Transport Canada

Economic Analysis

TP 14664E

Costs of Non-Recurrent Congestion in Canada

Final Report

Ottawa

11 December 2006

transportation planning
and traffic consultants

Transport Canada

Economic Analysis

Costs of Non-Recurrent Congestion in Canada

Final Report

Ottawa

11 December 2006

iTRANS Consulting Inc.
1565 Carling Avenue, Suite 608
Ottawa, ON K1Z 8R1
Tel: (613) 722-6515
Fax: (613) 722-8890
Email: itrans@itransconsulting.com
www.itransconsulting.com

Project 3662

EXECUTIVE SUMMARY

This research has estimated the costs of non-recurrent congestion in Canada's nine largest urban areas. The method built upon that of Transport Canada's first study of *The Costs of Urban Congestion in Canada* for recurrent congestion. It did so by applying a modified version of the Buffer Index, which measures travel time reliability, to the average peak hour volumes and speeds as modelled by the various urban areas. The Buffer Index was used as the basis for two reasons: according to the findings of a comparison of treatments in the literature, and because it could be applied to model-based estimates of volumes and speeds. Using travel time data provided by some of the urban authorities, the consultant developed Modified Buffer Index values of 127% for expressways and 134% for arterials. From these, estimates of the costs of non-recurrent congestion were developed for the nine urban areas, for the three impacts calculated in *The Costs of Urban Congestion in Canada* study: delay, wasted fuel and greenhouse gas emissions. The total costs of congestion, recurrent plus non-recurrent, are summarized in **Table ES-1**.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$737	$927	$1,087
Edmonton	$96	$116	$135
Calgary	$185	$211	$222
Winnipeg	$121	$169	$216
Hamilton	$20	$33	$48
Hamilton (old)	$17	$23	$30
Toronto	$1,858	$2,474	$3,072
Ottawa-Gatineau	$100	$172	$246
Ottawa-Gatineau (no rural)	$97	$166	$238
Montréal	$1,179	$1,390	$1,580
Québec City	$73	$104	$138
Total, base	$4,370	$5,596	$6,745
Total, Old Ham. / no rural Ottawa-Gat.	$4,364	$5,580	$6,721

Table ES-1. Total Costs, Recurrent + Non-Recurrent Congestion (2000 $m)

The key findings are as follows:

- Non-recurrent and recurrent costs are approximately equal, with the non-recurrent costs representing 51% at the 50% threshold and recurrent costs representing 53% at the 70% threshold. In other words, non-recurrent costs double recurrent costs.

- The total costs of delay range from $4.4 billion, at the 50% threshold, to $6.7 billion annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate, since they measure only delays that accrue to auto drivers (not auto passengers, or travellers on other modes); they reflect only peak period congestion (not congestion that occurs at other times); and, they do not account for congestion impacts on trucks and commercial vehicles. These considerations all reflect the available data and models.

Finally, although the Modified Buffer Index is suitable for this application, it is important to note that further research is required in order to develop a method that could be applied to engineering and modelling studies.

TABLE OF CONTENTS

Appendices

A. Derivation of Skew-Normal Distribution
B. Calculation of Non-Recurrent Congestion and Costs *(spreadsheet)*

List of Tables

List of Figures

1. INTRODUCTION

1.1 Purpose

This report documents the findings of a research project that quantified *non-recurrent* congestion and its associated costs in the nine largest urban areas in Canada. The research expands upon the data, methods and findings of Transport Canada's first study of *The Costs of Urban Congestion in Canada*, which quantified *recurrent* congestion and its costs.

The primary objective of the research was to provide estimates of the costs of non-recurrent road congestion in large urban areas, contributing to the Phase 4 estimates of Transport Canada's Full Cost Investigation. There were two specific outcomes:

- Development and application of methods to estimate non-recurrent congestion and its costs, relative to and based upon the estimate of recurrent congestion and its costs from *The Cost of Urban Congestion in Canada*.
- Critical assessment of the method, its application and recommendations for further research, data collection, etc.

1.2 Organization of Report

The report is organized into seven chapters. The remainder of Chapter 1 provides a context for the research. Chapter 2 reviews the pertinent features of *The Costs of Congestion in Urban Canada* study, to provide the methodological basis for the current research. Chapter 3 explains the method used to estimate non-recurrent congestion. Chapter 4 develops the distribution and Buffer Index factors for expressways and arterials. Chapter 5 applies these to estimate the costs of non-recurrent congestion. Chapter 6 summarizes the findings, and recommends directions for future research. Chapter 7 provides a bibliography of sources.

Two appendices support the report. Appendix A explains the statistical derivation of the skew-normal distribution. Appendix B is a spreadsheet, provided under separate cover, that calculates non-recurrent congestion and its costs.

1.3 Relationship to the Full Cost Investigation

The results of the research are to be applied to Transport Canada's Full Cost Investigation (FCI) project.[1] Transport Canada initiated this project, in collaboration with Provincial and Territorial transportation ministries. The project is being steered by a Task Force reporting to the Policy and Planning Support Committee of the Council of Deputy Ministers Responsible for Transportation and Highway Safety.

[1] The ensuing discussion is excerpted from Transport Canada's terms of reference for the current research.

The FCI is intended to estimate the total financial and social costs of transportation by all of the major modes, to reveal the total amounts of resources consumed by transportation, and the impacts on the environment, health and well being. It is intended also to make comparisons among alternative modes of transportation, showing the resources consumed and other environmental and social impacts for realistic alternatives. For passenger transportation, these will include comparing private car / light truck with urban public transit and the various public intercity modes – air, bus and train. For freight transportation, they will include realistic comparisons and combinations of truck, rail, waterway and air modes.

The FCI has five phases. Phase 1 compiles the financial costs at the national level, to produce conceptual "national financial accounts," including the costs of the network infrastructure and transport services (commercial and private). These distinguish the basic modes, including road, air, rail, and marine, but do not allocate infrastructure costs by vehicle type. Phase 2 of the project then estimates the same financial costs at the provincial / territorial level. Phase 3 of the project allocates infrastructure costs by vehicle type, in sufficient detail to at least enable the comparisons among modes envisaged in the "conceptual national accounts." Phase 4 of the project estimates the social costs associated with vehicle activity. Finally, Phase 5 estimates marginal costs and compares these among the modes. It is envisioned that the marginal costs will be presented on the basis of a number of vehicle configurations and typical routes in Canada.[2]

One of the key cost elements in the Phase 4 on social cost is the costs due to delay caused by congestion. Even though congestion can occur anywhere and for any modes, it is mainly in large urban areas and on the road that such phenomena are observed. Accordingly, the results of the current research would inform that phase of the FCI.

1.4 Recurrent and Non-Recurrent Congestion

There are two types of congestion: recurrent and non-recurrent. *Recurrent* congestion reflects the day-to-day build-up of traffic on urban expressways and arterials; notably during the morning and afternoon commuter peak periods. The regularity of this congestion allows travellers to become accustomed to and adapt to conditions. For example, some auto drivers will change the start time of their journey to avoid congestion; and many goods and commercial trips are delayed until after the morning commuter peak period. Recurrent congestion was the focus of *The Cost of Urban Congestion in Canada* study.

Non-recurrent congestion reflects the delays caused by random incidents, such as stalled vehicles, accidents, truck spills, inclement weather, construction (scheduled and non-scheduled) and seasonal maintenance (e.g., snowploughing or street cleaning). Its randomness makes it difficult to predict. However, a series of stakeholder consultation meetings held with urban and provincial transportation planning authorities as part of *The*

[2] More information can be found at the FCI website: http://www.tc.gc.ca/pol/en/aca/fci/menu.htm.

Cost of Urban Congestion in Canada study identified the need to understand non-recurrent congestion, in addition to recurrent congestion. This is because 'reliability' is known to be a critical determinant in a traveller's decision to use transit. 'Schedule adherence' is similarly an important concern for transit operators, both for attracting riders and because of the additional costs imposed on driver salaries, vehicle operations and – ultimately – the purchase of additional vehicles to maintain service levels. 'Reliability' also is a concern for industry and for trucking companies, since delays in deliveries can have significant impact on production costs, which ultimately are passed on to the consumer.

Accordingly, non-recurrent congestion may figure more prominently than recurrent congestion in congestion mitigation schemes. However, as much as *The Costs of Urban Congestion in Canada* research provided a significant first step for the understanding of recurrent congestion in Canada, the analysis of non-recurrent congestion is only now emerging. A fundamental challenge in analyzing non-recurrent congestion is the general lack of data on the day-to-day (or hour-to-hour) variation in travel times at microscopic levels (second-by-second measurements), and the associated traffic volumes and information on the occurrence of incidents. Only Toronto and Montréal were known to have the required historical travel data; and these are available only for selected expressway sections. Other cities, such as Ottawa-Gatineau and Winnipeg, have travel time surveys, which measure variations in travel time over a given route, or traffic counts and incident records: however, the data sets are not linked temporally. Regardless, the travel time survey data generally are more available than the historical travel time data (which require the use of more sophisticated detector equipment, comprehensive analytical capabilities, etc.).

1.5 Sources of Monetary Values

This section describes the sources and bases for the unit costs that were used in this research. Most, but not all, were developed in *The Costs of Urban Congestion in Canada* study:

- Value of time. As specified in the terms of reference for *The Costs of Urban Congestion in Canada* study, Transport Canada's 1993 study, *Value of Passenger Time Savings*, report TP 1178 was used as the source for business and non-business traveller values of time. These values, updated to 2002, are shown respectively in **Table 1**.

  These represent 'unweighted' values – that is, there was a need to weight the values according to the proportion of trips made for business purposes (i.e., work / work-related) and non-business purposes (other purposes). These were based upon travel survey or other information provided by each urban area. The weighted values are summarized in **Table 2**.[3] The table also indicates the year for which the break downs were provided: these are the same years for which congestion was estimated.

[3] This approach and the application of Transport Canada's 1993 values, which had been developed for inter-urban applications, were discussed in detail in *The Costs of Urban Congestion* report.

Urban area	Business	Non-business
Vancouver	$29.72	$9.26
Edmonton	$25.48	$7.84
Calgary	$28.57	$8.79
Winnipeg	$24.71	$7.63
Hamilton	$29.64	$9.14
Toronto	$30.86	$9.50
Ottawa-Gatineau	$31.35	$9.67
Montréal	$27.32	$8.48
Québec City	$25.96	$8.15

Table 1. Travel Time Values, $/hr – Unweighted (2002 $)

Source: Tables 6 and 7, *The Costs of Urban Congestion in Canada*, p. 67.

Urban Area	Year	% Work / Work-Related	% Non-Work
Vancouver	2003	48%	52%
Edmonton	2000	31%	69%
Calgary	2001	37%	63%
Winnipeg	1992	88%	12%
Hamilton	2001	36%	64%
Toronto	2001	55%	45%
Ottawa-Gatineau	1995	43%	57%
Montréal	1998	70%	30%
Québec City	2001	58%	42%

Table 2. Break Down of Work / Non-Work Travel

Source: Table 29, *The Costs of Urban Congestion in Canada*, p. 112.

- Value of fuel. *The Costs of Urban Congestion* study developed unit prices for regular unleaded gasoline, based upon observed prices for each urban area. The values (cents per litre) are summarized in **Table 3**.

Urban area	Regular Unleaded Gasoline – excluding taxes
Vancouver	38.65 ¢/l
Edmonton	41.22 ¢/l
Calgary	42.09 ¢/l
Winnipeg	37.95 ¢/l
Toronto	38.20 ¢/l
Hamilton	36.30 ¢/l
Ottawa-Gatineau	37.30 ¢/l
Montréal	35.41 ¢/l
Québec City	37.49 ¢/l

Table 3. Regular Unleaded Gasoline's Prices for Each Urban Area (2002 $)

Source: Table 10, *The Costs of Urban Congestion in Canada*, p. 80.

- Value of GHG emissions. *The Costs of Urban Congestion* study used a value of \$32.82 per tonne (2002 \$). This was developed by Bell in 1994,[4] based upon 37 research studies and values proposed by governmental agencies in the United States. The values had been used by MTQ in congestion studies in the Montréal region.

- Deflator. *The Costs of Urban Congestion* study was developed for 2002 dollars, whereas the FCI uses 2000 dollars. Accordingly, where required, the values for this research were deflated according to the national Consumer Price Index (CPI), by a factor of 0.953.[5]

  The Costs of Urban Congestion study used the CPI and other means to inflate various values. As described in Section 6.24 (p. 65) of *The Costs of Urban Congestion* study, values of time were derived first as a function of the average wage rates for the base year of the respective models, in order to ensure consistency with the model results. Average wage rates for each urban area from Revenue Canada were used as the basis. These were then inflated to a common 2002 base, according to the 2002 average wage rates for each urban area for that year. Fuel prices similarly were inflated according to actual average fuel prices for the model's base year and for the year 2002 (see Section 6.3.2, p. 80). The GHG values were inflated according to the CPI (see Section 8.7.3, p. 120).

4 Bell, Kevin, 1994. *Valuing Emissions from Germiston Generating Project*. Seattle: Convergence Research.

5 CPI rose by 1.0489 from 2000 to 2002. Source: http://www40.statcan.ca/l01/cst01/econ09a.htm.

1.6 Acknowledgements

The guidance and direction provided by the members of Transport Canada's Steering Committee is gratefully acknowledged. These individuals are: Franziska Borer Blindenbacher (project manager), Muna Goran, Bruno Jacques and Cristobal Miller of Transport Canada; Louis Gourvil and Pierre Tremblay of the Ministère des Transports du Québec; and Andrew Liu of the Saskatchewan Department of Highways and Transportation.

We also acknowledge the provision of data and/or the permission to re-use data supplied earlier for *The Costs of Urban Congestion Study* from the urban authorities: Ministère des Transports du Québec (Québec City and Montréal); City of Ottawa (Ottawa-Gatineau); City of Toronto / Ministry of Transportation of Ontario (Greater Toronto Area); City of Hamilton; City of Winnipeg; City of Calgary; City of Edmonton; and, TransLink (Vancouver).

This report was prepared by iTRANS Consulting Inc., with contributions by David Kriger (consultant project manager), Dr. Maurice Masliah, Elizabeth Szymanski, June Too and Rhys Wolff. The authors maintain complete responsibility for the contents of this report. The report does not necessarily reflect the policies of Transport Canada, the contributing urban and provincial authorities, or the members of the Steering Committee. The findings of the work reported in this study make no implications regarding their potential applications to the Full Cost Investigation or to any other subsequent analysis.

