model can be accepted with regard to macroscopic analysis level of this research. The macro calculates fuel consumption based on average speed in the network for given distance. Average speed is based on travel time and distance matrices that reflect link characteristics. This macro allows users to change value of parameters to reflect conditions of the case study. Total fuel consumption is calculated on the basis of total vehicle kilometers of travel (VKT) under hot stabilized conditions and assuming that the engine is properly tuned. The macro begins with an equilibrium assignment with associated volumes and speeds. For each link, the average speed is computed based on travel time and distance matrices which are generated by the EMME/2. Then, fuel consumption rate is calculated based on average speed and auto characteristics. Finally, the fuel consumption is obtained by using fuel consumption rate and total vehicle kilometers. Accuracy of output of INRO fuel model can be accepted with regard to macroscopic analysis level of this research [22,23].

4.3 Estimation of Bus Fuel Consumption

A review of literature did not reveal suitable analytical methods for the estimation of fuel consumption of buses while operating on the Transitway as an important part of the transit network case study. Therefore, it was decided to modify a heavy vehicle fuel

consumption model for the estimation of bus fuel consumption.

A number of heavy vehicle (e.g., trucks) fuel consumption models have been developed. One of these is the Australian Road Research Board's Road Fuel Consumption Model (ARFCOM). This model can be used to estimate fuel consumption of vehicles ranging from cars to 40 tonne articulated trucks. The model incorporates vehicular parameters for ten classes of vehicles including three car, one van and six truck classes [24]. The logic of the model is based on the tractive forces acting on a vehicle at its wheels, which are estimated using basic Newtonian mechanics. The model estimates total power required to overcome resistance forces, to run vehicle accessories and to overcome internal engine friction. The total power required from the engine, in conjunction with power efficiency factors, are used as the basis of estimating fuel consumption [24].

In this research, a method based on ARFCOM, was developed for obtaining bus fuel consumption estimates which is related to each of the four modes of driving. A method for bus fuel consumption estimation is necessary in order to study fuel savings attributed to system improvements. Fuel consumption is related to each of the four modes of driving: acceleration, cruise, deceleration and idle during bus operation on a route. General information and final equations for estimation of bus fuel consumption are represented as follows [24,63,64] (details are included in Appendix C):

Propulsion Force: Propulsion of a vehicle must provide the force necessary to overcome resistance to motion and to accelerate the vehicle. The highest acceleration rate is required in moving the vehicle from a standing position. Power produced by an engine is usually expressed in kilowatts (kw). Indicated power is the total power the engine produces. Subtracting from it the internal losses in the engine, shaft bearings, and so on, the brake power is obtained. This power represents the net usable power produced by the

engine. That power is further reduced by the resistance between the engine and the tractive wheels. For heavy vehicles, these include resistances in the clutch, gear box (which is different for each gear), differential, and shaft and axle bearings. The power remaining after these resistances is the effective power at wheels (i.e., the net power available for traction). The rolling resistance as well as other resistances have to be overcome. The total power required to drive the vehicle is the sum of the tractive force, the power to overcome internal engine friction and the power to run accessories such as the cooling fan, air conditioners, etc. First, the total engine power (kw) required has to be calculated. Second, a fuel-to-power efficiency factor will be used to calculate the fuel required by the engine to satisfy the power demand.

In the case of bus operation, the various components of the bus movement have to be taken into account. These are: acceleration, cruise, deceleration and idle. The calculation procedures and accuracy of fuel consumption estimates will depend on the available data. The minimum items required for application of the fuel consumption model are Transitway section distance, cruise speed, stopped time and average grade.

Rolling Resistance: Rolling resistance is taken to be the total of all forces, apart from aerodynamic drag, acting on vehicle. It includes all frictional forces from the output of the gear box to the wheels and the tire resistance forces. It strongly relates to road type and roughness, tire type, pressure and diameter and the load on the tire.

Aerodynamic Resistance: The aerodynamic resistance is dependent on vehicle size, shape, and the speed of travel. Other factors that affect aerodynamic resistance are: wind speed and direction, and density of air. The density of air varies with atmospheric pressure and therefore with temperature and altitude.

Inertial Force: The inertial force includes the forces required to accelerate the total vehicle mass and to accelerate the rotating parts within the vehicle. The major

components of the vehicle contributing to rotational inertia are the wheels and drive-train.

Gradient Resistance: The force required to overcome grades is defined by mass and percent grade.

Cornering Resistance: A vehicle moving around a curve is subject to a centrifugal force. Past research found the cornering stiffness to be dependent on the type and size of tire and to the load on the tire.

Drive-Line Efficiency: The tractive force required at the wheels for vehicle movement is provided by the engine and transmitted through such devices as the gear box, differential and clutch. It varies with the power load on the engine. The drive-line efficiency drops off slightly at low loads.

Power For Vehicle Accessories: The power required to run vehicle accessories, such as the engine cooling fan, air compressor and air conditioning, can add to the total power required to drive the vehicle.

Fuel Consumption Rate: The engine efficiency is a measure of how well the engine converts fuel to power. The fuel-to-power efficiency factor is used as a measure of engine fuel efficiency in the fuel consumption model. This in turn gives the fuel consumption (ml/s) per unit power (kw) of the engine. The vehicle requires very low power primarily when the vehicle is stationary, travelling down grades or at the start of a deceleration. A separate measure of idle fuel consumption could be used when the vehicle is stationary or if the power required of the engine is less than zero [24,63,64] (details are represented in Appendix C).

4.3.1 Acceleration Fuel Consumption

The following equations can be used to estimate fuel consumed during an initial speed of zero (at the station) to a final speed (cruise speed) of V. For articulated buses,

by using Equation C.41 (Appendix C), RPM (the engine speed) and then P_{tot} (the total power required by the engine) and β (the fuel-to-power efficiency factor) can be estimated by the following equations:

$$\begin{aligned} RPM = 600 + 44.1\ V + [\frac{221.26\ V}{(3.6\ V + 10)}]\ [\ 0.582 \\ + 6.55*10^{-5}\ M + 1.09*10^{-4}\ M*G + 5.73*10^{-4}\ V^{1.5} \\ + 2.22*10^{-3}\ V^2 + (1.1*10^{-3}M + 0.81125)\ a \\ + \frac{M\ (V^2/R_c - 0.981)^2}{82170 - 1.026\ M}] \end{aligned} \tag{4.1.1}$$

$$RPM = 2100 \tag{4.1.2}$$

RPM is equal to minimum values of Equations 4.1.1 and 4.1.2. P_{acs} can be estimated by using Equation C.24 (Appendix C).

$$P_{acs} = 1.42*10^{-3}\ RPM + 1.033*10^{-8}\ RPM^{2.5} \tag{4.2}$$

$$\begin{aligned} P_{tot} = 3.55 + V\ [\ 0.47 + 6.55*10^{-5}\ M + 1.09*10^{-4}\ M*G \\ + 2.22*10^{-3}\ V^2 + (1.1*10^{-3}M + 0.81125)\ a \\ + \frac{M\ (V^2/R_c - 0.981)^2}{82170 - 1.026\ M}\ ] + 1.42*10^{-3}\ RPM \\ + 6.12*10^{-6}\ RPM^2 + 1.033*10^{-8}RPM^{2.5} \end{aligned} \tag{4.3}$$

$$\beta = 0.059 + V\,[\,2.91*10^{-5} + 4.07*10^{-9}\,M + 6.77*10^{-9}\,M*G + 10^{-7}\,V^2 + (6.84*10^{-8}M+5.04*10^{-5})\,a + \frac{M\,(V^2/R_c - 0.981)^2}{1.32*10^9 - 16504\,M}\,] + 8.62*10^{-8}\,RPM + 6.06*10^{-13}\,RPM^{2.5} \quad (4.4)$$

where

P_{acs} : the power required to run the accessories (kw)
P_{tot} : the total power required by the engine (kw)
β : the fuel-to-power efficiency factor (ml/s/kw)
M : the total mass of vehicle (kg)
V : the speed (m/s)
a : the acceleration rate (m/s^2)
G : the percent grade (negative for downhill)
R_c : the radius of the curve (m)
RPM: the engine speed (rpm)

Thus, by using β, P_{tot} and Equation C.33.1 or C.33.2 (Appendix C), acceleration fuel consumption rate can be estimated.

By using the same procedure for standard buses, and using Equation C.45 (Appendix C), RPM and then P_{tot} and β can be estimated by:

$$RPM = 600 + 44.1\,V + [\frac{364.35\,V}{(3.6\,V + 10)}]\,[\,0.4062 + 6.44*10^{-5}\,M + 1.09*10^{-4}\,M*G + 4.56*10^{-4}\,V^{1.5} + 2.22*10^{-3}\,V^2 + (1.1*10^{-3}M+0.49167)\,a + \frac{M\,(V^2/R_c - 0.981)^2}{82170 - 1.723\,M}] \quad (4.5.1)$$

$$RPM = 2100 \tag{4.5.2}$$

RPM is equal to minimum values of Equations 4.5.1 and 4.5.2. P_{acs} can be calculated by using Equation C.24 (Appendix C).

$$P_{acs} = 1.42*10^{-3}\ RPM + 6.27*10^{-8}\ RPM^{2.5} \tag{4.6}$$

$$\begin{aligned} P_{tot} = {} & 2.16 + V\ [\ 0.2812 + 6.44*10^{-5}\ M + 1.09*10^{-4}\ M*G \\ & + 2.22*10^{-3}\ V^2 + (1.1*10^{-3}M+0.49167)\ a \\ & + \frac{M\ (V^2/R_c - 0.981)^2}{82170 - 1.723\ M}\ ] + 1.42*10^{-3}\ RPM \\ & + 4*10^{-6}RPM^2 + 6.27*10^{-8}\ RPM^{2.5} \end{aligned} \tag{4.7}$$

Therefore, by using β, P_{tot} and Equation C.33.1 or C.33.2 (Appendix C), acceleration fuel consumption can be estimated.

4.3.2 Deceleration Fuel Consumption

The equation for deceleration fuel consumption is similar to that for acceleration fuel consumption to estimate fuel consumed during initial speed of V (cruise speed) to a final speed of zero (at the station). The total tractive power term can be negative when the vehicle is decelerating. During the whole deceleration process, the total tractive force is less than zero or equal to zero. If $P_{tr} \geq 0$, P_{tot} and β can be estimated by Equations 4.3 and 4.4 for articulated buses. If $P_{tr} < 0$ and $P_{ntr} \geq P_{acs} + P_{eng}$, the following equation can be used to estimate fuel consumption during deceleration.

$$P_{tot} = 3.55 + V\,[\,0.3796 + 5.3*10^{-5}\,M + 0.882*10^{-4}\,M*G + 1.8*10^{-3}\,V^2 + (0.891*10^{-3}M+0.6571)\,a + \frac{M\,(V^2/R_c - 0.981)^2}{101444 - 1.267\,M}\,] + 1.42*10^{-3}\,RPM + 6.12*10^{-6}RPM^2 + 1.033*10^{-8}\,RPM^{2.5} \quad (4.9)$$

Where

P_{tr} : the total tractive power at the drive wheels (kw)
P_{acs}: the power required to run the accessories (kw)
P_{eng}: the power required to overcome engine drag (kw)
P_{ntr}: the tractive power available at the engine (kw) when tractive power is negative (when the vehicle is decelerating or travelling downhill)

It is assumed that if $P_{tr}<0$ and $P_{ntr}\leq P_{acs}+P_{eng}$ fuel consumption rate is equal α (m lit/s) [63].

For standard buses if $P_{tr}\geq 0$, P_{tot} and β can be estimated by Equations 4.7 and 4.8. If $P_{tr}\leq 0$ and $P_{ntr}\geq P_{acs}+P_{eng}$, P_{tot} can be estimated by:

$$P_{tot} = 2.16 + V\,[\,0.2278 + 5.21*10^{-5}\,M + 0.882*10^{-4}\,M*G + 1.8*10^{-3}\,V^2 + (0.891*10^{-3}M+0.3982)\,a + \frac{M\,(V^2/R_c - 0.981)^2}{101444 - 2.127\,M}\,] + 1.42*10^{-3}\,RPM + 4*10^{-6}RPM^2 + 6.27*10^{-8}\,RPM^{2.5} \quad (4.10)$$

It is assumed that if $P_{tr}<0$ and $P_{ntr}\leq P_{acs}+P_{eng}$ fuel consumption rate is equal α (m lit/s) [63].

4.3.3 Cruise Fuel Consumption

Cruise mode is defined as travel from the end of an acceleration process which starts from a stopped to the initiation of the next deceleration [64]. The following equations

for constant-speed cruise mode can be used to calculate fuel consumption for articulated buses.

$$\beta = 0.059 + V\,[\,3.61*10^{-5} + 4.07*10^{-9}\,M + 6.77*10^{-9}\,M*G + 3.56*10^{-8}\,V^{1.5} + 10^{-7}\,V^{2} + \frac{M\,(V^{2}/R_{c} - 0.981)^{2}}{1.32*10^{9} - 16504\,M}\,] \tag{4.11}$$

$$P_{tot} = 3.55 + V\,[\,0.582 + 6.55*10^{-5}\,M + 1.09*10^{-4}\,M*G + 0.038\,V + 5.73*10^{-4}\,V^{1.5} + 2.22*10^{-3}\,V^{2} + \frac{M\,(V^{2}/R_{c} - 0.981)^{2}}{82170 - 1.026\,M}\,] \tag{4.12}$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
G : the percent grade (negative for downhill)
R_c: the radius of the curve (m)

For the standard buses, the following equations can be used:

$$\beta = 0.059 + V\,[\,4.15*10^{-5} + 6.59*10^{-9}\,M + 1.116*10^{-8}\,M*G + 4.67*10^{-8}\,V^{1.5} + 2*10^{-7}\,V^{2} + \frac{M\,(V^{2}/R_{c} - 0.981)^{2}}{8.03*10^{8} - 18529\,M}\,] \tag{4.13}$$

$$P_{tot} = 2.16 + V\,[\,0.4062 + 6.44*10^{-5}\,M + 1.09*10^{-4}\,M*G + 0.031V + 4.56*10^{-4}\,V^{1.5} + 2.22*10^{-3}\,V^{2} + \frac{M\,(V^{2}/R_{c} - 0.981)^{2}}{82170 - 1.706\,M}\,] \tag{4.14}$$

Therefore, by using β, P_{tot} and Equation C.33.1 or C.33.2 (Appendix C), cruise fuel consumption rate can be estimated.

4.3.4 Fuel Consumption While Stopped (Idle)

By using the results for articulated buses, idle fuel rate (m lit/s) is 0.5926 m lit/s and for standard buses, it is 0.3989 m lit/s. The mentioned values were estimated by using power for vehicle accessories (Appendix C).

4.3.5 Estimation of Total Bus Fuel Consumption

The total fuel consumption for an acceleration-cruise-deceleration-idle cycle for bus operation on the Transitway can be estimated by:

$$F_{tot} = F_a + F_c + F_d + F_i \tag{4.15}$$

where

F_{tot} : total fuel consumption
F_a : fuel consumption during acceleration
F_c : fuel consumption during cruise speed
F_d : fuel consumption during deceleration
F_i : fuel consumption during idle mode

4.3.6 Validation of the Modified Model

Validation of the fuel consumption model is described here. Due to lack of tests on bus engines in the laboratory, results of this modified model were checked against of the 1994 OC Transpo average bus fuel consumed for various types of buses. The OC Transpo report describes average fuel consumption (km/liter) of standard (40') and articulated (60') buses during each month of year 1994 (Appendix C). According to this report, average fuel consumption for articulated and standard buses are 0.797 and 0.591 liters/km, respectively in 1994. The modified model for bus fuel consumption estimation for each of the four modes of driving, namely acceleration, cruise, deceleration and idle

was used for the Transitway from Blair station to Laurier station (seven links) and from Lebreton station to Baseline station (six links). The OC Transpo actual (test) data for buses operating on the Ottawa-Carleton Transitway were used to obtain the required parameters such as cruise speed and travel time during acceleration, deceleration and cruise mode between stations. By using the following assumptions, Equations C.20, C.21 (Appendix C), 4.1-4.14, and values of Table 4.1 for the above distances (link 1-13), average fuel consumption for articulated and standard buses was calculated (Appendix C). The assumptions are as follows:

- acceleration rate=0.96 m/s^2
- deceleration rate=1.72 m/s^2
- mass of articulated bus (without passenger)=17120 kg
- max. passengers for an articulated bus=95 pass
- mass of standard bus (without passenger)=10720 kg
- max. passengers for a standard bus=85 pass
- load factor=0.40 (including peak and off-peak hours)
- the cornering resistance force (because of curve)=0
- average dwell time=30 seconds
- average percent grade=%1

A comparison of the average fuel consumption of articulated and standard buses as found from OC Transpo data and estimates obtained from the model shows favourable results (Table 4.2).

For application purpose, a macro was prepared, based on the modified model, in the EMME/2 format for bus fuel consumption estimation on the Transitway. Bus fuel consumption for access and egress to the Transitway was estimated by using a macro developed by INRO Consultants based on average speed and total vehicle kilometres for

using in EMME/2 [22,23].

4.4 Fuel Consumption Projection and Technology Changes

Fuel consumption of bus and auto traffic was estimated under hot stabilized conditions and assuming that the engine is properly tuned. Subject to availability of information, these estimates can be further refined by interested researchers in order to take into account cold and/or improperly tuned engine effects [22,23,24].

It is reasonable to expect that fuel consumption for vehicles in the future (2011 in this study) will be different from what they are today due to technology improvements. Khan undertook a study for Transport Canada in order to provide fuel and emission factors for passenger transportation [65]. The projection year in the Khan's study was 2010. Selected results of this study were used for the estimation of fuel consumption in the case study. It can be assumed that there is a five year time lag between the new car fleet and over-the-road fleet. According to Khan's study, the automobile fuel consumption (liter/100 km) for urban application in 2010 is expected to experience a reduction of 20.3% as compared with the 1987-1990 fuel intensity.

Due to technology improvements, the fuel consumption rate of intercity buses was projected to be 90% of their current rate for years beyond 2000. This study does not focus on transit bus case. Due to lack of information it was assumed that improvements in the urban bus would be similar to that of intercity bus. Thus, the same factor for increase in fuel efficiency of future intercity buses is assumed for the urban transit case [65].

Table 4.1-Fuel consumption of articulated and standard buses (Appendix C)

Stations	Dist.(km)	Articulated Bus(litres)					Standard Bus(litres)				
		acce.	cruise	dece.	idle	total	acce.	cruise	dece.	idle	total
link 1	1.77	0.969	0.591	0.006	0.018	1.584	0.773	0.444	0.004	0.012	1.233
link 2	1.02	1.190	0.336	0.006	0.018	1.550	0.966	0.260	0.004	0.012	1.242
link 3	1.25	0.561	0.378	0.005	0.018	0.962	0.439	0.273	0.003	0.012	0.727
link 4	1.37	0.503	0.414	0.005	0.018	0.940	0.392	0.297	0.003	0.012	0.704
link 5	0.74	0.283	0.206	0.003	0.018	0.510	0.218	0.144	0.003	0.012	0.376
link 6	1.02	0.500	0.300	0.004	0.018	0.822	0.390	0.216	0.003	0.012	0.621
link 7	0.54	0.139	0.148	0.002	0.018	0.307	0.107	0.101	0.002	0.012	0.222
link 8	2.06	0.618	0.655	0.005	0.018	1.296	0.485	0.475	0.003	0.012	0.975
link 9	1.55	0.814	0.498	0.005	0.018	1.335	0.645	0.369	0.004	0.012	1.030
link 10	4.68	0.579	1.535	0.005	0.018	2.137	0.452	1.104	0.003	0.012	1.572
link 11	1.42	0.648	0.440	0.005	0.018	1.111	0.509	0.321	0.003	0.012	0.846
link 12	0.45	0.693	0.125	0.004	0.018	0.840	0.552	0.094	0.003	0.012	0.661
link 13	1.12	0.638	0.340	0.005	0.018	1.001	0.502	0.248	0.003	0.012	0.765
TOTAL FUEL(lit)				14.395					10.972		
AVERAGE FUEL (lit/km)				0.758					0.578		

Table 4.2-Comparison of estimation of fuel consumption from the model and OC Transpo data

	Articulated Bus(liters/km)	Standard Bus(liters/km)
OC Transpo estimate	0.797	0.591
Model estimate	0.758	0.578
% Difference	4.9%	2.2%

Due to technology improvements, the fuel consumption rate of intercity buses was projected to be 90% of their current rate for years beyond 2000. This study does not focus on transit bus case.

Next chapter contains a description of how to estimate air pollution emissions (i.e., HC, CO, NO_x and CO_2) in this research.

CHAPTER 5

ESTIMATION OF EMISSIONS

5.1 Overview

Transportation is a major and growing source of pollutants while pollution from many other sources has either been declining or at least stabilizing. A similar pattern is seen in the trend of fuel consumption where the transportation sector's consumption was seen to be on the rise while the use of energy by other sectors was declining or growing slowly [68]. As with energy use, pollutants can be calculated on a per km basis. Transportation energy use and transportation pollution are very strongly related, since emissions result from the burning of fuels (i.e., gasoline and diesel). Four types of emissions, including CO, NO_x, HC and CO_2, are investigated in this chapter.

5.2 Carbon Monoxide (CO)

Vehicles that use the internal combustion engine are the main source of this pollutant. Carbon monoxide is harmful to human life because it interferes with the absorption of oxygen by red blood cells. CO combines with haemoglobin over 200 times faster than oxygen, thereby blocking its function and restricting the supply of oxygen by the blood to body tissue. CO can also inhibit the utilization of oxygen by tissues. Exposure to high levels of carbon monoxide can affect the central nervous system, vision and judgement. The amount of CO absorbed by blood is a function not only of the CO concentration in the air, but also of the duration of a person's exposure to the polluted air. It is known that CO emission rate decreases if the average vehicle speed increases. On the other hand,

if traffic congestion is high, the CO concentration is expected to be higher in congested urban corridors [26,68].

5.3 Nitrogen Oxides (NO_x)

Nitrogen oxides can have a variety of direct and indirect effects on human life. In emission investigations, a number of "nitrogen oxides" (NO_x) consist of NO, NO_2 and other compounds. NO_2 is mainly a secondary pollutant whose presence in the air is caused by oxidation of nitric oxide (NO). Acute exposure to NO_2 decreases gaseous exchanges in blood and has an adverse impact on the lung function. In general, the most serious health effects of nitrogen oxides occur in combination with other air pollutants. They are especially dangerous for persons with existing health problems [68].

5.4 Hydrocarbon (HC)

Hydrocarbons are compounds of carbon and hydrogen. Motor vehicle exhaust is a major HC source. In urban areas, most hydrocarbons are not directly harmful. Some hydrocarbons can cause unpleasant effects such as eye irritation, coughing and sneezing, drowsiness and symptoms akin to drunkenness, but these effects occur at relatively high concentrations [68].

5.5 Carbon Dioxide (CO_2)

CO_2 is colourless and a natural constituent of air. It is also a major component of greenhouse gases. The concentration of carbon dioxide varies due to changes in natural biological activity and the combustion of carbon-based fuels such as gasoline and diesel. It is well known that carbon dioxide is linked with global warming or the greenhouse

effect. Carbon dioxide in the atmosphere traps heat between the surface of the earth and the upper atmosphere. Increasing carbon dioxide may trap enough heat in the atmosphere to cause an increase in the earth's temperature. The current concern of scientists is that CO_2 and other greenhouse gases are being added to the atmosphere which will accelerate global warming [26].

5.6 Estimation of Emissions

For the purpose of this study, there is a need to estimate emissions of CO, NO_x, HC and CO_2 for urban transportation corridors. Two major vehicular modes of travel are involved in this research; auto and bus.

Recent studies have suggested that vehicle emissions can be predicted with reasonable accuracy by the MOBILE model (the vehicle emission factor computer software developed by the United States Environmental Protection Agency, EPA) [69,70]. The model was recently updated and the current version is called MOBILE5a. A modified version for Canadian use (adapted by Environment Canada), called MOBILE5c is based on MOBILE5a. The model represents average estimates of emission responses to changes in specific (environmental and vehicular) variables as found in vehicle tests. MOBILE5c provides values of these variables for Canadian provinces (e.g., Ontario, Quebec) [25].

The MOBILE5c computer program is used to estimate average emission factors in terms of grams per vehicle miles (kms) of travel. The program's scope is limited to the three major classes of regulated pollutants, namely: carbon monoxide (CO), nitrogen oxides (NO_x) and hydrocarbons (HC). These emission factors are estimated for specified classes of on-road motor vehicles under a variety of environmental and operating conditions.

Emission factors are affected by variables such as the age of the vehicle, pollution control equipment used and the type of fuel which is consumed. In addition, ambient temperature and especially speed of vehicles are important for the estimation of emission factors in MOBILE5c program. Type of vehicles that can be considered in this program are as follows:

- LDGV : light-duty gasoline-fuelled vehicles
- LDGT1 : light-duty gasoline-fuelled trucks1 (up to 6000 lb GVW)
- LDGT2 : light-duty gasoline-fuelled trucks2 (6001-8500 lb GVW)
- LDGT : light-duty gasoline-fuelled trucks
- HDGV : heavy-duty gasoline-fuelled vehicles (over 8500 lb GVW)
- LDDV : light-duty diesel vehicles
- LDGT : light-duty diesel trucks (up to 8500 lb GVW)
- HDDV : heavy-duty diesel vehicles (over 8500 lb GVW)
- MC : motorcycles

Emissions of LDGV vary considerably with ambient temperature. This does not hold for the HDDV to the same degree. The minimum and maximum daily temperatures are used directly in MOBILE5c. Emission factors of HDDV and LDGV are affected strongly with the average speed of vehicles.

The emission rates obtained from the MOBILE5c model reflect the Federal Test Procedure (FTP) which represents an urban vehicle trip in typical driving conditions. The model is a macroscopic representation of the driving cycle on a link or a series of links forming a route. Driving condition is specified in the form of average speed.

Since the outputs of a traffic assignment process are average speed and vehicle-kms on a link/route, the MOBILE5c model, which is based on trip characteristics, can be

consistent with the traffic assignment methodology used in this research [70].

In transportation, emissions are produced when: (a) a vehicle is started after being idle for a relatively long period of time (i.e., cold start emissions), (b) when the vehicle is re-started after a shorter interval (i.e., hot start emissions), (c) while running and, (d) after the vehicle is parked (i.e., evaporative emissions) [25]. This defines three modes for vehicle operation: cold start, hot start and hot stabilized. Emissions generally are highest when a vehicle is in cold start mode (i.e., during this phase the engine and emission control systems have not reached operating temperature). Emissions are generally somewhat lower in hot start and lowest when the vehicle is operating in stabilized mode.

The MOBILE5c model takes into account various operating modes (e.g., cold starts, etc.) in the process of estimating emission factors [25,71]. The FTP is based on the assumption that 43% of all vehicle starts are cold starts and 57% of starts are hot starts. Furthermore, the FTP assumes a trip length of 12 kms (7.5 miles). If the average trip length for an urban area is different than the FTP value, there would be differences between actual vehicle engine operating temperature and that implied by model application [70].

A number of other limitations of the MOBILE5c model should be noted here. This model does not take into account the effect of grade on emission factors. The FTP assumes level roadway in its driving tests. Therefore, in emission testing, additional power required for a vehicle to climb a grade is not taken into account. However, given that most routes in urban areas may have a net grade of zero, this limitation is not expected to introduce significant errors in emission estimation process.

For the long range type of planning problems, users of this model have expressed concern that it cannot take into account the dynamic behaviour of vehicles that are expected to occur due to adaptive traffic control systems. Such systems are expected to be in existence beyond year 2005. Furthermore, there appears to be a lack of an

explanation of how the MOBILE5c program incorporates the effects of mandatory inspection and maintenance (I/M) program.

Despite these limitations noted here, the accuracy of the outputs of this model can be accepted at a macroscopic level of analysis. Presently, this model is used extensively by transportation departments of governments, universities and consultants. In this research, its application is compatible with the macroscopic nature of traffic assignment and fuel estimation components of the overall modelling framework.

INRO Consultants developed an EMME/2 macro for the analysis of pollutant emissions (EMISSION.MAC). This macro was not prepared for the public, but its use was authorized in this research. This macro uses the results provided by the MOBILE5c software. The emission rates obtained from MOBILE5c are used to develop emission rate functions. For the estimation of emissions rates, some parameters such as weather (the seasons) and the vehicle fleet (i.e., age distribution, average weight and engine size) were used. This model is executed in several steps: (a) estimation of the emission rates by use of MOBILE5c, (b) developing of emission rate curves, and (c) calculation of traffic assignment and the resulting emissions. These three steps result in the development of the EMISSION.MAC macro [22,23]. The parameters considered in the macro are as follows:

- Pollutants: Estimation of emissions of HC, CO and NO_x by using MOBILE5c software for mobile road sources. In this model, two types of vehicles are considered including the Light-Duty Gasoline Vehicles (LDGV) and the Heavy-Duty Diesel Vehicles (HDDV) which correspond to the urban transit buses.
- Age of Vehicles: The estimation of the emission factors is based on the distribution of the age of the vehicle fleet. These data are provided by MOBILE5c.
- Seasonal Effects: For estimation of emissions, temperature is an important

parameter. The year was divided into four seasons for measuring the impact of the seasonal variations on the emissions. The MOBILE5c software manual provides the observed average temperature for each of these seasons.

- Operating Mode: This parameter of a vehicle is important for emission rates. There are three operating modes including the cold start, the hot start and the cruising mode (i.e., hot stabilized conditions). In this macro, two modes are considered: cold start and cruising modes. It was assumed that all automobiles starts are cold starts.
- Speed: This parameter has an important impact on rate of the emissions. The information provided by MOBILE5c shows that the emission rates are high at low speeds.

Although it is possible to use the emission rates/speed relations in a discrete form directly, it appears more precise when estimation of the emissions are based on continuous curves. The use of such curves reduces the computation time and better reflects the nature of the emission rates/speed relations [22,23].

These emission rates obtained from MOBILE5c were used to develop emission rate functions by treating speed as a variable. The fitting of the curves was achieved by non-linear regression analysis. Different combinations of pollutants, seasons (i.e., four different seasons are included in this macro), vehicles and modes were modelled. The curves provided are polynomials of degree 5 for the LGDV and HDDV [22,23].

In this research, the INRO macro (EMISSION.MAC) was used to estimate emissions (i.e., HC, CO and NO_x emissions) on the links. The outputs of the EMME/2 were used as inputs to this macro. The macro starts with an equilibrium assignment which produces the volumes for various operating modes (i.e., cold start period and cruising mode). Following this, emissions are computed by using the emission functions corresponding to the specified season for the study [22,23].

It is reasonable to expect that emissions from transportation sources in the future will be different from today due to technology improvements. The MOBILE5c model can estimate emission factors for future years up to 2010 [25]. By using the outputs of the model for years between 1994 and 2010 in terms of various conditions, reduction factors for HC, NO_x and CO were estimated. These values for Light-Duty Gasoline Vehicles are 0.650, 0.694 and 0.683 for CO, NO_x and HC, respectively (i.e., as compare with 1994 emissions factors). The values for Heavy-Duty Diesel Vehicles are 0.887, 0.441 and 0.778 for CO, NO_x and HC, respectively.

For the estimation of CO_2, emission factors based on fuel types were used. For each type of fuel, emissions of carbon dioxide, expressed as tonnes of carbon, were estimated by converting the energy contents of the fuels to mass per energy unit. On the basis of the estimates of gasoline and diesel fuel consumption and emission factors shown in Table 5.1, carbon dioxide emission were calculated [26].

Table 5.1-The CO_2 emission factors

Type of Fuel	CO_2 (tonnes/kilo litre)
Diesel	2.73
Gasoline	2.36

Next chapter covers an optimization methodology, based on direct search method which was used in this research.

CHAPTER 6

OPTIMIZATION METHODOLOGY FOR AN INTEGRATED MULTIMODAL CORRIDOR

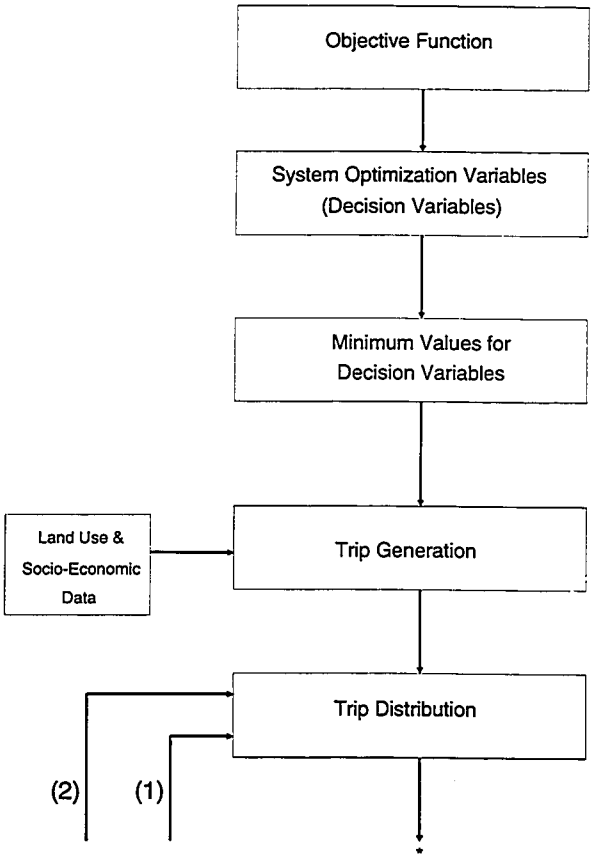
6.1. Introduction

A methodology was developed that enabled the optimization of the multimodal corridor in terms of improving traffic flow efficiency, energy efficiency and environmental quality. Objective function may lead to mathematical statements in terms of the decision variables of the system . The choice of optimization criteria was guided by policy factors [37].

6.2 Optimization Framework

A methodological framework for the optimization of a major transportation corridor is shown in Figure 6.1. A sequence of steps, noted below, is required to reach the optimal system design and operation.