2. THE COSTS OF URBAN CONGESTION IN CANADA

2.1 Overview

In 2002, Transport Canada initiated the first comprehensive analysis of congestion in urban Canada. *The Costs of Urban Congestion in Canada* study was part of the department's ongoing research in understanding the factors that influence sustainable transportation; specifically, the greenhouse gas (GHG) emissions that are caused by vehicles operating under congested conditions. In its research, Transport Canada also recognizes that pricing has an important role in understanding traveler behaviour (that is, in the way that people make decisions about their travel). The understanding of congestion and its costs provides an essential basis for urban authorities to develop their own ways to address their transportation needs, sustainable transportation and climate change.

The findings of *The Costs of Urban Congestion in Canada* were released by Minister Cannon in March 2006.[6] The specific purposes of this research were to establish an analytical basis of definitions and measures; estimate the socio-economic costs of urban congestion per se and the impact of congestion on the quality of life of Canadian and on the economy; develop methods for consistent measurement; and, recommend potential methodological and data improvements for the future. A study prepared for the Montréal region by the Ministère des Transports du Québec provided a comprehensive and systematic prototype for *The Costs of Urban Congestion in Canada* study.

The research applied the resultant measures to Canada's nine largest urban areas: Québec City, Montréal, Ottawa-Gatineau, Toronto, Hamilton, Winnipeg, Calgary, Edmonton and Vancouver. The nine urban areas represented just over half - 51% - of Canada's population in 2001, ranging in size from 500,000 (Hamilton) to 5,100,000 (Toronto) residents. It should be noted that these urban areas approximate, but do not coincide precisely with, Statistics Canada's definition of a "Census Metropolitan Area" (CMA). Thus, any comparison between a given model's population or other demographic or spatial characteristics and those as defined by the CMA must be made with caution. More important, the models generally do cover the areas of the metropolitan region in which congestion occurs.

The quantification of the components of congestion then was translated to monetary values, to develop a cost of congestion for each urban area.

[6] Kriger, D., M. Baker, F. Joubert and G. Joubert. Costs of Urban Congestion in Canada. Final Report. Transport Canada, Ottawa. 2005.
A summary may be found at http://www.tc.gc.ca/programs/Environment/EconomicAnalysis/menu.htm.

2.2 Approach

Two key factors influenced the approach used for *The Costs of Urban Congestion Study*: comparability of the findings, and the engineering and economic approaches to congestion. These are discussed below.

2.2.1 Comparability

Transport Canada initially proposed the development of indicators and measures similar to those developed by the Texas Transportation Institute (TTI) in its annual *Urban Mobility Report*. The object was to enable a comparison and ranking of congestion among the nine urban areas. However, it was recognized that these methods could not be applied for this cross-Canada research, because of the lack of common nation-wide data with which to make comparative analyses. Notably, there is no Canadian equivalent to the Federal Highway Administration's Highway Performance Monitoring System (HPMS) data base. Standards, definitions, frequencies and methods for the collection of traffic counts and travel time surveys vary among – and sometimes within – provinces.

At the same time, it was recognized that the rich and well-developed travel demand forecasting models available in each of the nine urban areas provided a unique opportunity both to quantify congestion and to develop practical methods that could be applied by individual local authorities for their own planning needs. However, the research had to develop means to account for the underlying differences in model composition, structure and data.

Thus, the initial goal of developing a Canadian set of indicators, comparisons and rankings was abandoned. On the other hand, the 'top-down' data in the US provide a more limited perspective than the 'bottom-up' model-based data in the nine Canadian urban areas, since they may mask many of the nuances that are critical to understanding the phenomenon of congestion. As well, identifying the underlying differences and possible ways to address them proved to be an important outcome of this research, both for possible future initiatives in this topic and in helping urban authorities improve their own practical analytical and planning capabilities. Finally, an acknowledgement of the underlying differences was important to addressing concerns of some urban authorities; specifically, that a comparison and ranking might not be consistent with (or could be used to contradict) the transportation plans and investment priorities that had been agreed by their local councils.

2.2.2 Engineering and Economic Approaches to Congestion

A second determinant of the approach was that congestion has two perspectives: the *engineering* approach, which focuses on the direct and physical characteristics of congestion; and the *economic* approach, which considers congestion in a market context of travel supply and demand and in terms of its broader societal impacts. The reconciliation of the two approaches can be problematic, given that urban transportation analysis focuses on the engineering approach with comparatively little consideration of the economic approach being included in urban transportation planning and decisions.

It was agreed at the outset that the research would be based upon the engineering approach, for reasons of practicality. However, it was recognized that the use of travel demand forecasting models, which incorporate a region's demographic and socio-economic characteristics, provides a potential means to bridge the two perspectives.

The models also provide a potential basis for consideration of economic efficiencies. From an economic point of view, traffic congestion is an externality that occurs when the cost of travel is increased by the presence of other vehicles. By definition, externalities refer to costs (or benefits) that are not market-priced and which accrue to third parties as a result of actions taken by individuals. Congestion externalities arise because the presence of additional road users increases travel times for other vehicles.

In terms of measurement, from an economic standpoint, the cost of congestion has a precise meaning only if it refers to an optimal situation based on a determined level-of-service objective accompanied by the full economic price of this level of service. In other words, the congestion that is observed is compared to an optimal traffic level. Therefore, an alternative method to consider is to measure the congestion that would be eliminated by efficient congestion pricing, where such efficient pricing included the marginal external costs associated with congestion, including the costs of delays, wasted fuel, additional costs due to increased use of vehicles, accidents and environmental damage imposed by users on others. Remaining congestion, as well as remaining accidental and environmental damage and other costs, would be "efficient" in the sense of being internalized. In choosing instruments for congestion reduction, it is useful to differentiate between this "external" congestion and "internal" or "potentially-internalized" congestion.

To this end, as an initial step the research adapted a working definition for congestion, which focuses upon the engineering approach but also accounts for the economic approach.

> "The inconvenience and increased costs that travelers impose on each other while using their vehicles, attempting to use the road network at the same time, because of the relationship that exists between traffic density and speed (with due consideration of capacity)."

The definition took into account earlier definitions from the US and international literature - for example, Lomax et al.[7] and Weisbrod et al.[8] The definition also took into account the findings of a series of consultation meetings held among local transportation authorities. Notably, the reference to "travellers" was intended to broaden the discussion to account for

[7] Lomax, T., S. Turner, G. Shunk, H.S. Levinson, R.H. Pratt, P.N. Bay and G.B. Douglas. Quantifying Congestion. *NCHRP Report 398*. TRB, National Research Council, Washington, DC. 1997.

[8] Weisbrod, G., D. Vary and G. Treyz. Economic Implications of Congestion. *NCHRP Report 463*. TRB, National Research Council, Washington DC. 2001.

transit – i.e., the impact of congestion on and by buses and rail operating in mixed traffic. The difference allows a more holistic approach, even if the focus of this research necessarily remained on vehicular movement (due to data considerations).

2.3 Method

2.3.1 Use of Thresholds

The method drew upon that used by the MTQ for the aforementioned congestion study of the Montréal region. The MTQ research applied the concept of congestion "thresholds" to its travel demand forecasting model. The threshold represents the point at which congestion becomes apparent and is deemed unacceptable. It is only against this quantifiable reference point that the socio-economic costs can be measured. The evaluation of congestion depends greatly on this threshold and can be very sensitive to it.

Congestion is a function of a reduction in speeds (i.e., which is the direct cause of loss of time [delays]) and leads to increased vehicle operating costs, fuel consumption and emissions of air pollutants and GHGs. Therefore, the setting of a threshold that is directly related to travel speeds is most appropriate. A speed-based threshold thus appears to account for more of the impacts of congestion than would a threshold that is based on capacity. Because it is concerned with a reduction in speeds, it circumvents the problems that are associated with the use of free-flow conditions. Therefore, the threshold was based upon a percentage of the free-flow speed.

In other words, it is important to note that although free-flow conditions can be fixed, the percentage of free-flow speed that represents the threshold varies according to local conditions (quantitative) and perceptions (qualitative). The process of selecting the values of the threshold is a function of three related tasks: review of observed travel time – traffic flow conditions (according to such data as may exist); perceptions of local travelers as to when congestion 'seems' to begin; and, extrapolation of these threshold values to reflect the entire system (using the travel demand forecasting model as the platform).[9]

On this basis, a range of threshold values of 50% to 70%, in 10% increments, was adopted for different types of facilities (expressways and arterials: by definition, congestion is considered to occur only on these higher-order facilities). It is important to note that some urban areas consider thresholds of 70% and 80% to be more reflective of local perceptions of congestion. These higher thresholds also were closer to the traditional level of service boundaries that are used to identify the need for new capacity in many long-range transportation master plans (e.g., service levels D, E and sometimes F).

[9] Gourvil, L. and F. Joubert. Évaluation de la congestion routière dans la région de Montréal. Ministère des transports du Québec, Montréal. 2004.

2.3.2 Role of Models in Congestion Analysis

Ideally, the thresholds should be based upon extensive observed data for each urban area. However, the required data (specifically, measurements of traffic volumes and speeds, and the variation by hour of day, day and year) were available only for limited sections of roads over limited time periods in each urban area. Generally, these available data were too sparse to serve as the basis for a meaningful extrapolation. As noted, detailed observed data were available only for expressways in Toronto and Montréal (and only for some sections of these expressways); and no consistent data were available for arterials. In addition, the definition of what constituted an 'arterial' or an 'expressway' varied among urban areas. Finally, as noted, the available observations could not easily be compared among urban areas: the quality, coverage, frequency, currency, collection methods and even the type of basic traffic and speed information was known to vary among urban areas and provinces.

Accordingly, outputs from the transportation (travel demand forecasting) models in each urban area were requested as a key source of data. This required the development, in consultation with the urban authorities, of common categorizations of how the nine urban models define expressways, arterials and other road links, and how they treated the modelling of travel demand. As well, there was a need to reconcile the speeds computed in the models with actual posted speeds and/or observed free-flow speeds. Through this analysis, it became apparent that there were many differences in data and modelling methods, and that there were gaps in the available data. Nonetheless, given these constraints and with the extensive cooperation of the urban and provincial authorities, a consistent set of measures was developed for this research.

In sum, it is important to note that neither the available data nor the transportation models provide the complete picture of travel. However, for the purposes of this research, the available transportation models provided the best platform upon which to develop the measures of congestion.

3. METHOD

3.1 Introduction

Non-recurrent congestion is the result of random incidents that cause traffic delays. Because this congestion is a result of unpredictable incidents, travel *times* and *reliability* can vary significantly on the same route, daily or even hourly. That is, whereas the methodological focus of this research is on the estimation of non-recurrent trip travel *times*, trip *reliability* is what is important to travellers because reliability impacts the time that a traveller 'budgets' in order to complete his/her journey so as to arrive within a designated time period.

The two components are related. Accordingly, this chapter explains the two components, and how they are related. Section 3.2 describes the Buffer Index, which measures *reliability*. Section 3.3 describes the skew-normal probability distribution, which is used to estimate the distribution of travel *times*, which in turn is a key input to the derivation of the Buffer Index. Both discussions use applications from the literature to illustrate.

A related methodological issue concerned the treatment of outliers: that is, given the potentially wide variation in travel times, how should extreme observations be treated? This is discussed in Section 3.4.

Finally, although the treatment of non-recurrent (and recurrent) congestion is relatively new to Canada - the current research represents the first model-based application of non-recurrent congestion in the country – the subject has been examined in greater depth in the United States and Europe. The aforementioned methods are based largely on applications in the United States: this emphasis reflects the availability of methods. However, the European experience also is described as a complement, in Section 3.5.

3.2 Buffer Index

Earlier research by the consultant for Transport Canada identified various methods to quantify non-recurrent congestion.[10] The research evaluated the practical applicability of four methods to model-based estimates, such as those developed in *The Costs of Urban Congestion in Canada* study. The research found that the "Buffer Index" provided the most promising practical approach to Canadian models, and recommended that this approach be examined further.

The Buffer Index was developed by the Texas Transportation Institute (TTI) as a measurement of trip reliability. The index is developed using historical data of travel times for a particular route. The "buffer" time is the extra time needed to arrive on schedule for 95% of a traveller's trips. Through assembling travel time survey data from each of the nine

[10] Kriger, D. and Molloy, S. *Methods to Estimate Non-Recurrent Congestion in Canada*,. Transport Canada, Ottawa. 2005.

urban areas, a buffer index can be developed to calculate an overall cost of non-recurrent congestion.

A 2003 TTI research report, *Selecting Travel Reliability Measures*, explains the approach and method.[11] The report discusses developing reliability measures, factors to consider before selecting a measure, and calculation procedures for typical reliability analyses. The report notes that some current practices of separating "recurring" and "non-recurring" congestion are not meaningful: this is because unpredictable events like weather, traffic volume and a range of other factors can be termed "recurring" but have traditionally been included outside the "regular" congestion label.

There are three broad performance measure categories: statistical range (variability measures), buffer time measures (illustrates reliability), and tardy trip indicators (measures reliability). The buffer measures (buffer time, buffer time index, and the planning time index) were used to assess uncertainty in travel conditions including weather, incidents, construction zones, holiday or special event traffic or other disruptions or traffic irregularities. Comparing the real traffic conditions to those that occur on an average day or most frequently can relate the effect of uncertainty in decision-making.

Reliability statistics are most easily calculated from continuous and calibrated data collection systems that are used as part of a monitoring and information system. These are more often found on large city freeways and infrequently on urban streets. The Buffer Time Index formula (in the equation below) relies on archived data to support the generation of a measure for urban freeway systems.[12]

$$\text{Buffer Time Index} = \text{Average of All Sections (Using VMT to Weight the Section)} \left[\frac{\text{95th Percentile Travel Rate (in minutes per mile)} - \text{Average Travel Rate (in minutes per mile)}}{\text{Average Travel Rate (in minutes per mile)}} \right] \times 100\%$$

In order to provide background to the Buffer Index and explain further the circumstances under which it can be used, the consultant conducted a literature of various applications. The findings are summarized below.

- **International Border Crossing Truck Travel Time for 2001**.[13] This study was completed by the TTI and Battelle Memorial Institute in 2002, for the purpose of determining a benchmark border crossing delay measure for commercial vehicles. The results of the survey were to be used for future policy and infrastructure improvements. In this survey, seven ports of entry were chosen on the international

[11] Lomax, T., Schrank, D., Turner, S. and Margiotta, R. *Selecting Travel Reliability Measures.* Texas Transportation Institute, College Station, TX. 2003.

[12] In the equation, the term "VMT" refers to vehicle-miles travelled.

[13] Texas Transportation Institute et al. *International Border Crossing Truck Travel Time for 2001.* US Federal Highway Administration, Washington, DC. 2002.

borders between Canada, the United States, and Mexico. Two delay measures were chosen for this study: Average Delay and the Buffer Index.

Data for this study were collected by entering the license plate of all commercial vehicles passing the first point before and after the primary inspection booth during peak hour crossings. The data were combined to estimate the time used to travel between the two points, and then calculated to form the Buffer Index.

The Buffer Index is the Buffer Time expressed as a percentage of average time: that is, the extra percentage of time that must be budgeted to cross the border. The study eliminated differences in physical length of the crossing and provided a standardized measure among ports. The study defines Buffer Time as a measure of travel reliability and it was calculated by ranking all crossing times of each truck at each port of entry. The difference between the 95^{th} percentile crossing time and average crossing time for all trucks is called the buffer time. The buffer time is the "extra time" above the average that a driver must budget to cross the border and arrive "on time" for 95% of their trips.

Average delay times were also calculated for each port of entry. The delay time was calculated as the difference between the average crossing time and the free-flow crossing time.

- **Development of Congestion Performance Measures Using ITS Information**.[14] This study was prepared in 2003 by the Virginia Transportation Research Council. The purpose of this study was to define a performance measure to be used to show congestion levels on specific corridors and to develop a method to select and calculate performance measures to quantify congestion. The results of this study will be used to compare the changing congestion levels over time. The two performance measures used were total delay and the buffer index. The report advised that the buffer index is more suitable for use by the public as it addresses individual vehicle trip travel times and can be used for trip planning. However, in addition, it can also be used as a measure of variability for transportation professionals.

  Performance measures should define the quality of traffic flow and be useful in determining where improvements need to be made within a transportation system. The report points out that there are currently no widely accepted set of performance measures for all transportation professionals to monitor system conditions even though there is a need for reliable congestion performance measures for specific routes in a region and understandable by the public.

  Sources of data for this study were collected from reviewing a collection of literature and from the Smart Travel Lab at the University of Virginia. The Smart Travel Lab

[14] Medley, S. and Demetsky, M. *Development of Congestion Performance Measures Using ITS Information*, Final Report. Virginia Transportation Research Council, Charlottesville, VA. 2003.

houses a database with real-time data connections to three traffic centres in the study region.

In their literature review, of the 19 congestion performance measures gathered, two were selected for analysis. One of them was the Buffer Index.

Before the data was used, it was screened for errors using five criteria. All data had to meet a maximum occupancy of 95 percent, a collection length of at least 90 seconds, an average vehicle length between 9 and 60 ft., an overall maximum volume of 3,100 vehicles per hour per lane, and a maximum volume threshold for records with 0 occupancy, set as the corresponding volume for an average vehicle length of 10 ft and 2 percent occupancy.

The buffer index was calculated using data from 2000 to the first quarter of 2002. The results from 2001 and 2002 were compared to 2000 data for changes that occurred over time using the morning and evening peak periods for all weekdays. The 95th percentile was estimated and based on the average speed.

- **The 2005 Urban Mobility Report**.[15] This report was prepared by the Texas Transportation Institute and the Texas A&M University System in 2005. This report, which has been produced annually for several years, provides a picture of the congestion problem in all urban areas of the US with a population of greater than 500,000 people.

  This report used multiple measures to illustrate the congestion problem. It states that a minimum of two "intensity" measures and one "magnitude" measure should be used. Measures used in the report are: travel time index, delay per traveler, cost of congestion, and change in congestion.

  In the appendix, the report discusses reliability problems as traced to incidents, work zones, weather, demand changes, special events, traffic control devices, and inadequate road or transit capacity. The report recommends the Buffer Time Index as a measurement of reliability.

- **NCHRP Current State of Research**.[16] This 2003 report reviewed the most influential works on performance measures. The report defined performance measures, principles for development, data requirements and reporting needs and methods.

[15] Schrank, D. and Lomax, T. *The 2005 Urban Mobility Report.* Texas Transportation Institute and Texas A&M University System, College Station, TX. 2005.

[16] National Cooperative Highway Research Program. *National Highway Cooperative Research Program: Current State of Research.* Transportation Research Board, Washington, DC. 2003.

Reliability performance measures have been defined as an indicator of the operational consistency of a facility over an extended period of time - measured as some function of the amount of recurrent and non-recurrent delay that occurs over that period. One of the techniques for measuring reliability described in the text is the Buffer Index, referenced to the TTI's 2000 Urban Mobility Report. This report points out that operations research has shown the percent of trips accomplished within an "acceptable time" is a more direct measure of reliability as experienced by the user.

- **Performance Measures and Targets for Transportation Asset Management (NCHRP 551)**.[17] The objectives of this NCHRP research report were to investigate performance measures suitable for asset management and to develop a framework for establishing performance measures and setting targets for use in asset management. A large body of literature on transportation performance measures from different countries and agencies was reviewed for this report.

  The performance measures were allocated within the following categories: preservation of assets, mobility and accessibility, operations and maintenance, and safety.

  The report included a description of the criteria used to select performance measures, current performance measurement framework structures, kinds of measurements are included, and how performance measures are used to gauge impacts of transportation investments. It recommends a framework for transportation agencies to identify and integrate performance measures and to establish performance targets.

  The appendix provides a list of performance measures to be considered for transportation asset management. The most appropriate measurement depends on the characteristics of the implementing agency. Among the mobility and accessibility performance measures for travel time reliability is the buffer time index.

3.3 Skew-Normal Distribution

Travel time data are expected to have a normal distribution with a lack of symmetry – that is, a "skew-normal distribution." This is because the shortest travel time is bounded by the operating speed limits of the road – that is, there is always a practical minimum travel time on a given section of road, whereas the longest travel times may vary quite a bit depending upon the circumstance (such as, the level of congestion). Thus, the distribution curve is skewed to the left or right. The mean travel time is expected to be larger than the median travel time.

To illustrate, the consultant examined the travel times of 38 different commuter runs between two Greater Toronto Area suburbs (Newmarket, the place of residence; and Richmond Hill,

[17] Cambridge Systematics et al. *Performance Measures and Targets for Transportation Asset Management*. NCHRP Report 551. Transportation Research Board, Washington, DC. 2006.

the place of work). Each run was made on the same route, on different weekdays but always at approximately the same time of day. The data were collected with iTRANS's *iTREC*® GPS-based travel time survey system. As **Figure 1** illustrates, the runs demonstrate a skew-normal distribution: the *x* axis measures travel time in seconds, and the *y* axis measures the number of observations. Details of the test are provided in **Appendix A**.

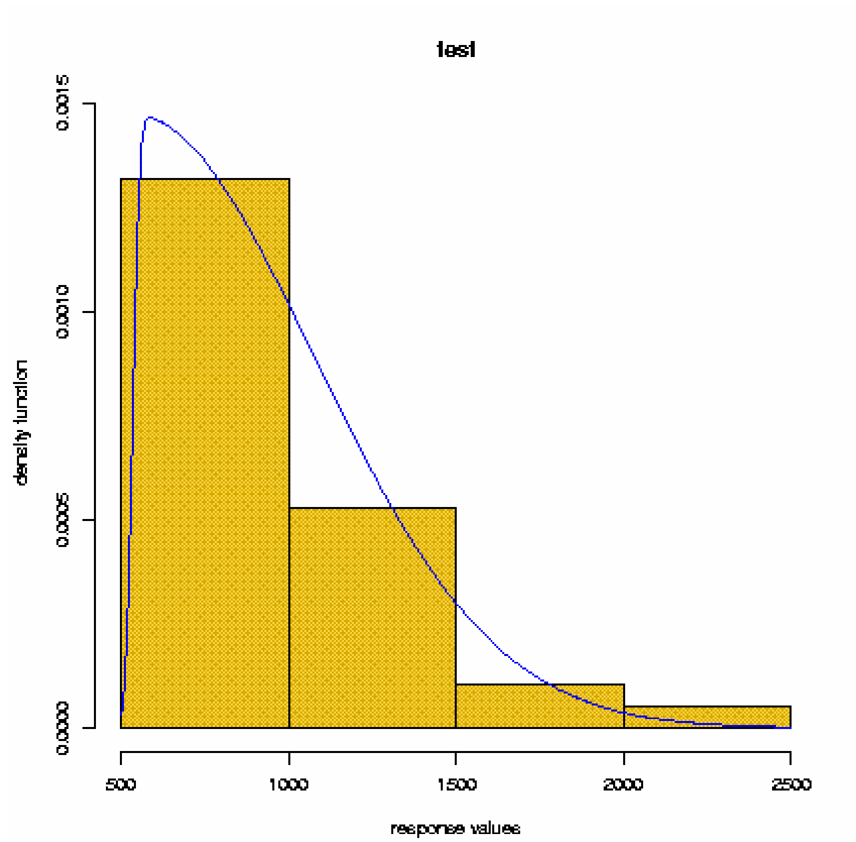

Figure 1. Skew-Normal Distribution of Travel Times – Greater Toronto Area

The applicability of the skew-normal distribution to travel time data is verified by several examples from the literature. These are described below.

- **Examining Travel Time Variability Using AVI Data**.[18] This 2004 research report explores the use of travel time variability information to improve "the reliability of traffic information services and increasing the accuracy of travel time predictions." To identify the reason for variable travel time, information on travel time distribution properties is required.

[18] Li, R. *Examining travel time variability using AVI data.* Institute of Transport Studies, The Australian Key Centre in Transport Management, Victoria, Australia. 2004.

The report notes that a previous study performed by "Kwon et al. (2000) analyzed the daily pattern of travel times observed from probe vehicles." Their analysis revealed a right skewed normal travel time distribution. One drawback in their research approach is that the sample size of travel time collected from probe vehicles was so limited that they had to interpolate the values of travel time between two consecutive runs.

Results from the data revealed "that the travel time distribution analysis in different scale time window indicates that the distribution tends towards a normal distribution as the time window decreases." Previous studies that "analyzed the distribution of travel times in a small time window (1 minute) and also found that it is approximately normal."

- **Monitoring and Predicting Freeway Travel Time Reliability**.[19] Common approaches to conceiving reliability are to consider the width of the travel time distribution and/or to look at the travel time distribution. The second method is associated with the misery index (MI), "which calculates the distance between the mean travel time of the 20% most unfortunate travelers."

  The report describes (**Figure 2**) "4 phases that yield distinctively different shapes of the day-to-day travel time distribution." Figure 2A is a normal distribution which results from free flow conditions. In this condition, "the median travel times are low and the spread of the distribution is small." Figure 2B shows congestion onset which results in a right skewed normal distribution. As this is congestion onset, most travel times are still low, but a number of days where "congestion has already occurred, [result] in travel times much higher than median." Figure 2C shows a left skewed normal distribution with a wide distribution. In a period of congestion, "different degrees of severity [yield] a wide range of possible travel times." Figure 2D shows congestion dissolve where the distribution is right skewed and most travel times are low again.

- **Robust Route Guidance Model Based on Advanced Traveler Information Systems**.[20] This paper discusses the Robust Optimization model for route guidance based on expected travel time and the time at risk. Travel time distribution as displaying skewness and kurtosis is assumed and "taken into consideration" in this research.

  The paper provides an example of an arc travel time distribution from a real traffic network in California that is asymmetric and skewed to the left. "This implies that the multivariate normal distribution cannot represent the actual arc cost distribution

[19] Van Lint, J.W.C., Van Zuylen, H.J. *Monitoring and predicting freeway travel time reliability.* Transportation Research Board Annual Meetings, Washington, DC. 2005.

[20] Lu, J., Ban X., Qiu, Z. Yang, F., and Ran, B. *Robust route guidance model based on advanced traveler information systems.* Transportation Research Board Annual Meetings, Washington, DC. 2005.

closely, especially if the influence of incidents and construction is taken into consideration," (Lu et al., 2005).

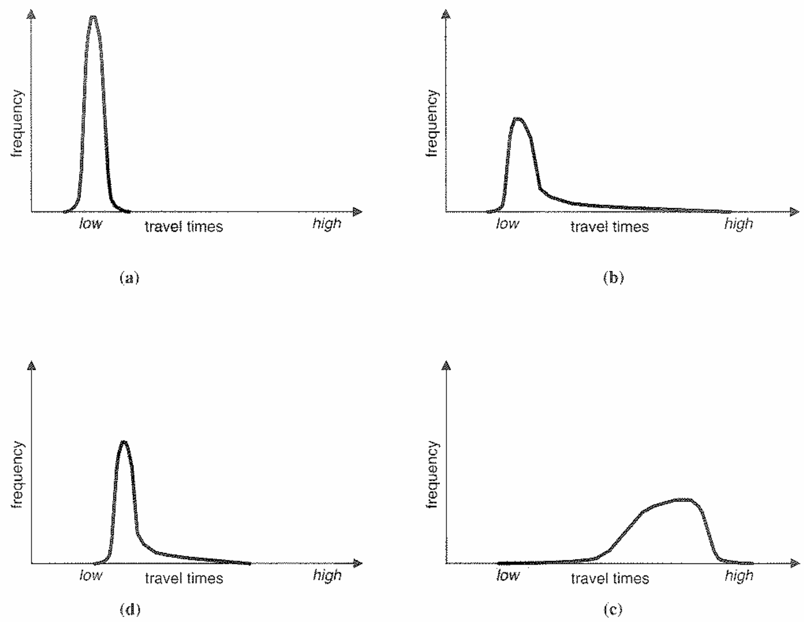

Figure 2. Different Shapes of Travel Time Distributions

Source: Van Lint et al., 2005

3.4 Treatment of Outliers

As with all data collection, unusual situations or survey error may bias results. In the case of travel time data, the consultant proposed to 'cap' travel time variations by excluding obvious outliers. This was supported, generally, by the literature: the ensuing discussion reviews how others treated travel time outliers in their survey data.