1. Statement of the objectives and optimization criteria (i.e., minimizing in-vehicle travel time/pass-km, fuel consumption/pass-km, and emissions (HC, CO, NO_x and CO_2)/pass-km).
2. Selection of a set of optimization variables (i.e., fare, parking fee, toll, etc.).
3. Determination of acceptable range of values for the variables.
4. Model initialization (i.e., including four-step demand model) for initial estimation of travel demand for various available modes on the network in EMME/2 framework.
5. Calculation of level of service variables (e.g., travel time) in equilibrium road


Objective Function
System Optimization Variables
(Decision Variables)
Minimum Values for
Decision Variables
Land Use &
Socio-Economic
Data
Trip Generation
Trip Distribution
(2)
(1)

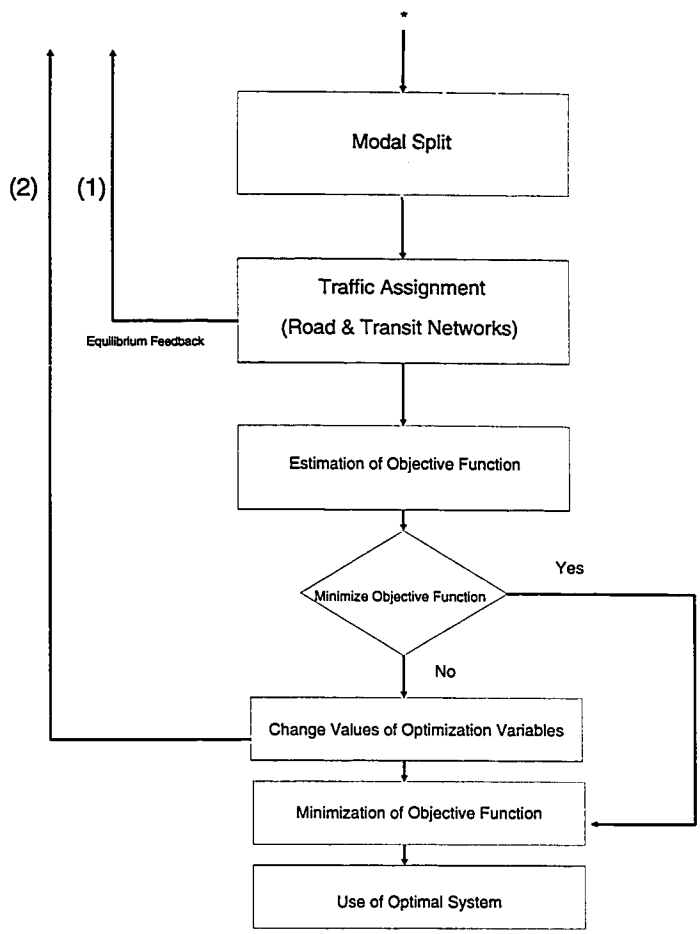


Figure 6.1-Methodological Framework for Optimization of A Major Transportation Corridor

condition by using EMME/2.

6. Estimation of corridor travel demand (person-trips) for various modes, in the equilibrium condition, based on the optimization variables (e.g., parking charge, fare, etc.).
7. Estimation of the objective functions (i.e., in-vehicle travel time/pass-km, fuel consumption/pass-km and emissions/pass-km).
8. Identification of the best values for optimization variables which include fare, parking fees and freeway tolls based on an optimization method. By changing values of the optimization variables and using trip distribution model as well as modal split and traffic assignment models, new volumes on routes are estimated in the corridor. These new volumes have new level of service effects in the network. Next, the objective function based on the new level of service and optimization variables is calculated. The resulting objective function value is compared with its previously calculated value. The design of the optimization model will signal to the user to change values of decision variables in order to move in the direction of finding the minimum value of the objective function.
9. Use of optimal system.

6.3 Solving the Optimization Problem

For the minimization of the objective functions, a method is needed to solve the optimization problem. After a literature review on optimization methods, the direct search method as a formal approach was selected for the minimization of objective functions in this research. The direct search method directly deals with the objective function, avoiding the difficulties of calculating the derivative of function. Here are the reasons

for choosing this method: Firstly, the functions used in this study are non-linear and finding the absolute values of their derivatives are difficult making the use of analytical methods (i.e. nonlinear programming methods) unfeasible. Secondly, the route capacity is the only constraint in this case, and also the relationship between optimization variables is very difficult to find. The direct search method was selected as a suitable optimization method for application in this study. This method provides the rules for moving from point to point in the path across the feasible region. It guides the user in the choice of a new direction and suggests how far to move [72,73]. The objective function is estimated at a series of points. These form a directed search across the feasible region. This method can be described in terms of base points and temporary positions. The starting point is the minimum values of variables. These can be called the first base point, denoted by:

$$B^{(0)} = (b_1^{(0)}, b_2^{(0)}, \ldots b_n^{(0)}) \qquad (6.1)$$

Where $B^{(0)}$ is the first based point and $b_1^{(0)}, \ldots, b_n^{(0)}$ are the values of initial variables.

The objective function is estimated at $B^{(0)}$. Then a step length δ_i is chosen for each variable. This will be expressed in the vector Δ_i whose ith component is δ_i. All the rest are the minimum values for each variable (according to the constraint). The next step is changing the variable by amounts $+\delta_i$ or $-\delta_i$ each time. The change can be accepted if it leads to an improvement. When variables have been perturbed, they can lead to the new base point $B^{(1)}$. Thus, by using the new base point ($B^{(0)} + \Delta_1 = B^{(1)}$), the objective function will be estimated. If $f(B^{(1)})<f(B^{(0)})$, then the point $B^{(1)}$ is called the temporary position and designated by $T_1^{(0)}$. Otherwise if $f(B^{(1)})\geq f(B^{(0)})$, it should be estimated as $f(B^{(0)} - \Delta_1)$ (except the first value, in this case). If it is less than $f(B^{(0)})$, this is the

temporary position. If this offers no improvement, $B^{(0)}$ is denoted as the temporary position. The next variable is perturbed about the temporary position $T_1^{(0)}$ instead of the original base , $B^{(0)}$. The $T_2^{(0)}$ will be computed as the new temporary position. In general, the ith temporary position, $T_i^{(0)}$, is obtained from $T_{i-1}^{(0)}$ by the following equation:

$$T_i^{(0)} = \begin{cases} T_{i-1}^{(0)}+\Delta_i, \text{ if } f(T_{i-1}^{(0)}+\Delta_i) < f(T_{i-1}^{(0)}) \\ T_{i-1}^{(0)}-\Delta_i, \text{ if } f(T_{i-1}^{(0)}-\Delta_i) < f(T_{i-1}^{(0)}) < f(T_{i-1}^{(0)}+\Delta_i) \\ T_{i-1}^{(0)} \quad \text{ if } f(T_{i-1})^{(0)} < \min[\, f(T_{i-1}^{(0)}+\Delta_i), f(T_{i-1}^{(0)}-\Delta_i)] \end{cases} \tag{6.2}$$

This equation covers all i ($0 \le i \le n$). This approach can be continued for other variables. When all the variables have been dealt with, the last temporary point $T_n^{(0)}$ is denoted as the second base point $B^{(1)}$. All these moves, which determine the movement from first point to second point, establish a pattern of movement. In this step, it can be assumed that the pattern continues with the start of the next temporary search to a position, not at $B^{(1)}$ but a point $2(B^{(1)} - B^{(0)})$ away from $B^{(0)}$. Therefore, $T_0^{(1)}$ can be calculated by:

$$T_0^{(1)} = B^{(0)} + 2(B^{(1)} - B^{(0)}) = 2B^{(1)} - B^{(0)} \tag{6.3}$$

To calculate $T_i^{(1)}$ for i=1,2,...,n, the process is the same as given by the equations for $T_i^{(0)}$, with superscript 1 replacing zero. Next, if the final temporary position $T_n^{(1)}$ improves the value of the objective function at $B^{(1)}$, this becomes the new base point.

$$B^{(2)} = T_n^{(1)} \quad \text{ if } f(T_n^{(1)}) < f(B^{(1)}) \tag{6.4}$$

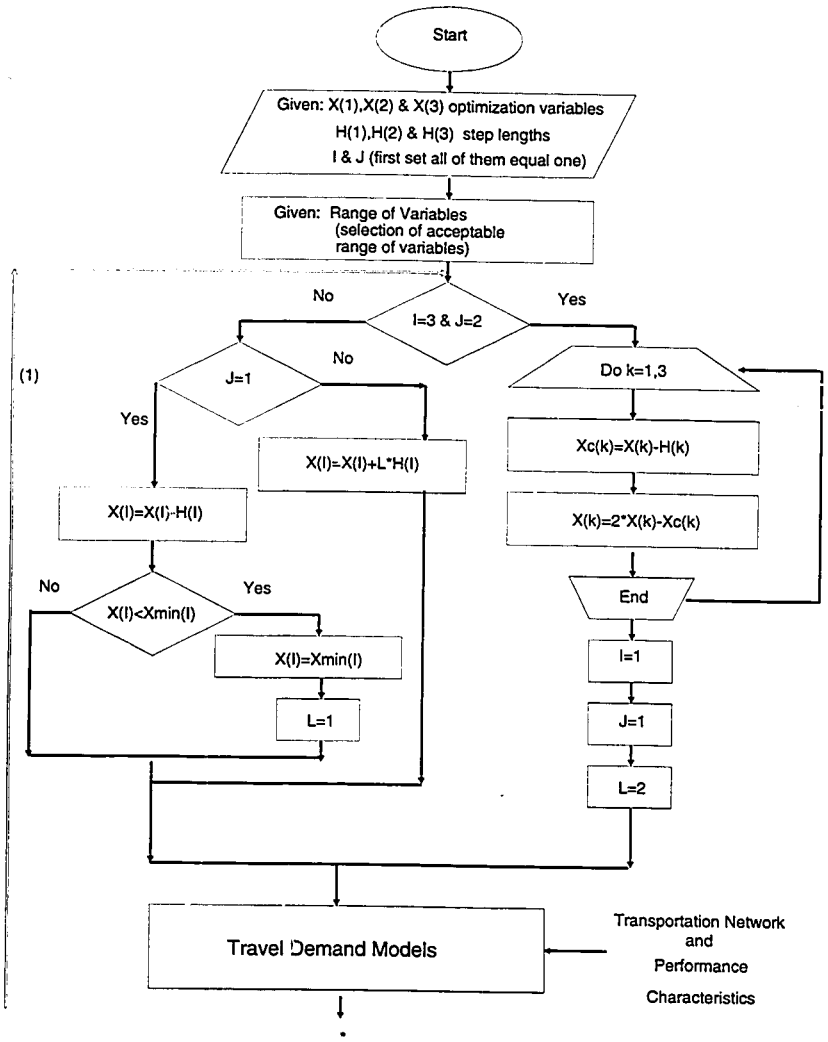
If this move turns out to be a false move, the previous base point should be used. After continuing this procedure, if there is no improvement, the step lengths should be changed

to smaller step lengths than the initial step lengths. The whole procedure should be repeated until the required accuracy is obtained. Figure 6.2 shows a flow chart of this process based on a set of defined step lengths [71,72].

A brief description of this flow chart based on the optimization variables is given here. X(1), X(2) and X(3) are the optimization variables. Their values should be determined as input data. The initial values of these variables are minimum values of the decision variables (i.e., Xmin(1), Xmin(2) and Xmin(3)). By decreasing and increasing step lengths (i.e., H(1), H(2) and H(3)) based on the direct search method, the new values of the variables can be obtained. In Figure 6.2, I is number of the decision variables. That is, its value is 1, 2 or 3. Based on decreasing and increasing step lengths for the variables, the value of J is 1 or 2. For decreasing step length J=1 and increasing step length for each value of the decision variable, J=2.

In the first step, for all optimization variables, there is only one option to change values of the variables (regarding the initial values of the variables). Only increasing the variables by step lengths can be accepted. After this step, there are two options for each variable to change (i.e. decreasing and increasing by step length). For each run, there is a new set for values of the decision variables. These can be used as input data for each run. Initial values of I and J are 1 for the first run, but these values will change after each run. This flow chart is for any defied step lengths.

For each run, level of service variables (e.g., travel time) are determined by using the EMME/2. In reference to Figure 6.1, the objective function is estimated after each run. This procedure should be continued until there is no improvement in changing values of the decision variables for minimization of the objective function. Then, by using last values of the variables as their initial values, the step lengths should be changed to smaller step lengths (as compared with the initial step lengths) and the whole procedure


Start
Given: X(1),X(2) & X(3) optimization variables
H(1),H(2) & H(3) step lengths
I & J (first set all of them equal one)
Given: Range of Variables
(selection of acceptable
range of variables)
I=3 & J=2
No
Yes
(1)
J=1
No
Yes
X(I)=X(I)+L*H(I)
X(I)=X(I)-H(I)
X(I)<Xmin(I)
No
Yes
X(I)=Xmin(I)
L=1
Do k=1,3
Xc(k)=X(k)-H(k)
X(k)=2*X(k)-Xc(k)
End
I=1
J=1
L=2
Travel Demand Models
Transportation Network
and
Performance
Characteristics

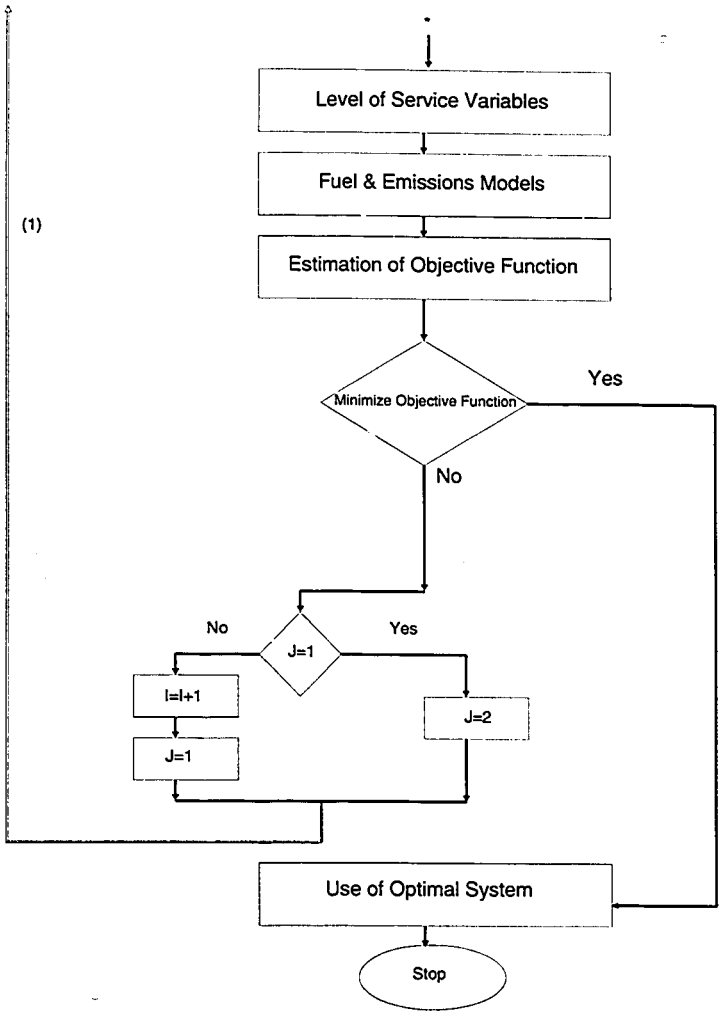


Figure 6.2-Flow Chart of Optimization Process

should be continued, as shown in Figure 6.2, until the required accuracy is obtained. The methodology developed in this research calls for the use of an Electronic Toll Collection (ETC) system, which is a part of the Advanced Traffic Management System.

CHAPTER 7

APPLICATION OF THE METHODOLOGY FOR TRAVEL CORRIDORS OPTIMIZATION

7.1 Introduction

The methodology developed in this research was applied to a major multimodal travel corridor in the Regional Municipality of Ottawa-Carleton (RMOC) for the p.m. peak period.

The RMOC covers an area of approximately 2,767 square kilometres. The Official Plan of the RMOC incorporates three major urban centers outside the green belt as the key locations for the region's future development. Three major travel corridors, namely the eastern corridor, the western corridor and the south-western corridor connect theses outlying centers with the Ottawa-Hall central business districts. These corridors feature high volume commuter routes, good express transit services and the highest level of traffic congestion experienced during the peak periods [2]. The eastern corridor was selected as area of the case study. The travel demand, infrastructure and other factors correspond to the year 2011.

Specifically, it was intended to determine the best values of tolls on freeway, parking charges in central area and public transit fare in order to minimize in-vehicle travel time as well as fuel consumption and air pollution emissions per pass-km during the p.m. peak period in the urban travel corridor. A specific combination of freeway toll, parking charge and transit fare was defined as a scenario for demand management.

As a part of demand management strategies, tolls were assumed for the freeway, implemented through electronic toll collection technology. Another assumption for the

case study is that there is no ramp metering involved, given the policy of charging a fee for the use of the freeway. The projected arterial traffic control system is the same as used at present. It was assumed that arterials serve the access and egress function in addition to line haul function in the corridor.

Direct search method (i.e., formal approach) was selected to minimize objective function (see Chapter 6 for details). This method provides the rules for moving from point to point in the path across the feasible region. It guides the user in the choice of a new direction and suggests how far to move [72,73]. Based on this method, for each optimization process, one objective function should be determined (e.g., in-vehicle time). There are some objective functions that have the same direction for increasing or decreasing (e.g., vehicle fuel consumption and emissions) based on changes of optimization variables. However, the minimization of in-vehicle travel time per pass-km was selected as the first objective for the case study. In-vehicle travel time is an important level of service variable and can be responsive to planning and policy strategies. Also, total travel time per pass-km and user cost (i.e., based on parking cost, operating cost, toll and public transit fare) per pass-km were estimated as well for all scenarios tested. Furthermore, the minimization of fuel consumption and emissions per pass-km were used as other objectives in this research. The results obtained from an analysis of scenarios are illustrated by suitable tables and figures, reported in the following sections of this chapter.

The EMME/2 was used as framework for developing and testing scenarios in order to find best values of optimization variables based on minimization of the objective functions. An EMME/2 macro was developed to forecast travel demand based on the

calibrated four-step travel demand model (see Chapter 2). Travel times were obtained from the use of the EMME/2 software. Fuel consumption and emissions were calculated by using the models described in Chapters 4 and 5.

For the case study, three modes (bus, car and carpool) were specified. Since the 1986 database did not include "park-and-ride" mode and the modal split model did not include this travel option, this case does not differentiate between trips by this mode and other transit trips. The methodological framework has the capability to include this level of detail provided that O-D data become available. Automobiles and buses are the main modes of travel in the region. It was assumed that the Transitway is used only for buses. The Transitway, due to its access control nature, enables the achievement of bus speeds that are higher than achievable in mixed traffic environment. The Transitway-based rapid bus transit service is much more attractive to the passenger than buses operating in mixed traffic [74]. The assumption of the availability of bus rapid transit service is realistic since the Transitway is expected to be completed by 2011 [75]. For the case study, possible location of new stations on the Transitway were obtained from RMOC and OC Transpo. As noted earlier, it was assumed that the Transitway is used only for buses. The freeway is used by automobiles and arterials serve automobile traffic and also provide the feeder function for buses.

7.2 Specification of the Variables for the Demand Models

Forecasts of land use and socio-economic conditions (e.g., population, employment and car ownership), based on the 258-zone system, were obtained from RMOC for 2011.

During p.m. peak period, most trips from the central district are HBW trips.

According to literature, work trips in urbanized areas show some sensitivity to travel cost and travel time [76]. Increasing charges for the use of the automobile during peak travel periods can manage demand by reducing or shifting some travellers to other modes [8]. Travel cost for automobile users includes parking charge in the central area, toll on freeway and vehicle operating cost. For bus users, fare is their travel cost. Travel cost elements that can be influenced by demand management strategies are used as the control (optimization) variables. As noted earlier, theses are parking charges, tolls and bus fare. Furthermore, other assumptions which were used for the development of the demand models are assumed to apply to the case study (see Chapter 2).

According to the direct search method, a reasonable range of values should be determined for all optimization variables (e.g., parking charge, fare and toll). Thus, based on literature review and 1986 data, a range of $1.50-$5.50 (in 1986 dollars) was assumed for parking charge/day in the central district and $0.85-$2.10 for public transit fare/trip. The parking charges might appear rather low, but it should be noted that these are averages in 1986$ and cover the entire central district. While parking charges are high in the core of the district, this is not the case everywhere in the central district. Freeway toll is another policy variable. A range of 0-20 ¢/km is regarded as a reasonable range for link-based toll.

Although, in this study, travel costs are expressed in 1986 dollars, Equation 2.24 can be used to convert 1986 dollars to 2011 dollars or vice-versa. In this research, this equation was not used.

In the application of the optimization method, based on the direct search method, the first step lengths for changing the values of variables were selected to be $0.25, $0.50 and

5 ¢/km for fare/trip of buses, average parking charge/day and toll on freeway, respectively (see Chapter 6 for more details). Within the ranges of optimization variables and for the values of first step lengths, this method can search for the best values of the optimization variables. After continuing this procedure, if there is no improvement, the step lengths will be changed to smaller step lengths than initial step lengths. In this case study, second step lengths for changing the values of variables were selected to be $0.05, $0.10 and 1 ¢/km for fare/trip, average parking charge/day and toll on freeway, respectively. The base scenario (i.e., the starting point of the optimization process) was developed by using minimum values of control variables.

7.3 Case Study of Travel Corridor

As previously noted, the corridor linking the Ottawa central area with the eastern area was selected as a case study in this research. Figure 7.1 shows location of the case study corridor. This travel corridor include freeways (e.g., Highway 417, Highway 17), arterials (e.g., Montreal Rd., St. Joseph Blvd.) and the Transitway. Based on the location of the travel corridor, the 258-zone system of the transportation planning division of the RMOC, is used to aggregate the zones into a 21 district systems (Table 7.1 and Figure 7.1). Districts 18-21 are external to the coverage area of the National Capital Region and District 2 is external to the corridor because, it is located west of the central area. This case study corresponds to the year 2011. The forecasts of land use (i.e., population, employment and car ownership) and travel related information were obtained from RMOC. This information was aggregated for the 21-district system. Figure 7.2 shows a part of the base network for the case study. Highway 417 (Queensway) and Highway 17 connect the eastern area and the Ottawa central area with 3 lanes for each direction.

Table 7.1-The conversion of 258 traffic zones to 21 districts (case study)

Districts	Traffic Zones
1	1-3 , 11-17
2	18-20 , 25-70 , 113, 117-131, 140, 146-152 , 163 , 206-229 , 256-258
3	178 , 203-204 , 235 , 238-244
4	4-10 , 201
5	153-159 , 160-162, 164, 165-170 , 252-255
6	96-98
7	90-95 , 99-101 , 106
8	102-105 , 109 , 171-172
9	173-174 , 176 , 248-251
10	175 , 202
11	107-108
12	143 , 236-237 , 245-247
13	110 , 141-142 , 234
14	87-89 , 111 , 205 , 230-232
15	81-86
16	21-23 , 75-80 , 112 , 114-116 , 233
17	24 , 71-74
18	132-135 , 190-194
19	182-184 , 186-187
20	177 , 179-181 , 185 , 188
21	138-139, 144-145 , 195-200

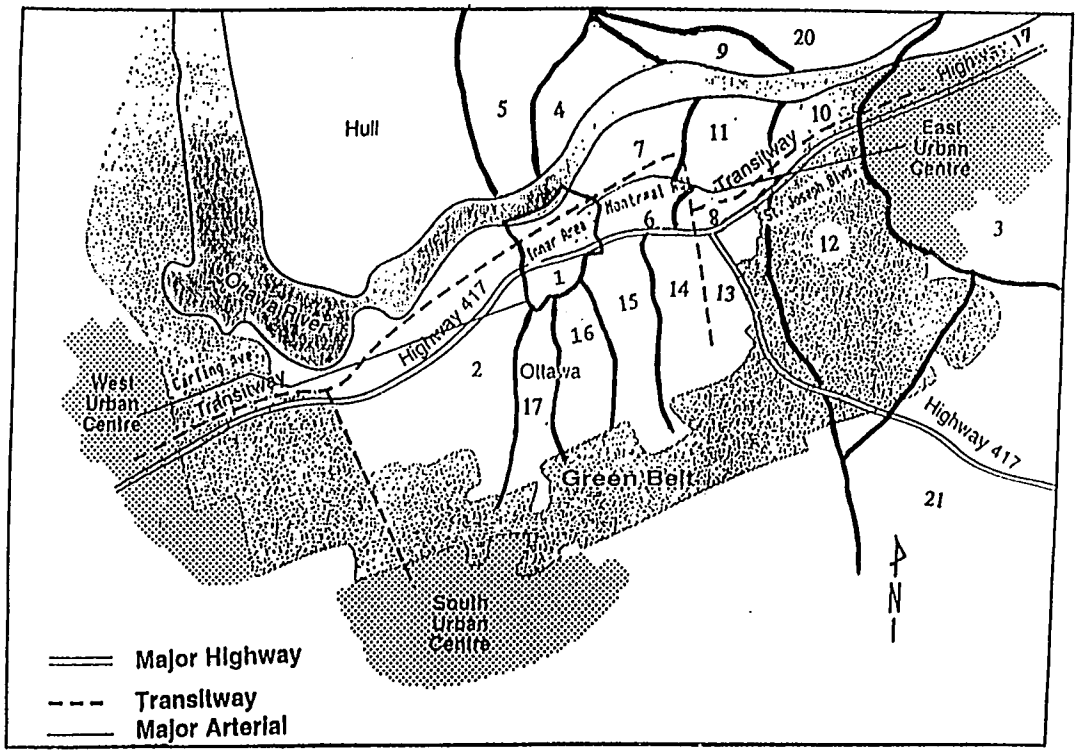


Figure 7.1- District System (Case Study)

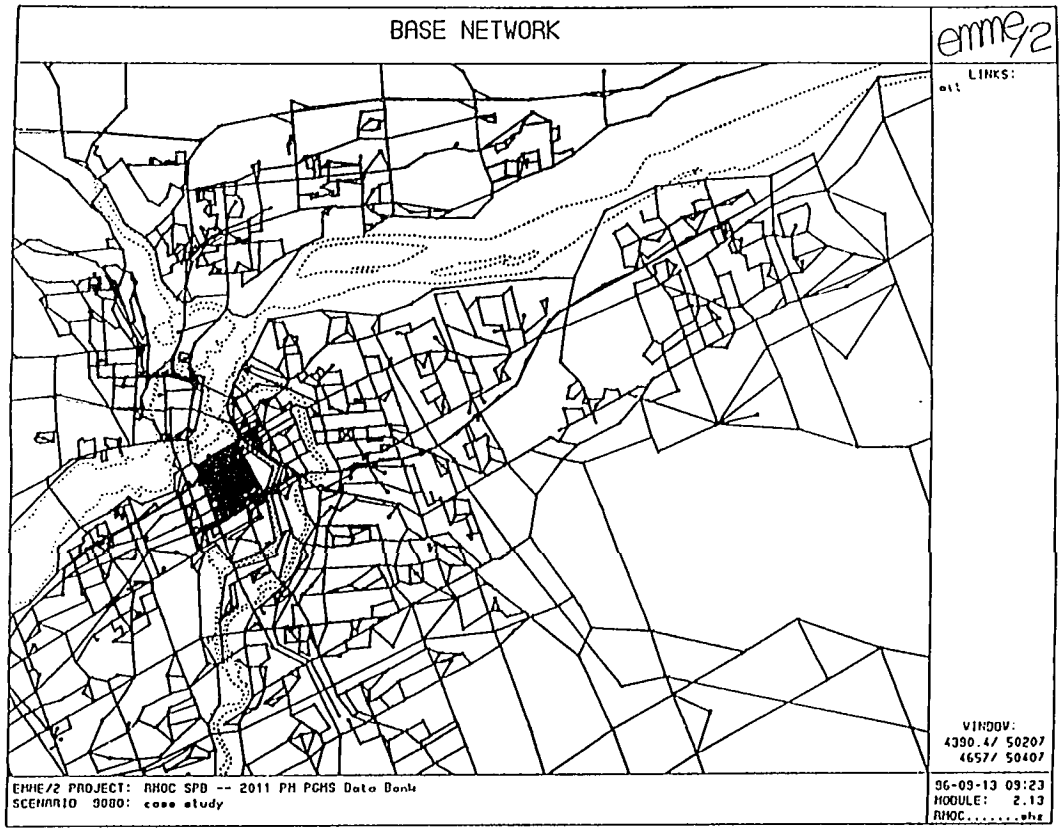


Figure 7.2 Case Study Base Network

Highway 17 is expected to be upgraded to freeway standard by year 2011 [77]. The Transitway is used exclusively for buses. Arterials are used for automobiles and buses.

The methodology developed in this research was used to implement the scenarios in order to identify optimal values of decision variables for minimizing in-vehicle travel time per pass-km as first objective function. For various scenarios, fuel consumption and air pollution emissions (HC, NO_x, CO and CO_2) per pass-km were estimated. Total travel time and user cost per pass-km were also estimated as outputs for all scenarios.

In EMME/2, it is possible to include road tolls in the traffic assignment process. For this purpose, impedance functions were developed that incorporate the effect of the road tolls [20]. Thus, the route choice is based on the sum of travel times and freeway tolls that were converted into equivalent time by using value of time. The value of time can change one unit of the cost variable to the travel time unit.

Estimates of the value of time for 1986 for the Ottawa-Carleton Region could not be obtained from available sources. However, such estimates were available for 1995 [78]. These are: $0.21/minute for a.m. peak period and $0.14/minute for off-peak period. This implies a higher value of time for work trips than for non-work travel. These estimated values of time are based on average wage rate.

Studies carried out in Toronto [79] and Montreal confirm that travellers on work trips were found to have generally higher values of time than non-work trips.

Since estimation of value of time for the p.m. peak period was not available for the Ottawa-Carleton Region, the a.m. peak period value was used. On the basis of trip purpose data for the p.m. peak period in the case study, a weighted value of time was estimated to be $0.19/minute in 1995 dollars. This value is close to the estimates of the

value of time for p.m. peak period found by Toronto study ($0.19/minute in 1994 dollars) [79]. Since travel costs are to be expressed in the 1986 dollars, the consumer price index was used to convert the value of time to the 1986 dollars [80].

For finding equilibrium level flows in the network, the values of optimization variables and the calculated values of the system performance measures were fed into the travel demand models (i.e., trip distribution, modal split and route split). The new estimates of system performance were fed again into the model, thus allowing more interaction between demand and performance. This feedback process continued until approximate equilibrium between supply and demand was achieved.

The first scenario was defined to represent minimum values of variables. The total demand is about 21,500 person-trips (per hour) for case study travel corridor. The weighted average in-vehicle travel time and total travel time per pass-km for each scenario are shown in Table 7.2. The results are computed values in terms of per passenger-km for various scenarios, figures with two digits are shown. In this case study, Scenario 11 is best for the minimization of in-vehicle travel time/pass-km (Figure 7.3). Values of the variables of this scenario are $4.00, $0.85 and 5 ¢/km for average parking charge/day in the central area, fare/trip and toll on freeway, respectively. All dollars are in 1986$. This scenario is based on reasonable average parking charges for auto, fare for bus travel, and a moderate level of toll in 1986 dollars. According to the results, the best values of the control variables to minimize in-vehicle travel time/pass-km are not the same as for fuel consumption and emissions per pass-km. These results are logical since fuel and emissions are minimized under conditions that are highly favourable to public transit. On the other hand, in-vehicle travel time is minimized under balanced

Table 7.2-Predicted travel time, fuel consumption and emissions per pass-km for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Weighted Avg. Time(sec.)/pass-km		Emissions (g/pass-km)				Fuel Consumption(ml/pass-km)
				in-veh	total	HC	CO	NO_x	CO_2	
1	1.50	0.85	0	120.71	249.55	0.91	8.03	0.68	143.47	60.49
2	2.00	0.85	0	120.16	255.12	0.86	7.56	0.64	134.01	56.48
3	2.00	0.85	5	118.95	256.18	0.85	7.50	0.63	132.20	55.71
4	2.00	1.10	5	119.56	253.34	0.87	7.71	0.65	136.09	57.36
5	2.50	0.85	10	118.72	264.83	0.79	6.97	0.58	121.84	51.32
6	3.00	0.85	10	118.53	270.46	0.74	6.53	0.54	113.65	47.85
7	3.00	0.85	5	118.30	267.49	0.74	6.59	0.55	114.94	48.40
8	3.00	1.10	5	118.58	264.60	0.76	6.76	0.56	118.23	49.79
9	3.50	0.85	0	118.57	270.87	0.70	6.24	0.52	108.37	45.61
10	3.50	0.85	5	118.11	272.71	0.70	6.20	0.51	107.39	45.20
11	4.00	0.85	5	117.83	277.53	0.65	5.82	0.48	100.58	42.31
12	4.00	1.10	5	118.19	275.04	0.67	5.97	0.49	103.30	43.47
13	5.00	0.85	5	118.03	285.76	0.59	5.24	0.43	90.30	37.96
14	5.50	0.85	5	118.30	289.16	0.57	5.03	0.41	86.62	36.40
15	4.50	0.85	5	117.95	281.70	0.62	5.51	0.45	95.10	39.99
16	5.00	1.10	5	118.13	283.68	0.60	5.35	0.44	92.25	38.78
17	5.00	0.85	10	118.73	288.80	0.59	5.25	0.43	90.42	38.00
18	4.10	0.85	5	117.92	278.48	0.65	5.75	0.47	99.36	41.80
19	3.90	0.85	5	117.89	276.53	0.66	5.89	0.48	101.81	42.84
20	4.00	0.85	6	118.00	278.15	0.65	5.82	0.48	100.54	42.30
21	4.00	0.85	4	117.86	277.02	0.66	5.83	0.48	100.81	42.41
22	4.00	0.90	5	118.08	277.24	0.66	5.86	0.48	101.32	42.63
23	5.50	0.85	10	118.98	292.44	0.57	5.05	0.41	86.96	36.54

Note: 1) All dollars ($) are in 1986 constant dollars ($).

2) Including access, egress and line haul components

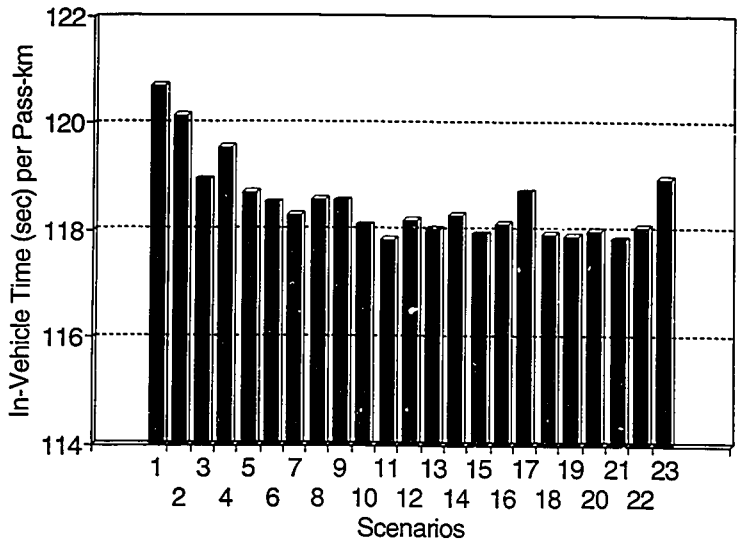


Figure 7.3-Predicted Time/Pass-km for Various Scenarios in 2011(Case Study)

transportation conditions.

Estimates of fuel consumption and emissions (i.e., HC, CO, NO_x and CO_2) per pass-km for various scenarios, are shown in Table 7.2. Due to the comprehensive nature of scenarios that were developed for the purpose of identifying conditions leading to the minimization of in-vehicle travel time/pass-km, these can also suggest values of decision variables for minimization of fuel and emissions. According to the results which are shown in Table 7.2, Scenario 14 would be the choice as a starting point for further search of control variable values that minimize fuel and emissions per pass-km. Based on the selected ranges of values of the variables and step lengths, the direct search procedure was used to develop new scenarios. Scenario 23 was created according to the direct search method. However, it did not show improvement in the objective functions values. By using the second step lengths for changing the value of optimization variables, further scenarios development and testing also produced insignificant changes to fuel consumption and emissions. Therefore, Scenario 14 is accepted as the optimal demand management scenario for minimizing fuel consumption and emissions. Results presented in Table 7.2 and Figures 7.4-7.8 show that from an energy and emissions perspective, Scenario 14 is best since it represents highly favourable conditions for public transit (i.e., average parking charge of $5.50/day, toll of 5 ¢/km and fare equal to $0.85/trip).