- **Freight Data from Intelligent Transportation System Devices**.[21] The Freight Data from Intelligent Transportation System Devices report was written by the Washington State Transportation Centre. The report investigates using a variety of ITS devices to develop a comprehensive database of freight and truck flow information.

[21] Hallenbeck, M.E., McCormack, E., Nee, J. and Wright, D. *Freight data from intelligent transportation system devices.* Washington State Transportation Centre, Seattle, WA. 2003.

A concern of the researchers were that outliers in their data were caused by drivers stopping in between measuring points for rest breaks, or picking up and dropping off freight, therefore skewing the "average travel time". An algorithm was developed that filtered out outliers with travel times greater than other vehicles with similar reader start times, but with a much lower travel time to pass the second reader.

Outliers were identified by "sudden significant changes in segment travel time between trucks that are traveling on the same freeway segment but at consecutive 5-minute trip start intervals." It was assumed that "freeway performance ordinarily changes in a relatively smooth manner within a short period (say ≤ 20 minutes or so), assuming there are no blocking incidents, and that therefore the travel times of trucks traveling on the same segment but only minutes apart should not be significantly different."

"Significance," that is, the minimum difference that is considered "significantly slower" was decided as 15 minutes. "If truck X is significantly slower than at least one of the two trucks (X-1, X+1), truck X is assumed to have made a stop, and therefore its data cannot be used to estimate freeway segment performance." A second filtering method was completed for trucks not significantly slower then the two trucks it was compared with previously. The start interval in the second method was expanded to 10 minutes before and after truck X. "If truck X is significantly slower than one of these two trucks, it is filtered out."

- **Methods of Travel Time Measurement in Freight –Significant Corridors**.[22] The report indicates that with more results, there "exist greater changes of including outliers…If a segment has a "particularly" high number of outliers, such as a segment that has a great numbers of trucks stopping for routine deliveries, refueling and hours-of-service compliance, there exists a greater chance of falling outside the standard deviation." They are currently in the process of filtering these non-recurrent factors from their data.

- **Evaluation of Travel Time Methods to Support Mobility Performance Monitoring – Otay Mesa**.[23] The survey in this report collected data for truck travel times across the US – Mexican border at Otay Mesa, California (San Diego, California – Tijuana, Mexico) by recording the license plate and time at consecutive locations, and matching them up for the total travel time.

  Outliers were revealed during the data post-processing phase to identify any abnormalities in the data. Outliers were usually "records that indicated travel times significantly greater than typical for that time period," and were often caused by,

[22] Jones, C., Murray, D. and Short, J. *Methods of travel time measurement in freight-significant corridors.* American Transportation Research Institute, Alexandria, VA. 2005.

[23] Battelle Memorial Institute *Time methods to support mobility performance monitoring – Otay Mesa Site Report*. Federal Highway Administration, Washington, DC. 2002.

"recording the license plate of a vehicle only some of the time as it made repeated trips across the border during a single day." This invalid travel time would be easily identified by manual inspection of the data, aided by highlighting those travel times above a specific, but variable, threshold."

- **Urban Spatial Structure and Household Travel Time**.[24] This research develops an empirical model used to test the relationship between accessibility of defined economic centres and total household travel time. The goal of this research was to determine whether urban sprawl causes increases in total household travel time.

  From the household travel time database, extreme outliers were identified and removed from calculations by deleting any average travel times that required a speed in excess of 28 miles per hour from the centre of the transportation analysis zone to another identified centre.

- **Using GPS Technology to Measure On-Time Running of Scheduled Bus Services**.[25] The aim of the project was to develop a cost-effective Geographic Information System program to process and analyze GPS data collected on buses operating on a specific route.

  The article presents an overview of the steps taken to collect the input data used in the project, and details the trip-processing and timetable query program developed for processing and analyzing the GPS data. It is concluded that for operators of most sizes, passive GPS is an attractive method of collecting data on performance.

  In the section to assess on-time running, an average was calculated between actual GPS travel time and schedules travel times for buses. The authors noted that the average may be influenced by a few outliers. Therefore, there was a need to identify outliers "and flag them, or exclude them from the dataset."

3.5 European Travel Time Reliability Measures

Based on the sources reviewed, investigations of travel-time reliability and ways to measure it in Europe are at the research stage. Although there is widespread interest in the concept, travel time data are not widely collected currently. The most significant work, according to the literature, is being done in The Netherlands, with the United Kingdom having conducted a large survey to gather perceptions regarding travel and congestion. A key finding is that – whereas the US approaches focus on actual travel time measurements – the European

24 Fina, M.H. *Urban Spatial Structure and Household Travel Time*. (Chapter 5) Unpublished PhD. dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, VA. 2001.

25 Bullock, P., Jiang, Q. and Stopher, P.R. *Using GPS technology to measure on-time running of schedules bus services.* Journal of Public Transportation, Vol. 8, No. 1, 2005.

approaches attempt to derive reliability indices as a function of traveller perceptions. Other key points of the reviewed sources are described below.

- **European Commission ATLANTIC International Workshop on ITS Benefits, Evaluation and Costs**.[26] This 2002 workshop featured a discussion on Measuring Travel Time Reliability, and included European and American presenters. The European presentations concentrated on driver information systems. However, an American presenter introduced and described the Buffer Index and its uses for measuring reliability in the United States. It was agreed that more investigations were needed to ascertain whether this was the best way to measure travel time variability.

- **Performance Indicators for the Road Sector: Summary of the Field Tests**.[27] In 2001, the Organisation for Economic Cooperation and Development surveyed selected countries on their practices relating (among other things) to travel time and reliability measurements. European respondents comprised Belgium, Finland, Hungary, Portugal, Sweden and the United Kingdom. However, of these only Finland and Sweden replied that they collected travel time data at all, and these were not collected or used regularly. The extent of collection and application of travel time data in Europe came well below that in Australia and the United States.

- **Using the standard deviation of the travel time distribution as an indicator for valuing the reliability of travel time**.[28] This 2005 paper from the Dutch Transport Research Centre reported on a three-stage research program from 2003-2006 to identify the importance and value of travel time reliability for cost-benefit analyses – i.e., to find a way accurately to estimate the improvement in reliability measured against the cost of an infrastructure project.

  In Phase One of this study, a literature review confirmed that reliability is an important issue and identified three methods that have been used for deriving reliability performance indicators – mean versus variance, or standard deviation against average travel time; the difference between a defined percentile (80 or 90 – with more extreme times treated as outliers and not considered) and the median travel time; and, measuring unreliability based on the number of minutes by which arrival is earlier or later than preferred. The study decided to proceed with the first method

[26] No author given. *ATLANTIC – Proceedings of International Workshops on ITS Benefits, Evaluation and Costs at the 9th ITS World Congress, Chicago*. European Commission Directorate General Information Society. October 2002.

[27] No author given. *Performance Indicators for the Road Sector: Summary of the Field Tests*. Organisation for Economic Cooperation and Development, Paris. 2001.

[28] Warffemius, P. *Using the standard deviation of the travel time distribution as an indicator for valuing the reliability of travel time*. Transport Research Centre, Dutch Ministry of Transport, Public Works and Water Management, The Hague. 2005.

(mean versus variance). The literature review found no generally accepted values for reliability / cost conversions.

Phase Two involved an international meeting in 2004 to determine a common reliability indicator and provisional reliability values for each mode of transport and major trip purpose (i.e., auto commuting, auto business, auto other, public transit train and urban, and freight ransport by road, rail, water and air). The report cited a 2002 paper by Copley, Murphy and Pearce (ETC 2000, Cambridge) on Understanding and valuing journey time variability. This established from a Manchester, UK survey that a minute of standard deviation time, deriving from unexpected congestion and delays, is valued 1.3 times as much as a minute of travel time (thus implying a reliability ratio of 1.3).

Phase Three was a survey lasting into 2006 to identify the values of these indicators from which the results were not yet available. This survey requested information on individual trip durations, average trip durations and travel costs.

The authors concluded by saying that current traffic forecasting models typically lack the ability to estimate standard deviations or percentiles of travel times on links. Although an attempt is underway to develop this ability in the Dutch model, considerable further work is anticipated.

- **Reliability Ratios voor het Goederenvervoer (Reliability Ratios for Freight Movements)**.[29] This June 2005 working paper, in Dutch but with an English summary, examined how reliability ratios should be changed when reliability improves. It cited the Transport Research Centre of the Dutch Ministry of Transport's aforementioned work with reliability ratios (value of reliability as measured by the standard deviation / value of time) but did not use it further as it did not investigate buffer times. Instead, the authors made assumptions that 50% of carriers keep a constant buffer time and 50% postpone their departure to keep a constant probability of arriving late when confronted with an improved reliability. This resulted in a derived reliability ratio of 1.2 for road freight transport, but the authors stressed the need for further research to reduce the level of assumptions.

- **Real-time modelling travel time reliability on freeways**.[30] This 2005 analysis was based upon real-time traffic data collected from a freeway-urban mixed network in the southwest area of The Netherlands, where loops detectors have been set up to monitor traffic. Travel time reliability was then calculated in real time as a probabilistic function of "route-based density" (the number of vehicles for a particular trip over the length of the trip), which can be determined and updated

[29] Kouwenhoven, M., de Jong, G. and Rietveld, P. *Reliability Ratios voor het Goederenvervoer – Eindrapport / Reliability ratios for freight movements – Working Paper*. RAND Europe, The Hague. 2005.

[30] Tu, H., van Lint, H. and van Zuylen, H. *Real-time modelling travel time reliability on freeways*. Consiglio Nzionale delle Richerche IASI. Rome, 2005.

automatically from the flow and speed data coming in. Reliability was defined as "the probability that a certain trip can be made successfully within a specified travel time as a function of route-based density."

- **Perceptions of and attitudes to congestion**.[31] This 2001 public survey was conducted by the UK Department for Transport to explore public attitudes towards congestion and ways of measuring it. The response indicated that the overwhelmingly most helpful measure of congestion was the extra time required to make a trip with respect to the free-flow time, with 51% of respondents identifying this first. Other options considered were the risk of serious delay (26%), the average speed on different road types (18%) and the amount of time spent stationary or travelling at less than 10 mph (10%).

- **Congestion Charge Impacts monitoring – Congestion (Second Annual Report**).[32] This report from April 2004 deal largely with the impact of the London congestion charge, but did identify the possibility of using the congestion charge monitoring cameras to evaluate travel time reliability. Such an evaluation was not possible using the existing traffic speed data, which come from moving car observations.

[31] No author given. *Perceptions of and attitudes to congestion* (survey). United Kingdom Department for Transport, London. 2001.

[32] No author given. *Congestion charging impacts monitoring second annual report (Part 2 – congestion)*. Transport for London, London. 2004.

4. APPLICATION

4.1 Purpose

This chapter presents the findings of the development of probability distributions for travel time (speed) distributions from several cities. The purpose is to present the distributions in order to:

- Confirm the shape of the distributions, and examine differences among the distributions. As discussed below, not all of the distributions followed the expected shape (skew-normal distribution).

- Examine their applicability to other urban areas, and recommend appropriate proxies. That is, because data were available only for some urban areas, it is necessary to determine the criteria for applying distributions developed for some urban areas to others (as well as the limitations).

- Develop and explain the rationale behind a modified Buffer Index, as the basis for factors that are to be used to add the non-recurrent increment to the costs of recurrent congestion.

- Finally, develop factors to be applied to the estimates of non-recurrent congestion for expressways and arterials (Chapter 5).

4.2 Data and Sources

Travel time or travel speed data were received for the following urban areas:

- Montréal (from the Ministère des Transports du Québec [MTQ]): primarily expressways with some arterials.
- Ottawa-Gatineau (from the City of Ottawa): mixture of expressways and arterials throughout the urban area.
- Toronto (from the City of Toronto and the Ministry of Transportation of Ontario [MTO]): mostly expressways, with one arterial highway (Highway 27).
- Hamilton (City of Hamilton): primarily expressways with some arterials.
- Winnipeg (City of Winnipeg): arterials only. It should be noted that the only expressway in Winnipeg is the city's perimeter highway.

Most of the data were gathered manually, with the 'floating car' method (Montréal, Toronto, Hamilton, Winnipeg). This method records times with a vehicle that attempts to move at the average speed of traffic, overtaking and being overtaken by approximately the same number of people. The Ottawa-Gatineau data were gathered with *iTREC*, iTRANS' GPS-based travel time survey recorder. These data provide greater precision than the manual methods: in particular, they provide second-by-second records.

Data were provided in different forms, ranging from raw data (Montréal and Ottawa-Gatineau) to summary spreadsheets by section (Toronto and Hamilton) and summary results (Winnipeg). The data also represent different numbers of routes, with the most comprehensive set provided for Ottawa-Gatineau: data were gathered for 13 individual routes, with 20 runs for each route in each of the AM and PM peak periods. The Montréal data provided a comprehensive temporal coverage, over several months. Finally, the number of data points processed for a given location or route (among all the data) ranged from less than 5 in some Hamilton examples to 40,000 in Ottawa-Gatineau (reflecting the second-by-second GPS observations).

4.3 Development of Modified Buffer Index

The following approach was used:

- Routes and runs from different cities were selected, according to usability and to the ability to separate expressways from arterials.

- The separated data for the selected routes and runs were input to a spreadsheet. (It is noted that the processing of raw data is beyond the scope of this mandate.)

- Speeds for each run on a given route were calculated from the provided information. It is important to note that the calculation was based upon individual routes – that is, sequences of links – rather than on individual links. For example, Highway 417 from Eagleson Road in Kanata to Bronson Avenue in downtown Ottawa was used to represent one of the expressway calculations in Ottawa: the individual links were not analyzed separately. This was done in order [a] to maximize the number of observations available for a given dataset; [b] to provide a more representative treatment of the data, given – for example - that the data showed that some links consistently move very slowly while others consistently move very quickly (i.e., the data are weighted); in turn, this provides [c] a more appropriate basis for extrapolation to the development of factors that can be applied to the model-based congestion method.

- The last point means that travel *speeds* rather than travel *times* were used as the basis for the Buffer Index factors. The two are related. However, times are specific to individual links whereas speeds are applicable to individual or sequences of links. Whereas the Buffer Index searches for the 95th percentile travel time (i.e., the travel time that is not to be exceeded 95% of the time) as the basis for identifying the factor, for the purposes of this analysis we seek the 5th percentile travel speed – i.e., the minimum travel speed 95% of the time.