Table 7.3 and Figure 7.9 show modal split and user cost/pass-km for various scenarios. In the case of the best scenario (i.e., Scenario 11) for minimization of in-vehicle travel time/pass-km, estimated modal shares for bus, car and carpool are 46.75%, 39.29%, and 13.96%, respectively. Modal shares under scenario most favourable to the achievement of energy and emissions reduction objective (i.e., Scenario 14) are: 51.51%

for bus, 35.34% for car and 13.15% for carpool.

The results shown in Tables 7.2-7.3 suggest the following observations:

- The demand management instruments (i.e., public transit fare, parking charges and freeway tolls) have a high effect on modal split. The following are the modal split range.
  - Lowest public transit market share (Scenario 1): 34.46%
  - Highest public transit market share (Scenario 23): 51.72%
- Although there is a wide variation in modal split caused by the various scenarios, there is a very minor change in average in-vehicle travel time/pass-km.
  - Worst average in-vehicle travel time (Scenario 1): 120.71 sec/pass-km
  - Best average in-vehicle travel time (Scenario 11): 117.83 sec/pass-km

  For other application contexts, the methodology developed in this research has the potential to estimate more significant changes in delay (if applicable).
- The total travel time (in-vehicle + out-of-vehicle) characteristics of automobile and public transit are dissimilar. Shifting travel to public transit is responsible for an increase in the average out-of-vehicle travel time and as a consequence, total travel time rises.
  - Best total travel time (Scenario 1): 249.55 sec/pass-km
  - Worst total travel time (Scenario 23): 292.44 sec/pass-km.

  The best total travel time occurs when the modal share for public transit is lowest. The reason is that out-of-vehicle time for transit bus is much higher than automobile in the case study.
- Figures 7.4-7.8 illustrate predicted fuel consumption and emissions per pass-km

Table 7.3-Predicted modal split and user cost per pass-km for various scenarios in 2011 (case study)

Scenario	Parking Charge ($)/day	Fare($)/trip	Toll(¢)/km	Modal Split (%)			User Cost (¢/pass-km)
				bus	car	carpool	
1	1.50	0.85	0	34.46	51.00	14.54	16.29
2	2.00	0.85	0	37.04	48.45	14.51	18.88
3	2.00	0.85	5	37.48	48.01	14.51	19.36
4	2.00	1.10	5	36.07	49.07	14.86	20.73
5	2.50	0.85	10	40.42	45.07	14.51	22.02
6	3.00	0.85	10	42.82	42.81	14.37	23.96
7	3.00	0.85	5	42.38	43.23	14.39	23.59
8	3.00	1.10	5	41.05	44.19	14.76	25.20
9	3.50	0.85	0	44.28	41.51	14.21	25.02
10	3.50	0.85	5	44.61	41.18	14.21	25.41
11	4.00	0.85	5	46.75	39.29	13.96	27.03
12	4.00	1.10	5	45.55	40.08	14.37	28.81
13	5.00	0.85	5	50.16	36.41	13.43	30.16
14	5.50	0.85	5	51.51	35.34	13.15	31.70
15	4.50	0.85	5	48.52	37.76	13.72	28.62
16	5.00	1.10	5	49.20	36.98	13.82	32.02
17	5.00	0.85	10	50.39	36.22	13.39	30.52
18	4.10	0.85	5	47.12	38.96	13.92	27.35
19	3.90	0.85	5	46.32	39.66	14.02	26.71
20	4.00	0.85	6	46.76	39.28	13.96	27.13
21	4.00	0.85	4	46.65	39.37	13.98	26.97
22	4.00	0.90	5	46.45	39.49	14.06	27.44
23	5.50	0.85	10	51.72	35.18	13.10	32.09

Note: All dollars ($) are in 1986 constant dollars ($).

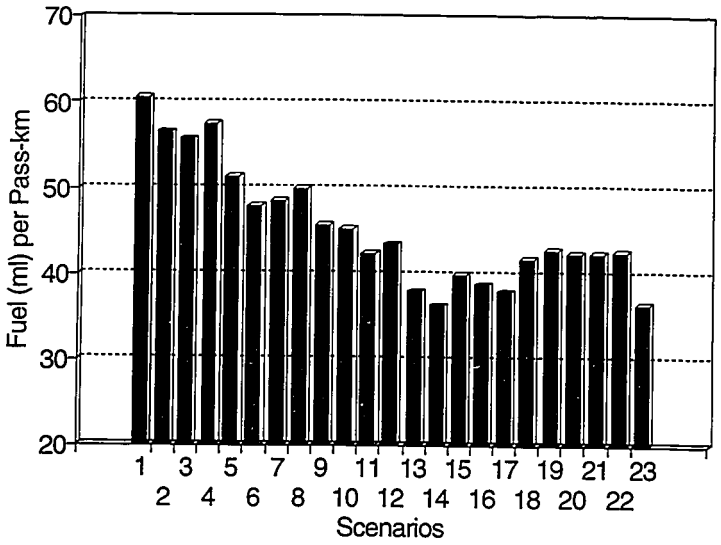


Figure 7.4-Predicted Fuel/Pass-km for Various Scenarios in 2011(Case Study)

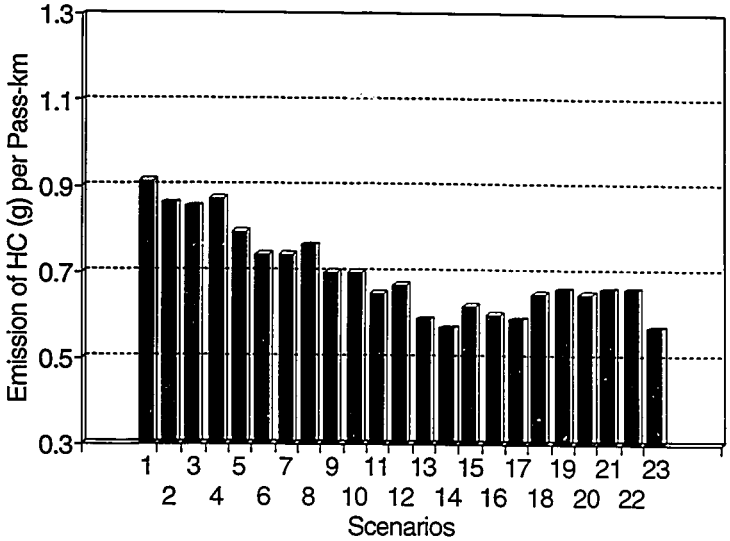


Figure 7.5-Predicted HC / Pass-km for Various Scenarios in 2011(Case Study)

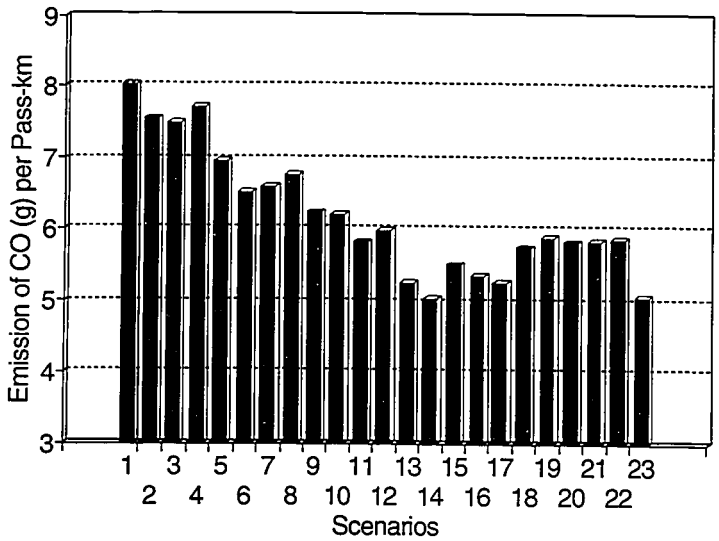


Figure 7.6-Predicted CO / Pass-km for Various Scenarios in 2011(Case Study)

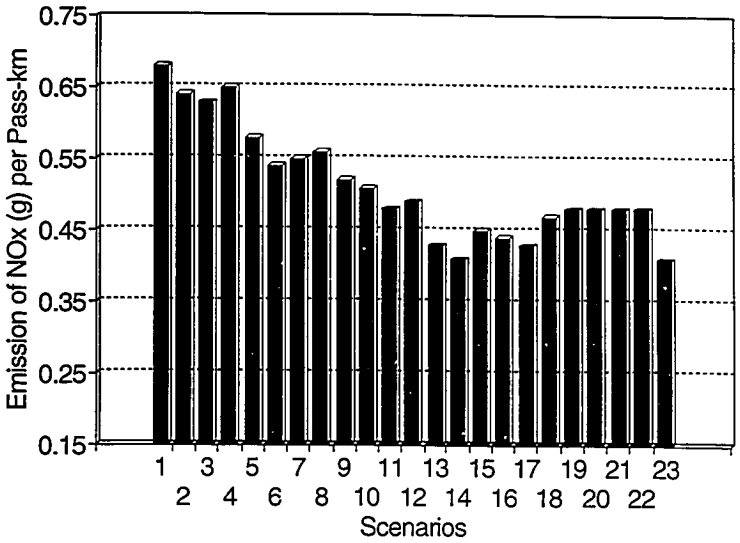


Figure 7.7-Predicted NOx / Pass-km for Various Scenarios in 2011(Case Study)

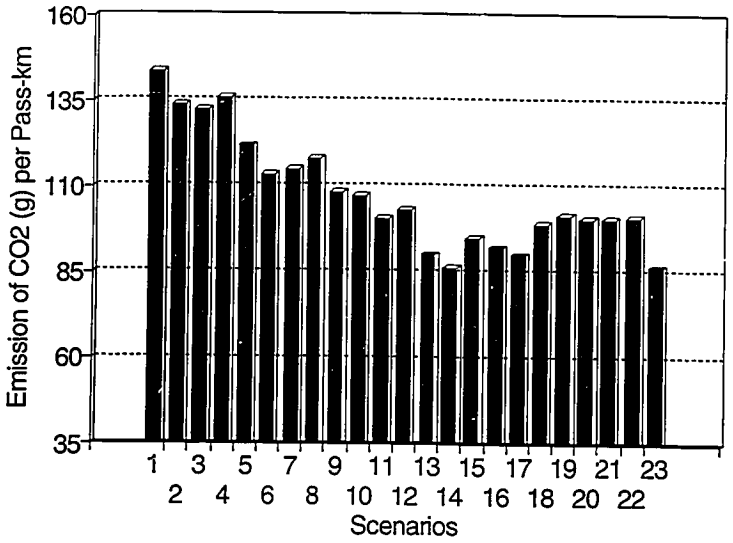


Figure 7.8-Predicted CO2 / Pass-km for Various Scenarios in 2011(Case Study)

for various scenarios in 2011. As noted earlier, Scenario 14 is the best for minimization of fuel consumption and air pollution emissions per pass-km. The best values of variables for minimizing fuel consumption and emissions occur when public transit modal split is high. There are significant differences between different scenarios in terms of emissions and fuel consumption per pass-km. This result is logical, given that public transit is more efficient than automobile in terms of energy and emissions.

- Scenario 1, representing low parking charge, absence of tolls and low bus fare, is the worst in terms of fuel consumption and emissions per pass-km.
- As compared with Scenario 1 (based on minimum values of control variables), Scenario 14 results in the following fuel saving and emission reduction levels.
    - Fuel saving (m lit/pass-km): 39.8%
    - Reduction of emissions (g)/pass-km: HC 37.4%, CO 37.3%, NO_x 39.7%, and CO_2 39.6%.

In this research, there are multiple-objective functions such as in-vehicle travel time, fuel consumption and emissions (e.g., HC, CO, NO_x and CO_2) per pass-km. According to the results of the case study, Scenario 11 is best for minimization of in-vehicle travel time/pass-km. For minimization of fuel consumption and emissions per pass-km, Scenario 14 is the best. As compared with Scenario 11, Scenario 14 would result in 14% saving in fuel consumption (ml/pass-km), 12.3% reduction of HC (g/pass-km), 13.6% reduction of CO (g/pass-km), 14.6% reduction of NO_x (g/pass-km) and 13.9% reduction of CO_2 (g/pass-km). On other hand, an increase of less than 0.4% in-vehicle travel time (sec./pass-km) occurs. Thus, in this case study, with regard to fuel consumption,

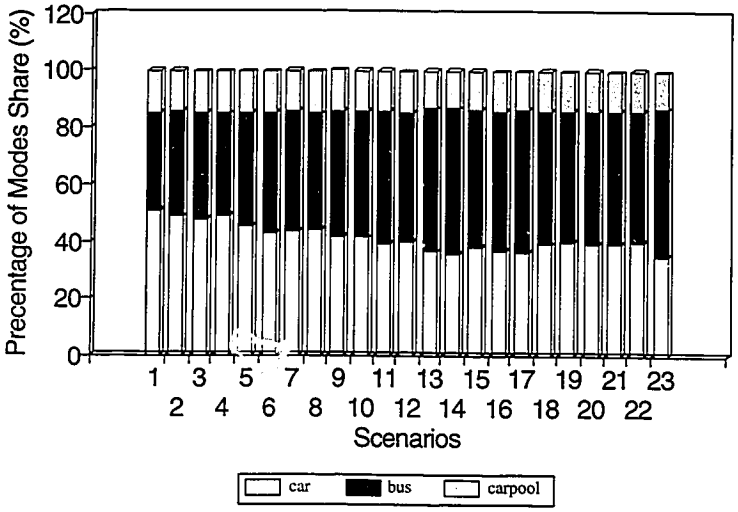


Figure 7.9-Modes share Prediction for Various Scenarios in 2011(Case Study)

emissions and in-vehicle travel time as objective functions, Scenario 14 can be accepted as the best for minimizing these objective functions, provided that the objective functions have the same weight in the evaluation process. In general, following the identification of the best scenario for various objective functions (i.e., in-vehicle travel time, energy and emissions), multiple-objective evaluation methods can be used for the selection of the best scenario [81].

7.4 Sensitivity Analysis

In order to study changes in the objective functions in response to variations in the decision variables, the base scenario (developed by minimum values of control variables) of the case study was used as the starting point. Next the effect of changes in parking charges was studied while keeping other control variable values constant. Tables 7.4-7.5 show, the effect of changes in average parking charge in the central area on objective function values. While both fare/trip and toll/km on the freeway are constant, average parking charge/day was changed from $1.50 to $5.50 by step length of $0.50. Figures 7.10-7.15 show results of this sensitivity test. It can be observed that while other variables are held constant at the base level, increasing parking charge leads to reduction of fuel consumption and emissions per pass-km. Also, the results show that in-vehicle travel time/pass-km decreases with increasing average parking charge/day. While fare/trip of transit bus and toll/km on freeway are constant, people can be discouraged to use their automobiles by increasing parking charges in the central area. Thus, the use of transit bus can be encouraged (Figure 7.16). Due to this change, there will be less auto users on the freeway as well as arterials. Therefore, fuel consumption and emissions could be

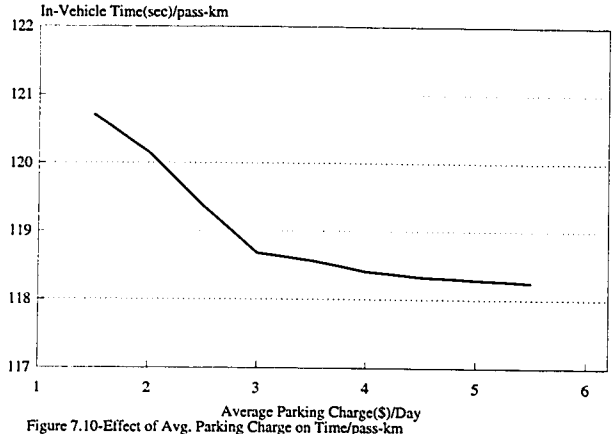


Figure 7.10-Effect of Avg. Parking Charge on Time/pass-km for Base Scenario (Case Study)

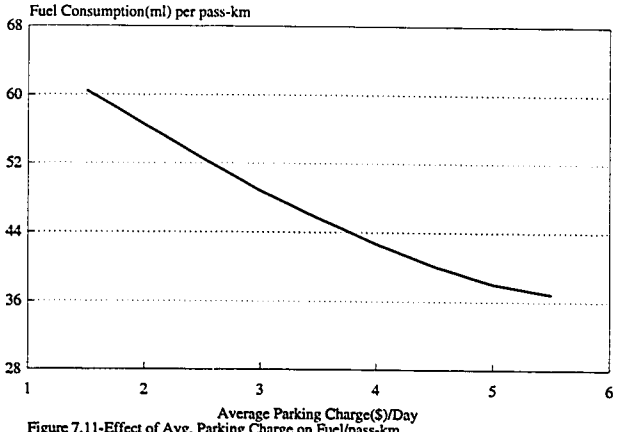


Figure 7.11-Effect of Avg. Parking Charge on Fuel/pass-km for Base Scenario (Case Study)

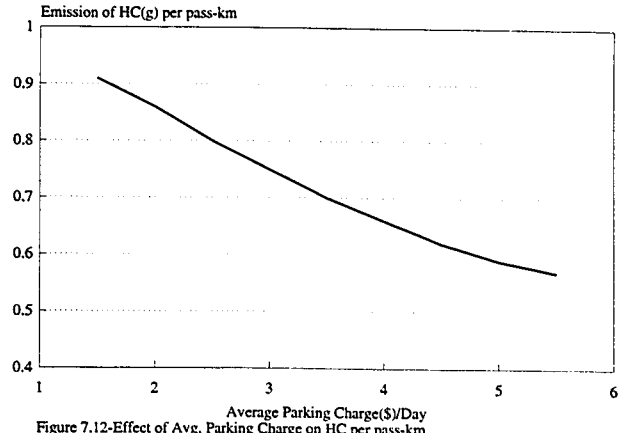


Figure 7.12-Effect of Avg. Parking Charge on HC per pass-km for Base Scenario (Case Study)

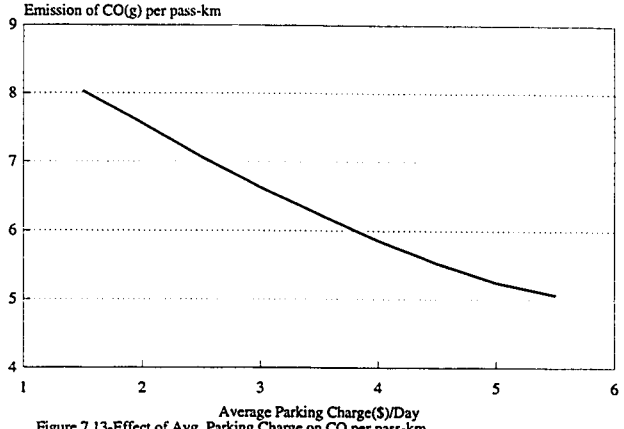


Figure 7.13-Effect of Avg. Parking Charge on CO per pass-km for Base Scenario (Case Study)

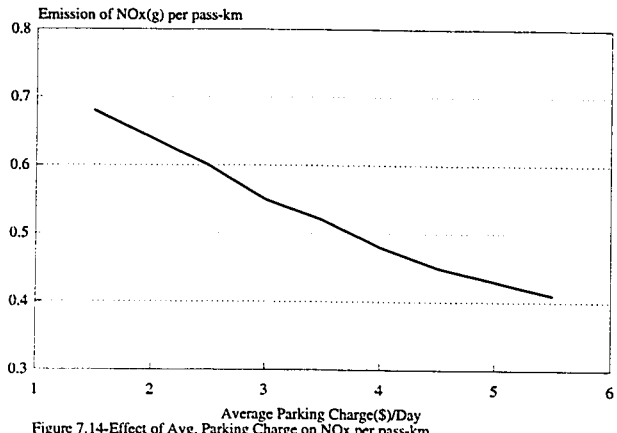


Figure 7.14-Effect of Avg. Parking Charge on NOx per pass-km for Base Scenario (Case Study)

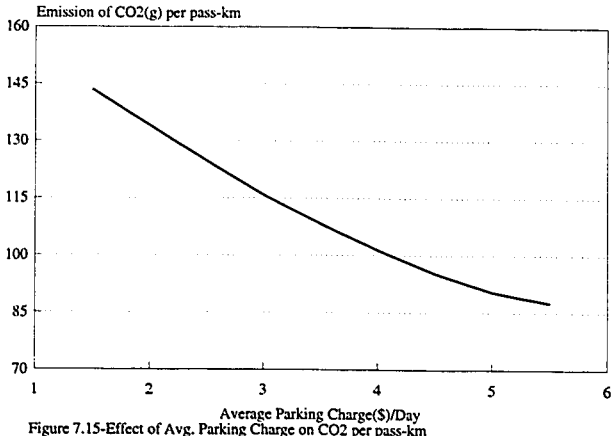


Figure 7.15-Effect of Avg. Parking Charge on CO2 per pass-km for Base Scenario (Case Study)

decreased in the corridor.

Next, changes were made to fare/trip and objective functions were estimated while both average parking charge/day and toll/km on freeway were held constant. The average fare/trip was changed from $0.85 to $2.10 by step length of $0.25. The results are shown in Tables 7.6 and 7.7 and are illustrated in Figures 7.18-7.23.

As expected, as average fare/trip increases in the corridor, while other variables are held constant at the base scenario level, in-vehicle travel time/pass-km, fuel consumption/pass-km and air pollution emissions/pass-km will increase. The reason is that because, while parking charge/day in the central area and toll/km on freeway are constant, increasing average fare/trip encourages people to use automobiles (Figure 7.17). Due to this change, there is more congestion for auto users on freeway as well as arterials.

Tables 7.8-7.9 show sensitivity test results for freeway tolls. While both fare/trip and parking charge/day were held constant (at the base level), toll was changed from 0 to 20 ¢/km by using a step length of 2.5 ¢/km. Between 0 and 10 ¢/km, if toll/km on the freeway increases, while other variables are held constant at the base level, in-vehicle travel time/pass-km, fuel consumption/pass-km and emissions/pass-km will decrease (Figures 7.24-7.25). If toll charge continues to increase beyond 10 ¢/km, in-vehicle travel time/pass-km will increase. The reason is the increasing automobile traffic on arterials, leading to high levels of delay. While fare/trip for transit bus and parking charge/day are held constant through freeway tolls, auto users can be discouraged to use congested freeway. In addition to route shifts resulting in the use of parallel arterials, travellers shift to public transit. Increased use of public transit results in decreases in fuel consumption and emissions/pass-km. Beyond the optimal value of toll/km, it becomes counter-

Table 7.4-Prediction of effect of parking charge/day on travel time per pass-km and modal split for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Weighted Avg. Time(sec.)/pass-km		Modal Split(%)		
				in-veh	total	bus	car	carpool
1	1.50	0.85	0	120.71	249.55	34.5	51.0	14.5
2	2.00	0.85	0	120.16	255.12	37.0	48.5	14.5
3	2.50	0.85	0	119.37	260.44	39.6	45.9	14.5
4	3.00	0.85	0	118.68	265.62	42.0	43.6	14.4
5	3.50	0.85	0	118.57	270.87	44.3	41.5	14.2
6	4.00	0.85	0	118.41	275.82	46.4	39.6	14.0
7	4.50	0.85	0	118.33	280.05	48.3	38.0	13.7
8	5.00	0.85	0	118.29	283.61	49.9	36.6	13.5
9	5.50	0.85	0	118.25	287.21	51.3	35.5	13.2

Table 7.5-Prediction of effect of parking charge/day on fuel consumption, emissions and user cost per pass-km for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Emissions (g/pass-km)				Fuel Consumption (ml/pass-km)	User cost (¢/pass-km)
				HC	CO	NO_x	CO_2		
1	1.50	0.85	0	0.91	8.03	0.68	143.47	60.49	16.29
2	2.00	0.85	0	0.86	7.56	0.64	134.01	56.48	18.88
3	2.50	0.85	0	0.80	7.07	0.60	124.67	52.52	21.16
4	3.00	0.85	0	0.75	6.63	0.55	115.84	48.78	23.16
5	3.50	0.85	0	0.70	6.24	0.52	108.37	45.61	25.02
6	4.00	0.85	0	0.66	5.86	0.48	101.44	42.68	26.70
7	4.50	0.85	0	0.62	5.53	0.45	95.38	40.11	28.26
8	5.00	0.85	0	0.59	5.25	0.43	90.52	38.05	29.79
9	5.50	0.85	0	0.57	5.07	0.41	87.67	36.93	31.33

Note: All dollars ($) are in 1986 constant dollars ($).as arterial.

Table 7.6-Prediction of effect of fare/trip on travel time per pass-km and modal split for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Weighted Avg. Time(sec.)/pass-km		Modal Split(%)		
				in-veh	total	bus	car	carpool
1	1.50	0.85	0	120.71	249.55	34.5	51.0	14.5
2	1.50	1.10	0	121.50	247.11	33.2	52.1	14.7
3	1.50	1.35	0	122.80	245.01	31.8	53.2	15.0
4	1.50	1.60	0	123.88	242.82	30.5	54.3	15.2
5	1.50	1.85	0	125.17	240.85	29.2	55.3	15.5
6	1.50	2.10	0	126.81	239.37	27.9	56.4	15.7

Table 7.7-Prediction of effect of fare/trip on fuel consumption, emissions and user cost per pass-km for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Emissions (g/pass-km)				Fuel Consumption (ml/pass-km)	User cost (¢/pass-km)
				HC	CO	NO_x	CO_2		
1	1.50	0.8:-	0	0.91	8.03	0.68	143.47	60.49	16.29
2	1.50	1.10	0	0.95	8.30	0.70	147.49	62.19	17.50
3	1.50	1.35	0	0.97	8.53	0.72	151.95	64.08	18.64
4	1.50	1.60	0	0.99	8.69	0.74	155.97	65.79	19.67
5	1.50	1.85	0	1.02	8.94	0.76	160.18	67.57	20.63
6	1.50	2.10	0	1.04	9.11	0.78	164.34	69.33	21.51

Note: All dollars ($) are in 1986 constant dollars ($).

Table 7.8-Prediction of effect of toll/km on travel time per pass-km and modal split for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Weighted Avg. Time(sec.)/pass-km		Modal Split(%)		
				in-veh	total	bus	car	carpool
1	1.50	0.85	0	120.71	249.55	34.5	51.0	14.5
2	1.50	0.85	2.5	120.46	249.99	34.6	50.9	14.5
3	1.50	0.85	5.0	119.69	250.45	34.9	50.6	14.5
4	1.50	0.85	7.5	119.61	251.69	35.1	50.4	14.5
5	1.50	0.85	10	119.46	252.75	35.5	50.0	14.5
6	1.50	0.85	12.5	119.83	254.79	35.7	49.8	14.5
7	1.50	0.85	15	120.64	257.13	36.0	49.5	14.5
8	1.50	0.85	17.5	121.13	259.14	36.3	49.2	14.5
9	1.50	0.85	20	121.28	260.48	36.6	48.9	14.5

Table 7.9-Prediction of effect of toll/km on fuel consumption, emissions and user cost per pass-km for various scenarios in 2011 (case study)

Scenario	Parking Charge($)/day	Fare($)/trip	Toll(¢)/km	Emissions (g/pass-km)				Fuel Consumption (ml/pass-km)	User cost (¢/pass-km)
				HC	CO	NO_x	CO_2		
1	1.50	0.85	0	0.91	8.03	0.68	143.47	60.49	16.29
2	1.50	0.85	2.5	0.91	8.03	0.68	143.30	60.41	16.59
3	1.50	0.85	5	0.91	7.99	0.68	141.69	59.73	16.84
4	1.50	0.85	7.5	0.90	7.94	0.67	141.07	59.47	17.11
5	1.50	0.85	10	0.89	7.93	0.67	139.83	58.94	17.34
6	1.50	0.85	12.5	0.88	7.86	0.66	139.10	58.64	17.59
7	1.50	0.85	15	0.88	7.84	0.66	138.33	58.31	17.83
8	1.50	0.85	17.5	0.88	7.79	0.66	137.33	57.88	18.08
9	1.50	0.85	20	0.87	7.75	0.65	136.00	57.32	18.26

Note: All dollars ($) are in 1986 constant dollars ($).

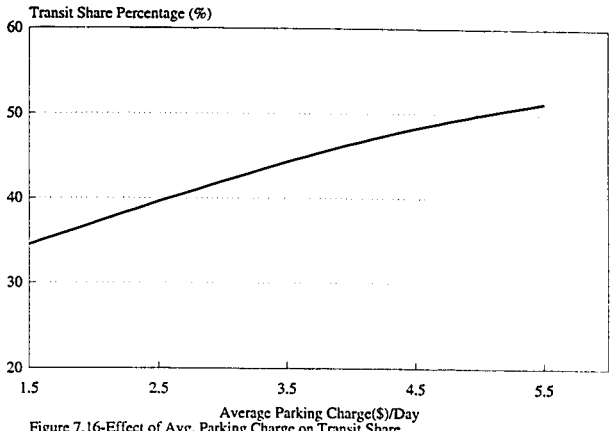


Figure 7.16-Effect of Avg. Parking Charge on Transit Share for Base Scenario (Case Study)

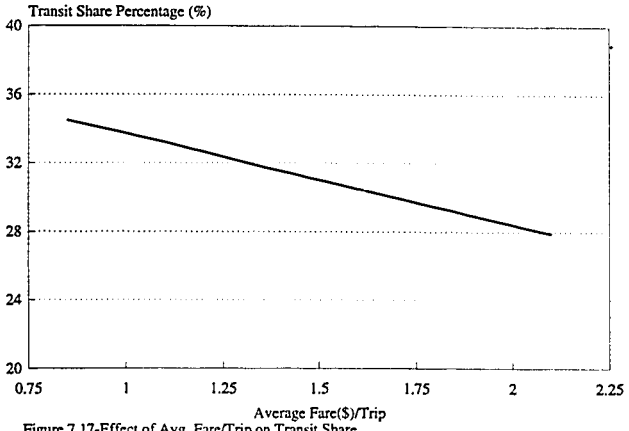


Figure 7.17-Effect of Avg. Fare/Trip on Transit Share for Base Scenario (Case Study)

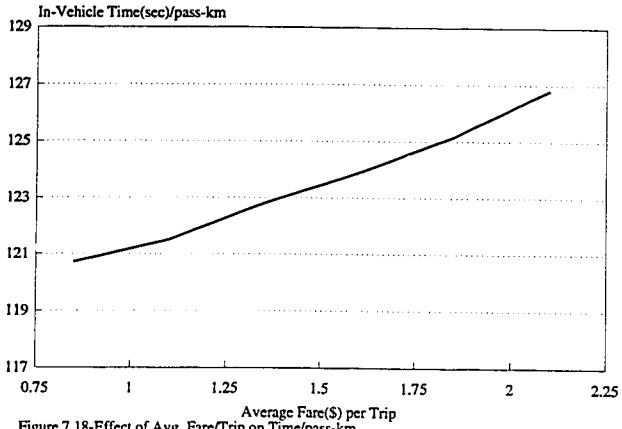


Figure 7.18-Effect of Avg. Fare/Trip on Time/pass-km
for Base Scenario (Case Study)

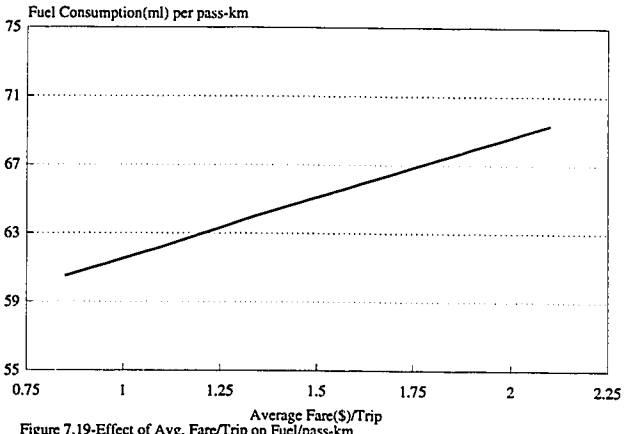


Figure 7.19-Effect of Avg. Fare/Trip on Fuel/pass-km
for Base Scenario (Case Study)

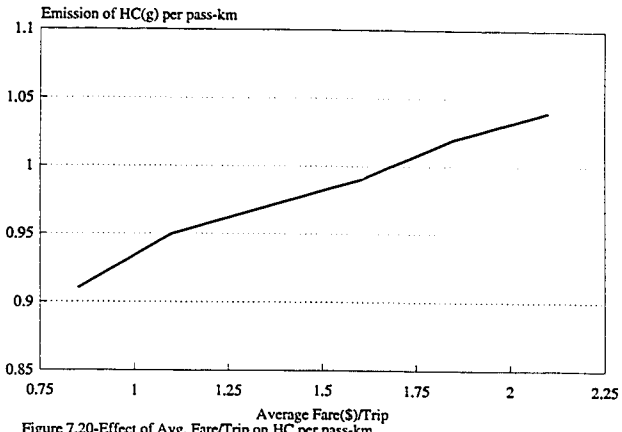


Figure 7.20-Effect of Avg. Fare/Trip on HC per pass-km for Base Scenario (Case Study)

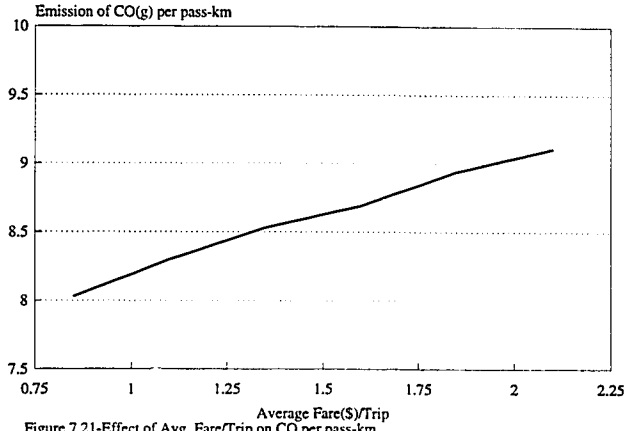


Figure 7.21-Effect of Avg. Fare/Trip on CO per pass-km for Base Scenario (Case Study)

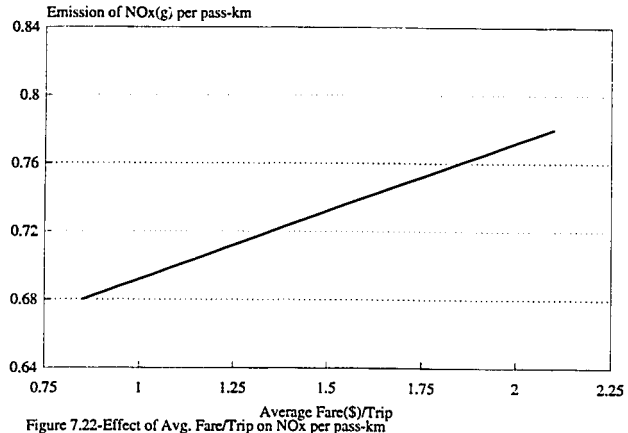


Figure 7.22-Effect of Avg. Fare/Trip on NOx per pass-km for Base Scenario (Case Study)

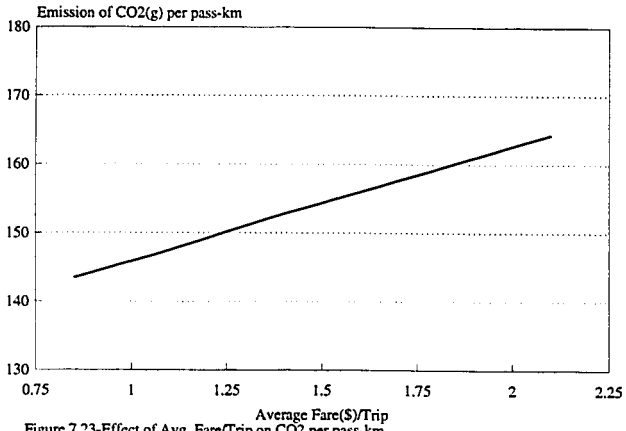


Figure 7.23-Effect of Avg. Fare/Trip on CO2 per pass-km for Base Scenario (Case Study)

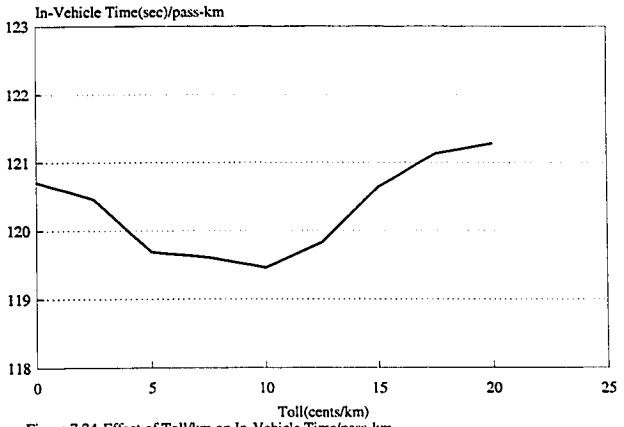


Figure 7.24-Effect of Toll/km on In-Vehicle Time/pass-km for Base Scenario (Case Study)

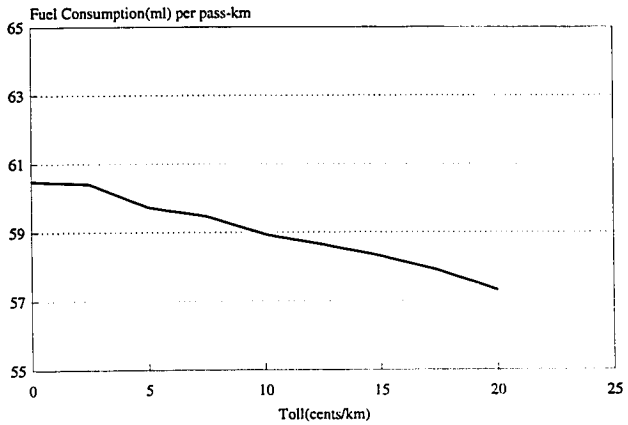


Figure 7.25-Effect of Toll/km on Fuel Consumption/pass-km for Base Scenario (Case Study)

productive to raise tolls that lead to highly congested arterials. As expected, route shifts are likely before public transit is chosen for commuting [79]. For this reason, this variable has a relatively lower effect than other control variables.

7.6 Optimal Values of Variables

The first scenario of the case study based on minimum values of control variables is the starting point for the optimization process. However, it should be noted that this scenario does not represent the base line condition in year 2011.

For practical implementation of demand management instruments, it is, of course, necessary to define one set of optimal values of decision variables for a given application context. This can be achieved by simulating overall urban level travel and the identification of the optimal scenario. On the other hand, if major corridors are studied independently, their results can be compared and a common set of answers can be adopted for practical implementation (e.g., average of the answers obtained for the various corridors). Another implementation issue is that of transit authority option for a fare level that is different than the "optimal" fare. In such a case, the fare to be charged can be held fixed and values of other variables can be found from the optimization process.

It is logical to question the mechanism for implementing parking charges when the output from the optimization methodology is a "weighted average" parking charge. The answer to this implementation-related question is that the proportion of each type of parking (i.e., long term contracts and short term parking charges) has to be estimated and then an attempt can be made to influence parking charges of each type (e.g., through special taxes).

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

The purpose of this research was to develop a methodology for the optimization of integrated multimodal urban travel corridors, according to the criteria of (a) minimization of in-vehicle travel time per pass-km, (b) minimizing fuel consumption per pass-km, and (c) minimization of air pollution emissions (HC, CO, NO_x and CO_2) per pass-km. The decision variables are policy-sensitive travel cost components (i.e., public transit fare, parking charges in the central area and freeway tolls).

This research investigated demand management measures within a strategic framework of infrastructure and technologies. It called for the development of a methodological framework for studying the optimal use of the corridor through the interaction of demand and supply. For given corridor system and demand management options, travel simulation models are required to estimate trips by each mode and route. Therefore, this research required a demand modelling framework that should satisfy a number of requirements. The models treated the private and public modes of travel such as car, carpool and bus which were modelled in an interactive fashion, based on behavioral theories of travel demand.

In this research, the Urban Transportation Modelling System (UTMS) was used for prediction of interzonal trips. For development of the demand models, results of the latest available 1986 O-D survey from the Regional Municipality of Ottawa-Carleton (RMOC) were used. In this study, the EMME/2 was used as framework for developing demand models and finding equilibrium of demand and supply. This study deals only with the

afternoon peak period travel, consisting mostly of home-based work (HBW) trips (from central district). Based on the above noted data, the demand models were calibrated and evaluated. In this research, travel cost are expressed in 1986 dollars. The actual cost for a specific future year (i.e., 2011) can be obtained by using the average expected inflation rate between 1986 and that future year (i.e., 2011).

An optimization methodology had to be developed for finding the best combination of values of travel demand management variables for given operating and system design factors. Based on operational and policy aspects of the transportation system, the optimization variables including tolls on freeway, parking charges in the central area for automobile users and public transit fare, were selected. In this research, bus fare based on a fare policy is regarded as a user cost variable. The travel cost for auto user includes perceived vehicle operating cost, parking charge and freeway toll.

In this research, the EMME/2 framework was used to implement various scenarios. This required methodological innovations to supplement EMME/2 macros available to the author. For instance a macroscopic simulation model for buses operating on the Transitway was developed in this research.

In order to meet objectives of this research, emissions of HC, NO_x, CO and CO_2 were estimated. For this purpose, the INRO model, which is based on MOBILE5c, was used to estimate HC, CO and NO_x. For the estimation of CO_2, the emission factors based on fuel types were used.

A method based on ARFCOM, was developed for obtaining bus fuel consumption estimates. For the modification of the ARFCOM model, data for an articulated bus and a standard bus obtained from OC Transpo were used for various modes of driving of buses. For the automobile case, the INRO model was used to estimate fuel consumption.

For the minimization of the objective functions, a direct search method was used to

solve the optimization problem.

The developed methodology is generally applicable to any urban transportation corridor. To illustrate the specific application of the methodology developed in this research, a case study in the Regional Municipality of Ottawa-Carleton was conducted. The methodology was applied to analyze year 2011 travel occurring during the p.m. peak hour for the eastern corridor. Scenarios were defined by using the 2011 socio-economic factors which were obtained from RMOC. The technology and infrastructure are held fixed, except the electronic toll option included in some scenarios. The demand management (policy) variables formed the basis of defining alternative scenarios. The results of the case study are reported in Chapter 8 and conclusions are presented below.

8.2 Conclusions

1. A number of methodological contributions were made in this research. These include:
    - the concept of the optimal use of an integrated multimodal corridor and the development of an optimization methodology to accomplish this objective
    - developing a methodology to investigate the travel service quality, energy and emission effects of a combination of demand management measures (i.e., freeway toll, parking charge, and public transit fare) in an urban travel corridor
    - methodological capability to find the values of the demand management (i.e., price) variables for the optimal use of travel corridors
    - development of models for the estimation of demand for various available modes on routes
    - modification of a method for the estimation of bus fuel consumption

- development of a macroscopic simulation model of the Transitway for the estimation of in-vehicle travel time, fuel consumption and emissions, and
- incorporation of the new technology of Electronic Toll and Traffic Management (ETTM) system.

2. The attempt to develop an optimization framework for a complex multimodal system proved to be successful. Due to interrelated application of many models and multiple control variables, most standard optimization techniques cannot be of assistance. The direct search method addresses the requirements of the corridor optimization. The sensitivity analyses provide further valuable insight into changes in objective functions in response to incremental changes to one control variable at a time.

3. Demand models were developed that incorporate the private and public modes of travel, consisting of car, carpool and transit bus. These models can explain the response of modal and intermodal travel markets to system and pricing policy changes. The demand models can allow trip distribution and modal split to be responsive to changes in the modal/intermodal price and service variables.

4. The Transitway simulation model of macroscopic nature is very appropriate for this type of policy analysis study since it avoids the details of a microscopic simulation model and yet it is a much more realistic simulator than the use of average travel time values. In the case of urban areas with rail-based systems, the Transitway simulation model can be replaced with a rail system simulator.

5. The p.m. peak period work trip modal split model based on logit function offer the ability to treat user travel behaviour with high confidence. The utility equations developed on the basis of the 1986 RMOC data, show that travel cost components (i.e., parking and vehicle operating costs for car and carpool, and fare for bus) have a somewhat higher effect than travel time (i.e., in-vehicle and out-of-vehicle times) on mode choice. However, another data base may reflect different travel characteristics. The models are detailed enough to capture the unique aspects of travel behaviour in a given urban area.

6. The energy and emission models are of appropriate specification for corridor optimization.

7. The results of the corridor optimization case study in the Regional Municipality of Ottawa-Carleton suggest the following conclusions:
   - The optimal scenarios for saving fuel and minimizing emissions and in-vehicle travel time occur when the modal share for transit bus is high.
   - There is a role for tolls in conjunction with other demand management variables.
   - At moderate bus fare level, increasing parking charges and tolls are effective in inducing the use of public transit in urban corridors. That is, link-based congestion pricing (i.e., freeway tolls) if supplemented by high parking charges encourages the use of public transport. However, extreme values of control variables (e.g., high tolls, high parking charges) need not be the important ingredients of optimal strategies.
   - The demand management instruments (i.e., transit fare, parking charges,

and freeway tolls) have a high effect on modal split.

- The optimal values of control variables found from different corridor optimization studies within the same region can be averaged for practical implementation. In the case of weighted average parking charges, the proportion of short term and long term (contract) type of parking demand has to be estimated. The presence of municipal parking facilities special taxes, and policies on parking supply can assist in influencing parking charges.
- The methodology developed in this research can be used in conjunction with any land use plan since inputs to the demand model can characterize the spatial distribution of population, employment, car ownership, the formation of major travel corridors, and integrated multimodal transportation systems serving major corridors.

8. The optimization methodology has much potential in assisting urban transportation planners and policy analysts to find the most appropriate demand management (i.e., price) levels that would lead to the desired results. That is, the developed methodology gives an opportunity to determine the optimal values of travel demand management variables for the minimization of congestion, fuel consumption and emissions in urban corridors. Although the methodology is not intended to make value judgments on the objectives, it is intended to help achieve the best results for selected objective functions. For example, if the policy makers wish to minimize fuel and emissions, this methodology can help in achieving this end. On the other hand, should it be the intent to offer the best level of in-vehicle travel time, the product of this research can be of assistance. Furthermore,

through the use of goal (objective) achievement methodology, the best scenario for achieving multiple objectives can be identified. From the results of the case study it is clear that due to the complexity of the system and many non-linear relationships imbedded in the methodologies, it is not easy to specify the best strategies without the use of the developed methodology. For example, the optimal scenario may not incorporate high values of control variables (i.e. parking charges and freeway tolls). It is the most appropriate blending of values of variables that leads to the optimal scenario and such answers cannot be found without this methodology.

8.3 Recommendations

From this research, the following recommendations are made.

- The scope of this research was limited to optimization on the basis of in-vehicle travel time, fuel consumption and emissions in the urban travel corridors. These are not the only relevant objectives in the transportation corridors. Transportation systems are expected to be safe and accessible. The methodology can be modified to incorporate other objective functions.

- Mode choice is a very important variable in this research. The case study reported here reflects existing and projected modes in the Ottawa-Carleton Region, based on the continuation of the bus rapid transit policy. However, should rail-based public transit system be considered for this region and for the application of the developed methodology to other urban regions, the products of this research can still be used effectively. There will, of course, be the need for a model to

estimate the performance of the rail-based mode. Other changes required would involve energy and emissions methodologies.

- In this research, due to data limitations, inter-period cross-elasticities of travel demand could not be investigated. Although literature studies indicate the absence of any significant cross-elasticities (i.e., commuters rather incur the expenses of peak travel than to change their travel departure time to a shoulder period), from a research perspective, it would be beneficial to study inter-period travel interaction.

- In this research, for developing demand models, results of the latest available 1986 comprehensive O-D survey from the Regional Municipality of Ottawa-Carleton (RMOC) were used. Although, the 1995 O-D survey was available in July 1996, these data did not include travel cost components (e.g., parking cost, fare) for 258 zones system. It is expected that the complete data base will become available at the end of 1996 or during early 1997. Therefore, the demand model can be re-calibrated and analyses can be updated.

- The case study deals with p.m. peak period travel, consisting mostly of home-based work (HBW) trips. Thus, the developed demand models, are based on p.m. peak period travel. More research is required to work with HBW trips in the morning peak period. The work-to-home trips often involve some secondary trips, such as shopping and other social activities and there may not be as much pressure to arrive home at a pre-set time. Therefore, a work-to-home commuting trip in the afternoon, may be different than a home-to-work commuting trip in the

morning. Also, for urban travel corridors, it would be useful to have knowledge of both a.m. and p.m. peak period travel characteristics.

- Since the methodology as well as results are believed to be of much value to urban regions, it is recommended that, major aspects of this research should be adopted by transportation departments of urban regions. The Transitway simulation model can be readily replaced by a simulator for a rail-based system. Likewise, other changes can be made without incurring a high expense.

- One of the major operational issues affecting the Transitway is the decision regarding what vehicle groups will be allowed to use the Transitway. In this research, it was assumed that the Transitway is only for bus use. However, from a research perspective, corridor travel optimization studies could explore the policy of allowing other vehicles (e.g., vanpool, taxi) on the Transitway.

- The finding of this research in terms of the effectiveness of demand management instruments in enabling the optimization of urban corridors should be of interest to urban governments. For example, moderate fares for public transit, the use of tolls on major freeways and increased cost of parking could be used for developing effective demand management strategies.

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APPENDIX A

TRAVEL DEMAND MODELS

Appendix A.1: Trip Generation Model Calibration Results

(Equations 2.1-2.4)

```
09 Jul 96   SPSS Release 4.0 for Sun 4
                                                Page 1
10:00:19    SPSS -- Carleton University    Sun-4            SunOS 4.0


For SunOS 4.0           SPSS -- Carleton University       License Number 21295
This software is functional through August 31, 1999.

Try the new SPSS Release 4.0 features:

* LOGISTIC REGRESSION procedure                  * CATEGORIES Option:
* EXAMINE procedure to explore data              *   conjoint analysis
* FLIP to transpose data files                   *   correspondence analysis
* MATRIX Transformations Language                * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

   1  0  DATA LIST FILE='spsnw1.dat'
   2  0      /sumnw1 1-6 sumnw2 7-12 acnwor 13-24
   3  0       ipop 25-30 pop1 31-35 pop2 36-40 pop3 41-45
   4  0       pop4 46-50 iemp 51-55 empre 56-61 empot 62-67
   5  0       dunit 68-73 gla 74-80.

This command will read 1 records from spsnw1.dat

Variable   Rec   Start     End         Format

SUMNW1       1       1       6         F6.0
SUMNW2       1       7      12         F6.0
ACNWOR       1      13      24         F12.0
IPOP         1      25      30         F6.0
POP1         1      31      35         F5.0
POP2         1      36      40         F5.0
POP3         1      41      45         F5.0
POP4         1      46      50         F5.0
IEMP         1      51      55         F5.0
EMPRE        1      56      61         F6.0
EMPOT        1      62      67         F6.0
DUNIT        1      68      73         F6.0
GLA          1      74      80         F7.0

   6  0  SAVE OUTFILE='spsnwork.sys'.

Time stamp on saved file:  09 JUL 96 10:00:21
File contains 13 variables, 104 bytes per case before compression
258 cases saved

Preceding task required .31 seconds CPU time;  .79 seconds elapsed.

   7  0  GET FILE='spsnwork.sys'.

File spsnwork.sys
   Created:  09 JUL 96 10:00:21 - 13 variables

   8  0  REGRESSION VARIABLES = sumnw1,ipop,iemp,gla
   9  0     /DEPENDENT = sumnw1
  10  0    /ENTER iemp,ipop,gla.
```

```
09 Jul 96   SPSS Release 4.0 for Sun 4
                                        Page 2
10:00:22    SPSS -- Carleton University   Sun-4          SunOS 4.0

There are 203,448 bytes of memory available.
The largest contiguous area has 202,824 bytes.

     1788 bytes of memory required for REGRESSION procedure.
        0 more bytes may be needed for Residuals plots.
```

* * * * M U L T I P L E R E G R E S S I O N * * * *

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. SUMNW1

Block Number 1. Method: Enter IEMP IPOP GLA

Variable(s) Entered on Step Number 1.. GLA
2.. IPOP
3.. IEMP

		Analysis of Variance	DF	Sum of Squares	Mean Square
Multiple R	.87426				
R Square	.76434				
Adjusted R Square	.76155	Regression	3	352411121.23990	117470373.74663
Standard Error	654.05061	Residual	254	108656678.27948	427782.19795

F = 274.60323 Signif F = .0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
GLA	.004284	3.3934E-04	.388766	12.623	.0000
IPOP	.134628	.011128	.368832	12.098	.0000
IEMP	.289752	.013777	.648192	21.031	.0000
(Constant)	208.950043	59.272198		3.525	.0005

End Block Number 1 All requested variables entered.

Preceding task required .15 seconds CPU time; 1.14 seconds elapsed.

```
  11  0  CORRELATIONS sumnwl,iemp,gla,ipop.
```

PEARSON CORR problem requires 352 bytes of workspace.

- - Correlation Coefficients - -

	SUMNW1	IEMP	GLA	IPOP
SUMNW1	1.0000	.6908**	.4863**	.3456**
IEMP	.6908**	1.0000	.1471*	-.0395
GLA	.4863**	.1471*	1.0000	.0061
IPOP	.3456**	-.0395	.0061	1.0000

* - Signif. LE .05 ** - Signif. LE .01 (2-tailed) " . "
printed if a coefficient cannot be computed

Preceding task required .07 seconds CPU time; .18 seconds elapsed.

```
  12  0  DESCRIPTIVES sumnw1,iemp,ipop,gla.
```

There are 203,880 bytes of memory available.
The largest contiguous area has 203,288 bytes.

304 bytes of memory required for the DESCRIPTIVES procedure.
16 bytes have already been acquired.
288 bytes remain to be acquired.

Number of valid observations (listwise) = 258.00

Variable	Mean	Std Dev	Minimum	Maximum	Valid N	Label
SUMNW1	1272.87	1339.42	0	10942	258	
IEMP	1586.31	2996.36	0	29490	258	
IPOP	3126.18	3669.51	0	16385	258	
GLA	42815.74	121558.22	0	841605	258	

```
09 Jul 96   SPSS Release 4.0 for Sun 4
                                                    Page 116
10:00:28    SPSS -- Carleton University    Sun-4            SunOS 4.0

Preceding task required .04 seconds CPU time;  .04 seconds elapsed.

 103  0  FINISH.

   103 command lines read.
     0 errors detected.
     0 warnings issued.
     4 seconds CPU time.
     8 seconds elapsed time.
       End of job.
```

```
03 Jul 96   SPSS Release 4.0 for Sun 4
                                                Page 1
16:32:01    SPSS -- Carleton University    Sun-4            SunOS 4.0


For SunOS 4.0           SPSS -- Carleton University       License Number 21295
This software is functional through August 31, 1999.

Try the new SPSS Release 4.0 features:

* LOGISTIC REGRESSION procedure                  * CATEGORIES Option:
* EXAMINE procedure to explore data              *   conjoint analysis
* FLIP to transpose data files                   *   correspondence analysis
* MATRIX Transformations Language                * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

   1  0  DATA LIST FILE='spsnw.dat'
   2  0     /sumw1 1-6 sumw2 7-12 sumnw1 13-18 sumnw2 19-24
   3  0      ipop 25-30 pop1 31-35 pop2 36-40 pop3 41-45
   4  0      pop4 46-50 iemp 51-55 empre 56-61 empot 62-67
   5  0      dunit 68-73 gla 74-80.

This command will read 1 records from spsnw.dat

Variable   Rec   Start     End         Format

SUMW1        1       1       6         F6.0
SUMW2        1       7      12         F6.0
SUMNW1       1      13      18         F6.0
SUMNW2       1      19      24         F6.0
IPOP         1      25      30         F6.0
POP1         1      31      35         F5.0
POP2         1      36      40         F5.0
POP3         1      41      45         F5.0
POP4         1      46      50         F5.0
IEMP         1      51      55         F5.0
EMPRE        1      56      61         F6.0
EMPOT        1      62      67         F6.0
DUNIT        1      68      73         F6.0
GLA          1      74      80         F7.0

   6  0  SAVE OUTFILE='spsnwork1.sys'.

Time stamp on saved file:  03 JUL 96 16:32:04
File contains 14 variables, 112 bytes per case before compression
258 cases saved

Preceding task required .34 seconds CPU time;  1.10 seconds elapsed.

   7  0  GET FILE='spsnwork1.sys'.
```

```
03 Jul 96    SPSS Release 4.0 for Sun 4
                                                Page 14
16:32:06     SPSS -- Carleton University        Sun-4            SunOS 4.0

Preceding task required .04 seconds CPU time;  .04 seconds elapsed.

  18  0  REGRESSION VARIABLES = sumnw2,dunit,iemp,gla
  19  0      /DEPENDENT = sumnw2
  20  0    /ENTER iemp,dunit,gla.

There are 203,456 bytes of memory available.
The largest contiguous area has 202,760 bytes.

     1804 bytes of memory required for REGRESSION procedure.
        0 more bytes may be needed for Residuals plots.
```

```
                    * * * *   M U L T I P L E   R E G R E S S I O N   * * * *

Listwise Deletion of Missing Data

Equation Number 1    Dependent Variable..   SUMNW2

Block Number  1.  Method:  Enter      IEMP     DUNIT    GLA

Variable(s) Entered on Step Number  1..    GLA
                                    2..    DUNIT
                                    3..    IEMP

Multiple R            .89281          Analysis of Variance
R Square              .79711                          DF      Sum of Squares      Mean Square
Adjusted R Square     .79472          Regression       3     301361493.80015  100453831.26672
Standard Error     549.53220          Residual       254      76704351.99830     301985.63779

                                       F =      332.64440       Signif F =  .0000

------------------ Variables in the Equation ------------------

Variable              B         SE B        Beta          T  Sig T

GLA             .004524  2.8510E-04     .453412     15.868  .0000
DUNIT           .620455     .024592     .713273     25.230  .0000
IEMP            .088798     .011569     .219372      7.675  .0000
(Constant)   220.941840   48.767757                  4.530  .0000

End Block Number   1   All requested variables entered.
```

Preceding task required .06 seconds CPU time; .11 seconds elapsed.

```
  21  0  CORRELATIONS sumnwZ,iemp,gla,dunit.
```

PEARSON CORR problem requires 352 bytes of workspace.

- - Correlation Coefficients - -

	SUMNW2	IEMP	GLA	DUNIT
SUMNW2	1.0000	.3025**	.4837**	.7171**
IEMP	.3025**	1.0000	.1471*	.0231
GLA	.4837**	.1471*	1.0000	-.0028
DUNIT	.7171**	.0231	-.0028	1.0000

* - Signif. LE .05 ** - Signif. LE .01 (2-tailed) " . "
printed if a coefficient cannot be computed

```
Preceding task required .05 seconds CPU time;  .05 seconds elapsed.

  22  0  DESCRIPTIVES sumnw2,iemp,dunit,gla.

There are 203,824 bytes of memory available.
The largest contiguous area has 203,240 bytes.


304 bytes of memory required for the DESCRIPTIVES procedure.
16 bytes have already been acquired.
288 bytes remain to be acquired.
```

Number of valid observations (listwise) = 258.00

Variable	Mean	Std Dev	Minimum	Maximum	Valid N	Label
SUMNW2	1272.84	1212.88	0	5924	258	
IEMP	1586.31	2996.36	0	29490	258	
DUNIT	1156.16	1394.32	0	6975	258	
GLA	42815.74	121558.22	0	841605	258	

```
03 Jul 96    SPSS Release 4.0 for Sun 4                    Page 124
16:32:12     SPSS -- Carleton University     Sun-4                SunOS 4.0

Preceding task required .04 seconds CPU time;  .05 seconds elapsed.

 118  0  FINISH.

   118 command lines read.
     5 errors detected.
     0 warnings issued.
     4 seconds CPU time.
    12 seconds elapsed time.
       End of job.
```

```
09 Jul 96    SPSS Release 4.0 for Sun 4
                                                Page 1
09:56:11     SPSS -- Carleton University     Sun-4            SunOS 4.0


For SunOS 4.0            SPSS -- Carleton University       License Number 21295
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Try the new SPSS Release 4.0 features:

* LOGISTIC REGRESSION procedure                    * CATEGORIES Option:
* EXAMINE procedure to explore data                *   conjoint analysis
* FLIP to transpose data files                     *   correspondence analysis
* MATRIX Transformations Language                  * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

   1  0  DATA LIST FILE='spsw1.dat'
   2  0      /sumw1 1-6 sumw2 7-12 sumnw1 13-18 sumnw2 19-24
   3  0       ipop 25-30 pop1 31-35 pop2 36-40 pop3 41-45
   4  0       pop4 46-50 iemp 51-56 empre 57-62 empot 63-68
   5  0       dunit 69-73 acwor 74-80.

This command will read 1 records from spsw1.dat

Variable    Rec    Start      End          Format

SUMW1         1        1        6          F6.0
SUMW2         1        7       12          F6.0
SUMNW1        1       13       18          F6.0
SUMNW2        1       19       24          F6.0
IPOP          1       25       30          F6.0
POP1          1       31       35          F5.0
POP2          1       36       40          F5.0
POP3          1       41       45          F5.0
POP4          1       46       50          F5.0
IEMP          1       51       56          F6.0
EMPRE         1       57       62          F6.0
EMPOT         1       63       68          F6.0
DUNIT         1       69       73          F5.0
ACWOR         1       74       80          F7.0

   6  0  SAVE OUTFILE='spswork.sys'.

Time stamp on saved file:  09 JUL 96 09:56:13
File contains 14 variables, 112 bytes per case before compression
258 cases saved

Preceding task required .24 seconds CPU time;  .71 seconds elapsed.

   7  0  GET FILE='spswork.sys'.
```

```
09 Jul 96   SPSS Release 4.0 for Sun 4
                                                Page 2
09:56:14    SPSS -- Carleton University    Sun-4            SunOS 4.0


File spswork.sys
   Created:  09 JUL 96 09:56:13 - 14 variables

   8  0  REGRESSION VARIABLES = sumwl,iemp
   9  0     /DEPENDENT = sumwl
  10  0    /ENTER iemp.

There are 203,408 bytes of memory available.
The largest contiguous area has 202,760 bytes.

     1364 bytes of memory required for REGRESSION procedure.
        0 more bytes may be needed for Residuals plots.
```

* * * * M U L T I P L E R E G R E S S I O N * * * *

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. SUMW1

Block Number 1. Method: Enter IEMP

Variable(s) Entered on Step Number 1.. IEMP

Multiple R	.93293
R Square	.87036
Adjusted R Square	.86985
Standard Error	529.76323

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	482342087.76189	482342087.76189
Residual	256	71846164.81563	280649.08131

F = 1718.66619 Signif F = .0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
IEMP	.457212	.011029	.932930	41.457	.0000
(Constant)	-138.376132	37.334379		-3.706	.0003

End Block Number 1 All requested variables entered.

```
Preceding task required .15 seconds CPU time;  .79 seconds elapsed.
  11  0  CORRELATIONS sumw1,iemp.
PEARSON CORR problem requires 80 bytes of workspace.
```

- - Correlation Coefficients - -

	SUMW1	IEMP
SUMW1	1.0000	.9329**
IEMP	.9329**	1.0000

* - Signif. LE .05 ** - Signif. LE .01 (2-tailed) " . "
printed if a coefficient cannot be computed

```
Preceding task required .05 seconds CPU time;  .14 seconds elapsed.

  12  0  DESCRIPTIVES sumw1,iemp.

There are 203,832 bytes of memory available.
The largest contiguous area has 203,352 bytes.


152 bytes of memory required for the DESCRIPTIVES procedure.
8 bytes have already been acquired.
144 bytes remain to be acquired.
```

Number of valid observations (listwise) = 258.00

Variable	Mean	Std Dev	Minimum	Maximum	Valid N	Label
SUMW1	586.90	1468.46	0	18138	258	
IEMP	1586.31	2996.36	0	29490	258	

```
09 Jul 96    SPSS Release 4.0 for Sun 4
                                                    Page 67
09:56:17     SPSS -- Carleton University    Sun-4            SunOS 4.0

Preceding task required .05 seconds CPU time;  .05 seconds elapsed.

  73  0  FINISH.

    73 command lines read.
     9 errors detected.
     0 warnings issued.
     2 seconds CPU time.
     7 seconds elapsed time.
       End of job.
```

```
03 Jul 96    SPSS Release 4.0 for Sun 4
                                                Page 1
12:57:37     SPSS -- Carleton University    Sun-4            SunOS 4.0

For SunOS 4.0            SPSS -- Carleton University       License Number 21295
This software is functional through August 31, 1999.

Try the new SPSS Release 4.0 features:

* LOGISTIC REGRESSION procedure                  * CATEGORIES Option:
* EXAMINE procedure to explore data              *   conjoint analysis
* FLIP to transpose data files                   *   correspondence analysis
* MATRIX Transformations Language                * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

   1  0  DATA LIST FILE='spsw.dat'
   2  0      /sumw1 1-6 sumw2 7-12 sumnw1 13-18 sumnw2 19-24
   3  0       ipop 25-30 pop1 31-35 pop2 36-40 pop3 41-45
   4  0       pop4 46-50 iemp 51-56 empre 57-62 empot 63-68
   5  0       dunit 69-75 carow 76-80.

This command will read 1 records from spsw.dat

Variable    Rec   Start     End         Format

SUMW1         1       1       6         F6.0
SUMW2         1       7      12         F6.0
SUMNW1        1      13      18         F6.0
SUMNW2        1      19      24         F6.0
IPOP          1      25      30         F6.0
POP1          1      31      35         F5.0
POP2          1      36      40         F5.0
POP3          1      41      45         F5.0
POP4          1      46      50         F5.0
IEMP          1      51      56         F6.0
EMPRE         1      57      62         F6.0
EMPOT         1      63      68         F6.0
DUNIT         1      69      75         F7.0
CAROW         1      76      80         F5.0

   6  0  SAVE OUTFILE='spswork1.sys'.

Time stamp on saved file:  03 JUL 96 12:57:40
File contains 14 variables, 112 bytes per case before compression
258 cases saved

Preceding task required .26 seconds CPU time;  .56 seconds elapsed.

   7  0  GET FILE='spswork1.sys'.
```

```
03 Jul 96    SPSS Release 4.0 for Sun 4
                                                Page 20
12:57:42     SPSS -- Carleton University        Sun-4            SunOS 4.0

Preceding task required .05 seconds CPU time;  .05 seconds elapsed.

  23  0  REGRESSION VARIABLES = sumw2,ipop
  24  0     /DEPENDENT = sumw2
  25  0    /ENTER ipop.

There are 203,472 bytes of memory available.
The largest contiguous area has 202,760 bytes.

     1364 bytes of memory required for REGRESSION procedure.
        0 more bytes may be needed for Residuals plots.
```

* * * * M U L T I P L E R E G R E S S I O N * * * *

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. SUMW2

Block Number 1. Method: Enter IPOP

Variable(s) Entered on Step Number 1.. IPOP

Multiple R	.95073
R Square	.90389
Adjusted R Square	.90351
Standard Error	221.55274

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	118178389.77147	118178389.77147
Residual	256	12565918.35256	49085.61856

F = 2407.59704 Signif F = .0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
IPOP	.184797	.003766	.950731	49.067	.0000
(Constant)	9.207107	18.134950		.508	.6121

End Block Number 1 All requested variables entered.

```
Preceding task required .06 seconds CPU time;  .11 seconds elapsed.
  26  0  CORRELATIONS sumw2,ipop.
PEARSON CORR problem requires 80 bytes of workspace.
```

- - Correlation Coefficients - -

	SUMW2	IPOP
SUMW2	1.0000	.9507**
IPOP	.9507**	1.0000

* - Signif. LE .05 ** - Signif. LE .01 (2-tailed) " . "
printed if a coefficient cannot be computed

```
Preceding task required .04 seconds CPU time;  .04 seconds elapsed.

  27  0  DESCRIPTIVES sumw2,ipop.

There are 203,832 bytes of memory available.
The largest contiguous area has 203,352 bytes.


152 bytes of memory required for the DESCRIPTIVES procedure.
8 bytes have already been acquired.
144 bytes remain to be acquired.
```

Number of valid observations (listwise) = 258.00

Variable	Mean	Std Dev	Minimum	Maximum	Valid N	Label
SUMW2	586.91	713.26	0	3182	258	
IPOP	3126.18	3669.51	0	16385	258	

```
Preceding task required .09 seconds CPU time;  .24 seconds elapsed.

  64  0  FINISH.

    64 command lines read.
     1 errors detected.
     0 warnings issued.
     2 seconds CPU time.
     7 seconds elapsed time.
       End of job.
```

Appendix A.2: Modal Split Model Calibration Results

(Equations 2.16.1-2.16.3)

LOGIT MODEL ESTIMATION VERSION 5.1

DATA SET: 1986 PM WORK TRIPS SURVEY SAMPLE
MODEL: UNTITLED MODEL

PAR:	a	b	c	e	f	g	h
driver	1	0	tcostc	0	carint	numveh	0
passgr	0	0	tcostp	0	cptime	0	numveh
transt	0	1	farcos	busint	busovt	0	0

FINAL PARAMETER VALUES

NUMBER	NAME	VALUE	T-STAT
1	a	0.14697E+01	10.4363
2	b	0.15498E+01	10.5748
3	c	-.54179E+00	-18.4663
4	e	-.11293E-01	-2.6674
5	f	-.19922E-01	-3.5151
6	g	0.61065E+00	9.2106
7	h	0.28874E+00	3.7145

GOODNESS-OF-FIT STATISTICS

No. of weighted observations=	3105
No. of cases=	5909
No. of parameters estimated=	7
Degrees of freedom=	5902
Log likelihood at B=0,=	-3289.1
Log likelihood at conv.=	-2390.4
Log likelihood ratio=	1797.5
RHO-square=	0.2732
Adjusted RHO-square=	0.2724
Horowitz' RHO-square=	0.2722
Expected percent right=	55.6

RUN PARAMETERS:

No. of data records=	3105	Max. no. of iterations=	10	Data file delete switch=	1
No. of model parameters=	7	Convergence criterion=	1	Parameter corr. print switch=	1
Max. no. of alternatives=	3	EPS=	0.0010		
No. of const. parameters=	0	TOL=	0.1000		
		SQTOL=	0.1000		

MODEL PARAMETERS & INITIAL VALUES:

a	b	c	e	f	g	h
0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Log likelihood at zero parameter values= -3289.1
Log likelihood at initial parameter values= -3289.1

INTERMEDIATE RESULTS: Parameter name, value & change in value from last iteration.