  In sum, speeds are used to weight travel times. This is important, because the Texas Transportation Institute's (TTI's) Buffer Index equation calls for the use of vehicle-miles travelled (vehicle-kilometres travelled) in order to weight the travel times.

However, the requisite traffic volumes were not available (i.e., traffic volumes were not recorded at the same time as the travel time surveys were conducted).

Thus, for the purposes of this analysis, a modified version of the TTI's Buffer Index likely must be used. Taking into account the use of speeds rather than times, this translates into the following relationship:

$$\text{Modified Buffer Index} = 1 / \left[\frac{\text{Mean Speed} - 5^{th}\text{ Percentile Speed}}{\text{Mean Speed}} \right] \times 100\%$$

The calculation is inverted because we are dealing with speeds (distance / time) rather than time rates (time / distance).

- This is a simplification of the TTI's Buffer Index. However, this modified version [a] provides a workable means of using the available data and resources at a scale that is appropriate for application to regional models while [b] respecting the basic approach and [c] providing factors, suitable to this study's level of analysis, for adding the incremental costs attributed to non-recurrent congestion (i.e., over recurrent congestion). As is described in Section 5, the Modified Buffer Index results in a factor that is used to approximate the 5^{th} percentile speed, as a function of the average (mean) speed.

4.4 Expressway Distributions and Factors

This section presents key distributions for expressways, for Toronto, Hamilton, Montréal and Ottawa-Gatineau.

4.4.1 Greater Toronto Area

Figure 3 presents the distribution for expressways in the Greater Toronto Area (GTA; i.e., the Toronto-centred urban region). **Figures 4** and **5** break down these data according to 'congested' and 'less-congested' direction (for each link). **Figures 3**, **4** and **5** summarize data for several urban and suburban expressway sections; namely, Highways 400, 401, 403, 404, 407 Electronic Toll Road, 409, 410 and 427, the Queen Elizabeth Way (QEW), the Gardiner Expressway and the Don Valley Parkway.

The *x* axis in each figure represents speed in kilometres per hour. The *y* axis represents the number of observations within each 5-kph speed bin.

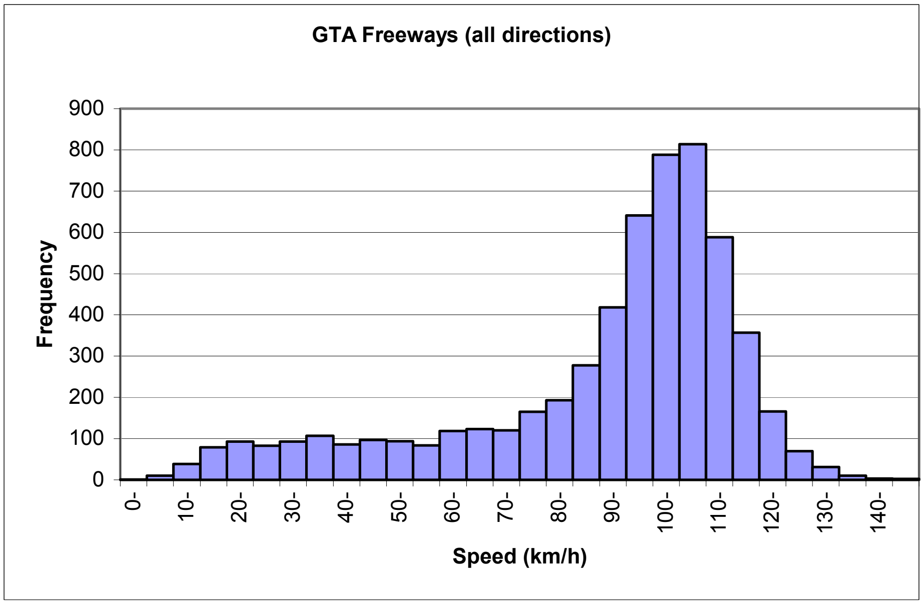

Figure 3. Distribution of Expressway Travel Speeds – AM peak period, GTA (various expressways)

Finally, **Table 4** summarizes the distribution of speeds for the three GTA data sets. This summary is drawn from the data on which Figures 1 through 3 are based.

Summary of Speeds	GTA (all)	GTA (congested)	GTA (less-congested)
Mean speed (km/h)	91	82	99
Standard deviation (km/h)	27	31	20
5th percentile speed (km/h)	24	16	46
Modified Buffer Index	136%	125%	188%

Table 4. Distribution of Expressway Speeds - AM peak period, Greater Toronto Area

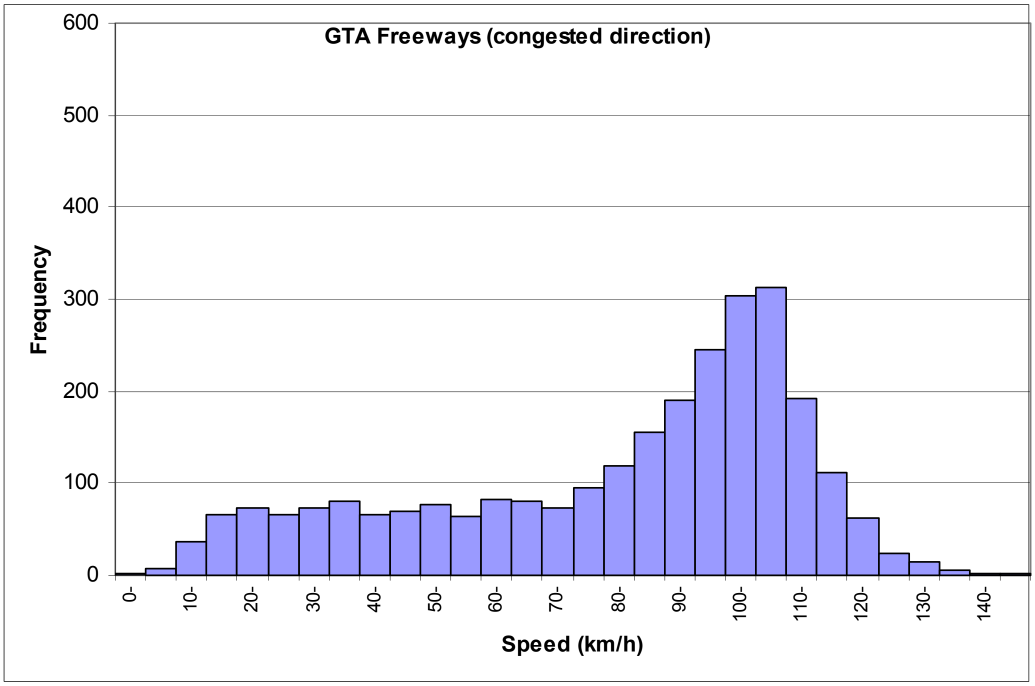

Figure 4. Distribution of Expressway Travel Speeds – AM peak period, GTA (congested direction)

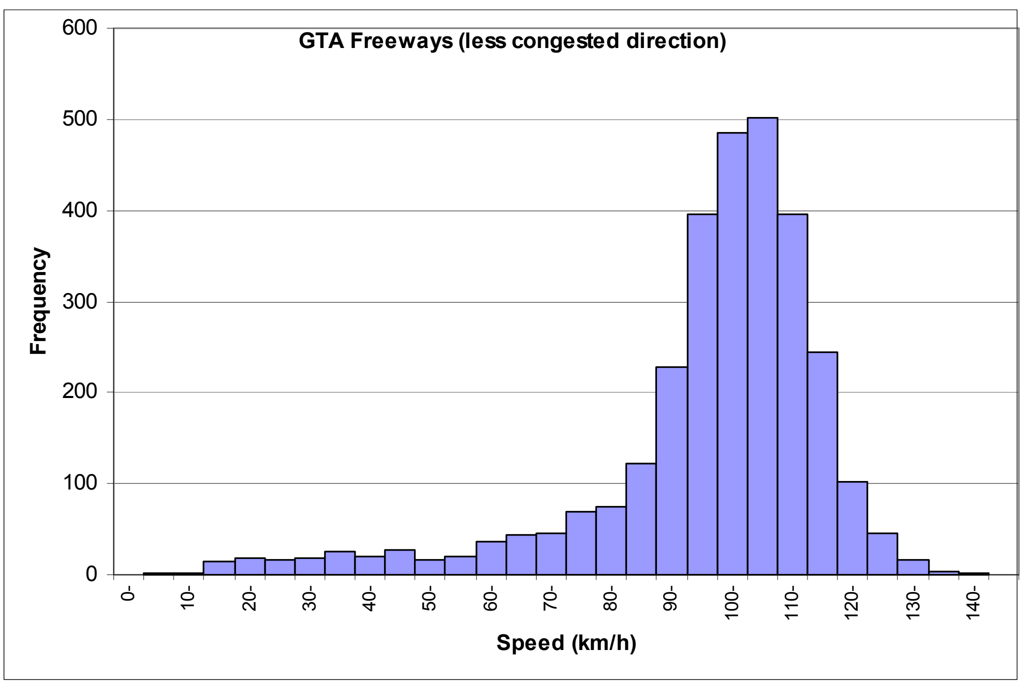

Figure 5. Distribution of Expressway Travel Speeds – AM peak period, GTA (less-congested direction)

From the three figures and **Table 4**, it can be seen that:

- The data follow the expected skew-normal distribution. Because the distribution is based upon *speeds*, the tail is to the left (rather than to the right, as it would be for *times*).

- However, the congested and less-congested directions present different characteristics. The tail for the congested direction is 'fatter' than that of the less-congested direction, and the speeds for the less-congested direction are clustered more closely together.

- Consistent with expectations, the mean speed is higher for the less-congested direction than for the congested direction, at 99 km/h and 82 km/h, respectively. The 5th percentile speeds are similarly higher for the less-congested direction, albeit at a much greater difference (46 km/h and 16 km/h, respectively). These differences are reflected in the Modified Buffer Index value, at 125% for the congested direction and 188% for the less-congested direction.

- In essence, the less-congested sections are operating at or close to free-flow conditions: the mean speed of 99 km/h is close to or exceeds the posted speed limits for the facilities, which range between 90 km/h and 100 km/h. Accordingly, the relative small standard deviation (20 km/h), the high 5th percentile speed (46 km/h) and the resultant high Modified Buffer Index value of 188% all suggest that it is not appropriate to include non-congested facilities in this analysis.

- The previous point also indicates that the differences between congested and less-/non-congested directions are masked by the values for the combined totals (all directions).

4.4.2 Hamilton

The distributions for sections of Highway 403 and the Queen Elizabeth Way (QEW) in Hamilton illustrate the importance of having data that reflect congested conditions. **Figures 6** and **7** break down the distributions by congested and less congested directions, respectively; and **Table 5** summarizes the key characteristics of the two figures.

Summary of Speeds	**Hamilton (congested)**	**Hamilton (less-congested)**
Mean speed (km/h)	106	110
Standard deviation (km/h)	12	15
5th percentile speed (km/h)	85	88
Modified Buffer Index	505%	500%

Table 5. Distribution of Expressway Speeds
- AM peak period, Hamilton (Hwy 403 and QEW)

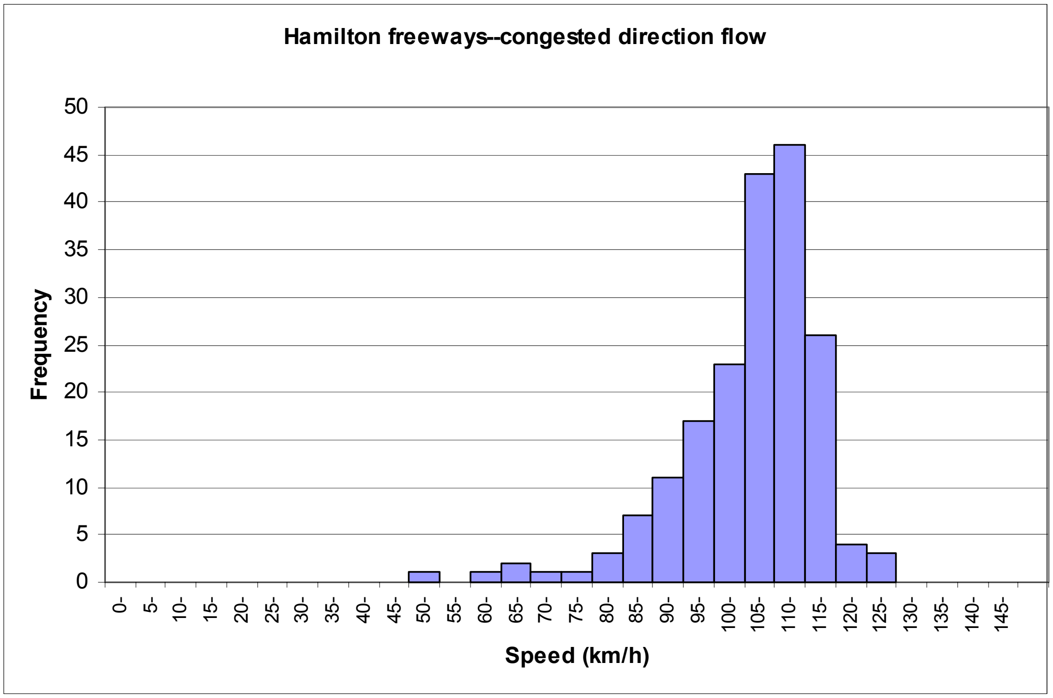

Figure 6. Distribution of Expressway Travel Speeds – AM peak period, Hamilton (Hwy 403 and QEW – congested direction)

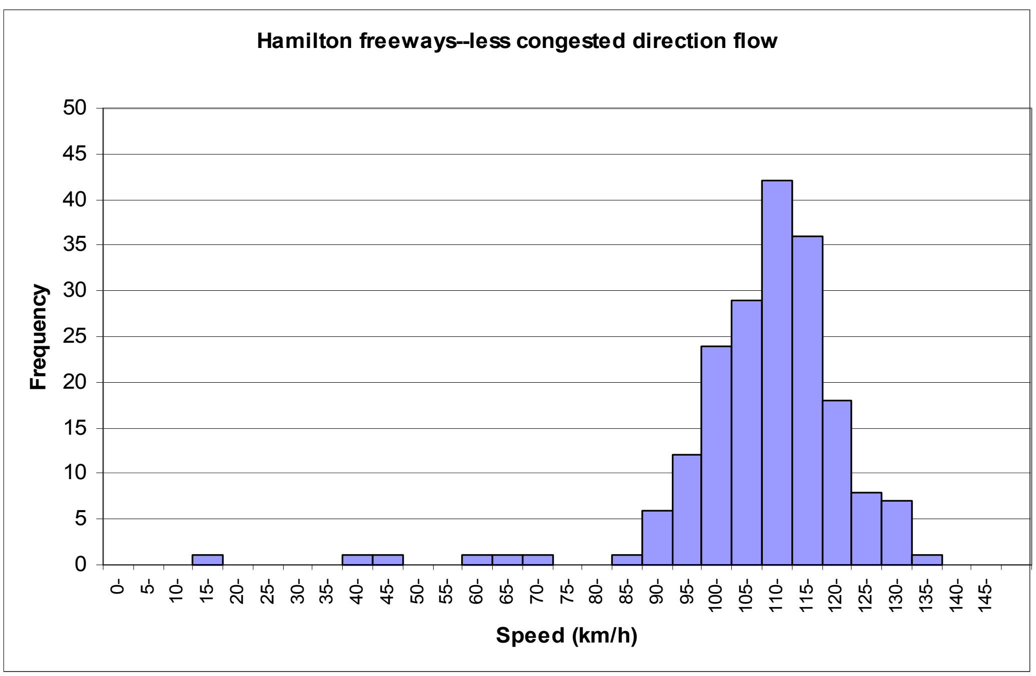

Figure 7. Distribution of Expressway Travel Speeds – AM peak period, Hamilton (Hwy 403 and QEW – less-congested direction)

The figures and **Table 5** illustrate clearly that these facilities are operating with mean speeds above the posted speed limit of 100 km/h, the remaining speeds are clustered closely around the mean speed (as demonstrated by the small standard deviation speeds) and the 5th percentile speeds are relatively close to the mean speeds (85 km/h – 88 km/h). The apparent lack of congestion is reflected in the very high Modified Buffer Indices of 500% - in other words, the Hamilton data are not meaningful for this analysis, because they represent uncongested conditions.