Iteration No. 1:

a	b	c	e	f	g	h
0.1502E+01	0.1145E+01	-.6555E+00	-.7642E-02	-.6310E-02	0.5086E+00	0.2048E+00
-.1502E+01	-.1145E+01	0.6555E+00	0.7642E-02	0.6310E-02	-.5086E+00	-.2048E+00

Log likelihood= -2405.9

Iteration No. 2:

a	b	c	e	f	g	h
0.1491E+01	0.1492E+01	-.5525E+00	-.8913E-02	-.1401E-01	0.6088E+00	0.2803E+00
0.1109E-01	-.3477E+00	-.1030E+00	0.1271E-02	0.7702E-02	-.1002E+00	-.7548E-01

Log likelihood= -2391.0

Iteration No. 3:

a	b	c	e	f	g	h
0.1475E+01	0.1543E+01	-.5437E+00	-.1097E-01	-.1913E-01	0.6102E+00	0.2880E+00
0.1573E-01	-.5104E-01	-.8848E-02	0.2057E-02	0.5123E-02	-.1332E-02	-.7694E-02

Log likelihood= -2390.4

Iteration No. 4:

CONVERGENCE ACCORDING TO CONV. OPTION 1 HAS BEEN ACHIEVED.

PARAMETER VARIANCE-COVARIANCE MATRIX

	a	b	c	e	f	g	h
a	0.0198						
b	0.0086	0.0215					
c	-0.0011	0.0004	0.0009				
e	0.0001	-0.0003	0.0000	0.0000			
f	0.0002	-0.0002	-0.0001	0.0000	0.0000		
g	-0.0037	0.0026	-0.0001	0.0000	0.0000	0.0044	
h	0.0054	0.0080	-0.0001	0.0000	0.0000	0.0022	0.0060

PARAMETER FIRST-ORDER CORRELATION COEFFICIENTS

	a	b	c	e	f	g	h
a	1.0000						
b	0.4179	1.0000					
c	-0.2563	0.1042	1.0000				
e	0.1521	-0.5301	-0.1291	1.0000			
f	0.2757	-0.2831	-0.5116	0.5073	1.0000		
g	-0.1969	0.2660	-0.0632	0.0477	-0.0168	1.0000	
h	0.4932	0.6993	-0.0309	0.0600	-0.0421	0.4354	1.0000

```
                UNTITLED MODEL
 3  7 43 28  3  0  0  1  1
 1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
31 32 33 34 35 36 37 38 39 40
a       b       c       e       f       g       h
driver   passgr   transt
homzo1 homzo2 wrkzo1 wrkzo2 modech drvlic numveh numwor numper sexind
age241 age441 provin wrkcbd twyhom twywrk tripta triptt parkct ovtt-p
walk-t wait-t auivtt audist pkcost trivtt trcost
1       0       busint busovt farcos pcostc pcoscp ocostc ocoscp carint
cptime freque frebus ocostp tcostc tcostp
  28  29  42  29  37   7  29
  29  29  43  29  38  29   7
  29  28  32  30  31  29  29
14
 6.0 26.0 29.0 0.100000E+01 30.0
 1.0 22.0 21.0 0.000000E+00 31.0
 6.0 27.0 29.0 0.100000E+01 32.0
 6.0 25.0 29.0 0.100000E+01 33.0
 6.0 25.0 29.0 0.500000E+00 34.0
 6.0 24.0 29.0 0.600000E-01 35.0
 6.0 35.0 29.0 0.100000E+01 36.0
 5.0 23.0 29.0 0.500000E+01 37.0
 5.0 37.0 29.0 0.500000E+01 38.0
14.0 22.0 29.0 0.000000E+00 39.0
 6.0 39.0 29.0 0.300000E+02 40.0
 6.0 36.0 29.0 0.500000E+00 41.0
 1.0 33.0 35.0 0.000000E+00 42.0
 1.0 34.0 41.0 0.000000E+00 43.0
 6   6
  6   1 0.900000E+01
  7   1 0.990000E+02
  8   1 0.990000E+02
 10   1 0.900000E+01
 11   1 0.900000E+01
 12   1 0.900000E+01
0
```

```
  7   0   7
 0.146974E+01 0.154983E+01-0.541790E+00-0.112935E-01-0.199219E-01 0.610646E+00
 0.288744E+00
 0.1983E-01 0.8625E-02 -.1059E-02 0.9071E-04 0.2201E-03 -.3706E-02 0.5399E-02
 0.2148E-01 0.4479E-03 -.3289E-03 -.2352E-03 0.2585E-02 0.7967E-02
 0.8608E-03 -.1604E-04 -.8508E-04 -.1228E-03 -.7056E-04
 0.1793E-04 0.1217E-04 0.1339E-04 0.1976E-04
 0.3212E-04 -.6317E-05 -.1854E-04
 0.4395E-02 0.2244E-02
 0.6042E-02
3105
-0.239039E+04
```

Appendix A.3: The Elasticities of Multinomial Logit Mode

For multinomial logit model, elasticities can be estimated by using the following equation [36,46]

$$E_{Y_{ik}}(P_i) = (1-P_i)\ \delta_{ik}\ Y_{ik} \qquad (A.3.1)$$

where

E : point direct elasticity (of the multinomial logit model) for P_i with respect to Y_{ik}

Y_{ik}: kth attribute of the ith mode

P_i : probability of choosing mode i

δ_{ik}: coefficient of kth attribute of ith mode

For example, auto travel cost by using average values of variables $\Rightarrow P_i = 0.5336$ for car (i.e., P_{bus}=0.3466 & $P_{carpool}$=0.1198)

$E_{Yik}(P_i)$ = (1-0.5336)*(-0.542)*($2.12)=-0.536

Multinomial Logit Direct Elasticities Based on Average Values of Variables (1986 Data):

Mode	Independent Variable	Direct Elasticity
Car	Travel Cost ($)	-0.536
	Total Travel Time (min)	-0.192
	Car Ownership	+0.442
Carpool	Travel Cost ($)	-0.506
	Total Travel Time (min)	-0.450
	Car Ownership	+0.394
Bus	Fare ($)	-0.336
	In-Vehicle Time (min)	-0.165
	Out of Vehicle Time (min)	-0.248

APPENDIX B

THE SIMULATION MODEL FOR TRANSITWAY

Appendix B.1: The Transitway Simulation Model Computer Program

(TRNSIM)

```
c     ***************************************************************
c     *     macroscopic simulation model of bus operating on transitway   *
c     *                                                                   *
c     *                    Last revised : 1995                            *
c     ***************************************************************
      dimension grade(9000),length(9000),u(9000),ipaxbo(9000),
     .umax(9000),q(9000),trtime(50,9000),timest(50,9000),
     .ipaxa(2000),ipaxb(2000),timede(50,9000),qm(2000),
     .tstand(9000),qr(9000),kr(9000),loads(9000),trtime(9000),
     .qs(9000),us(9000),tisort(9000),itstand(50,9000),delay(9000),
     .tstand(9000),itotpab(9000),itotpaa(9000),itrtime(9000),
     .nmaxbus(9000),tovkmt(9000),mcapbus(9000),paxkm(9000),
     .qtm(9000),ipaxboa(9000),ipaxali(9000),ipax(9000),maxbus(9000),
     .adelay(9000),itotpax(9000),ipaxal(9000),mtstand(9000),
     .atravel(9000),avespe(9000),uaverage(9000),capmax(9000),
     .cap(9000),arunning(9000),kind(9000),capmax1(9000),
     .chddv(2500,10),cldgv(2500,10),esyshc(9000),esysco(9000),
     .esysnox(9000),temhc(9000),temco(9000),temnox(9000),
     .toesyshc(9000),toesysco(9000),toesysnox(9000),atofuel(9000),
     .tofuels(9000),tofuelsp(9000),curve(9000),aload(9000),
     .uavg(9000),volume(9000),toesysco2(9000),esysco2(9000),
     .timepkm(9000)
      integer x
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
c     input file for hddv emission calender factor
      open(unit=9,file='fhddv.in')
c     input file for ldgv emission calender factor
      open(unit=10,file='fldgv.in')
      open(unit=7,file='tranlr.in')
      open(unit=6,file='tran2r.in')
      open(unit=8,file='tran.out')
```

```
      im=1
c     study time in minutes;itimstu
c     number of places for bus stopping at station ;ns
c     percent of articulated buses;ptypea & percent of standard buses;ptypes
c     headway from origin in seconds;heaorig
c     percent of buses should be stopped at each station;plisto
c     average of alighting passengers based on survey;ameapa
c     standard devation of alighting passengers based on survey;asigm
c     average of boarding passengers based on survey;bmeapa
c     standard devation of boarding passengers based on survey;bsigm
c     average of bus load based on survey;ameanl
c     standard devation of bus load based on survey;astnl
c     type of stations,off-line ; itypstat=1,on-line; itypstat=2
      read(6,*)itimstu,numlin,ka,ns,ptypea,ptypes,heaorig,plisto,
     .ameapa,asigm,bmeapa,bsigm,ameanl,astnl,itypstat
c     ntem; ambient temperature (c)
c     nyear; calender year (1994-2011)
c     accepted range for average speed is (5 to 105 km/h)
c     accepted range for average ambient temperature is(-18 to 49 c)
c     seed for random number between 1-100; x
c     npeak for peak hour is 2 and for off-peak is 1
c     cloadfc; peak over off-peak ratio
c     determination input file ; mf=1 oc-transpo data
c     nf; determination of kind of formula (1:following vehicles logic
c                                          2:oc transpo data)
      read(6,*)nyear,ntem,x,npeak,cloadfc,mf,nf,a1,b1
c     k5; index: hc=1, co=2 and nox=3
      do 505 k4=1994,2011
      do 605 k5=1,3
      read(9,*)chddv(k4,k5)
c     format(f10.7)
      read(10,*)cldgv(k4,k5)
c     format(f10.7)
605   continue
505   continue
      itimstu=itimstu*60
      ptypea=ptypea/100.
      ptypes=ptypes/100.
      plisto=plisto/100.
      do 888 ii=1,ka
      call initlz
      qt=3600./heaorig
      qa=3600./heaorig
      do 88 ik=1,numlin
c     qr for on-ramp and kr for off-ramp
c     exit and entrance are begining of link ( after stations),
c     curve; radius of curve (m); if there is no curve; curve=1e+30
      read (7,*)length(ik),grade(ik),umax(ik),qr(ik),
     .kr(ik),curve(ik)
      qtm(ik)=qr(ik)
      qa=qa+qtm(ik)-kr(ik)
      if (qa .lt. 0.)qa=0.
      qm(ik)=qa
      if(qtm(ik) .eq. 0.)go to 891
      cmeapax=qtm(ik)
```

```
c       using poisson distribuation for bus arriving at stations
        call timesta(cmeapax,numpax)
        qtm(ik)=numpax
891     qt=qt+qtm(ik)-kr(ik)
        if(qt .lt. 0.)qt=0.
        q(ik)=qt
        volume(ik)=q(ik)
88      continue
        capstf1=0.
c       minimum headway at off-line station is 15 seconds
c       minimum headway at on-line station is 20 seconds
        if(itypstat .eq. 1)then
        headmin=15.
        else
        headmin=20.
        endif
c       maximum authorized capcity ; autcap
        autcap=3600./headmin
        do 404 in=1,2
        do 880 mn=1,numlin
        if((in .eq. 2) .or. (volume(mn) .ge. autcap))then
        call typebus
        amaxmea=capbus
        call initlz
        bmeapax=cloadfc*(bmeapax*amaxmea/(bmen/cloadfc))
        ameapax=cloadfc*(ameapax*amaxmea/(bmen/cloadfc))
        endif
        clock=0.
        iq=0
        ik1=0
        k=1
        totrti=0.
        travel=0.
        totrun=0.
        toavsp=0.
        totavsp=0.
        umid=0.
        todelay=0.
        tlo=0.
        tb=0.
        ta=0.
        tisort(k)=0.
        totstand=0.
        tocapbus=0.
        toesysh=0.
        toesysc=0.
        toesysn=0.
        tofuel=0.
        rc=curve(mn)
        if((mn .ge. 2) .and. (in .eq. 1))bmen=bmen1
        if(in .eq. 2)then
        if (nf .eq. 1)then
        call flow1
        else
        call flow2
```

```
      endif
      q(mn)=qs(mn)
      autcap=3600./headmin
      if(q(mn) .gt. autcap)q(mn)=autcap
      if(in .eq. 2)volume(mn)=q(mn)
      endif
      headsc=3600./q(mn)
c     generation a new bus based on random numbers
333   ik1=ik1+1
c     maximum station capcity at transitway
      call typebus
      call dweelti
      call movement
      call headway
      pstop=rand(x)
      mp=mn/5
      if(mn .eq. 5*mp)go to 209
      if(pstop .gt. plisto)tstand(ik1)=0.
c     time for arriving to transitway(from stations);timest(mn,ik1)
209   if(ik1 .eq. 1)then
      timeini=0.
      headtem=timeini
      go to 642
      endif
      headtem=expon(headsc)
642   timest(mn,ik1)=headtem+clock
      clock=timest(mn,ik1)
      if(clock .gt. itimstu)go to 879
      cap(ik1)=capbus
      capmax1(ik1)=capwa1
      if(ik1 .eq. 1)cmincap=capmax1(ik1)
      if(ik1 .gt. 1)then
         if(capmax1(ik1) .lt. cmincap)cmincap=capmax1(ik1)
      endif
      if(volume(mn) .gt. cmincap)volume(mn)=cmincap
      avespe(ik1)=(length(mn)/1000.)/(tratim/3600.)
      toavsp=avespe(ik1)+toavsp
      uavg(mn)=toavsp/(ik1)
      umid=us(ik1)+umid
      u(mn)=umid/(ik1)
c     running time between stations;trtime(mn,ik1)
      trtime(mn,ik1)=tratim
c     time for arriving to stations;timede(mn,ik1)
      timede(mn,ik1)=timest(mn,ik1)+tratim
      if(ik1 .eq. 1)then
      tisort(k)=timede(mn,ik1)
      endif
      if (ik1 .eq. 1)timeini=timede(mn,ik1)+tstand(ik1)
      if(itype .le. 3)weigbus=weigbus+64.04*loads(ik1)
      if(in .eq. 1)xw=avespe(ik1)/3.6
      call fuel
      atofuel(ik1)=fuela*tac+fuelc*tcr+fueld*tde+fueli*tid
      if(itype .le. 3)then
           tottim=trtime(mn,ik1)+tstand(ik1)
           avespm1=length(mn)/tottim
```

```
      else
           if(itype .eq. 4)then
c          there is no stop for vanpools
           tottim=trtime(mn,ikl)
           avespm2=length(mn)/trtime(mn,ikl)
           endif
      endif
      call emission
      temhc(ikl)=esysh
      temco(ikl)=esysc
      temnox(ikl)=esysn
      if(capst .gt. autcap)capst=autcap
c     plisto is percent of buses are stopped at each estation
      gs=rand(x)
      if(gs .le. plisto)then
      go to 786
      else
      delay(ikl)=0.
      go to 555
      endif
786   if(in .eq. 2)go to 787
      if(ikl .ge. ns+1)then
787        timefi=timede(mn,ikl-ns)+tstand(ikl-ns)
           if(timede(mn,ikl) .lt. timefi)then
              delay(ikl)=timefi-timede(mn,ikl)
              trtime(mn,ikl)=trtime(mn,ikl)+delay(ikl)
              timede(mn,ikl)=timest(mn,ikl)+trtime(mn,ikl)
           else
                delay(ikl)=0.
           endif
      else
           delay(ikl)=0.
      endif
555   if((delay(ikl-1) .eq. 0.) .and. (ikl .ge. 2))then
            if(timede(mn,ikl)-timede(mn,ikl-1) .lt. headmin)then
                 diff=(timede(mn,ikl)-timede(mn,ikl-1))
                 timede(mn,ikl)=headmin-diff+timede(mn,ikl)
            endif
      endif
      if(timest(mn,ikl) .ge. tisort(k))then
666       k=k+1
          if(k .gt. 1)then
             tlo=tlo+loads(k-1)
             itotpax(k-1)=tlo
             tb=tb+ipaxb(k-1)
             itotpab(k-1)=tb
             ta=ta+ipaxa(k-1)
             itotpaa(k-1)=ta
             tocapbus=tocapbus+cap(k-1)
             maxbus(mn)=k-1
             tisort(k)=timede(mn,k)
             travel=(trtime(mn,k-1)+travel+tstand(k-1))
             totrun=totrun+trtime(mn,k-1)
             atravel(mn)=travel/(k-1)
             atime=(trtime(mn,k-1)+tstand(k-1))/3600.
```

```
            aspeed=(length(mn)/1000.)/atime
            totavsp=aspeed+totavsp
            uaverage(mn)=totavsp/(k-1)
            arunning(mn)=totrun/(k-1)
            if(capmaxl(k-1) .lt. cmincap)cmincap=capmaxl(k-1)
            totrti=totrti+trtime(mn,k-1)
            itrtime(mn)=totrti/(k-1)
            tovkmt(mn)=(length(mn)/1000.)*(k-1)
            totstand=totstand+tstand(k-1)
            mtstand(mn)=totstand/(k-1)
            paxkm(mn)=itotpax(k-1)*length(mn)/1000.
            timepax(mn)=(itrtime(mn)+mtstand(mn))/(paxkm(mn)/(k-1))
            todelay=todelay+delay(k-1)
            adelay(mn)=todelay/(k-1)
            mcapbus(mn)=tocapbus+ipaxa(k-1)
            ipax(mn)=itotpax(k-1)
            aload(mn)=(ipax(mn)*1.)/((k-1)*1.)
            ipaxbo(mn)=itotpab(k-1)
            ipaxal(mn)=itotpaa(k-1)
            toesysh=toesysh+temhc(k-1)
            toesysc=toesysc+temco(k-1)
            toesysn=toesysn+temnox(k-1)
c           emissions of HC,CO and NOx (g)
            toesyshc(mn)=toesysh/(k-1)
            toesysco(mn)=toesysc/(k-1)
            toesysnox(mn)=toesysn/(k-1)
c           emissions of HC,CO and NOx (g/km)
            esyshc(mn)=toesysh/((length(mn)/1000.)*(k-1))
            esysco(mn)=toesysc/((length(mn)/1000.)*(k-1))
            esysnox(mn)=toesysn/((length(mn)/1000.)*(k-1))
c           fuel consumption (L)
            tofuel=tofuel+atofuel(k-1)
            tofuels(mn)=tofuel/(k-1)
c           fuel consumption (L/km)
            tofuelsp(mn)=tofuel/((length(mn)/1000.)*(k-1))
c           estimation of emissions (co2)(kg/pass-km)
c                at the transitway by using fuel consumption estimation
c                diesel :2.73 tonnes/kilo litre
            toesysco2(mn)=2.73*tofuel
            esysco2(mn)= toesysco2(mn)/((length(mn)/1000.)*(k-1))
  endif
      endif
      ipaxboa(mn)=ipaxbo(mn)
      ipaxali(mn)=ipaxal(mn)
      if(timest(mn,ikl) .ge. tisort(k))then
            if(timest(mn,ikl) .lt. tisort(k-1))go to 666
      endif
      if(k .gt. 1)then
         if(timest(mn,ikl) .ge. itimstu)then
         go to 879
         else
         if(tisort(k-1) .ge. itimstu)then
            go to 879
         endif
         endif
```

```
      go to 333
      else
         if(clock .lt. itimstu)go to 333
      endif
879   if(in .eq. 1)then
        kload=ipax(mn)/maxbus(mn)
c       avgload; average bus load
        if(kload .lt. avgload)then
          if(mn .le. 4)then
            kload=avgload*cloadfc
          else
            kload=avgload
          endif
         endif
      tkload=kload*maxbus(mn)
      bmen1=(cloadfc*(tkload-ipaxali(mn)+ipaxbo(mn)))/(maxbus(mn)*1.)
      endif
      if(cmincap .gt. autcap)cmincap=autcap
      capmax(mn)=cmincap
      if(in .eq. 1)then
      capstf1=capstf+capstf1
      capstf2=capstf1/mn
      endif
880   continue
      if(in .eq. 1)then
      call report1
      call report2
      endif
      if(in .eq. 2)call report3
404   continue
      im=im+1
888   continue
      stop
      end



      subroutine initlz
c     initialization routine
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
```

```
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
c     initialize simulation
      tt=0.
c     preception raction time (sec.)
      tr=1.
c     bmen; average of number of passengers for each bus;
      if((npeak .eq. 1) .and. (in .eq. 2))then
      bmen=ameanl
      else
      bmen=cloadfc*ameanl
      endif
c     avgload; average bus load at transitway
      avgload=bmen
c     standard devation of passengers for each bus
      if((npeak .eq. 1) .and. (in .eq. 2))then
      bsig=astnl
      else
      bsig=cloadfc*astal
      endif
c     clearence time(lost time):(9 to 20 sec.)
      c=9.
c     deceleration rate between 1.3 & 3 m/s^2 for normal deceleration
      dece=1.72
c     deceleration rate 4 m/s^2 emergency deceleration
      deceem=4.
c     acceleration rate between 0.8 & 1 m/s^2 for type 1
      accele1=0.96
c     marginal safety after stopping (0.5 to 1 m )
      s0=1.
c     safety regime c
      regime=3.
c     average of alighting passengers based on survey
      ameapax=ameapa
c     standard devation of alighting passengers based on survey
      asigma=asigm
c     average of boarding passengers based on survey
      bmeapax=bmeapa
c     standard devation of boarding passengers based on survey
      bsigma=bsigm
      return
      end


      subroutine typebus
```

```
c     determination of type of bus, by using random number generator
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype-dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm ameanl,astnl
c     percentage buses on transitway;
c     ptypea;articulated buses & ptypes;standard buses
      typbus=rand(x)
c     type of buses or van (1:small bus;2:standard bus;
c                           3:articu.ated bus;4:vanpool)
      if(typbus .le. ptypea)itype=3
      if((typbus .gt. ptypea) .and. (typbus .le. ptypea+ptypes))itype=2
c     type 1 is related to small bus
c     load factor for buses (percent of full passenger who are
c                                       sitting and standing)
      faclod=1.
c     percentage number of passengers allow for standing
c                        based on level of service(0.0-1.0)
      allow=1.
      if(itype .eq. 1)then
      lenbus=9
      capbus=(31+allow*19)*faclod
      weigbus=8562.
      umaxv=90.
      a=a1
      b=b1
      go to 99
      else
      go to 678
      end if
c     type 2 is related to standard bus
678   if(itype .eq. 2)then
      lenbus=12
      capbus=(49+allow*32)*faclod
```

```
      weigbus=10720.
      umaxv=90.
      a=a1
      b=b1
      go to 99
      else
      go to 778
      end if
c     type 3 is related to articulated bus
778   if(itype .eq. 3)then
      lenbus=18
      capbus=(58+allow*37)*faclod
      weigbus=17120.
      umaxv=80.
c     35% reduction of alighting time passenger due to double doors
      a=0.65*a1
c     0.4 sec. reduction of boarding time due to using bus pass
      b=b1-0.4
      go to 99
      else
      go to 878
      end if
c     type 4 is related to vanpool
878   if(itype .eq. 4)then
      lenbus=4
      capbus=9
      weigbus=2856.
      umaxv=90.
      end if
99    return
      end



      subroutine movement
c     calculation of travel time
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
```

```
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,al,bl
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      if(regime .eq. 1.)go to 5000
      if(regime .eq. 2.)go to 6000
      if(regime .eq. 3.)go to 7000
5000  dec=(1/(2*dece))
      go to 8000
6000  dec=(1/(2*dece)-1/(2*deceem))
      go to 8000
7000  dec=(1/(2*deceem))
8000  uml=sqrt((lenbus+s0)/dec)
      capwa01=((uml)/((uml)*tr+dec*(uml)*(uml)+(lenbus+s0)))*3600.
      if(length(mn) .ge. 400)then
      if(grade(mn) .le. 0.)f=1.
      if((grade(mn) .eq. 1.) .or. (grade(mn) .eq. 2.))f=0.94
      if((grade(mn) .eq. 3.) .or. (grade(mn) .eq. 4.))f=0.94
      if(grade(mn) .eq. 5.)f=0.5
      if(grade(mn) .eq. 6.)f=0.3
      else
      f=1.
      endif
      if(ikl .eq. 1)mcapwa=0
      capwa02=capwa01*f
c     practical capacity function based on expreiences
      f1=0.95
      capwa=capwa02*f1
      mcapwa=mcapwa+capwa
      capwal=mcapwa/ikl
      if(nf .eq. 1)then
      call speed1
      else
      call speed2
      endif
      xw=us(ikl)*(1000./3600.)
      tcr=(length(mn)-xw*xw*(1./(2.*accelel)+1./(2.*dece)))/xw
      if(tcr .lt. 0.)tcr=0.
      tac=xw/accelel
      tde=xw/dece
      tratim=tac+tcr+tde
      return
      end


      subroutine dweelti
c     calculation of dwell time at station
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespml,avespm2,uavg(9000)
```

```
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      bt=b
      at=a
c     load is average number of passenger for each bus;initial load
110   load=normal(bmen,bsig)
      if(load .lt. 0)go to 110
      if(npeak .eq. 1)then
      bmeapax1=bmeapax
      bsigma1=bsigma
      else
      bmeapax1=cloadfc*bmeapax
      bsigma1=cloadfc*bsigma
      endif
      cmeapax=normal(bmeapax1,bsigma1)
      call timesta(cmeapax,numpax)
      npax1=numpax
      ipaxb(ik1)=npax1
      load=load+npax1
      if(npeak .eq. 1)then
      ameapax1=ameapax
      asigma1=asigma
      else
      ameapax1=cloadfc*ameapax
      asigma1=cloadfc*asigma
      endif
      cmeapax=normal(ameapax1,asigma1)
      call timesta(cmeapax,numpax)
      npax2=numpax
      ipaxa(ik1)=npax2
      load=load-npax2
      if(load .lt. 0)then
      load=load-(npax1-npax2)
      go to 110
      else
```

```
      go to 112
112   endif
      if(load .gt. capbus)load=capbus
      loads(ikl)=load
      if(itype .eq. 1)then
c     tstand=a*numpax(boarding passenger)+
c            b*numpax(alighting passenger)+c
      tstand(ikl)=bt*npax1+at*npax2+c
      else
      tstand(ikl)=amax1(bt*npax1,at*npax2)+c
      endif
      if((npax1 .eq. 0) .and. (npax2 .eq. 0.))tstand(ikl)=0.
      tid=tstand(ikl)
      return
      end



      subroutine headway
c     calculation of minimum headway & capacity
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .ittotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fuel1,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ t1(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      call arrival(numbus)
      qs(mn)=numbus
      if(nf .eq. 1)then
      call speed1
      else
      call speed2
      endif
      xw1=us(ikl)*(1000./3600.)
c     time for deceleration of buses
```

```
      tdece=xw1/dece
c     time for leaving previous bus which arrived at station
c     ta=sqrt(2*lenbus/accele1) or ta=0.
      ta=0.
      if(ik1 .eq. 1)theadst=0.
c     minimum headway at station
      headst=tr+tstand(ik1)+tdece+ta
      theadst=theadst+headst
      aheadst=theadst/ik1
c     percentage buses are stopped at each stations;plisto
c     capacity at station
      capst=(3600./aheadst)*ns*(1./plisto)
      capstf=capst
      if(itypstat .eq. 1)then
      headst1=15.
      else
      headst1=20.
      endif
      caps1=3600./headst1
      if(capst .gt. caps1)capst=caps1
      if((ik1 .eq. 1) .and. (mn .eq. 1))capstma=capstf
      return
      end



      subroutine report1
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxa1(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ t1(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      if(im .eq. 1)then
      write(8,3)
```

```
      write(8,22)
22    format('buses or vanpools operating on transitway ',/,
     .'from origin to destination',//)
3     format('a macroscopic simulation model of vehicles operating',/,
     . 'on transitway ',//)
      write(8,27)itimstu/60
27    format('time study= ',2x,i6,2x,'minutes',//)
      write(8,2)ns
2     format('number of buses could be stopped at platforms'
     .,/,' of stations are =',2x,i2,2x,'buses',//)
      write(8,4)plisto*100
4     format('percentage of buses should be stopped at each stations='
     .,2x,'%',f5.1,//)
83    write(8,11)
11    format('-------------------------------------------------------------
     .-----------------------------')
      write(8,14)
14    format(3x,'link',10x,'length(m)',2x,'mean flow(veh/h)',2x,
     .'st. capacity(veh/h)')
      write(8,11)
      do 77 ik=1,numlin
      write(8,15)(ik),(ik+1),length(ik),qm(ik),capmax(ik)
15    format(i2,1x,'-',1x,,i2,11x,i5,10x,f5.0,12x,f7.0)
77    continue
      endif
      write(8,11)
      write(8,16)
      write(8,99)clock/60.
99    format('time period =',2x,f10.2,
     .2x,'minutes')
      y=clock/3600.
      write(8,16)
16    format(//)
      write(8,11)
      write(8,17)
17    format(3x,'link',12x,'(vkmt)',4x,
     .'avg. speed (km/h)',8x,'pass/bus')
      write(8,11)
      do 288 ik3=1,numlin
      runtime=(itrtime(ik3)*1.)/60.
      timepkm(ik3)=runtime/(1.*length(ik3)/1000.)
      vehicle=real(maxbus(ik3)/(itimstu/3600.))
      write(8,18)(ik3),(ik3+1),totvkmt(ik3)/y,uaverage(ik3),
     .aload(ik3)
18    format(i2,1x,'-',1x,i2,7x,f10.2,6x,f7.2,17x,f6.2)
288   continue
      write(8,11)
      write(8,16)
      write(8,16)
      write(8,16)
      write(8,11)
      write(8,19)
19    format(2x,'link',4x,'avg. dweel',8x,'total',8x,'total',
     .7x,'total',7x,'total')
      write(8,100)
```

```
100   format(10x,'time(min)',8x,'loadind',5x,'unloding',5x,
     .'pass.',7x,'pass.km')
      write(8,11)
      do 388 ik4=1,numlin
      write(8,200)(ik4),(ik4+1),mtstand(ik4),ipaxboa(ik4)/y,
     .ipaxali(ik4)/y,ipax(ik4)/y,paxkm(ik4)/y
200   format(i2,' - ',i2,4x,i5,9x,2(f8.0,4x),f9.0,3x,f10.2,3x)
388   continue
      write(8,11)
      write(8,16)
      write(8,11)
      write(8,21)
21    format(2x,'link',10x,'HC',10x,'CO',10x,'NOx',9x,'CO2',
     .9x,'fuel')
      write(8,122)
122   format(15x,' g/km',7x,' g/km',7x,' g/km',7x,'kg/km',
     .7x,'l/km')
      write(8,11)
      do 488 ik5=1,numlin
      write(8,300)(ik5),(ik5+1),esyshc(ik5),esysco(ik5),
     .esysnox(ik5),esysco2(ik5),
     .tofuelsp(ik5)
300   format(i2,' - ',i2,6x,4(e10.4,2x),f8.6)
488   continue
      write(8,11)
      write(8,16)
      return
      end


      subroutine report2
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
```

```
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      write(8,16)
16    format(//)
      write(8,11)
11    format('-------------------------------------------------------------
     .-----------------------------------')
      write(8,91)
91    format(2x,'link',8x,'pass./hr',5x,
     .'avg. time(min) ',3x,'avg. delay(min)',3x,'flow(veh/h) ')
      write(8,11)
      yl=clock/3600.
      lentol=0
      runnin=0.
      travtot=0.
      totcap=0.
      tesyshc=0.
      tesysco=0.
      tesysnox=0.
      tfuel=0.
      do 68 ih=1,numlin
      capfin=mcapbus(ih)/yl
      lentol=lentol+length(ih)
      travtot=travtot+atravel(ih)
      runnin=runnin+arunning(ih)
      tl(ih)=(length(ih)/atravel(ih))*3.6
      spetot=(lentol/travtot)*3.6
      if(ih .eq. 1)then
      spemin=tl(ih)
      spemax=tl(ih)
      ccapmin=capfin
      ccapmax=capfin
      endif
      if(tl(ih) .le. spemin)spemin=tl(ih)
      if(tl(ih) .ge. spemax)spemax=tl(ih)
      if(capfin .le. ccapmin)ccapmin=capfin
      if(capfin .ge. ccapmax)ccapmax=capfin
      totcap=totcap+capfin
      avecap=totcap/ih
      tesyshc=tesyshc+toesyshc(ih)
      tesysco=tesysco+toesysco(ih)
      tesysnox=tesysnox+toesysnox(ih)
      tfuel=tfuel+tofuels(ih)
68    write(8,32)ih,(ih+1),capfin,atravel(ih)/60.,
     .adelay(ih)/60.,q(ih)
32    format(i2,' - ',i2,6x,f8.0,9x,f6.2,11x,f6.2,12x,f6.0)
      tesysco2=tfuel*2.73
      write(8,11)
      write(8,16)
      write(8,190)(numlin+1),travtot/60.
190   format('* travel time between station  1 and station',1x,i3,/,
     .' =',f6.0,2x,'mintues',//)
      write(8,180)(numlin+1),spetot
180   format('* average speed between station  1 and station',1x,i3,/,
     .' =',f9.2,2x,'(km/h)',//)
```

```
      write(8,183)(numlin+1),spemin
183   format('* minimum speed between station  1 and station',1x,i3,/,
     .' =',f9.2,2x,'(km/h)',//)
      write(8,185)(numlin+1),spemax
185   format('* maximum speed between station  1 and station',1x,i3,/,
     .' =',f9.2,2x,'(km/h)',//)
      write(8,197)(numlin+1),avecap
197   format('* average passenger momvement ',/,
     .'between station  1 and station',1x,i3,' =',
     .f8.0,2x,'(pass./hr)',//)
      write(8,198)(numlin+1),(travtot/60.)/(lentol/1000.)
198   format('* avg. travel time (min) per km ',/,
     .'between station 1 and station',1x,i3,' =  ',f12.2,2x,/)
      write(8,208)(numlin+1),(tesyshc)/(lentol/1000.)
208   format('* avg. HC (g) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,218)(numlin+1),(tesysco)/(lentol/1000.)
218   format('* avg. CO (g) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,228)(numlin+1),(tesysnox)/(lentol/1000.)
228   format('* avg. NCx (g) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,248)(numlin+1),(tesysco2)/(lentol/1000.)
248   format('* avg. CO2 (kg) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,238)(numlin+1),(tfuel)/(lentol/1000.)
238   format('* avg. fuel (l) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,16)
      write(8,16)
      return
      end


      subroutine report3
c     report for capacity of passenger movement on transitway
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuell/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
```

```
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,al,bl
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,amean1,astn1
      y1=clock/3600.
      write(8,16)
16    format(//)
      write(8,11)
11    format('-------------------------------------------------------
     .---------------------------------')
      write(8,91)
91    format(2x,'link',2x,'capacity of pass. movement(/hr)',2x,
     .'avg. time(min) ',2x,'max. flow(veh/h) at capacity')
      write(8,11)
      y1=clock/3600.
      lentol=0
      runnin=0.
      travtot=0.
      totcap=0.
      tesyshc=0.
      tesysco=0.
      tesysnox=0.
      tfuel=0.
      do 68 ih=1,numlin
      capfin=mcapbus(ih)/y1
      lentol=lentol+length(ih)
      travtot=travtot+atravel(ih)
      runnin=runnin+arunning(ih)
      tl(ih)=(length(ih)/atravel(ih))*3.6
      spetot=(lentol/travtot)*3.6
      if(ih .eq. 1)then
      spemin=tl(ih)
      spemax=tl(ih)
      ccapmin=capfin
      ccapmax=capfin
      endif
      if(tl(ih) .le. spemin)spemin=tl(ih)
      if(tl(ih) .ge. spemax)spemax=tl(ih)
      if(capfin .le. ccapmin)ccapmin=capfin
      if(capfin .ge. ccapmax)ccapmax=capfin
      totcap=totcap+capfin
      avecap=totcap/ih
      avecap=totcap/ih
      tesyshc=tesyshc+toesyshc(ih)
      tesysco=tesysco+toesysco(ih)
      tesysnox=tesysnox+toesysnox(ih)
      tfuel=tfuel+tofuels(ih)
68    write(8,32)ih,(ih+1),capfin,atravel(ih)/60.,maxbus(ih)/y1
32    format(i2,' - ',i2,10x,f8.0,17x,f6.2,25x,f6.0)
      tesysco2=tfuel*2.73
      write(8,11)
```

```
      write(8,16)
      write(8,190)(numlin+1),travtot/60.
190   format('* travel time at maximum capacity',/,
     .'between station  1 and station',1x,i3,' =',f6.0,2x,'mintues',//)
      write(8,180)(numlin+1),spetot
180   format('* average speed at maximum capacity',/,
     .'between station  1 and station',1x,i3,' =',f9.2,2x,'(km/h)',//)
      write(8,183)(numlin+1),spemin
183   format('* minimum speed at maximum capacity',/,
     .'between station  1 and station',1x,i3,' =',f9.2,2x,'(km/h)',//)
      write(8,185)(numlin+1),spemax
185   format('* maximum speed at maximum capacity',/,
     .'between station  1 and station',1x,i3,' =',f9.2,2x,'(km/h)',//)
      write(8,187)(numlin+1),ccapmin,ccapmax
187   format('* min. & max. capacity passenger momvement ',/,
     .'between station  1 and station',1x,i3,' =',
     .f8.0,2x,'&',2x,f8.0,2x,'(pass./hr)',//)
      write(8,197)(numlin+1),avecap
197   format('* average capacity passenger momvement ',/,
     .'between station  1 and station',1x,i3,' =',
     .f8.0,2x,'(pass./hr)',//)
      write(8,198)(numlin+1),(travtot/60.)/(lentol/1000.)
198   format('* avg. travel time(min) per km at maximum capacity',/,
     .'between station 1 and station',1x,i3,' =  ',f12.2,2x,/)
      write(8,308)(numlin+1),(tesyshc)/(lentol/1000.)
308   format('* avg. HC (g) per km at maximum capacity',/,
     .'between station 1 and station',1x,i3,' =  ',e10.4,2x,/)
      write(8,318)(numlin+1),(tesysco)/(lentol/1000.)
318   format('* avg. CO (g) per km at maximum capacity',/,
     .'between station 1 and station',1x,i3,' =  ',e10.4,2x,/)
      write(8,328)(numlin+1),(tesysnox)/(lentol/1000.)
328   format('* avg. NOx (g) per km at maximum capacity',/,
     .'between station 1 and station',1x,i3,' =  ',e10.4,2x,/)
      write(8,348)(numlin+1),(tesysco2)/(lentol/1000.)
348   format('* avg. CO2 (kg) per km at maximum capacity',/,
     .'between station 1 and station',1x,i3,' =  ',e10.4,2x,/)
      write(8,334)(numlin+1),(tfuel)/(lentol/1000.)
334   format('* avg. fuel (l) per km between station 1 and',/,
     .'station',1x,i3,' =  ',e10.4,2x,/)
      write(8,16)
      write(8,16)
      return
      end


      subroutine timesta(cmeapax,numpax)
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      if(cmeapax .ge. 15.)go to 1200
      p=1.
```

```
      w=-cmeapax
      xp=exp(w)
      do 1150 k=1,100
      rn=rand(x)
      p=p*rn
      if(p .lt. xp)numpax=k-1
      if(p .lt. xp)go to 1300
1150  continue
1200  u1=0.
      s=1.
177   x1=rand(x)
      x2=rand(x)
      if(kh .eq. 0)then
      z1=sqrt(-2.*alog(x1))*cos(2.*3.14159*x2)
      z=u1+s*z1
      kh=1
      else
      z2=sqrt(-2.*alog(x1))*sin(2.*3.14159*x2)
      z=u1+s*z2
      kh=0
      endif
      numpax=(cmeapax+sqrt(cmeapax)*z-0.5)
1300  if (numpax .lt. 0) go to 177
      return
      end
```

```
      subroutine arrival(numbus)
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      cmean=3600./headsc
      if(cmean .ge. 15.)go to 2200
      p=1.
      xp=exp(-cmean)
      do 2150 k=1,1000
      rn=rand(x)
      p=p*rn
      if(p .lt. xp)numbus=k-1
      if(p .lt. xp)go to 2300
2150  continue
2200  u2=0.
      s=1.
222   x1=rand(x)
      x2=rand(x)
      if(mod(numbus,2) .eq. 0)then
      z=u2+s*(sqrt(-2.*alog(x1))*cos(2*3.14159*x2))
      else
      z=u2+s*(sqrt(-2.*alog(x1))*cos(2*3.14159*x2))
      endif
```

```
      numbus=(cmean+(cmean**(1/2))*z-0.5)
2300  if (numbus .lt. 0) go to 222
      return
      end


      subroutine speed1
c     vehicle-follow logic
c     assumption:fundamental equation of speed-flow relationship
c     flow-speed ; q=u/[tr*u+(1/(2*df)-1/(2*dl))*u^2+(l+s0)]
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
      if(regime .eq. 1.)go to 1000
      if(regime .eq. 2.)go to 2000
      if(regime .eq. 3.)go to 3000
1000  dec=(1./(2.*dece))
      go to 5000
2000  dec=(1./(2*dece)-1./(2.*deceem))
      go to 5000
3000  dec=(1./(2.*deceem))
5000  um=sqrt((lenbus+s0)/dec)
      qmax=((um)/((um)*tr+dec*(um)*(um)+(lenbus+s0)))*3600.
      if(qmax .ge. capwa)then
      q1=capwa
      else
      q1=qmax
      endif
      if(q(mn) .gt. q1)then
      q4=q1
      uu2=((1./(q4/3600.)-tr)+sqrt((1./(q4/3600.)-tr)*(1./(q4/3600.)-tr)
     .-4.*(lenbus+s0)*dec))/(2.*dec)
      uu=uu2*3.6
```

```
      else
      q5=q(mn)
      uu2=((1./(q5/3600.)-tr)+sqrt((1./(q5/3600.)-tr)*(1./(q5/3600.)-tr)
     .-4.*(lenbus+s0)*dec))/(2.*dec)
      uu=uu2*3.6
      endif
      if(umax(mn) .gt. umaxv)then
          uf=umaxv
      else
          uf=umax(mn)
      endif
      if(uu .gt. uf)uu=uf
c     speed in km/h
      us(ikl)=uu
      return
      end



      subroutine speed2
c     assumption:the equation of speed-flow relationship
c     develoment of the equation speed-flow based on OC Transpo data
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ t1(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astrl
c     1)s=78-0.34f+1.3e-3f^2        f<68
c     2)s^2=4818-6.5f              154>f>=68
      if(q(mn) .lt. 68.)then
      uu=78.216543-0.345*q(mn)+0.0013*q(mn)*q(mn)
      else
      if(q(mn) .ge. 739.)q(mn)=730.
      uu=sqrt(4818.784-6.5149*q(mn))
```

```
      endif
      if(umax(mn) .gt. umaxv)then
          uf=umaxv
      else
          uf=umax(mn)
      endif
      if(uu .gt. uf)uu=uf
c     speed in km/h
      us(ikl)=uu
      return
      end



      subroutine flow1
c     vehicle-follow logic
c     assumption:fundamental equation of speed-flow relationship
c     flow-speed ; q=u/[tr*u+(1/(2*df)-1/(2*dl))*u^2+(1+s0)]
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwa1,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
c     practical capacity function based on expreiences
      f1=0.95
      if(regime .eq. 1.)go to 1001
      if(regime .eq. 2.)go to 2001
      if(regime .eq. 3.)go to 3001
1001  dec=(1./(2.*dece))
      go to 5001
2001  dec=(1./(2.*dece)-1/(2.*deceem))
      go to 5001
3001  dec=(1./(2*deceem))
5001  um=sqrt((lenbus+s0)/dec)
```

```
      qmax=((um)/((um)*tr+dec*(um)*(um)+(lenbus+s0)))*3600.
      qs(mn)=fl*qmax
      return
      end


      subroutine flow2
c     calculation of minimum headway & capacity
c     assumption:the equation of speed-flow relationship
c     develoment of the equation speed-flow based on OC Transpo data
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
c     calculation of minimum headway & capacity
      xwl=20*0.2778
c     time for deceleration of buses
      tdece=xwl/dece
c     time for leaving previous bus which arrived to station
c     ta=sqrt(2*lenbus/accelel) or ta=0.
      ta=0.
c     minimum headway at station
      headstl=tr+averahe+tdece+ta
c     percentage buses are stopped at each stations;plisto
c     maximum capacity at station
      capstl=(3600./headstl)*ns*(1/plisto)
      if(itypstat .eq. 1)then
      headst2=15.
      else
      headst2=20.
      endif
```

```
      caps2=3600./headst2
      if(capst1 .gt. caps2)capst1=caps2
c     1)s=78-0.34f+1.3e-3f^2        f<68
c     2)s^2=4818-6.5f               154>f>=68
      qs(mn)=capst1
      return
      end



      function normal(pmean,psigma)
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /variables/ t1(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      integer x
      data kd/0/, pi/3.14159/
193   rone=rand(x)
      rtwo=rand(x)
c     generate two normal(0,1) random variables
      zone=sqrt(-2*alog(rone))*cos(2*pi*rtwo)
      ztwo=sqrt(-2*alog(rone))*sin(2*pi*rtwo)
c     compute normal random variable with parameters
c             (mean,sigma) for mean and standard deviation
      if(kd .eq. 1)go to 187
      normal=zone*psigma+pmean
      kd=1
      go to 197
c     compute normal random variable, n(mean, sigma **2)
187   normal=ztwo*psigma+pmean
      kd=0
197   if(normal .lt. 0)go to 193
      return
      end



      function expon(fmean)
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accele1,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /variables/ t1(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
c     generate a u(0,1) random number
      r=rand(x)
c     generate an exponential random variate with mean 'fmean'
      expon=-fmean*alog(r)
      return
      end
```

```
      real function rand(istrm)
c     Prime modulus multiplicative linear congruential generator
c     z(i)=(630360016*z(i-1))(mod(2**31-1)),based on Marse and
c     Roberts' portable random-number generator UNIRAN. Multiple
c     (100) streams are suupportted, with seeds spaced 100000 apart.
c     Throughout, input argument ISTRM must be an INTERGER giving
c     the desired stream number.
c     Usage :(three options)
c     1. to obtain the next U(0,1) random number from stream ISTRM,
c        execute
c          U=RAND(ISTRM)
c        The real variable U will contain the next random number.
c     2. to set the seed for stream ISTRM to a desired value IZSET,
c     excute
c          CALL RANDST(IZSET,ISTRM)
c     where IZSET must be an integer constant or variable set to the
c     desired seed, a number between 1 and 2147483646 (inclusive).
c     3. to get the current (most recently used) integer in the
c     sequence being generated for stream ISTRM into the integer
c     variable IZGET,
c        execute
c          IZGET=IRANDG(ISTRM)
      integer b2e15,b2e16,hi15,hi31,ovflow,zi,randst,zrng(100)
c     force saving of ZRNG between calls
      save zrng
c     define the constants.
      data mult1,mult2/24112,26143/
      data b2e15,b2e16,modlus/32768,65536,2147483647/
c     set the default seeds for all 100 stream.
      data zrng/197327291,281629770,20006270,128068983,209673032,
     .    193357605,913566091,246780520,136377487,604901985,
     .    151119214,125985194,824064364,150493284,24270853,
     .    75253171,196447294,120229997,23321732,191121600,
     .    726370533,40349814,99323222,110320553,76243069,
     .    192280317,138551692,76271663,413682397,726466604,
     .    33615705,143265038,112046390,595778810,87772289,
     .    104657444,68911991,208836701,748545416,622401386,
     .    212237883,64069090,177480651,213254569,207924957,
     .    78130110,852776735,118786727,135142350,164597308,
     .    199704913,922510944,204551287,898585771,243649545,
     .    100481877,773686606,403188473,372279877,190163346,
     .    49806749,208775955,493157915,597104727,153094079,
     .    181449627,53644488,166315365,85550373,67784357,
     .    143240447,619691088,119025595,880802310,176192644,
     .    111678007,277854671,136658035,114248397,2026948561,
     .    105392074,786262391,179220383,149466777,192301139,
     .    143370003,124418461,114729710,539712780,154592971,
     .    190641742,164539042,264907697,620389253,150207485,
     .    92771116,36484919,204957605,638580085,547070247/
c     generate the next random number
      zi=zrng(istrm)
      hi15=zi/b2e16
      lowprd =(zi-hi15*b2e16)*mult1
      low15=lowprd/b2e16
      hi31=hi15*mult1+low15
```

```
      ovflow=hi31/b2e15
      zi=(((lowprd-low15*b2e16)-modlus)+(hi31-ovflow*b2e15)*
     .b2e16)+ovflow
      if(zi .lt. 0)zi=zi+modlus
      hi15=zi/b2e16
      lowprd=(zi-hi15*b2e16)*mult2
      low15=lowprd/b2e16
      hi31=hi15*mult2+low15
      ovflow=hi31/b2e15
      zi=(((lowprd-low15*b2e16)-modlus)+(hi31-ovflow*b2e15)*
     .b2e16)+ovflow
      if(zi .lt. 0)zi=zi+modlus
      zrng(istrm)=zi
      rand=(2*(zi/256)+1)/16777216.0
      return
c     set the current ZRNG for stream ISTRM to IZSET.
      entry randst(izset,istrm)
      zrng(istrm)=izset
      return
c     return the current ZRNG for stream ISTRM
      entry irandg(istrm)
      irandg=zrng(istrm)
      return
      end


      subroutine emission
c     calculation of  air pollution in the system
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ik1,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,a1,b1
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
```

```
c     vm1r; vehicle speed (bus) on transitway (km/h)
c     vm2r; vehicle speed (van) on transitway (km/h)
      if(itype .le. 3)then
      vm1r=avespm1*3.6
      else
      vm2r=avespm2*3.6
      endif
c     ntem; ambient temperature (c)
c     nyear; calender year (1994-2010)
c     accepted range for average speed is (5 to 105 km/h)
c     accepted range for average ambient temperature is(-18 to 49 c)
c     calculation of air pollution factor for buses on transitway(gr/km)
      if(itype .le. 3)then
      fhvh=chddv(nyear,1)*(15.535296*vm1r**(1./3.)-
     .10.111846*vm1r**(1./2.)+0.344271*vm1r-0.000425*vm1r**2.)
      fhvc=chddv(nyear,2)*(124.985559*vm1r**(1./3.)-
     .85.946398*vm1r**(1./2.)+3.343039*vm1r-0.004817*vm1r**2.)
      fhvn=chddv(nyear,3)*(56.344156*vm1r**(1./3.)-
     .31.32289*vm1r**(1./2.)+0.019551*vm1r**2.-0.00022*vm1r**3.+
     .9.780836e-7*vm1r**4.)
      else
c     calculation of air pollution factor for van on transitway(gr/km)
      flvh=cldgv(nyear,1)*(130.124884*vm2r**(1./3.)-
     .110.725342*vm2r**(1./2.)+8.445382*vm2r-
     .0.065918*vm2r**2.+0.00046*vm2r**3.-1.403466e-6*vm2r**4.)
      flvc=cldgv(nyear,2)*(933.068968*vm2r1**(1./3.)-
     .751.251834*vm2r**(1./2.)+48.363899*vm2r-0.246857*vm2r**2.+
     .0.000847*vm2r**3.-0.6672472*ntem)
      flvn=cldgv(nyear,3)*(5.680214*vm2r1**(1./3.)-
     .3.168182*vm2r1**(1./2.)+0.081093*vm2r-0.02422*ntem)
      endif
c     calculation emissions in the system(emission(gr/km))
      if(itype .le. 3)then
c     unit of ehvh, ehvc and ehvn is g
      ehvh=fhvh*(length(mn)/1000.)
      ehvc=fhvc*(length(mn)/1000.)
      ehvn=fhvn*(length(mn)/1000.)
      esysh=ehvh
      esysc=ehvc
      esysn=ehvn
      else
c     unit of elvh, elvc and elvn is g
      elvh=flvh*(length(mn)/1000.)
      elvc=flvc*(length(mn)/1000.)
      elvn=flvn*(length(mn)/1000.)
      esysh=elvh
      esysc=elvc
      esysn=elvn
      endif
      return
      end
```

```
      subroutine fuel
c     calculation of fuel consumption in the system
      common /buses/ type,lenbus,acce,dece,headsc,weigbus,capbus,
     .accelel,itype,dec,deceem,regime,plisto,ptypea,
     .ptypes,typbus,avespm1,avespm2,uavg(9000)
      common /route/ grade(9000),length(9000),tovkmt(9000),mcapbus(9000)
      common /pax/ ameapax,bmeapax,asigma,bsigma,npax1,npax2,a,
     .ipaxa(9000),ipaxb(9000),load,loads(9000),bsig,bmen,cloadfc,npeak,
     .itotpax(9000),ipaxbo(9000),ipaxal(9000),ipaxboa(9000),b,c,
     .ipaxali(9000),ipax(9000),maxbus(9000),capwal,ipaxv,aload(9000)
      common /traffic/ u(9000),umax(9000),q(9000),mtstand(9000),
     .capwa,capst,headwa,headst,qm(9000),us(9000),qs(9000),umaxv,
     .itimstu,capmax(9000),avespe(9000),uaverage(9000)
      common /stat/ extra,heaorig,tisort(9000),nmaxbus(9000),im,
     .itrtime(9000),atravel(9000),kind(9000),capstma,in,capstf
      common /fuel1/ rc,fuela,fueld,fuelc,fueli,tofuels(9000),
     .tofuelsp(9000),toesysco2(9000),esysco2(9000)
      common /del/ delay(9000),adelay(9000),timepax(9000),arunning(9000)
      common /time1/ tratim,clock,trtime(50,9000),timest(50,9000),
     .timear(9000),timede(50,9000),tstand(9000),itstand(50,9000)
      common /time2/ tac,tcr,tde,tid,runtime,timepkm(9000)
      common /variables/ tl(9000),mn,s0,tr,x,xw,ikl,numlin,ns,
     .paxkm(9000),nf,itypstat,avgload,al,bl
      common /emi/ esysh,esysc,esysn,chddv(2500,10),cldgv(2500,10),
     .esyshc(9000),esysco(9000),esysnox(9000),nyear,ntem,
     .toesyshc(9000),toesysco(9000),toesysnox(9000)
      common /passmore/ ameapa,asigm,bmeapa,bsigm,ameanl,astnl
c     type of buses or van (1:small bus;2:standard bus;
c                           3:articulated bus;4:van)
c     if there is no curve; pk=0.
      if(rc .gt. 4000.)pk=0.
      if(itype .eq. 2)then
c     calculation of fuel for bus acceleration
      rpm1=600.+44.1*xw+((364.35*xw)/(3.6*xw+10.))*(0.4062+
     .6.44*10**(-5.)*weigbus+1.09*10**(-4.)*weigbus*grade(mn)+
     .4.56*10**(-4.)*xw**(1.5)+2.22*10**(-3.)*xw**2.+
     .(1.1*10**(-3.)*weigbus+0.49167)*accele1+
     .((weigbus*(xw**2./rc-0.981)**2.)/(82170.-1.723*weigbus))*pk)
      rpm2=2100.
      if(rpm1 .le. rpm2)then
         rpm=rpm1
      else
         rpm=rpm2
      endif
      ptota=2.16+xw*(0.2812+6.44*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+2.22*10**(-3.)*xw**2.+(1.1*10**(-3.)*
     .weigbus+0.49167)*accele1+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.723*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .4.*10**(-6.)*rpm**2.+6.27*10**(-8.)*rpm**(2.5)
      betaa=0.059+xw*(2.87*10**(-5.)+6.59*10**(-9.)*weigbus+1.12*
     .10**(-8.)*weigbus*grade(mn)+2.*10**(-7.)*xw**2.+
     .(10**(-7.)*weigbus+5.03*10**(-5.))*accele1+
     .((weigbus*(xw**2./rc-0.981)**2.)/(8.027*10**8.-16832.*weigbus))*
     .pk)+10**(-7.)*rpm+6.42*10**(-12.)*rpm**(2.5)
c     unit of fuel consumption is ml/s
```

```
      fuela=ptota*betaa/1000.
c     calculation of fuel for bus deceleration
      rpm1=600.+44.1*xw+((364.35*xw)/(3.6*xw+10.))*(0.4062+
     .6.44*10**(-5.)*weigbus+1.09*10**(-4.)*weigbus*grade(mn)+
     .4.56*10**(-4.)*xw**(1.5)+2.22*10**(-3.)*xw**2.+
     .(1.1*10**(-3.)*weigbus+0.49167)*dece+
     .((weigbus*(xw**2./rc-0.981)**2.)/(82170.-1.723*weigbus))*pk)
      rpm2=2100.
      if(rpm1 .le. rpm2)then
         rpm=rpm1
      else
         rpm=rpm2
      endif
      betad=0.059+xw*(2.87*10**(-5.)+6.59*10**(-9.)*weigbus+1.12*
     .10**(-8.)*weigbus*grade(mn)+2.*10**(-7.)*xw**2.+
     .(10**(-7.)*weigbus+5.03*10**(-5.))*dece+
     .((weigbus*(xw**2./rc-0.981)**2.)/(8.027*10**8.-16832.*weigbus))
     .*pk)+10**(-7.)*rpm+6.42*10**(-12.)*rpm**(2.5)
      ptr=xw*(0.25308+5.8*10**(-5.)*weigbus+9.81*10**(-5.)*
     .weigbus*grade(mn)+2.*10**(-3.)*xw**2.+(0.4425+10**(-3.)*
     .weigbus)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(0.913*10**5.-1.896*weigbus))*pk)
      ptotd1=2.16+xw*(0.2812+6.44*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+2.22*10**(-3.)*xw**2.+(1.1*10**(-3.)*
     .weigbus+0.49167)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.723*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .4.*10**(-6.)*rpm**2.+6.27*10**(-8.)*rpm**(2.5)
      ptotd2=2.16+xw*(0.2278+5.21*10**(-5.)*weigbus+0.882*10**(-4.)*
     .weigbus*grade(mn)+1.8*10**(-3.)*xw**2.+(0.891*10**(-3.)*
     .weigbus+0.3982)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(101444.-2.127*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .4*10**(-6.)*rpm**2.+6.27*10**(-8.)*rpm**(2.5)
      if(ptr .lt. 0.)then
         ptotd=ptotd2
      else
         ptotd=ptotd1
      endif
      if(ptotd .gt. 0.)then
        fueld=ptotd*betad/1000.
c     minimum fuel consumtion rate is the idle fuel consumption rate
c     standard bus idle fuel consumption rate is 0.3989 ml/s
        if(fueld .lt. 0.3989/1000.)fueld=0.3989/1000.
      else
        fueld=0.3989/1000.
      endif
c     calculation of fuel for bus cruise
      betac=0.059+xw*(4.15*10**(-5.)+6.59*10**(-9.)*weigbus+1.116*
     .10**(-8.)*weigbus*grade(mn)+4.67*10**(-8.)*xw**(1.5)+
     .2.*10**(-7.)*xw**2.+((weigbus*(xw**2./rc-0.981)**2.)/
     .(8.03*10**8.-18529.*weigbus))*pk)
      ptotc=2.16+xw*(0.4062+6.44*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+0.031*xw+4.56*10**(-4.)*xw**(1.5)+
     .2.22*10**(-3.)*xw**2.+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.706*weigbus))*pk)
      fuelc=ptotc*betac/1000.
```

```
c     calculation of fuel for bus idle
      fueli=0.3989/1000.
      endif
      if(itype .eq. 3)then
c     calculation of fuel for bus acceleration
      rpm1=600.+44.1*xw+((221.26*xw)/(3.6*xw+10.))*(0.582+
     .6.55*10**(-5.)*weigbus+1.09*10**(-4.)*weigbus*grade(mn)+
     .5.73*10**(-4.)*xw**(1.5)+2.22*10**(-3.)*xw**2.+
     .(1.1*10**(-3.)*weigbus+0.81125)*accele1+
     .((weigbus*(xw**2./rc-0.981)**2.)/(82170.-1.026*weigbus))*pk)
      rpm2=2100
      if(rpm1 .le. rpm2)then
         rpm=rpm1
      else
         rpm=rpm2
      endif
      ptota=3.55+xw*(0.47+6.55*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+2.22*10**(-3.)*xw**2.+(1.1*10**(-3.)*
     .weigbus+0.81125)*accele1+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.026*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .6.12*10**(-6.)*rpm**2.+1.033*10**(-8.)*rpm**(2.5)
      betaa=0.059+xw*(2.91*10**(-5.)+4.07*10**(-9.)*weigbus+6.77*
     .10**(-9.)*weigbus*grade(mn)+10**(-7.)*xw**2.+
     .(6.84*10**(-8.)*weigbus+5.04*10**(-5.))*accele1+
     .((weigbus*(xw**2./rc-0.981)**2.)/(1.32*10**9.-16504.*
     .weigbus))*pk)+8.62*10**(-8.)*rpm+6.06*10**(-13.)*rpm**(2.5)
c     unit of fuel consumption is mL/s
      fuela=ptota*betaa/1000.
c     calculation of fuel for bus deceleration
      rpm1=600.+44.1*xw+((221.26*xw)/(3.6*xw+10.))*(0.582+
     .6.55*10**(-5.)*weigbus+1.09*10**(-4.)*weigbus*grade(mn)+
     .5.73*10**(-4.)*xw**(1.5)+2.22*10**(-3.)*xw**2.+
     .(1.1*10**(-3.)*weigbus+0.81125)*dece+
     .((weigbus*(xw**2./rc-0.981)**2.)/(82170.-1.026*weigbus))*pk)
      rpm2=2100
      if(rpm1 .le. rpm2)then
         rpm=rpm1
      else
         rpm=rpm2
      endif
      betad=0.059+xw*(2.91*10**(-5.)+4.07*10**(-9.)*weigbus+6.77*
     .10**(-9.)*weigbus*grade(mn)+10**(-7.)*xw**2.+
     .(6.84*10**(-8.)*weigbus+5.04*10**(-5.))*dece+
     .((weigbus*(xw**2./rc-0.981)**2.)/(1.32*10**9.-16504.*weigbus))
     .*pk)+8.62*10**(-8.)*rpm+6.06*10**(-13.)*rpm**(2.5)
      ptr=xw*(0.4218+5.9*10**(-5.)*weigbus+9.81*10**(-5.)*
     .weigbus*grade(mn)+2.*10**(-3.)*xw**2.+(0.7375+10**(-3.)*
     .weigbus)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(0.913*10**5.-1.14*weigbus))*pk)
      ptotd1=3.55+xw*(0.47+6.55*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+2.22*10**(-3.)*xw**2.+(1.1*10**(-3.)*
     .weigbus+0.81125)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.026*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .6.12*10**(-6.)*rpm**2.+1.033*10**(-8.)*rpm**(2.5)
      ptotd2=3.55+xw*(0.3796+5.3*10**(-5.)*weigbus+0.882*10**(-4.)*
```

```
     .weigbus*grade(mn)+1.8*10**(-3.)*xw**2.+(0.891*10**(-3.)*
     .weigbus+0.6571)*(-dece)+((weigbus*(xw**2./rc-0.981)**2.)/
     .(101444.-1.267*weigbus))*pk)+1.42*10**(-3.)*rpm+
     .6.12*10**(-6.)*rpm**2.+1.033*10**(-8.)*rpm**(2.5)
      if(ptr .lt. 0.)then
         ptotd=ptotd2
      else
         ptotd=ptotd1
      endif
      if(ptotd .gt. 0.)then
        fueld=ptotd*betad/1000.
c     minimum fuel consumtion rate is the idle fuel consumption rate
c     articulated bus idle fuel consumption rate is 0.5926 mL/s
        if(fueld .lt. 0.5926/1000.)fueld=0.5926/1000.
      else
        fueld=0.5926/1000.
      endif
c     calculation of fuel for bus cruise
      betac=0.059+xw*(3.61*10**(-5.)+4.07*10**(-9.)*weigbus+6.77*
     .10**(-9.)*weigbus*grade(mn)+3.56*10**(-8.)*xw**(1.5)+
     .10**(-7.)*xw**2.+((weigbus*(xw**2./rc-0.981)**2.)/
     .(1.32*10**9.-16504.*weigbus))*pk)
      ptotc=3.55+xw*(0.582+6.55*10**(-5.)*weigbus+1.09*10**(-4.)*
     .weigbus*grade(mn)+0.038*xw+5.73*10**(-4.)*xw**(1.5)+
     .2.22*10**(-3.)*xw**2.+((weigbus*(xw**2./rc-0.981)**2.)/
     .(82170.-1.026*weigbus))*pk)
      fuelc=ptotc*betac/1000.
c     calculation of fuel for bus idle
      fueli=0.5926/1000.
      endif
      return
      end
```

Appendix B.2: A Sample of the Model Output Based on OC Transpo Data

a macroscopic simulation model for
bus operating on transitway

time period= 60 minutes

link	length(m)	mean flow(veh/h)	st. capacity(veh/h)
1 - 2	1770	24.	240.
2 - 3	1020	24.	240.
3 - 4	1250	34.	240.
4 - 5	1370	33.	240.
5 - 6	740	154.	240.
6 - 7	1020	154.	240.
7 - 8	540	153.	240.
8 - 9	200	153.	240.
9 - 10	2060	134.	240.
10 - 11	1550	127.	240.
11 - 12	4680	122.	240.
12 - 13	1420	43.	240.
13 - 14	450	46.	240.
14 - 15	1120	44.	240.

time period = 62.75 minutes

link	(vkmt)	avg. speed (km/h)	avg. pass/bus
1 - 2	37.24	53.39	33.45
2 - 3	18.53	44.32	25.21
3 - 4	38.25	47.74	26.09
4 - 5	37.99	50.96	29.55
5 - 6	113.22	34.57	27.05
6 - 7	131.67	45.84	26.46
7 - 8	78.49	31.94	25.98
8 - 9	31.75	13.69	25.99
9 - 10	260.01	56.56	25.58
10 - 11	203.05	49.29	25.86
11 - 12	474.36	53.71	26.55
12 - 13	57.03	50.54	26.43
13 - 14	24.10	28.20	27.41
14 - 15	38.55	46.35	30.00

link	avg. dweel time(min)	total loadind	total unloding	total pass.	total pass.km
1 - 2	23	101.	197.	704.	1245.68
2 - 3	21	75.	216.	458.	467.19
3 - 4	22	185.	304.	798.	998.05
4 - 5	19	116.	239.	819.	1122.68
5 - 6	27	706.	1616.	4139.	3062.49
6 - 7	18	550.	1265.	3416.	3483.91
7 - 8	21	646.	1521.	3776.	2039.09
8 - 9	20	695.	1491.	4125.	825.02
9 - 10	22	532.	1343.	3228.	6650.06
10 - 11	26	625.	1299.	3388.	5251.20
11 - 12	20	475.	1028.	2691.	12592.90
12 - 13	21	191.	415.	1061.	1507.19
13 - 14	22	281.	527.	1468.	660.51
14 - 15	20	180.	283.	1033.	1156.64

link	HC g/km	CO g/km	NOx g/km	CO2 kg/km	fuel l/km
1 - 2	0.1805E+01	0.7577E+01	0.1362E+02	0.1342E+01	0.491566
2 - 3	0.2136E+01	0.9302E+01	0.1417E+02	0.1857E+01	0.680099
3 - 4	0.1993E+01	0.8491E+01	0.1386E+02	0.1652E+01	0.605031
4 - 5	0.1885E+01	0.7965E+01	0.1372E+02	0.1577E+01	0.577632
5 - 6	0.2571E+01	0.1185E+02	0.1518E+02	0.2088E+01	0.764823
6 - 7	0.2068E+01	0.8902E+01	0.1401E+02	0.1806E+01	0.661670
7 - 8	0.2774E+01	0.1334E+02	0.1592E+02	0.2375E+01	0.869821
8 - 9	0.4416E+01	0.2624E+02	0.2215E+02	0.2742E+01	1.004293
9 - 10	0.1718E+01	0.7220E+01	0.1357E+02	0.1301E+01	0.476572
10 - 11	0.1917E+01	0.8037E+01	0.1367E+02	0.1496E+01	0.548138
11 - 12	0.1776E+01	0.7380E+01	0.1350E+02	0.6528E+00	0.239133
12 - 13	0.1895E+01	0.7997E+01	0.1372E+02	0.1495E+01	0.547627
13 - 14	0.3032E+01	0.1517E+02	0.1680E+02	0.2583E+01	0.945998
14 - 15	0.2041E+01	0.8737E+01	0.1394E+02	0.1802E+01	0.660214

link	pass./hr	avg. time(min)	avg. delay(min)	flow(veh/h)
1 - 2	1734.	2.02	0.00	24.
2 - 3	1556.	1.43	0.00	24.
3 - 4	2587.	1.61	0.00	32.
4 - 5	2334.	1.65	0.00	31.
5 - 6	12844.	1.31	0.00	156.
6 - 7	10875.	1.37	0.00	156.
7 - 8	12161.	1.07	0.00	155.
8 - 9	13328.	0.93	0.00	155.
9 - 10	10655.	2.21	0.00	136.
10 - 11	11099.	1.90	0.00	129.
11 - 12	8464.	5.24	0.00	124.
12 - 13	3346.	1.72	0.00	45.
13 - 14	4486.	1.02	0.00	51.
14 - 15	2940.	1.48	0.00	49.

* travel time between station 1 and station 15
= 25. mintues

* average speed between station 1 and station 15
= 46.11 (km/h)

* max. opert. speed between station 1 and station 15 = 55.84 (km/h)

* average passenger momvement
between station 1 and station 15 = 7029. (pass./hr)

* avg. travel time (min) per km
between station 1 and station 15 = 1.30

* avg. HC (g) per km between station 1 and
station 15 = 0.1980E+01

* avg. CO (g) per km between station 1 and
station 15 = 0.8576E+01

* avg. NOx (g) per km between station 1 and
station 15 = 0.1398E+02

* avg. CO2 (kg) per km between station 1 and
station 15 = 0.1411E+01

* avg. fuel (l) per km between station 1 and
station 15 = 0.5167E+00

link	capacity of pass. movement(/hr)	avg. time(min)	max. flow(veh/h) at capacity
1 - 2	18802.	2.14	224.
2 - 3	20780.	1.63	248.
3 - 4	18269.	1.78	217.
4 - 5	18767.	1.88	224.
5 - 6	17393.	1.51	208.
6 - 7	20241.	1.64	241.
7 - 8	19495.	1.23	231.
8 - 9	19769.	1.12	233.
9 - 10	17865.	2.49	212.
10 - 11	20967.	2.14	251.
11 - 12	17786.	5.44	211.
12 - 13	19886.	1.99	237.
13 - 14	17342.	1.12	206.
14 - 15	21215.	1.73	253.