4.4.3 Montréal

Figures 8 and **9** represent data from selected expressways (Autoroutes) in Montréal. The figures portray distributions on two distinct routes, using data taken from the month of October 2004. The MTQ has collected data for several months. However, this month was used because the autumn is considered by transportation planners as being the most stable and representative of annual travel conditions: related to this is the fact that the MTQ's models are based upon travel origin-destination surveys that were collected in the autumn.

Figure 8 represents a suburban-to-urban area route (Autoroute 15). **Figure 9** represents a route within the urbanized area (Autoroutes 10 and 15). The circuit designations that are noted in the figures (A2 and C1, respectively) are MTQ's references to the routes used for the travel time surveys.

The Montréal data represent weighted speeds, according to distance covered. In other words, a speed of 0 km/h yields a weight of 0. This was done because the unweighted distributions presented a pattern that did not follow the expected skew-normal distribution exhibited by the Toronto and Hamilton data. (This is similar to the Ottawa-Gatineau data, as discussed in Section 4.4.) Notwithstanding, it can be seen that the **Figure 8** data (Autoroute 15) do not follow the skew-normal distribution very well, whereas the **Figure 9** data (Autoroutes 10 and 15) much more closely approximate this shape.

Table 6 summarizes the distribution of speeds for the two data sets. This summary is drawn from the data on which **Figures 8** and **9** are based.

Summary of Speeds	Montréal (A15)	Montréal (A10/A15)
Mean speed (km/h)	67	64
Standard deviation (km/h)	N/A	N/A
5th percentile speed (km/h)	15	9
Modified Buffer Index	128%	116%

Table 6. Distribution of Expressway Speeds - AM peak period, Montréal (selected Autoroutes)

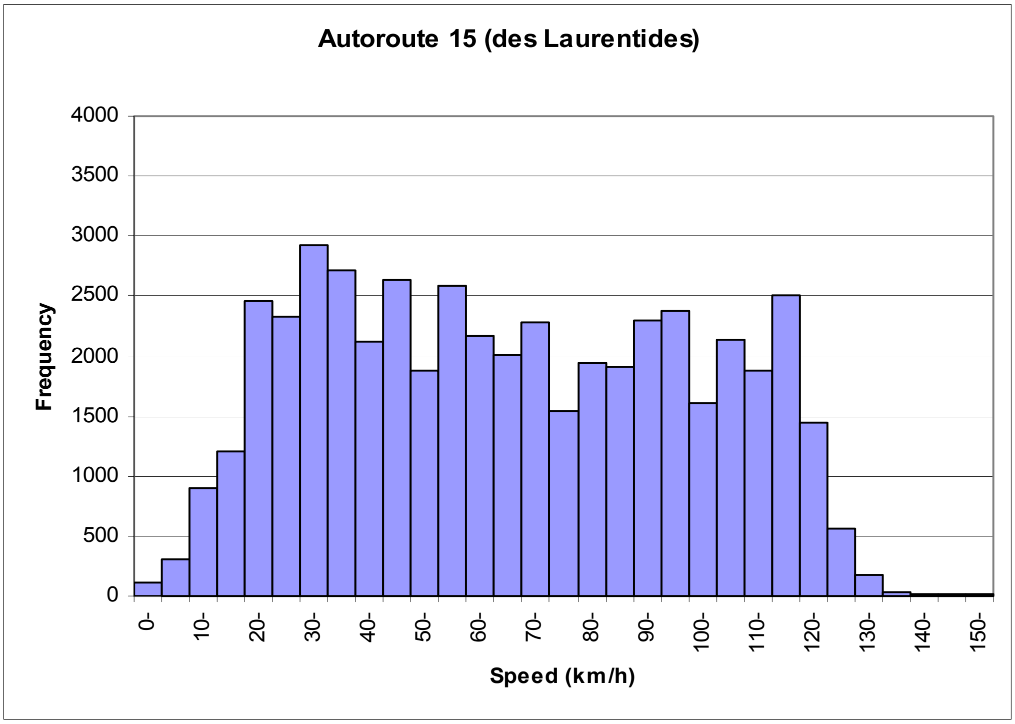

Figure 8. Distribution of Expressway Travel Speeds – AM peak period, October 2004, Montréal (A15 / circuit A2)

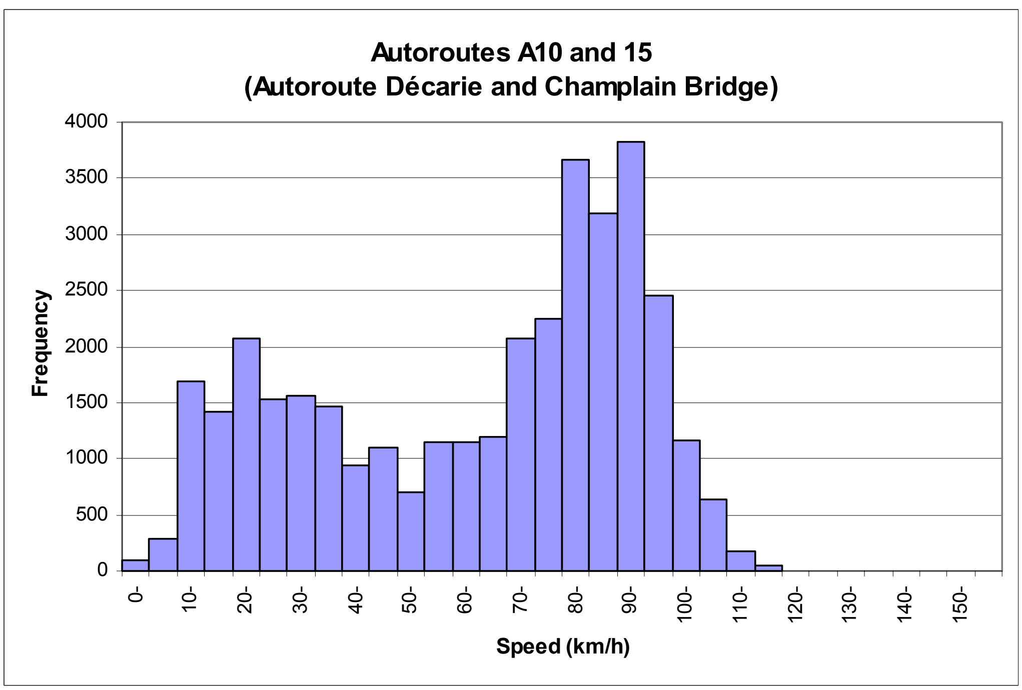

Figure 9. Distribution of Expressway Travel Speeds – AM peak period, October 2004, Montréal (A10/A15 / circuit C1

It also can be seen that the Montréal mean speeds are significantly lower means (64 and 67 km/h), compared with Toronto (91 km/h) and Hamilton (108 km/h). This suggests that the Montréal expressways are operating under more congested conditions than the other two urban areas.

4.4.4 Ottawa-Gatineau

By comparison, the Ottawa-Gatineau expressway data did not follow the expected pattern. As **Figure 10** shows, the skew is in the opposite direction; and the 'tail' displays a small peak. These data represent only the congested direction.

The apparent reason for this is that the Ottawa-Gatineau data are time-based (i.e., taken on a second-by-second basis from the GPS) while the Toronto and Hamilton data are distance-based. Thus, in Toronto / Hamilton, all sections are weighted equally irrespective of the state of congestion on them, while congested sections in Ottawa will have lower speeds, take more time to cover and therefore produce more observations than non-congested ones. This has the effect of lowering the average speed. (The Ottawa data represent over 40,000 observations.)

To address this, the consultant reworked the Ottawa-Gatineau data, to weight the speeds by the amount of distance covered in a fixed time (i.e., in 1 minute). This was analogous to the weighting of the Montréal data by distance covered. This translated the Ottawa-Gatineau data into a reasonably approximate distance basis. This also eliminated the second-by-second observations in which the vehicle was stopped; i.e., observations of 0 km/h were eliminated. (It should be noted that 6% of the second-by-second observations reflected null speeds.)

The weighted results are shown in **Figure 11**. It can be seen that the weighted distribution more closely approximates the expected skew-normal distribution – in particular, that of the A10/A15 distribution (**Figure 9**), with its long, relatively deep tail to the left and the second mini-peak at lower speeds.

Table 7 summarizes the distribution of speeds for the Ottawa-Gatineau data presented in **Figures 10** and **11**.

Summary of Speeds	**Ottawa-Gatineau – GPS data**	**Ottawa-Gatineau - weighted**
Mean speed (km/h)	45	70
Standard deviation (km/h)	33	N/A
5th percentile speed (km/h)	4	15
Modified Buffer Index	110%	127%

Table 7. Distribution of Expressway Speeds - AM peak period, Ottawa-Gatineau (unweighted and weighted)

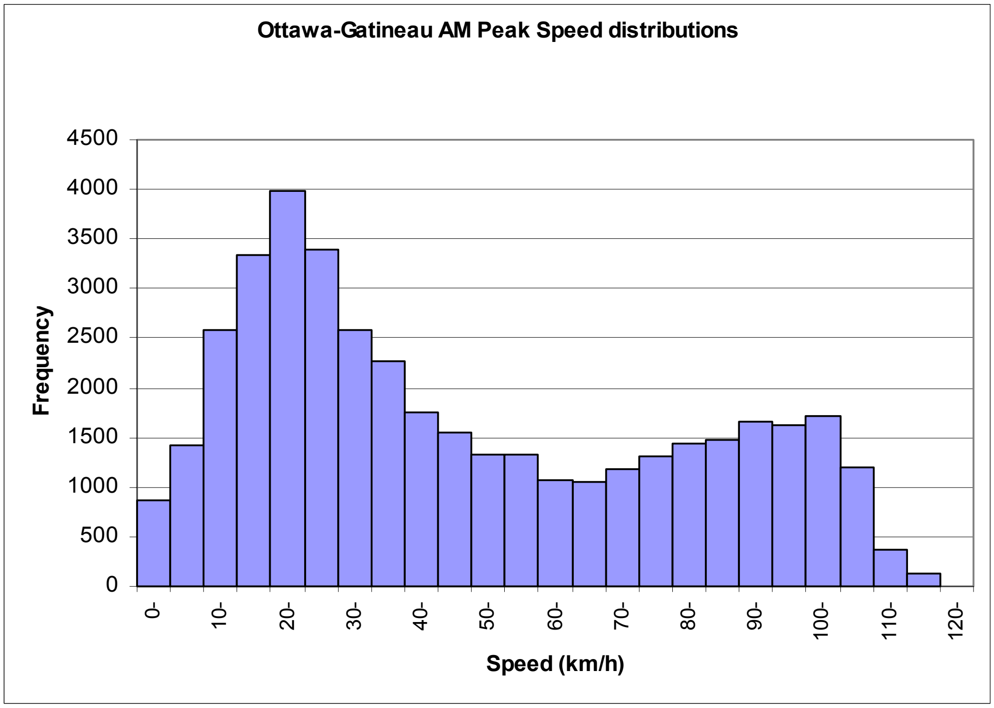

Figure 10. Distribution of Expressway Travel Speeds - AM peak period, Ottawa-Gatineau (Highway 417, Route 174 and A50)

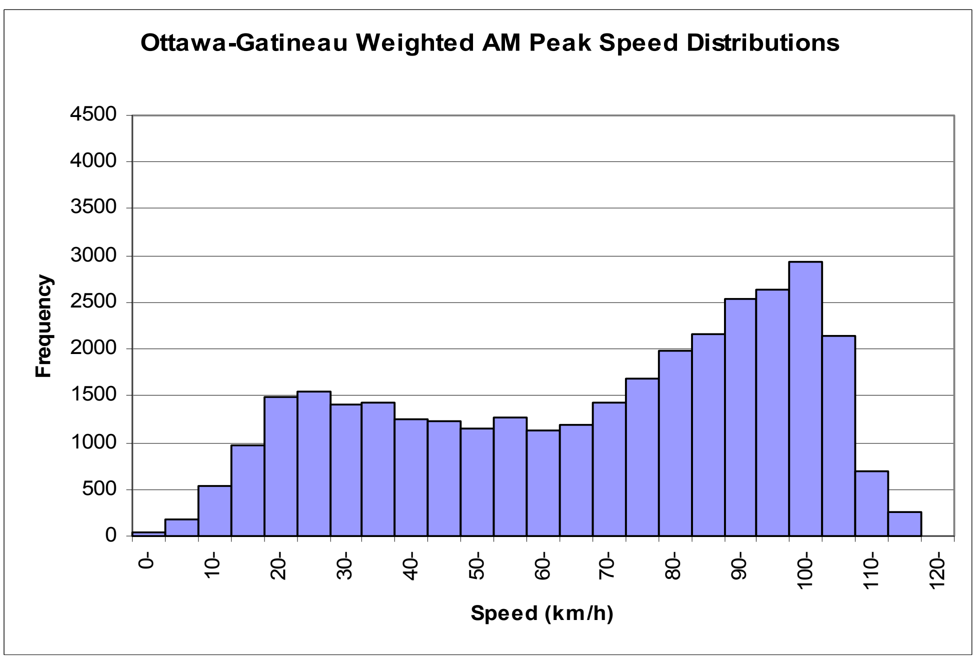

Figure 11. Weighted Distribution of Expressway Travel Speeds - AM peak period, Ottawa-Gatineau (Highway 417, Route 174 and A50)

It can be seen that:

- The mean and 5th percentile speeds for the original Ottawa data are significantly lower than for the weighted Ottawa data (45 km/ v. 70 km/h and 4 km/h v. 15 km/h, respectively). The weighted data generally are closer to the data from the Greater Toronto Area and Montréal.