* travel time at transitway capacity
between station 1 and station 15 = 28. mintues

* average speed at transitway capacity
between station 1 and station 15 = 41.34 (km/h)

* maximum operating speed at transitway capacity
between station 1 and station 15 = 51.58 (km/h)

* min. & max. passenger momvement at transitway capacity
between station 1 and station 15 = 17342. & 21215. (pass./hr)

* average passenger momvement at transitway capacity
between station 1 and station 15 = 19184. (pass./hr)

* avg. travel time(min) per km at tarnsitway capacity
between station 1 and station 15 = 1.45

* avg. HC (g) per km at transitway capacity
between station 1 and station 15 = 0.2067E+01

* avg. CO (g) per km at transitway capacity
between station 1 and station 15 = 0.9050E+01

* avg. NOx (g) per km at transitway capacity
between station 1 and station 15 = 0.1414E+02

* avg. CO2 (kg) per km at transitway capacity
between station 1 and station 15 = 0.2214E+01

* avg. fuel (l) per km between station 1 and
station 15 = 0.8109E+00

Appendix B.3: The Results of Regression Analysis for Validation of the Transitway Simulation Model by Using SPSS Package

```
22 Jan 96    SPSS Release 4.0 for Sun 4
                                                Page 1
08:40:20     SPSS -- Carleton University     Sun-4            SunOS 4.0


For SunOS 4.0            SPSS -- Carleton University       License Number 21295
This software is functional through August 31, 1999.

Try the new SPSS Release 4.0 features:

* LOGISTIC REGRESSION procedure                    * CATEGORIES Option:
* EXAMINE procedure to explore data                *   conjoint analysis
* FLIP to transpose data files                     *   correspondence analysis
* MATRIX Transformations Language                  * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

   1  0  DATA LIST FILE='spsmr.dat'
   2  0     /obs 1-3 sim 5-8.

This command will read 1 records from spsmr.dat

Variable   Rec   Start     End         Format

OBS          1       1       3         F3.0
SIM          1       5       8         F4.0

   3  0  SAVE OUTFILE='spsmr.sys'.

Time stamp on saved file:  22 JAN 96 08:40:22
File contains 2 variables, 16 bytes per case before compression
14 cases saved

Preceding task required .05 seconds CPU time;  .62 seconds elapsed.

   4  0  GET FILE='spsmr.sys'.

File spsmr.sys
   Created:  22 JAN 96 08:40:22 - 2 variables

   5  0  REGRESSION VARIABLES = obs sim
   6  0     /DEPENDENT = obs
   7  0    /ENTER sim.

There are 204,032 bytes of memory available.
The largest contiguous area has 203,632 bytes.

     1124 bytes of memory required for REGRESSION procedure.
        0 more bytes may be needed for Residuals plots.
```

* * * * M U L T I P L E R E G R E S S I O N * * * *

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. OBS

Block Number 1. Method: Enter SIM

Variable(s) Entered on Step Number 1.. SIM

Multiple R	.99000	Analysis of Variance:			
R Square	.98009		DF	Sum of Squares	Mean Square
Adjusted R Square	.97843	Regression	1	15.76339	15.76339
Standard Error	.16335	Residual	12	.32019	.02668

F = 590.78413 Signif F = .0000

---------- Variables in the Equation ----------

Variable	B	SE B	Beta	T	Sig T
SIM	1.036120	.042628	.989996	24.306	.0000
(Constant)	-.168683	.087646		-1.925	.0783

End Block Number 1 All requested variables entered.

```
22 Jan 96    SPSS Release 4.0 for Sun 4
                                                Page 3
08:40:24     SPSS -- Carleton University    Sun-4            SunOS 4.0

Preceding task required .10 seconds CPU time;  1.30 seconds elapsed.
   8  0  CORRELATIONS obs sim.
PEARSON CORR problem requires 80 bytes of workspace.
```

```
22 Jan 96    SPSS Release 4.0 for Sun 4
                                                Page 4
08:40:24     SPSS -- Carleton University    Sun-4            SunOS 4.0

                          - -  Correlation Coefficients  - -

              OBS        SIM

OBS          1.0000      .9900**
SIM           .9900**   1.0000

* - Signif. LE .05    ** - Signif. LE .01    (2-tailed)          " . " printed if
a coefficient cannot be computed
```

```
22 Jan 96    SPSS Release 4.0 for Sun 4
                                                Page 5
08:40:24     SPSS -- Carleton University     Sun-4            SunOS 4.0

Preceding task required .03 seconds CPU time;  .21 seconds elapsed.

   9  0  DESCRIPTIVES obs sim.

There are 204,456 bytes of memory available.
The largest contiguous area has 203,960 bytes.

152 bytes of memory required for the DESCRIPTIVES procedure.
8 bytes have already been acquired.
144 bytes remain to be acquired.
```

Number of valid observations (listwise) = 14.00

Variable	Mean	Std Dev	Minimum	Maximum	Valid N	Label
OBS	1.68	1.11	1	5	14	
SIM	1.78	1.06	1	5	14	

Preceding task required .03 seconds CPU time; .18 seconds elapsed.

```
  10  0  variable labels obs "observed"
  11  0  variable labels sim "simulation"
  12  0  Plot Hsize = 80
  13  0     /vsize = 40
```

There are 203,696 bytes of memory available.
The largest contiguous area has 203,696 bytes.

Preceding task required .02 seconds CPU time; .28 seconds elapsed.

```
  14  0  Plot format = regression
  15  0     /Plot = sim with obs
```

There are 203,568 bytes of memory available.
The largest contiguous area has 203,520 bytes.

PLOT requires 18176 bytes of workspace for execution.

. . . . . P L O T . . . . . .

Data Information

14 unweighted cases accepted

Size of the plot

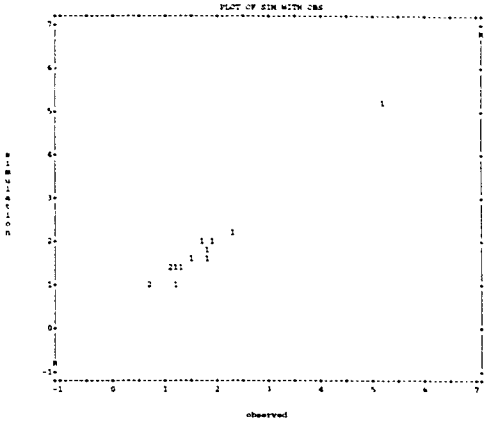
Horizontal size is 80
Vertical size is 40

Frequencies and symbols used (not applicable for control or overlay plots)

1 - 1	11 - B	21 - L	31 - V
2 - 2	12 - C	22 - M	32 - W
3 - 3	13 - D	23 - N	33 - X
4 - 4	14 - E	24 - O	34 - Y
5 - 5	15 - F	25 - P	35 - Z
6 - 6	16 - G	26 - Q	36 - *
7 - 7	17 - H	27 - R	
8 - 8	18 - I	28 - S	
9 - 9	19 - J	29 - T	
10 - A	20 - K	30 - U	

22 Jan 94 SPSS Release 4.0 for Run 4
09:42:25 SPSS -- Carleton University Sun-4 RuNOS 4.0 Page 4

PLOT OF SIM WITH OBS



16 cases plotted. Regression statistics of SIM on OBS:
Correlation .99000 R Squared .98009 S.E. of Est .15408 2-tailed Sig. .0000
Intercept(S.E.) .19505(.07751) Slope(S.E.) .94593(.01492)

Preceding task required .57 seconds CPU time; .34 seconds elapsed.

14 0 FINISH

14 command lines read.
1 errors detected.
0 warnings issued.
1 seconds CPU time
1 seconds elapsed time.
End of Job

Appendix B.4: Bus Arrival at the Stations

(including: Baseline, Leberton, Campus and Lees)
for Off-Peak (10:00 - 11:00) and
Peak (16:00 - 17:00) Hours During
Weekdays of September 1993
by Using Data Obtained from OC Transpo

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : LEES STARTING TIME: 16:00 P.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 17:00 P.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1	46, 50, 56, 61	4
1 - 2	85, 72, 76	3
2 - 3	73	1
3 - 4	95, 44, 65, 69	4
4 - 5	8, 86, 96, 16	4
5 - 6	51	1
6 - 7		0
7 - 8	95, 50	2
8 - 9	99, 62, 64, 78	4
9 - 10	85, 97, 57, 66	4
10 - 11	95, 41, 67	3
11 - 12	59	1
12 - 13	86, 55, 63, 70	4
13 - 14	95, 60, 61, 73	4
14 - 15	97, 50	2
15 - 16	46	1
16 - 17	85, 56	2
17 - 18	76	1
18 - 19	95, 44, 69, 75	4
19 - 20	8, 86, 96, 16, 66, 72	6
20 - 21	51, 62, 65	3
21 - 22	50	1
22 - 23	95, 67, 73	3
23 - 24	97, 99	2
24 - 25	85, 57, 70	3
25 - 26	95, 63	2
26 - 27	41, 56, 61	3
27 - 28	86	1
28 - 29	59, 64	2
29 - 30	95, 97, 50, 60, 78	5

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31		0
31 - 32	85, 46, 66	3
32 - 33	76	1
33 - 34	95, 55, 62	3
34 - 35	8, 86, 96, 16, 44, 73	6
35 - 36	69, 70	2
36 - 37	56, 67, 72	3
37 - 38	95, 50, 51	3
38 - 39	99, 65	2
39 - 40	85, 97, 61, 63	4
40 - 41	95, 57, 75	3
41 - 42	64, 66	2
42 - 43	86, 41	2
43 - 44		0
44 - 45	95, 97, 50	3
45 - 46	59, 60	2
46 - 47	85, 46, 56	3
47 - 48	62, 76	2
48 - 49	95, 73	2
49 - 50	8, 86, 96, 16, 67, 70	6
50 - 51	44	1
51 - 52	50, 61, 78	3
52 - 53	95, 63, 69, 72	4
53 - 54	99, 51	2
54 - 55	85, 97	2
55 - 56	95	1
56 - 57	55, 57, 65	3
57 - 58	86, 56, 66	3
58 - 59	41, 64	2
59 - 00	95	1

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : LEES
DATE : WEEKDAYS OF 1993

STARTING TIME: 10:00 A.M.
ENDING TIME : 11:00 A.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1		0
1 - 2		0
2 - 3		0
3 - 4	16	1
4 - 5	95, 86	2
5 - 6		0
6 - 7	96	1
7 - 8		0
8 - 9		0
9 - 10	95, 85	2
10 - 11	8	1
11 - 12		0
12 - 13		0
13 - 14		0
14 - 15	95, 97	2
15 - 16		0
16 - 17		0
17 - 18		0
18 - 19	16	1
19 - 20	95, 86	2
20 - 21		0
21 - 22	96	1
22 - 23		0
23 - 24		0
24 - 25	95, 85	2
25 - 26	8, 99	2
26 - 27		0
27 - 28		0
28 - 29		0
29 - 30	95, 97	2

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31		0
31 - 32		0
32 - 33		0
33 - 34	16	1
34 - 35	95, 86	2
35 - 36		0
36 - 37	96	1
37 - 38		0
38 - 39		0
39 - 40	95, 85	2
40 - 41	8	1
41 - 42		0
42 - 43		0
43 - 44		0
44 - 45	95, 97	2
45 - 46		0
46 - 47		0
47 - 48		0
48 - 49	16	1
49 - 50	95, 86	2
50 - 51		0
51 - 52	8, 96	2
52 - 53		0
53 - 54		0
54 - 55	95, 85	2
55 - 56	99	1
56 - 57		0
57 - 58		0
58 - 59		0
59 - 00	97	1

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : CAMPUS STARTING TIME: 16:00 P.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 17:00 P.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1	95	1
1 - 2	63, 67, 70	3
2 - 3	46, 56	2
3 - 4	85, 50, 76	3
4 - 5	95, 72	2
5 - 6	65	1
6 - 7	86, 16, 44, 61, 69, 73	6
7 - 8	96, 51	2
8 - 9	95, 8	2
9 - 10		0
10 - 11	50,62, 64, 78, 200, 202	6
11 - 12	95, 8, 57, 66	4
12 - 13	41	1
13 - 14	59, 67	2
14 - 15	86, 55, 63, 70	4
15 - 16	95, 60, 61	3
16 - 17	73	1
17 - 18	46, 50	2
18 - 19	85, 56	2
19 - 20	95	1
20 - 21	76	1
21 - 22	86, 16, 44, 66, 69, 75	6
22 - 23	96, 51, 62, 65, 72	5
23 - 24	95, 8	2
24 - 25	50	1
25 - 26	67	1
26 - 27	95, 85, 57, 70, 73	5
27 - 28	63, 64	2
28 - 29	41, 56, 61	3
29 - 30	86	1

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31	95, 59, 203	3
31 - 32	60	1
32 - 33	50, 78	2
33 - 34	85, 46, 66	3
34 - 35	95	1
35 - 36	55, 62, 76	3
36 - 37	86, 16	2
37 - 38	96, 44, 70, 73	4
38 - 39	95, 8, 56, 67, 69	5
39 - 40	51, 72	2
40 - 41	50, 65, 200	3
41 - 42	95, 85, 61, 63	4
42 - 43	57	1
43 - 44	64, 75	2
44 - 45	86, 41, 66	3
45 - 46	95	1
46 - 47		0
47 - 48	50, 59, 60	3
48 - 49	85, 46, 56	3
49 - 50	95, 62	2
50 - 51	76	1
51 - 52	86, 16, 67, 70, 73	5
52 - 53	96	1
53 - 54	95, 8, 44, 61	4
54 - 55	50, 63, 78	3
55 - 56	51, 69, 72	3
56 - 57	95, 85	2
57 - 58		0
58 - 59	55, 42, 65, 66	4
59 - 00	86	1

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : CAMPUS STARTING TIME: 10:00 A.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 11:00 A.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1	95	1
1 - 2	97	1
2 - 3		0
3 - 4		0
4 - 5		0
5 - 6	95, 16	2
6 - 7	86	1
7 - 8		0
8 - 9	96	1
9 - 10		0
10 - 11	95	1
11 - 12	85	1
12 - 13		0
13 - 14	8	1
14 - 15		0
15 - 16	95	1
16 - 17	97	1
17 - 18		0
18 - 19		0
19 - 20		0
20 - 21	95, 16	2
21 - 22	86	1
22 - 23		0
23 - 24	96	1
24 - 25		0
25 - 26	95	1
26 - 27	85	1
27 - 28	8	1
28 - 29		0
29 - 30		0

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31	95	1
31 - 32	97	1
32 - 33		0
33 - 34		0
34 - 35		0
35 - 36	95, 16	2
36 - 37	86	1
37 - 38		0
38 - 39	96	1
39 - 40		0
40 - 41	95	1
41 - 42	85	1
42 - 43		0
43 - 44	8	1
44 - 45		0
45 - 46	95	1
46 - 47	97	1
47 - 48		0
48 - 49		0
49 - 50		0
50 - 51	95, 16	2
51 - 52	86	1
52 - 53		0
53 - 54	96	1
54 - 55	8	1
55 - 56	95	1
56 - 57	85	1
57 - 58		0
58 - 59		0
59 - 00		0

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : LEBRETON STARTING TIME: 16:00 P.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 17:00 P.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1		0
1 - 2	65	1
2 - 3	69	1
3 - 4	95	1
4 - 5	96, 86, 73	3
5 - 6	64	1
6 - 7	50, 60, 62	3
7 - 8	95, 66	2
8 - 9	75	1
9 - 10	97, 108	2
10 - 11	95, 59	1
11 - 12	70	1
12 - 13	86, 63	2
13 - 14	15, 61, 76	3
14 - 15	95, 97, 72, 73	4
15 - 16	67	4
16 - 17	50, 65	1
17 - 18	69	2
18 - 19	95	1
19 - 20	96, 86	2
20 - 21	200, 202	2
21 - 22	95, 62, 64, 78	4
22 - 23	66	1
23 - 24	50, 108	2
24 - 25	97, 70	2
25 - 26	95, 59, 63	3
26 - 27	60, 61, 73	3
27 - 28	86, 67	2
28 - 29	15	1
29 - 30	95, 97	2

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31	50, 76	2
31 - 32	75	1
32 - 33	66, 69, 70	3
33 - 34	95, 62, 65	3
34 - 35	96, 86	2
35 - 36		0
36 - 37	70, 73	2
37 - 38	95, 50	2
38 - 39	63, 64, 108	3
39 - 40	97, 61, 67	2
40 - 41	95, 203	2
41 - 42		0
42 - 43	86, 59, 60, 78	4
43 - 44	15	1
44 - 45	95, 97	2
45 - 46	50, 76	2
46 - 47	62	1
47 - 48	70, 73	2
48 - 49	95	1
49 - 50	96, 86, 69, 70	4
50 - 51	200	1
51 - 52	65	1
52 - 53	95, 61, 63, 67	4
53 - 54	50, 75	2
54 - 55	97, 64, 108	3
55 - 56	95, 66	2
56 - 57		0
57 - 58	86	1
58 - 59	15, 60	2
59 - 00	95, 59	2

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : LEBRETON STARTING TIME: 10:00 A.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 11:00 A.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1		0
1 - 2	95, 86	2
2 - 3		0
3 - 4	96	1
4 - 5		0
5 - 6		0
6 - 7	95	1
7 - 8		0
8 - 9		0
9 - 10		0
10 - 11		0
11 - 12	95, 97	2
12 - 13		0
13 - 14		0
14 - 15		0
15 - 16		0
16 - 17	95, 86	2
17 - 18		0
18 - 19	96	1
19 - 20		0
20 - 21		0
21 - 22	95	1
22 - 23		0
23 - 24		0
24 - 25		0
25 - 26		0
26 - 27	95, 97	2
27 - 28		0
28 - 29		0
29 - 30		0

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31		0
31 - 32	95, 86	2
32 - 33		0
33 - 34	96	1
34 - 35		0
35 - 36		0
36 - 37	95	1
37 - 38		0
38 - 39		0
39 - 40		0
40 - 41		0
41 - 42	95, 97	2
42 - 43		0
43 - 44		0
44 - 45		0
45 - 46		0
46 - 47	95, 86	2
47 - 48		0
48 - 49	96	1
49 - 50		0
50 - 51		0
51 - 52	95	0
52 - 53		0
53 - 54		0
54 - 55		0
55 - 56		0
56 - 57	95, 97	2
57 - 58		0
58 - 59		0
59 - 00		0

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : BASELINE STARTING TIME: 16:00 P.M.
DATE : WEEKDAYS OF 1993 ENDING TIME : 17:00 P.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1		0
1 - 2		0
2 - 3		0
3 - 4	95	1
4 - 5		0
5 - 6	173	1
6 - 7	70	1
7 - 8	95	1
8 - 9		0
9 - 10		0
10 - 11	95	1
11 - 12	75	1
12 - 13	73	1
13 - 14		0
14 - 15	95	1
15 - 16		0
16 - 17		0
17 - 18	70, 72	2
18 - 19	95	1
19 - 20		0
20 - 21	173	1
21 - 22		0
22 - 23	95, 73	2
23 - 24		0
24 - 25		0
25 - 26	95	1
26 - 27		0
27 - 28		0
28 - 29		0
29 - 30	95	1

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31	70	1
31 - 32	75	1
32 - 33		0
33 - 34	95, 72, 73	3
34 - 35		0
35 - 36	173	1
36 - 37		0
37 - 38	95	1
38 - 39		0
39 - 40		0
40 - 41	95	1
41 - 42		0
42 - 43		0
43 - 44	70	1
44 - 45	95, 73	2
45 - 46		0
46 - 47		0
47 - 48		0
48 - 49	95	1
49 - 50		0
50 - 51	173	1
51 - 52		0
52 - 53	95	1
53 - 54	72	1
54 - 55	73, 75	2
55 - 56	95	1
56 - 57	70	1
57 - 58		0
58 - 59		0
59 - 00	95	1

LOCATION : OTTAWA-CARLETON TRANSITWAY
STATION : BASELINE
DATE : WEEKDAYS OF 1993

STARTING TIME: 10:00 A.M.
ENDING TIME : 11:00 A.M.

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
0 - 1		0
1 - 2	95	1
2 - 3		0
3 - 4		0
4 - 5		0
5 - 6	173	1
6 - 7	95	1
7 - 8		0
8 - 9		0
9 - 10		0
10 - 11		0
11 - 12	95	1
12 - 13		0
13 - 14		0
14 - 15		0
15 - 16		0
16 - 17	95	1
17 - 18		0
18 - 19		0
19 - 20		0
20 - 21		0
21 - 22		0
22 - 23		0
23 - 24		0
24 - 25		0
25 - 26		0
26 - 27	95	1
27 - 28		0
28 - 29		0
29 - 30		0

TIME	ROUTES NUMBER	No. OF BUSES (veh/min)
30 - 31		0
31 - 32	95	1
32 - 33		0
33 - 34		0
34 - 35		0
35 - 36	173	1
36 - 37	95	1
37 - 38		0
38 - 39		0
39 - 40		0
40 - 41		0
41 - 42	95	1
42 - 43		0
43 - 44		0
44 - 45		0
45 - 46		0
46 - 47	95	1
47 - 48		0
48 - 49		0
49 - 50		0
50 - 51		0
51 - 52	95	1
52 - 53		0
53 - 54		0
54 - 55		0
55 - 56		0
56 - 57	95	1
57 - 58		0
58 - 59		0
59 - 00		0

APPENDIX C
THE MODIFIED ARFCOM MODEL FOR ESTIMATION OF BUS FUEL CONSUMPTION

Appendix C.1: Modification of ARFCOM for Bus Fuel Consumption Estimation

Bus Fuel Consumption Estimation Based on Modification of ARFCOM

C.1.1 Overview

A number of the heavy vehicle (e.g., truck) fuel consumption models have been developed. One of these models used, is ARFCOM for the estimation of fuel consumption. Literature review did not reveal suitable analytical method or results of specific test to estimate fuel consumption of buses. The ARFCOM (ARRB Road Fuel Consumption Model) can be used for the estimation of fuel consumption of vehicles ranging from cars to 40 tonne articulated trucks. The model incorporates vehicular parameters for ten classes of vehicles including three car, one van and six truck classes. The logic of the model is based on the tractive forces acting on a vehicle at its wheels, which are estimated using basic Newtonian mechanics. The model estimates total power required to overcome resistance forces, to run vehicle accessories and to overcome internal engine friction. The total power required from the engine, in conjunction with power efficiency factors, are used as the basis of estimating fuel consumption [24]. In this research, a method based on ARFCOM, is developed for obtaining bus fuel consumption estimates. A modification of the model for various modes of driving of buses is represented as follows:

C.1.2 Propulsion Force

Propulsion of a vehicle must provide the force necessary to overcome resistance to motion and to accelerate the vehicle. The highest acceleration rate is required in moving

the vehicle from a standing position. Power produced by an engine is usually expressed in kilowatts (kw). Indicated power, noted for an engine is the total power the engine produces. Subtracting from it the internal losses in the engine, shaft bearings, and so on, the brake power is obtained. This power represents the net usable power produced by the engine. That power is further reduced by the resistance between the engine and the tractive wheels. For heavy vehicles, these include resistances in the clutch, gear box (which is different for each gear), differential, and shaft and axle bearings. The power remaining after these resistances is the effective power at wheels (i.e. the net power available for traction) [24]. The rolling resistance as well as other resistances have to be overcome. The total power required to drive the vehicle is the sum of the tractive force, the power to overcome internal engine friction and to run accessories such as the cooling fan, air conditions, etc. Therefore, first, the total engine power (kw) required has to be calculated. Second, a fuel-to-power efficiency factor will be used to calculate the fuel required by the engine to satisfy the power demand [63].

In the case of bus operation, the various components of the bus movement have to be taken into account. These are: acceleration, cruise, deceleration and idle. The calculation procedures and accuracy of fuel consumption estimates will depend on the available data. The minimum items required for application of the fuel consumption model are Transitway section distance, cruise speed, stopped time and average grade.

C.1.3 Rolling Resistance

Rolling resistance is taken to be the total of all forces, apart from aerodynamic drag, acting on vehicle. It includes all frictional forces from the output of the gear box to the wheels and the tire resistance forces. It strongly relates to road type and roughness, tyie

type, pressure and diameter and the load on the tire. The following is the expression for the rolling resistance [24]:

$$R_r = \frac{(\ 37N_w\ D_w + C_{r1}\ (\ 0.067M\ /\ D_w + 0.012V^2\ /\ N_w\ /\ D_w^2\ ))\ C_{r2}}{1000} \quad \text{(C.1)}$$

where

R_r : the rolling resistance force (kn)
N_w : the number of wheels on the vehicle
D_w : the diameter of the wheels (m)
C_{r1} : factor to allow for the type of tyre (see Table C.1)
C_{r2} : factor to allow for the road surface (see Table C.1)
M : the total mass of vehicle (kg)
V : the speed (m/s)

Tyre diameter can be related to the gross vehicle mass and the number of wheels. In case it is unknown, it can be estimated as follows [24]:

$$\begin{aligned} D_w &= 1.00\ \textit{if}\ 5000 \le M_g < 10000 \wedge M_g/N_w > 1600 \\ &= 1.00\ \textit{if}\ M_g \ge 10000 \wedge M_g/N_w < 2300 \\ &= 1.14\ \textit{if}\ M_g \ge 10000 \wedge M_g/N_w \ge 2300 \end{aligned} \quad \text{(C.2)}$$

where

M_g: the gross design rated mass of vehicle (kg)

In case M_g is not specified, M can be used as a substitute variable [24].

The various components of Equation C.1 require an explanation. The first part of model consists of the frictional forces within the vehicle and it reflects vehicle size. The second part represents tire rolling resistance and it is directly proportional to mass. The final component is speed dependent. It takes into account diameter and number of wheels. The correction factor, C_{r1}, is intended to take into account the effect on tire rolling resistance of different types of tires. The correction factor C_{r2} applies to all parts of Equation C.1 since surface type and road roughness affect all aspects of rolling resistance.

Table C.1-Rolling resistance factors, C_{r1} and C_{r2}, for various tire types and road surfaces [24].

C_{r1}	Tire Type	C_{r2}	Surface Type
1.3	Cross Ply Bias	0.74	Smooth Concrete
1.0	Radial	0.9	Smooth Texture Asphalt
0.9	Low Profile	1.0	Medium Texture Asphalt
0.91	Super Singles Bias Ply	1.1	Rough Texture Asphalt
0.84	Super Singles Radial	1.2	Hot Asphalt
		1.25	Rough Asphalt

For articulated buses, Equation C.1 can be expressed as follows:

by using given data:

N_w= 10 wheels
M = 17120 kg (without passengers)
M = 17120 + (64.04 * N_{pse}) + (64.04 * N_{pst}) kg (with passengers)

where

N_{pse} :number of seated passengers (seating capacity: 58)
N_{pst} :number of standee passengers (standing capacity: 37)

It is assumed that the average weight of one passenger is 150 lb or 64.04 kg

Then:

M = 23203.8 kg (full passenger load)

Based on Equation C.2, D_w is as follows:

$M = 23203.8 \geq 10000$ and $M/N_w = 23203.8/10 = 2320.38 \geq 2300$
$\Rightarrow D_w = 1.14$ m

By using information noted in Table C.1, the following factors are selected:

$C_{r1} = 1$ for tire type ; Radial
$C_{r2} = 1$ for Medium Texture

Then

$$R_r = 421.8 * 10^{-3} + 0.059 * 10^{-3} M + 0.092 * 10^{-5} V^2 \qquad \text{(C.3)}$$

where

M : the total mass of vehicle (kg)
V : speed (m/s)

Equation C.1 for standard buses, can be estimated by using the following data:

N_w= 6 wheels
M = 10720 kg (without passengers)
M = 10720 + (64.04 * N_{pse}) + (64.04 * N_{pst}) kg (with passengers)

where

N_{pse} :number of seated passengers (seating capacity: 52)
N_{pst} :number of standee passengers (standing capacity: 33)

Then:

M = 16163.4 kg (full passenger load)

Based on Equation C.2, D_w is as follows:

M = 16163.4 ≥ 10000 and M/N_w = 16163.4/6 = 2693.9 ≥ 2300
⇒ D_w = 1.14 m

by using Table C.1, it is assumed by:

C_{r1} = 1 for tire type : Radial
C_{r2} = 1 for Medium Texture

Then

$$R_r = 253.08 * 10^{-3} + 0.058 * 10^{-3} M + 0.15 * 10^{-5} V^2 \qquad \text{(C.4)}$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)

C.1.4 Aerodynamic Resistance

The aerodynamic resistance is dependent on vehicle size, shape, and the speed of

travel. Other factors that affect aerodynamic resistance are: wind speed and direction, and density of air. The density of air varies with atmospheric pressure and therefore with temperature and altitude. The aerodynamic resistance in zero wind conditions can be calculated by using the following equation [24]:

$$R_a = \frac{0.5\ \rho\ C_d\ F_a\ V^2}{1000} \qquad \text{(C.5)}$$

where

R_a : the aerodynamic resistance force (kn)
ρ : the density of air (kg/m^3)
C_d : the aerodynamic drag coefficient of the vehicle
F_a : the projected frontal area of the vehicle (m^2)
V : the speed of the vehicle (m/s)

For most vehicles, an estimation of F_a can be found by approximately 85% to 95% of product of the maximum width and maximum height. The area under the axles is not included. It has also been suggested that for a box shaped vehicle, the F_a can be estimated approximately by the product of the maximum width and the maximum height less the wheel radius of the vehicle.

The C_d is a dimensionless parameter reflecting the shape of the vehicle. A large study of vehicle fuel consumption, conducted by the World Bank in Brazil, found that the aerodynamic drag coefficient of a Merce. Benz Diesel bus is 0.65 [63]. This coefficient (C_d), for bus (MAN SL 202) was found to be 0.55 by Schubert and Drewitz [66].

For articulated buses, Equation C.5 can be estimated as follows:

ρ = 1.2 kg/m^3 (at 15 °C at an altitude of 200 m sea level)
bus width = 102 in = 2.5908 m
bus height= 124.7 in =3.16738 m
D_w = 1.14 m $\Rightarrow$ R_w = 0.57 m

Then

$F_a = 2.5908 * (3.16738 - 0.57) = 6.73\ m^2$

The aerodynamic drag coefficient is found by using wind tunnel tests on scale models of vehicles. Measurement of drag could be made over a range of g/H from 0.05 to 1.0. According to g/H ratio of a bus (Figure C.1) and by using the graph of Lakshmana and Vijay [67], the drag coefficient of the bus at zero wind condition as a function of ground clearance can be obtained.

g = 15 in
H = 124.7 - 15 = 109.7 in
g/H = 15/109.7 = 0.137

According to g/H=0.137, C_d is 0.52 [67].

Then, in zero wind conditions:

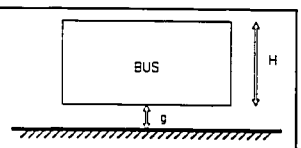


Figure C.1-Illustration of g & H for estimation of the aerodynamic drag coefficient of bus

$$R_a = 2 * 10^{-3}\ V^2 \qquad (C.6)$$

where

V : speed (m/s)

For standard buses Equation C.5, can be calculated as follows:

$\rho = 1.2\ kg/m^3$ (at 15 degree C at an altitude of 200 m sea level)
bus width = 102 in = 2.5908 m
bus height= 119.25 in =3.02895 m
$D_w = 1.14$ m $\Rightarrow$ $R_w = 0.57$ m

Then

$F_a = 2.5908 * (3.02895 - 0.57) = 6.37\ m^2$
g = 15 in
H = 119.25 - 15 = 104.25 in
g/H = 15/104.25 = 0.144

According to g/H=0.144, C_d is 0.51 [67].

Then, in zero wind conditions:

$$R_a = 1.98 * 10^{-3} V^2 \qquad \text{(C.7)}$$

where

V : speed (m/s)

C.1.5 Inertial Force

The inertial force includes the forces required to accelerate the total vehicle mass and to accelerate the rotating parts within the vehicle. The major components of the vehicle contributing to rotational inertia are the wheels and drive-train. The total inertial force can be estimated by [24]:

$$R_i = \frac{M_e\, a}{1000} \qquad \text{(C.8)}$$

where

R_i : the total inertial force (kn)
a : the acceleration rate (m/s^2)
M_e: the effective mass of the vehicle (kg), including rotational inertia

M_e can be estimated by [24]:

$$M_e = M + 0.59\, N_w\, M_w \qquad \text{(C.9)}$$

where

M : the total mass of the vehicle (kg)
N_w: the number of wheels
M_w: the mass of each wheel (kg)

The wheel mass is closely related to the wheel diameter and by using World Bank data collected in Brazil, the following expression was found [24]:

$$
\begin{aligned}
M_w &= 18 \quad \textit{if } D_w = 0.65 \\
&= 28 \quad \textit{if } D_w = 0.72 \\
&= 44 \quad \textit{if } D_w = 0.80 \\
&= 90 \quad \textit{if } D_w = 1.00 \\
&= 125 \quad \textit{if } D_w = 1.14
\end{aligned}
\tag{C.10}
$$

For articulated buses, Equation C.8 can be estimated as noted below.

The effective mass of the vehicle (kg), including rotational inertia, is calculated by using Equations C.9 and C.10:

$D_w = 1.14 \Rightarrow M_w = 125$
$M_e = M + 737.5$

Then

$$R_i = (0.7375 + 10^{-3} M) a \tag{C.11}$$

where

M : the total mass of vehicle (kg)
a : the acceleration rate (m/s^2)

For standard buses, R_i can be calculated as follows:

$D_w = 1.14 \Rightarrow M_w = 125$
$M_e = M + 442.5$

Then

$$R_i = (0.4425 + 10^{-3} M) a \tag{C.12}$$

C.1.6 Gradient Resistance

The force required to overcome grades is given by [24]:

$$R_g = \frac{9.81\ M*G}{10^5} \qquad \text{(C.13)}$$

where

R_g : the force to overcome grade (kn)
G : the percent grade (negative for downhill)

C.1.7 Cornering Resistance

A vehicle moving around a curve is subject to a centrifugal force. This force, which acts as a sidewards force on the tires, can be estimated by [24]:

$$R_{cu} = \frac{(\ M*V^2 / R_c - 9.81\ M*S_e\ )^2}{(\ N_w\ C_s\ )} * 10^{-6} \qquad \text{(C.14)}$$

where

R_{cu} : the cornering resistance force (kn)
R_c : the radius of the curve (m)
S_e : the superelevation slope of the curve (positive for slope inwards towards center of curve)
N_w : the number of wheels
C_s : the cornering stiffness of tires (kn/rad)
M : the total mass of the vehicle (kg)
V : the speed of the vehicle (m/s)

Past research found the cornering stiffness to be dependent on the type and size of tire and to the load on the tire. On the basis of data collected by past studies, the following equations were reported for the cornering stiffness of truck tires. Since bus tires are similar to truck tires, it is assumed here that the following equation can be used for buses [24]:

$$C_s = 0.0913\ M / N_w - 1.14 * 10^{-5}\ (M / N_w)^2 \qquad for\ D_w > 0.9 \quad (C.15)$$

For articulated buses, Equation C.14 can be obtained as follows:

$D_w = 1.14 > 0.9 \Rightarrow C_s = 0.00913\ M - 1.14 * 10^{-7}\ M^2$
$S_e = 0.1$ (it is assumed, because 0.1 is a typical value for a right curve) [63]

The use of the above parameters leads to:

$$R_{cu} = \frac{M\ (V^2 / R_c - 0.981)^2}{0.913*10^5 - 1.14\ M} \qquad (C.16)$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
R_c: the radius of the curve (m)

For standard buses, Equation C.14 can be modified, as noted below.