- The increment of time required for Ottawa drivers – 10% - with the original data is the lowest value among all the data sets. The weighted increment – 27% - is closer to the increments for the other cities.

- Thus, the inclusion or exclusion of the null speeds is significant.

Finally, **Figure 12** provides the weighted values for the same expressways, for the PM peak period. It can be seen that the general shape is similar to that of the AM peak period (**Figure 11**), with a long, deep tail to the left. The findings suggest that the results are similar, for a given facility, for both the AM and PM peak periods: however, it is important to note that analyses with further data, beyond the scope of this work, would be required to confirm this generalization.

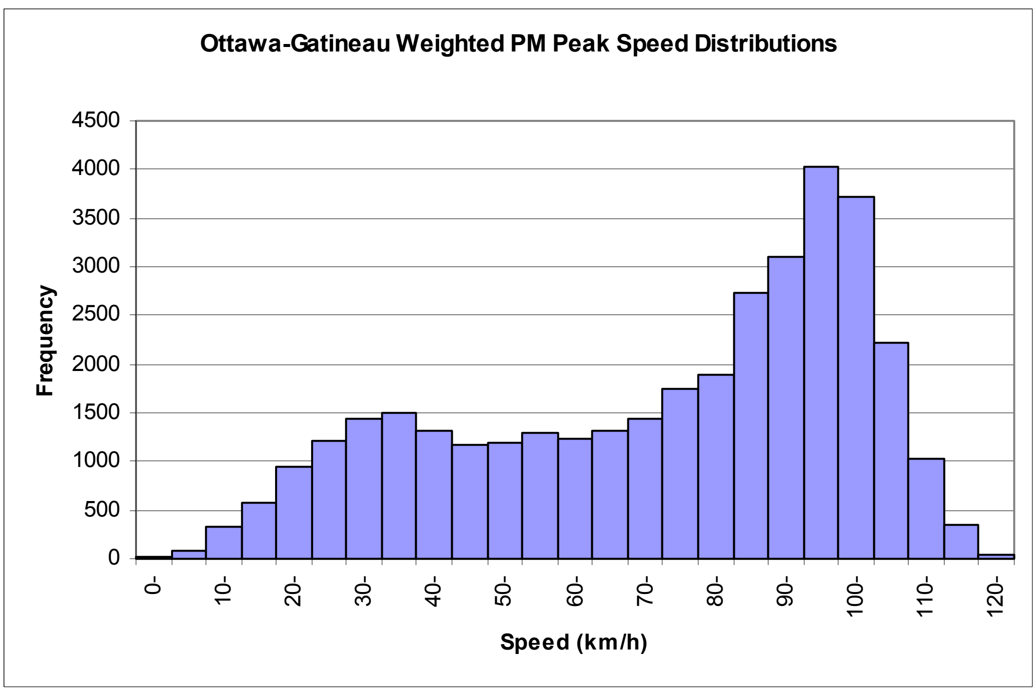

Figure 12. Weighted Distribution of Expressway Travel Speeds - PM peak period, Ottawa-Gatineau (Highway 417, Route 174 and A50)

Significantly, however, the PM mean and 5th percentile speeds and the modified Buffer Index value are all higher than those of the AM, as indicated in **Table 8**. Importantly, the Modified Buffer Index is 141%, which is higher than any of those cited for the AM for any of the cities. It is not clear whether these reflect the inherent differences between the AM and the PM peak, or whether they are specific to conditions in Ottawa-Gatineau: further analyses, beyond the scope of this work, would be required.

Summary of Speeds	**Ottawa-Gatineau – AM weighted**	**Ottawa-Gatineau – PM weighted**
Mean speed (km/h)	70	75
Standard deviation (km/h)	N/A	N/A
5th percentile speed (km/h)	15	22
Modified Buffer Index	127%	141%

Table 8. Weighted Distribution of Expressway Speeds
- AM and PM peak periods, Ottawa-Gatineau

4.4.5 Summary

Table 9 summarizes the characteristics of the applicable expressways.

Summary of Speeds	**GTA (congested)**	**Montréal (A15)**	**Montréal (A10/A15)**	**Ottawa-Gatineau – AM weighted**	**Ottawa-Gatineau – PM weighted**
Mean speed (km/h)	82	67	64	70	75
Standard deviation (km/h)	31	N/A	N/A	N/A	N/A
5th percentile speed (km/h)	16	15	9	15	22
Modified Buffer Index	125%	128%	116%	127%	141%

Table 9. Distribution of Expressway Speeds
- AM or PM peak period, selected facilities in GTA, Montréal and Ottawa-Gatineau

4.5 Arterial Distributions and Factors

This section presents key distributions for arterials. It is important to recall, first, that:

- The Buffer Index is intended for urban expressways. There is no corresponding index for arterials. Thus, the application to this study represents an adaptation.

- The attributes of the arterials from which the data were drawn vary considerably, in terms of posted speeds, number of lanes, cross-section (divided or undivided), the type and synchronization of traffic control at intersections, availability of on-street parking, curbside 'friction' (e.g., buses, trucks or taxis stopping along the route to load / unload people or goods), access to adjoining properties and so on. This is in contrast to the expressways, for which most of these variations do not apply (except for the number of lanes and the posted speeds).

- There were considerably fewer available data for arterials than for expressways.

Figure 13 presents data for all Winnipeg arterials. It can be seen that the distribution does not follow the skew-normal distribution. However, it is evident that these data reflect ranges of posted speeds, road configurations, etc. Moreover, the City of Winnipeg deliberately collects its travel time data under conditions that avoid or minimize non-recurrent congestion.

In contrast, the Hamilton arterials exhibited a skew-normal distribution - but with the tail to the right, as shown in **Figure 14**. The Hamilton data represent five sets of observations on three arterials (two directions on two arterials, one direction on the third arterial).

However, as shown in **Figures 15** and **16**, the combined data may mask differences in peaking characteristics. The figures depict Main Street East in Hamilton (the sections between downtown Hamilton and Highway 403; i.e., close to the urban core).

Although the volumes are higher in the eastbound direction (**Figure 15**), congestion is higher in westbound direction (**Figure 16**), as evidenced by the speed distributions. Eastbound volumes are of the order of 2,900 vehicles, compared with 1,200 vehicles westbound. However, the eastbound traffic displays significantly more traffic at high speeds, while the westbound traffic is concentrated at lower speeds.

Figures 17 and **18** present, respectively, weighted speed distributions for Ottawa-Gatineau arterials, for the AM and PM peak periods, respectively. (These are GPS data; hence the weighting – as per the expressways.) These data sets represent significantly more observations than either the Winnipeg or Hamilton data. It can be seen that both Ottawa-Gatineau data sets approximate the shape of the Winnipeg data; and that the forms of the AM and PM data sets are similar.

Finally, **Table 10** summarizes the distribution of speeds for the Winnipeg, Hamilton and Ottawa data presented in **Figures 13, 14, 17** and **18**.

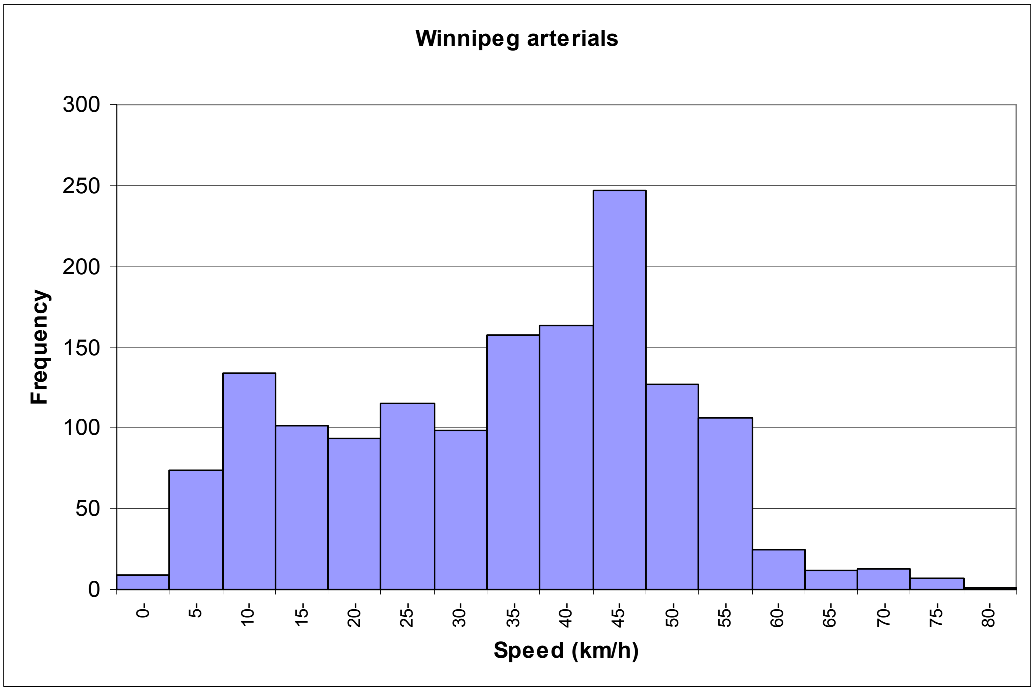

Figure 13. Distribution of Arterial Travel Speeds – Winnipeg (various locations)

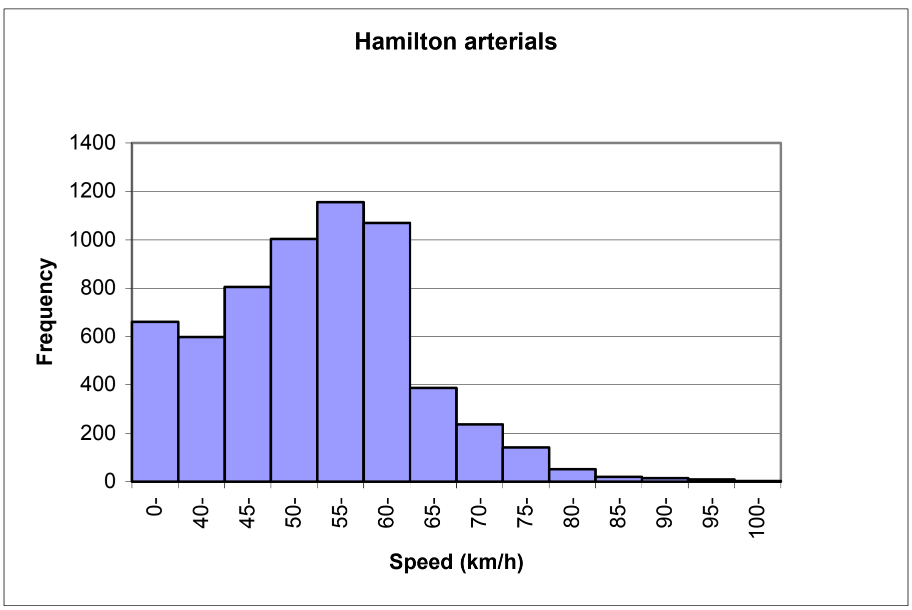

Figure 14. Distribution of Arterial Travel Speeds – Hamilton (various locations)