$D_w = 1.14 > 0.9 \Rightarrow C_s = 0.01522\ M - 3.16 * 10^{-7}\ M^2$
$S_e = 0.1$ (it is assumed)

with regard to the above parameters:

$$R_{cu} = \frac{M\ (V^2 / R_c - 0.981)^2}{0.913*10^5 - 1.896\ M} \qquad (C.17)$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
R_c: the radius of the curve (m)

C.1.8 Drive-Line Efficiency

The tractive force required at the wheels for vehicle movement is provided by the engine and transmitted through, such devices as the gear box, differential and clutch. The drive-train efficiency is typically between 0.80 and 0.92 [63]. It varies with the power

load on the engine. The drive-line efficiency drops off slightly at low loads. In the case of buses, it is assumed to be 0.90.

Although all tractive power components are affected by the drive-train efficiency factor, the power required to run the accessories and to overcome engine drag are not. Therefore, the total power required by the engine for vehicle motion given by [24]:

$$P_{tot} = \frac{P_{tr}}{e_{dt}} + P_{eng} + P_{acs} \qquad for\ P_{tr} > 0 \qquad \text{(C.18)}$$

where

P_{tot}: the total power required by the engine (kw)
P_{tr} : the total tractive power (kw) at the drive wheels
P_{eng}: the power required to overcome engine drag
P_{acs}: the power required to run the accessories
e_{dt} : the drive-train efficiency factor

The total tractive power (kw) at the drive wheels can be calculated by [22]:

$$P_{tr} = V\ (R_r + R_a + R_i + R_g + R_{cu}) \qquad \text{(C.19)}$$

where

R_r : the rolling resistance
R_g : the grade force
R_a : the aerodynamic drag resistance
R_i : the inertia force
R_{cu} : the cornering force
V : the speed of the vehicle (m/s)

Thus, the total tractive power of articulated buses, by using Equations C.3, C.6, C.11, C.13, C.16 and C.19, can be estimated as follows:

$$P_{tr} = V\ [\ 0.4218 + 5.9*10^{-5}\ M + 9.81*10^{-5}\ M*G + 2*10^{-3}\ V^2 + (\ 0.7375+10^{-3}M\ )\ a + \frac{M\ (V^2/R_c - 0.981)^2}{0.913*10^5 - 1.14\ M}\ ] \quad \text{(C.20)}$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
a : the acceleration rate (m/s^2)
G : the percent grade (negative for downhill)
R_c: the radius of the curve (m), (V^2/R_c will be zero if there is no curve and thus last part of the above equation will be approximately zero)

For standard buses, P_{tr}, by using Equations C.4, C.7, C.12, C.13, C.17 and C.19, can be calculated as follows:

$$P_{tr} = V\ [\ 0.2531 + 5.8*10^{-5}\ M + 9.81*10^{-5}\ M*G + 2*10^{-3}\ V^2 + (\ 0.4425+10^{-3}M\ )\ a + \frac{M\ (\ V^2/R_c - 0.981\ )^2}{0.913*10^5 - 1.896\ M}\ ] \quad \text{(C.21)}$$

The total tractive power term can be negative when the vehicle is decelerating or travelling downhill. During the whole deceleration, total tractive force is smaller than or equal to zero. The tractive power available at the engine can be approximately estimated by [24]:

$$P_{ntr} = -\ e_{dt}\ P_{tr} \qquad for\ P_{tr} < 0 \quad \text{(C.22)}$$

where P_{ntr} is the excess tractive power available at the engine (kw) when tractive power is negative. The total power, for negative tractive power, required by the engine, is given by [24]:

$$P_{tot} = e_{dt}\, P_{tr} + P_{eng} + P_{acs} \qquad for\ P_{tr} < 0 \tag{C.23}$$

It is assumed that if $P_{tr} \leq 0$ and $P_{ntr} \leq P_{acs} + P_{eng}$, fuel consumption rate is equal α (i.e., fuel required to run the engine and accessories when the engine is idling (ml/s)) [63].

C.1.9 Power For Vehicle Accessories

The power required to run vehicle accessories, such as the engine cooling fan, air compressor and air conditioning, can add to the total power required to drive the vehicle. The following equation can be used to estimate the power requirements of the accessories [24]:

$$P_{acs} = \frac{0.746\ XX\ RPM}{TRPM} + YY\ P_{max} \left(\frac{RPM}{TRPM}\right)^{2.5} \tag{C.24}$$

where

P_{acs} : the power required to run the accessories (kw)
RPM : the engine speed (rpm)
TRPM: the full load governed engine speed (rpm)
XX : the engine accessory load constant (see Table C.2)
YY : the engine cooling fan load constant (see Table C.3)
P_{max} : the maximum rated engine power (kw)

The relationship between engine speed and vehicle speed can be calculated by [55].

$$RPM = \frac{1000\ U_j\ w\ V}{60\ D_w\ \pi} \tag{C.25}$$

where

V : the vehicle speed (km/h)
RPM: the engine speed (rpm)
D_w : diameter of tractive wheels (m)
U_j : transmission ratio, different for each gear j

w : differential reduction ratio-constant for each vehicle

The engine speed of a vehicle, in top gear, can be calculated by [24]:

$$RPM = N_t V \tag{C.26}$$

where N_t is the ratio of engine speed to vehicle speed in top gear and V is vehicle speed (m/s). The ratio, N_t, can be calculated by using Equation C.25.

If TRPM is not known, the following equation can be used to estimate TRPM for diesel engines [24].

$$TRPM = 4600 - 18 P_{max} + 0.030 P_{max}^2 \tag{C.27}$$

For articulated buses, P_{acs} can be estimated as below.

By using the engine data of the articulated bus:

P_{max} = 280 hp =208.8 kw
TRPM = 2100 rpm

Table C.2-Engine accessary load constant [63]

XX (hp)	Accessories
1	Alternator (Alt) only
2	Alt and Air Compressor (A-Comp)
4	Alt+(A-Comp)+Power Steering (P-S)
8	Alt+(A-Comp)+(P-S)+Cabin Air Conditioning
20	Alt+(A-Comp)+(P-S)+Coach Air Conditioning

From Tables C.2 and C.3, XX and YY are assumed:

XX = 4
YY = 0.01

Table C.3-Engine cooling fan load constant [63]

Y	Accessory
0.05	Full Time Fan (front engine HD diesel)
0.10	Full Time Fan (front engine med. duty diesel and petrol engines)
0.10	Full Time Fan (rear transverse bus-diesel)
0.002	Thermo Controlled Fan (front eng. HD diesel)
0.004	Thermo Controlled Fan (front engine med. duty diesel and petrol engines)
0.01	Thermo Controlled Fan (rear transverse bus radiator-diesel)

In the top gear ratio (1.40:1) of articulated buses (Orion-Ikarus), the engine speed at vehicle speed of 96.2 km/h is 2100. Thus RPM, (the engine speed of vehicle) by using Equation C.25, can be obtained as follows:

$$RPM = 79\ V \tag{C.28}$$

where V is the vehicle speed (m/s).

Therefore, P_{acs} can be estimated by using the following equation:

$$P_{acs} = 0.112\ V + 5.73*10^{-4}\ V^{2.5} \tag{C.29}$$

where V is the vehicle speed (m/s).

On the basis of the result of the test for standard bus (6V92TA 253 DDEC Cy90) from OC Transpo, for various vehicle and engine speeds and by using regression analysis technique, the following linear equation was obtained with r^2=0.99 for top gear of the standard bus:

$$RPM = 88\ V \tag{C.30}$$

where V is the vehicle speed (m/s).

Thus, P_{acs} can be calculated, by using the engine data of the standard bus, as follows:

P_{max} = 170 hp =126.8 kw
TRPM = 2100 rpm

From Tables C.2 and C.3, XX and YY are assumed:

XX = 4
YY = 0.01

Therefore, P_{acs} is estimated by the following equation:

$$P_{acs} = 0.125\ V + 4.56*10^{-4}\ V^{2.5} \qquad \text{(C.31)}$$

where V is the speed of vehicle (m/s).

In case the vehicle is not in top gear, engine speed is affected by both vehicle speed and the power output by the engine. For most engines a maximum engine speed exists which is marginally higher than the maximum full load governed engine speed, TRPM. Engine speed can be estimated by the following equation, when the vehicle is in less than top gear [24].

$$RPM = RPM_0 + r_1\ TRPM\ V + r_2\ TRPM\ p_{out} / p_{max} / (3.6\ V + 10) \qquad \text{(C.32.1)}$$

$$RPM = TRPM \qquad \text{(C.32.2)}$$

RPM is equal to minimum values of Equations C.32.1 and C.32.2.

Where P_{out} is the power output by the engine (kw), r_1 and r_2 are parameters to be estimated by using limited speed and engine speed data.

The following estimates of r_1 and r_2 were obtained [24]:

r_1 = 0.021
r_2 = 22

C.1.10 Estimation of Fuel Consumption Rate

The fuel consumption per unit time can be estimated by [24]:

$$f = \beta P_{tot} \qquad \text{(C.33.1)}$$

$$f = \alpha \qquad \text{(C.33.2)}$$

f is equal to maximum values of Equations C.33.1 and C.33.2.

where

- f : the fuel consumption rate per unit time (ml/s)
- α : the idle fuel consumption rate with accessories operating (ml/s)
- β : the fuel-to-power efficiency factor (ml/s/kw)
- P_{tot}: the total power (kw) required to overcome the forces resisting vehicle motion, both internal (P_{eng}) and external (P_{out}) to the vehicle

It is assumed that fuel consumption during any operational phase does not fall below the idle fuel consumption rate under low or negative total power [63].

The engine efficiency is a measure of how well the engine converts fuel to power. The fuel-to-power efficiency factor is used as a measure of engine fuel efficiency in the fuel consumption model. This in turn gives the fuel consumption (ml/s) per unit power (kw) of the engine. Thus, low values of β suggest high engine efficiency. The vehicle requires very low power primarily when the vehicle is stationary, travelling down grades or at the start of a deceleration. A separate measure of idle fuel consumption could be used when the vehicle is stationary or if the power required of the engine is less than zero. Engine maps for several diesel engines were studied in order to establish the relationship between engine drag and engine speed and to estimate engine drag parameters and the engine efficiency. Engine drag can be estimated by the following equation [24]:

$$P_{eng} = c_{eng} + b_{eng} \left(\frac{RPM}{1000}\right)^2 \qquad \text{(C.34)}$$

where c_{eng} and b_{eng} are parameters to be determined from the engine map. These parameters could be estimated simultaneously with the engine efficiency. Parameter value of c_{eng} and b_{eng} were reported for diesel engines in the literature [24]:

$$c_{eng} = 0.017\ P_{max} \qquad \text{(C.35)}$$

$$b_{eng} = 0.7 + 0.026\ P_{max} \qquad \text{(C.36)}$$

Thus, calculation of the power required to overcome engine drag (P_{eng}) for articulated buses can be carried out as noted below.

By using P_{max}=280 hp=208.8 kw for articulated bus engine and Equations C.35 and C.36, c_{eng} and b_{eng} can be calculated:

$c_{eng} = 3.55$
$b_{eng} = 6.12$

Then , P_{eng} can be estimated by the following equation:

$$P_{eng} = 3.55 + 0.038\ V^2 \qquad \text{(C.37)}$$

For standard buses, c_{eng}, b_{eng} and P_{eng} can be obtained as follows:

$c_{eng} = 2.16$
$b_{eng} = 4$

Then

$$P_{eng} = 2.16 + 0.031\ V^2 \qquad \text{(C.38)}$$

where, it is assumed that for standard buses P_{max}=170 hp= 126.8 kw.

The following equation can be used for the estimation of engine efficiency (β) by [24]:

$$\beta = \beta_b \ (1 + e_{hp} \ P_{out} \ / \ P_{max}) \qquad \text{(C.39)}$$

where

β : the fuel-to-power efficiency factor (ml/s/kw)
β_b : the base engine efficiency, approximately equal to the efficiency at low to medium power level (ml/s/kw)
e_{hp} : the proportionate decrease in efficiency at maximum power
P_{max}: the maximum rated engine power (kw)
P_{out} : the total output power of the engine required to provide tractive force and run the accessories (kw):

where P_{out} can be estimated by [24]:

$$P_{out} = \frac{P_{tr}}{e_{dt}} + P_{acs} \qquad \text{(C.40)}$$

where

e_{dt} : the drive-train efficiency factor
P_{tr} : the total tractive power (kw) at the drive wheels
P_{acs}: the power required to run the accessories

The World Bank study in Brazil has resulted in values of 0.059 and 0.22 for β_b and e_{hp}, respectively for buses (Merce. Benz Diesel) [63]. Therefore, the engine efficiency of articulated buses can be estimated by using the following assumptions and estimation of P_{out} (by Equations C.20, C.29 and C.40) as follows:

$\beta_b = 0.059$
$e_{hp} = 0.22$
$e_{dt} = 0.90$

$$\begin{aligned} P_{out} = V \ [\ & 0.582 + 0.0655*10^{-3} \ M + 1.09*10^{-4} \ M*G \\ & + 5.73*10^{-4} \ V^{1.5} + 2.22*10^{-3} \ V^2 \\ & + (1.1*10^{-3}M+0.81125) \ a + \frac{M \ (V^2/R_c - 0.981)^2}{82170 - 1.026M} \ ] \end{aligned} \qquad \text{(C.41)}$$

Then, by using Equation C.39:

$$\beta = 0.059 + V\,[\,3.61*10^{-5} + 4.07*10^{-9}\,M + 6.77*10^{-9}\,M*G + 3.56*10^{-8}\,V^{1.5} + 10^{-7}\,V^{2} + (6.84*10^{-8}M+5.04*10^{-5})\,a + \frac{M\,(V^{2}/R_c - 0.981)^{2}}{1.32*10^{9} - 16504\,M}\,] \qquad \text{(C.42)}$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
a : the acceleration rate (m/s^2)
G : the percent grade (negative for downhill)
R_c: the radius of the curve (m)

If $P_{tr} \geq 0$,(where P_{tr} is the total tractive power (kw) at the drive wheels), P_{tot} , (the total power required by the engine (kw)), by using Equations C.18, C.20, C.29 and C.37 can be estimated as follows:

$$P_{tot} = 3.55 + V\,[\,0.582 + 6.55*10^{-5}\,M + 1.09*10^{-4}\,M*G + 0.038\,V + 5.73*10^{-4}\,V^{1.5} + 2.22*10^{-3}\,V^{2} + (1.1*10^{-3}M+0.81125)\,a + \frac{M\,(V^{2}/R_c - 0.981)^{2}}{82170 - 1.026\,M}\,] \qquad \text{(C.43)}$$

If $P_{tr}<0$ and $P_{ntr} \geq P_{acs}+P_{eng}$, by using Equation C.23, P_{tot} can be computed as follows:

$$P_{tot} = 3.55 + V\,[\,0.4916 + 5.31*10^{-5}\,M + 8.82*10^{-5}\,M*G + 0.038\,V + 5.73*10^{-4}\,V^{1.5} + 1.82*10^{-3}\,V^{2} + (0.9*10^{-3}M + 0.66375)\,a + \frac{M\,(V^{2}/R_c - 0.981)^{2}}{101444 - 1.27\,M}\,] \qquad \text{(C.44)}$$

Then by using Equations C.43 or C.44, C.42 and C.33 (C.33.1 or C.33.2), fuel consumption rate (m lit/s) can be found.

If $P_{tr}<0$ and $P_{ntr} \leq P_{acs}+P_{eng}$, fuel consumption rate (m lit/s) is equal α (the idle fuel consumption rate) [24].

The engine efficiency for standard buses can be calculated by using the same procedure. P_{out} , by using Equations C.21, C.31 and C.40, can be obtained:

$$P_{out} = V\ [\ 0.4062 + 6.44*10^{-5}\ M + 1.09*10^{-4}\ M*G + 4.56*10^{-4}\ V^{1.5} + 2.22*10^{-3}\ V^{2} + (1.1*10^{-3}M + 0.49167)\ a + \frac{M\ (V^{2}/R_{c} - 0.981)^{2}}{82170 - 1.723\ M}\ ] \qquad \text{(C.45)}$$

Then, by using Equation C.39:

$$\beta = 0.059 + V\ [\ 4.15*10^{-5} + 6.59*10^{-9}\ M + 1.116*10^{-8}\ M*G + 4.67*10^{-8}\ V^{1.5} + 2*10^{-7}\ V^{2} + (10^{-7}M + 5.03*10^{-5})\ a + \frac{M\ (V^{2}/R_{c} - 0.981)^{2}}{8.03*10^{8} - 18522\ M}\ ] \qquad \text{(C.46)}$$

If $P_{tr} \geq 0$, P_{tot} and f (m lit/s), can be calculated by the following equations: by using Equations C.18, C.21, C.31 and C.38:

$$P_{tot} = 2.16 + V\ [\ 0.4062 + 6.44*10^{-5}\ M + 1.09*10^{-4}\ M*G + 0.031\ V + 4.56*10^{-4}\ V^{1.5} + 2.22*10^{-3}\ V^{2} + (1.1*10^{-3}M + 0.49167)\ a + \frac{M\ (V^{2}/R_{c} - 0.981)^{2}}{82170 - 1.706\ M}\ ] \qquad \text{(C.47)}$$

where

M : the total mass of vehicle (kg)
V : the speed (m/s)
a : the acceleration rate (m/s^2)
G : the percent grade (negative for downhill)
R_c: the radius of the curve (m)

If $P_{tr} < 0$ and $P_{ntr} \geq P_{acs} + P_{eng}$, by using Equation C.23, P_{tot} can be computed by:

$$P_{tot} = 2.16 + V\,[\,0.3527 + 5.22*10^{-5}\,M + 8.82*10^{-5}\,M*G + 0.031\,V + 4.56*10^{-4}\,V^{1.5} + 1.82*10^{-3}\,V^2 + (0.9*10^{-3}M+03982)\,a + \frac{M\,(V^2/R_c - 0.981)^2}{101444 - 2.1\,M}\,] \quad \text{(C.48)}$$

Then, by using Equations C.47 or C.48, C.46 and C.33, f (m lit/s) can be estimated.

If $P_{tr}<0$ and $P_{ntr}\leq P_{acs}+P_{eng}$, fuel consumption rate (m lit/s) is equal to α [63].

The idle fuel consumption rate, α, is the fuel required by the engine to maintain operation with the throttle closed. It includes the fuel required to power the accessories and overcome engine drag at idle engine speed. Thus, if the idle fuel consumption rate is not known, the following equation can be used [24]:

$$\alpha=e_{lp}\beta_b\left[c_{eng}+b_{eng}\left(\frac{RPM_0}{1000}\right)^2+0.746\,XX\left(\frac{RPM_0}{TRPM}\right)+YY\,P_{max}\left(\frac{RPM_0}{TRPM}\right)^{2.5}\right] \quad \text{(C.49)}$$

where

RPM_0 : the idle engine speed (rpm)
XX : the engine accessory load constant (Table C.2)
YY : the engine cooling fan load constant (Table C.3)
TRPM : the maximum load governed engine speed (rpm)
e_{lp} : a factor allowing for lower engine efficiency at low engine power

The factor, e_{lp}, allows for the decrease in fuel efficiency of the engine and it is assumed 1.5 for diesel engines [63].

The idle fuel consumption rate, α, for articulated buses can be calculated, by using Equation C.49, the previous calculations and the following assumptions, as follows:

P_{max} = 208.8 kw
PRM_0 = 600 rpm
XX = 4
YY = 0.01
TRPM = 2100 rpm

$c_{eng} = 3.55$
$b_{eng} = 6.12$
$\beta_b = 0.059$
$e_{lp} = 1.5$

Then

$\alpha = 0.5926$ m lit/s

The idle fuel consumption rate, α, for standard buses can be calculated by using the previous calculations and the following assumptions:

$P_{max} = 126.8$ kw
$PRM_0 = 600$ rpm
$XX = 4$
$YY = 0.01$
$TRPM = 2100$ rpm
$c_{eng} = 2.16$
$b_{eng} = 4$
$\beta_b = 0.059$
$e_{lp} = 1.5$

Then

$\alpha = 0.3989$ m lit/s

Therefore, the overall method can predict fuel consumption over the acceleration-cruise-deceleration-idle cycle.

Appendix C.2: Results of the Modified Model Validation for Standard Bus

DATA: STANDARD BUSES

LINKS	DIS.(km)	RTIM(min)	Avg V(km/h)	ATIM(sec)	DTIM(sec)	DCru(km)	CTIM(sec)	CruV(m/s)	CruV(km/h)
LINK 1	1.77	1.7	62.47	18.08	10.09	1.526	73.83	20.67	74.412
LINK 2	1.02	1	61.2	17.71	9.88	0.785	32.41	24.22	87.192
LINK 3	1.25	1.5	50	14.47	8.07	1.093	67.46	16.2	58.32
LINK 4	1.37	1.7	48.35	13.99	7.81	1.224	80.2	15.26	54.936
LINK 5	0.74	1.2	37	10.71	5.98	0.654	55.31	11.82	42.552
LINK 6	1.02	1.3	47.08	13.62	7.6	0.881	56.78	15.52	55.872
LINK 7	0.54	1.2	27	7.81	4.36	0.494	59.83	8.26	29.736
LINK 8	2.06	2.3	53.74	15.55	8.68	1.879	113.77	16.52	59.472
LINK 9	1.55	1.6	58.13	16.82	9.39	1.338	69.79	19.17	69.012
LINK 10	4.68	5.2	54	15.63	8.72	4.497	287.65	15.63	56.268
LINK 11	1.42	1.6	53.25	15.41	8.6	1.242	71.99	17.25	62.1
LINK 12	0.45	0.6	45	13.02	7.27	0.323	15.71	20.56	74.016
LINK 13	1.12	1.3	51.69	14.96	8.35	0.953	54.69	17.43	62.748

DATA: ARTICULATED and STANDARD BUSES

	PAX.(max. 95)			PAX.(max. 85)					
AM(kg)	LF=0.40	AM'(kg)	SM(kg)	LF=0.40	SM'(kg)	G(%)	a(m/s^2)	d(m/s^2)	Rc(m)(no curve)
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21

STANDARD FUEL ESTIMATION

1)DECELERATION

PRM(1)	PRM(2)	PRM	b(ml/s)	Ptot1(kw)	Ptot2(kw)	Ptr	Ptot(kw)	F(ml/s)	DTIM(sec)	Fd(l)
4026	2100	2100	0.1389	-414.755	-329.238	-409.744	-329.238	0.3989	10.09	0.004025
4251	2100	2100	0.1532	-483.508	-384.925	-472.397	-384.925	0.3989	9.88	0.003941
3728	2100	2100	0.1214	-323.322	-255.178	-326.475	-255.178	0.3989	8.07	0.003219
3662	2100	2100	0.1178	-303.506	-239.126	-308.434	-239.126	0.3989	7.81	0.003115
3398	2100	2100	0.1047	-229.541	-179.211	-241.107	-179.211	0.3989	5.98	0.002385
3680	2100	2100	0.1188	-309.006	-243.581	-313.44	-243.581	0.3989	7.6	0.003032
3064	2100	2100	0.0912	-151.039	-115.62	-169.67	-115.62	0.3989	4.36	0.001739
3750	2100	2100	0.1227	-330.025	-260.607	-332.578	-260.607	0.3989	8.68	0.003462
3929	2100	2100	0.133	-384.627	-304.835	-382.301	-304.835	0.3989	9.39	0.003746
3688	2100	2100	0.1192	-311.328	-245.462	-315.555	-245.462	0.3989	8.72	0.003478
3801	2100	2100	0.1255	-345.231	-272.924	-346.423	-272.924	0.3989	8.6	0.003431
4019	2100	2100	0.1385	-412.566	-327.465	-407.75	-327.465	0.3989	7.27	0.0029
3813	2100	2100	0.1262	-348.962	-275.946	-349.821	-275.946	0.3989	8.35	0.003331

2)ACCELERATION

PRM(1)	PRM(2)	PRM	b(ml/s)	Ptot(kw)	F(ml/s)	ATIM(sec)	Fa(l)
3093	2100	2100	0.1074	398.362	42.7841	18.08	0.773537
3311	2100	2100	0.1162	469.259	54.5279	17.71	0.965689
2813	2100	2100	0.0967	313.954	30.3594	14.47	0.439301
2752	2100	2100	0.0945	296.792	28.0468	13.99	0.392375
2520	2100	2100	0.0866	235.435	20.3887	10.71	0.218363
2769	2100	2100	0.0951	301.52	28.6746	13.62	0.390548
2244	2100	2100	0.0787	173.893	13.6854	7.81	0.106883
2833	2100	2100	0.0975	319.839	31.1843	15.55	0.484916
3000	2100	2100	0.1038	369.483	38.3523	16.82	0.645086
2776	2100	2100	0.0954	303.525	28.9563	15.63	0.452587
2880	2100	2100	0.0992	333.35	33.0683	15.41	0.509583
3086	2100	2100	0.1071	396.224	42.4356	13.02	0.552512
2891	2100	2100	0.0996	336.7	33.5353	14.96	0.501688

3)CRUISE

b(ml/s)	Ptot(kw)	F(ml/s)	CTIM(sec)	Fc(l)
0.0664	90.517	6.0103	73.83	0.4437404
0.0685	117.205	8.0285	32.41	0.2602037
0.0643	63.025	4.0525	67.46	0.2733817
0.0639	58.008	3.7067	80.2	0.2972773
0.0625	41.611	2.6007	55.31	0.1438447
0.064	59.371	3.7997	56.78	0.215747
0.0614	27.443	1.685	59.83	0.1008136
0.0644	64.79	4.1725	113.77	0.4747053
0.0657	80.583	5.2943	69.79	0.3694892
0.064	59.953	3.837	287.65	1.1037131
0.0647	68.927	4.4596	71.99	0.3210466
0.0664	89.763	5.9603	15.71	0.0936363
0.0648	69.971	4.5341	54.69	0.2479699

4)IDLE

F(ml/s)	ITIM(sec)	Fi(l)
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967
0.3989	30	0.011967

Average Fuel Consumption For Standard Buses:

LINKS	DIS.(km)	TotalF(l)
LINK 1	1.77	1.23326888
LINK 2	1.02	1.24180093
LINK 3	1.25	0.72786829
LINK 4	1.37	0.70473448
LINK 5	0.74	0.37656012
LINK 6	1.02	0.62129366
LINK 7	0.54	0.22140273
LINK 8	2.06	0.97505064
LINK 9	1.55	1.03028755
LINK 10	4.68	1.57174543
LINK 11	1.42	0.84602665
LINK 12	0.45	0.66101483
LINK 13	1.12	0.76495583

Total Fuel Consumption (l)
10.97601
Total Distance (km)
18.99
Average Fuel consumption(l/km)
0.57798894

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Standard Buses(40')

Month	Kms	l	Avg.(l/km)
Jan	3257567	2038494	0.625771933
Feb	3172033	1940084	0.611621632
Mar	3419209	2118721	0.619652382
Apr	3174510	1896013	0.597261625
May	3382202	1902984	0.562646465
Jun	3317809	1944902	0.586200713
Jul	3052935	1760478	0.576650993
Aug	3201000	1819844	0.568523586
Sep	3324380	1924971	0.579046619
Oct	3310820	1931273	0.583321654
Nov	3475621	2050174	0.589872716
Dec	3314291	1969666	0.594294828

Appendix C.3: Results of the Modified Model Validation

for Articulated Bus

DATA: ARTICULATED BUSES

LINKS	DIS.(km)	RTIM(min)	AVG V(km/h)	ATIM(sec)	DTIM(sec)	DCru(km)	CTIM(sec)	CruV(m/s)	CRUSPE(km/h)
LINK 1	1.77	1.7	62.47	18.08	10.09	1.526	73.83	20.67	74.412
LINK 2	1.02	1	61.2	17.71	9.88	0.785	32.41	24.22	87.192
LINK 3	1.25	1.5	50	14.47	8.07	1.093	67.46	16.2	58.32
LINK 4	1.37	1.7	48.35	13.99	7.81	1.224	80.2	15.26	54.936
LINK 5	0.74	1.2	37	10.71	5.98	0.654	55.31	11.82	42.552
LINK 6	1.02	1.3	47.08	13.62	7.6	0.881	56.78	15.52	55.872
LINK 7	0.54	1.2	27	7.81	4.36	0.494	59.83	8.26	29.736
LINK 8	2.06	2.3	53.74	15.55	8.68	1.879	113.77	16.52	59.472
LINK 9	1.55	1.6	58.13	16.82	9.39	1.338	69.79	19.17	69.012
LINK 10	4.68	5.2	54	15.63	8.72	4.497	287.65	15.63	56.268
LINK 11	1.42	1.6	53.25	15.41	8.6	1.242	71.99	17.25	62.1
LINK 12	0.45	0.6	45	13.02	7.27	0.323	15.71	20.56	74.016
LINK 13	1.12	1.3	51.69	14.96	8.35	0.953	54.69	17.43	62.748

DATA: ARTICULATED and STANDARD BUSES

	PAX.(max. 95)			PAX.(max. 85)					
AM(kg)	LF=0.40	AM'(kg)	SM(kg)	LF=0.40	SM'(kg)	G(%)	a(m/s^2)	d(m/s^2)	Rc(m)(no curve)
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21
17120	38	19554	10720	34	12897	1	0.96	-1.72	1E+21

ARTICULATED FUEL CALCULATION

1)DECELERATION

PRM(1)	PRM(2)	PRM	b(ml/s)	Ptot1(kw)	Ptot2(kw)	Ptr	Ptot(kw)	F(ml/s)	DTIM(sec)	Fd(l)
3808	2100	2100	0.1145	-658.[illegible]	-526.355	-631.534	-526.355	0.5926	10.09	0.005979
4017	2100	2100	0.1244	-76[illegible]7	-615.923	-732.278	-615.923	0.5926	9.88	0.005855
3528	2100	2100	0.1023	-5[illegible]04	-409.633	-500.301	-409.633	0.5926	8.07	0.004782
3466	2100	2100	0.0998	-4[illegible].115	-384.611	-472.174	-384.611	0.5926	7.81	0.004628
3216	2100	2100	0.0905	-368.626	-291.864	-367.936	-291.864	0.5926	5.98	0.003544
3483	2100	2100	0.1005	-491.677	-391.547	-479.97	-391.547	0.5926	7.6	0.004504
2900	2100	2100	0.0811	-248.187	-194.297	-258.3	-194.297	0.5926	4.36	0.002584
3549	2100	2100	0.1032	-524.477	-418.117	-509.837	-418.117	0.5926	8.68	0.005144
3717	2100	2100	0.1104	-610.296	-487.636	-587.995	-487.636	0.5926	9.39	0.005565
3490	2100	2100	0.1008	-495.295	-394.478	-483.265	-394.478	0.5926	8.72	0.005167
3596	2100	2100	0.1052	-548.282	-437.401	-531.516	-437.401	0.5926	8.6	0.005096
3802	2100	2100	0.1142	-654.609	-523.533	-628.359	-523.533	0.5926	7.27	0.004308
3608	2100	2100	0.1056	-554.133	-442.141	-536.845	-442.141	0.5926	8.35	0.004948

2)ACCELERATION

PRM(1)	PRM(2)	PRM	b(ml/s)	Ptot(kw)	F(ml/s)	ATIM(sec)	Fa(l)
2889	2100	2100	0.0927	578.372	53.6151	18.08	0.969361
3082	2100	2100	0.0988	680.158	67.1996	17.71	1.1901049
2638	2100	2100	0.0852	455.069	38.7719	14.47	0.5610294
2583	2100	2100	0.0837	429.728	35.9682	13.99	0.5031951
2372	2100	2100	0.0781	338.439	26.4321	10.71	0.2830878
2599	2100	2100	0.0841	436.719	36.7281	13.62	0.5002367
2119	2100	2100	0.0724	245.92	17.8046	7.81	0.1390539
2657	2100	2100	0.0857	463.739	39.7424	15.55	0.6179943
2806	2100	2100	0.0902	536.441	48.387	16.82	0.8138693
2605	2100	2100	0.0843	439.681	37.0651	15.63	0.5793275
2698	2100	2100	0.087	483.601	42.0733	15.41	0.6483496
2883	2100	2100	0.0925	575.276	53.213	13.02	0.6928333
2709	2100	2100	0.0873	488.518	42.6476	14.96	0.6380081

3)CRUISE

b(ml/s)	Ptot(kw)	F(ml/s)	CTIM(sec)	Fc(l)
0.0651	123.063	8.0114	73.83	0.5914817
0.0665	155.775	10.359	32.41	0.3357352
0.0635	88.272	5.6053	67.46	0.3781335
0.0632	81.76	5.1672	80.2	0.4144094
0.0621	60.012	3.7267	55.31	0.2061238
0.0633	83.535	5.2878	56.78	0.3002413
0.0611	40.498	2.4744	59.83	0.1480434
0.0636	90.549	5.7589	113.77	0.6551901
0.0645	110.644	7.1365	69.79	0.4980563
0.0633	84.292	5.3357	287.65	1.5348141
0.0638	95.86	6.1159	71.99	0.4402836
0.065	122.126	7.9382	15.71	0.1247091
0.0639	97.195	6.2108	54.69	0.3396687

4)IDLE

F(ml/s)	ITIM(sec	Fi(l)
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778
0.5926	30	0.017778

Average Fuel Consumption For Articulated Buses:

LINKS	DIS.(km)	TotalF(l)
LINK 1	1.77	1.5846
LINK 2	1.02	1.549473
LINK 3	1.25	0.9617232
LINK 4	1.37	0.9400108
LINK 5	0.74	0.5105333
LINK 6	1.02	0.8227598
LINK 7	0.54	0.307459
LINK 8	2.06	1.2961061
LINK 9	1.55	1.3352682
LINK 10	4.68	2.1370871
LINK 11	1.42	1.1115076
LINK 12	0.45	0.8396286
LINK 13	1.12	1.000403

Total Fuel Consumption (l)
14.39656
Total Distance (km)
18.99
Average Fuel consumption(l/km)
0.7581127

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Articulated Buses(60')

month	Kms	l	Avg.(l/km)
Jan	851412	807195	0.948066271
Feb	811202	730733	0.900802759
Mar	895067	744332	0.831593613
Apr	789394	631067	0.799432223
May	840982	665515	0.791354631
Jun	840196	630455	0.750366581
Jul	849890	622870	0.732883079
Aug	865825	640807	0.740111454
Sep	746193	555391	0.744299397
Oct	722892	545042	0.753974314
Nov	739884	571873	0.772922512
Dec	735325	575877	0.783159827