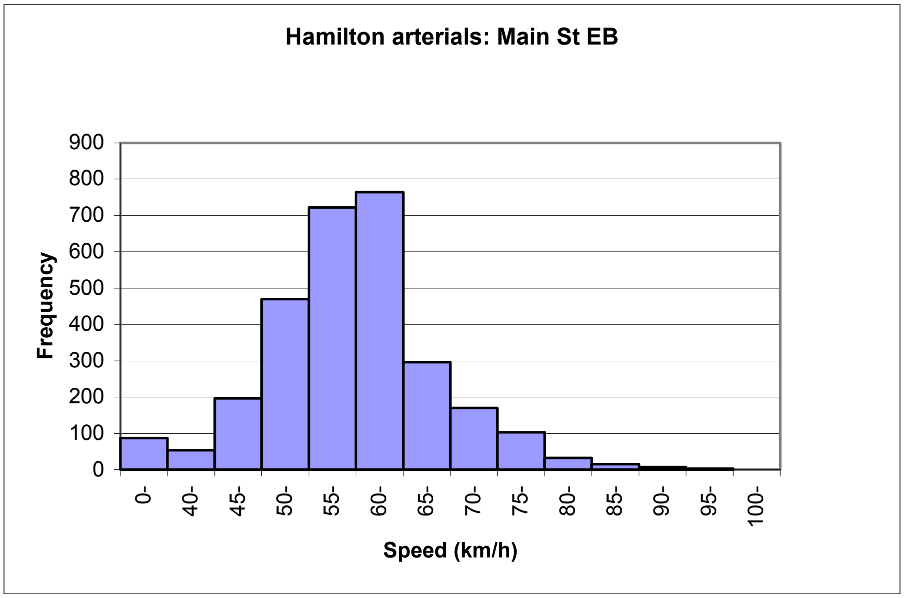

Figure 15. Main Street EB – AM peak period travel speeds

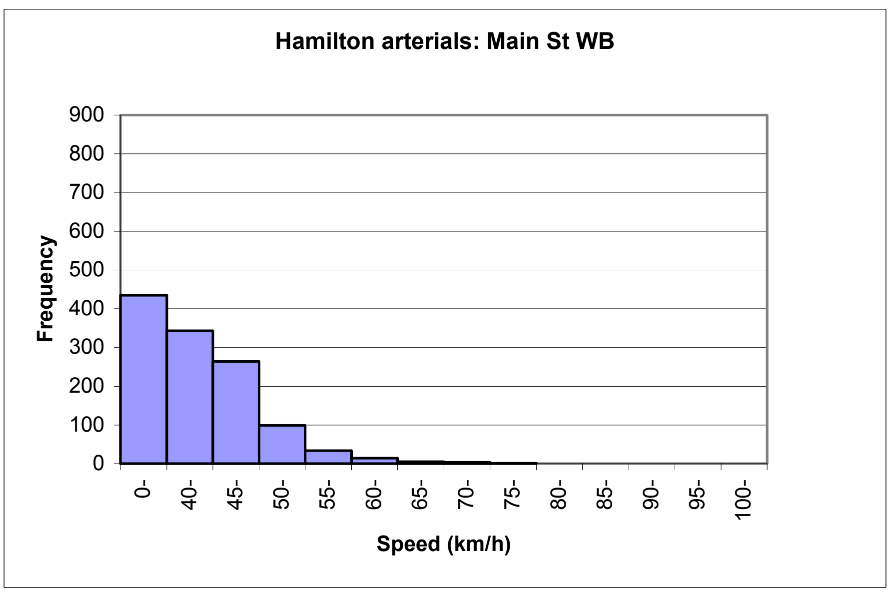

Figure 16. Main Street WB – AM peak period travel speeds

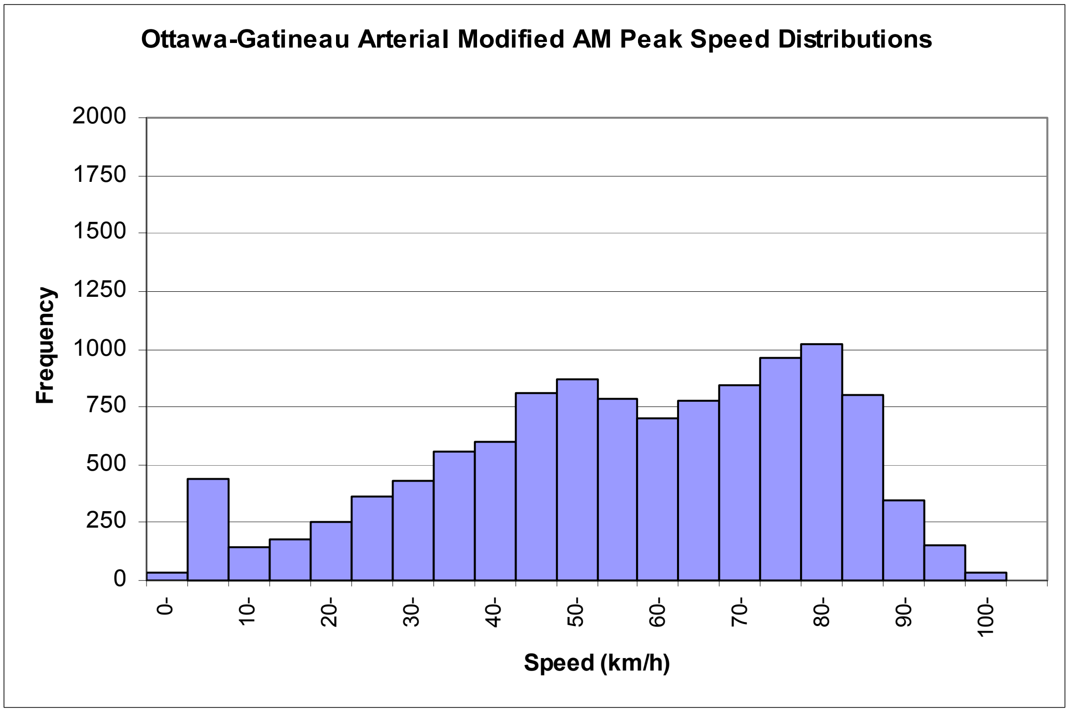

Figure 17. Weighted Distribution of Arterial Travel Speeds - AM peak period, Ottawa-Gatineau (various)

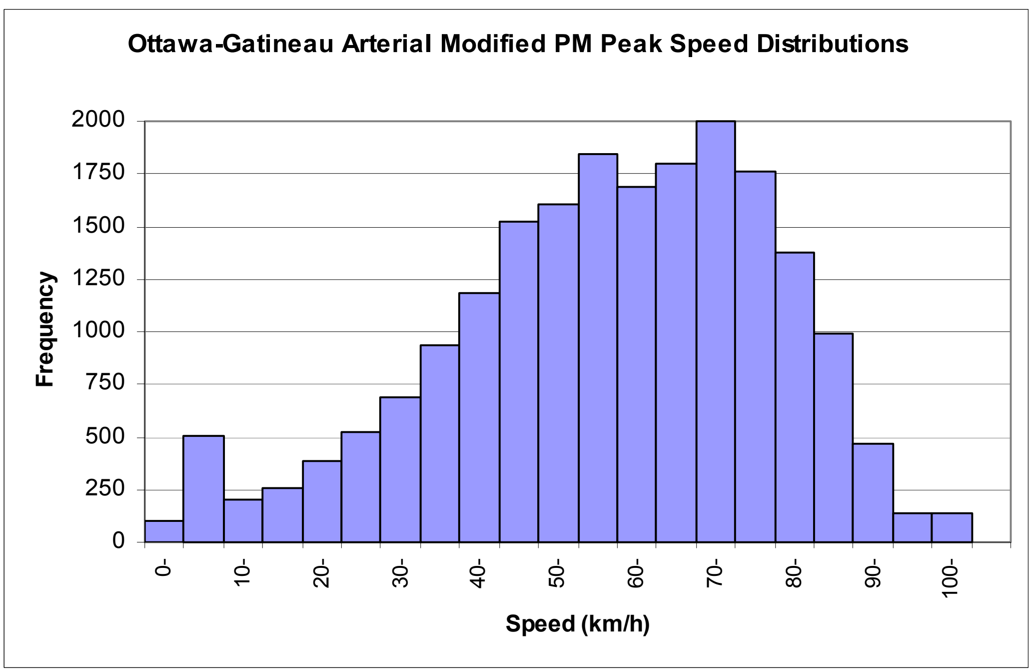

Figure 18. Weighted Distribution of Arterial Travel Speeds - PM peak period, Ottawa-Gatineau (various)

Summary of Speeds	Winnipeg	Hamilton	Ottawa-Gatineau – AM weighted	Ottawa-Gatineau – PM weighted
Mean speed (km/h)	36	53	59	59
Standard deviation (km/h)	16	31	N/A	N/A
5th percentile speed (km/h)	10	19	8	14
Modified Buffer Index	135%	154%	116%	131%

Table 10. Distribution of Arterial Speeds - Winnipeg, Hamilton and Ottawa

It can be seen that:

- As a group, the Modified Buffer Indices are higher than those of the expressways (**Tables 4, 6, 7** and **8**). This *suggests* an apparent reflection of the greater variability in arterial conditions compared with expressways. It is cautioned that this observation is based upon relatively fewer data points.

- The Ottawa-Gatineau indices are lower than those for Winnipeg and Hamilton, although the Ottawa-Gatineau PM index approximates the Winnipeg index.

- Although the Ottawa-Gatineau mean speeds are identical for both peak periods (and are greater than those for Winnipeg and Hamilton), the 5th percentile speeds are reasonably close among all four data sets.

- The Ottawa-Gatineau AM 5th percentile speed and the Modified Buffer Index value are lowest of all; and are lower than those for the Ottawa-Gatineau PM. It is not clear whether or how these findings reflect the inherent differences in the characteristics of the two peak periods, or whether these differences are applicable across all urban areas. Analyses with further data, beyond the scope of this work, would be required to address these issues.

It also is cautioned that the four sets of arterial data may not be directly comparable, as suggested by the significant difference in mean speeds; and – as noted – peak and off-peak differences may be masked.

4.6 Summary and Recommended Factors

This section presents findings regarding the development of probability distributions for available expressway and arterial travel times. Key points:

- A Modified Buffer Index was developed, based upon the available data. This index used speeds rather than travel times. Speeds also were used to weight the findings. For the purposes of this study (the development of the incremental costs of non-recurrent congestion), it is our opinion that this modification represents a reasonable and usable approach.

- The function was applied to selected expressway and arterial data from several urban areas.

- The skew-normal distribution does not always hold for all applications. For expressways, this may be a function of the type of data collection - specifically, the disaggregated second-by-second data points. For arterials, this may be a function of the wide variety in the attributes that define arterials.

- The arterial findings suggest that – compared with expressway distributions - the arterial distributions vary considerably, due to the function and operation of arterials and to specific local conditions.

- A detailed analysis of the reasons for these variations is beyond the mandate of this work, and also may be beyond the available data.

- Notwithstanding the stated limitations, the factors resulting from the application of the Modified Buffer Index can be used and applied to the development of non-recurrent costs of congestion, for the purpose of this analysis.

With respect to the development of proxy factors, there are differences in the Modified Buffer Index factors between expressways and arterials, with the latter – as a group – greater than those of the former. Beyond that, it is difficult to discern strong differences or patterns by city size. Accordingly, and in light of the available data and the cited limitations, for the purposes of this project, the consultant used the *average* Modified Buffer Index factors for expressways and for arterials, respectively, for all nine urban areas. From **Table 9**, the simple average for expressways is **127%**. From **Table 10**, the simple average for arterials is **134%**.

5. COSTS OF CONGESTION

5.1 Method

This chapter uses the Modified Buffer Index factors, developed in the preceding chapter, to estimate non-recurrent costs of congestion. This was done according to the following method:

- Recalculate the average peak hour speeds for all expressway and arterial links for each urban area. The reference here is to the link volumes that were provided for each city (except Calgary and Edmonton) from the respective travel demand forecasting models, for *The Costs of Urban Congestion in Canada* study. The volumes are expressed in terms of vehicle per (peak) hour, for each 'link' (section of road) and for each direction. The resultant average speeds for each link by direction also are provided, along with the free-flow or posted speed. The modelled average speeds reflect recurrent congestion.

  Thus, for example, a section of Ottawa's Highway 417 expressway might be modelled as carrying 4,300 autos during the (afternoon) peak hour, at an average speed of 68 km/h, compared with the posted speed of 100 km/h. This section would be considered as congested according to the 70% threshold (i.e., 70 km/h), but not according to the 50% or 60% thresholds. For all congested links the delay, expressed in vehicles-hours travelled, wasted fuel, which varies according to speed and GHG emissions (expressed as a function of wasted fuel) were calculated. The modelled volume (4,300 autos) and the associated average speed (68 km/h) reflect recurrent congestion.

  The original average speeds for each link were factored according to the Modified Buffer Index factors. In the aforementioned example, the resultant 5th percentile average speed equals 68 km/h divided by 1.27 (the average Modified Buffer Index value for expressways), or 54 km/h. In other words, the speed of 68 km/h represents the situation in which only recurrent congestion is considered. The speed of 54 km/h represents the situation in which non-recurrent speed also is taken into consideration, in addition to recurrent speed. In other words, the calculation moves the average link speed to the 5th percentile speed; in this case, 54 km/h.

  These new speeds are calculated for each expressway link and, using the appropriate factor (1.34), also for each arterial link. Once this is done, only those links that are under congestion, according to the specific threshold, are considered. For these, the delay, wasted fuel and GHG emissions are then calculated. These represent the *total* impacts; that is, the total of recurrent (previously calculated) and non-recurrent impacts. Thus, the non-recurrent incremental impacts are the difference between total and recurrent impacts.

The Costs of Urban Congestion study already calculated the congestion delay, wasted fuel and GHG emissions under recurrent congestion. We now apply the same calculation, but this time using the 5th percentile speed (54 km/h) as the link's speed. The 'difference' in the delay, wasted fuel and GHG emissions between the two speeds corresponds to the non-recurrent increment. Thus, to continue the example, suppose the average speed of 68 km/h results in recurrent congested delay of 1,000 vehicle-hours, 100 litres of wasted fuel and 246.89 kg of GHG emissions.[33] Let us further suppose that the average speed of 54 km/h results in total delay of 1,500 vehicle-hours, 170 litres of wasted fuel and 419.71 kg of GHG emissions. The differences between the two sets of values represent the non-recurrent portions; namely, 500 vehicle-hours of delay, 70 litres of wasted fuel and 172.82 kg of GHG emissions.

As well, the link is now considered to be operating under congestion for the 60% threshold as well as the 70% threshold, though still not for the 50% threshold.

As documented in *The Costs of Urban Congestion* study, instead of providing the aforementioned model outputs, from which the consultant calculated delay, fuel and greenhouse gas emissions, the cities of Calgary and Edmonton elected instead to calculate the congestion impacts themselves, according to the consultant's specifications. Thus, the link data were not available for these two cities.

The Costs of Urban Congestion study calculated daily impacts by assuming that congestion only occurred during the two peak commuter periods. This assumption was necessary because, except for Calgary and Edmonton, the models simulated morning or afternoon peak hour conditions (i.e., there was no base from which to estimate daytime or night-time off-peak congestion). Although practical and necessary, this assumption results in congestion estimates that are conservative. The peak *hour* results for a given city were expanded to represent the peak *period* for that urban area (e.g., 2 hours in Winnipeg, 3 hours in Toronto). Again due to a lack of data, congestion levels in the two peak periods were assumed to be equal, and so the peak *period* value was doubled to represent daily values. Finally, a factor of 250 working weekdays / year was applied to each daily value, in order to develop annual estimates of delay, wasted fuel and GHG emissions under congestion.

- Calculate the costs of non-recurrent congestion for delay, wasted fuel and GHG emissions. The unit costs for delay were developed in *The Costs of Urban Congestion in Canada* study, as a function of the average wage in each of the nine urban areas (in $ / hour) and as developed by Transport Canada in 1993 according to work and work-related v. non-work (i.e., all other) trip purposes. The division by

[33] The CO_2 equivalent rate of 2,468.89 g/l of gasoline was used, as per *The Costs of Urban Congestion* study. Source: *Greenhouse Gas Inventory*, Federal House in Order website (http://www.fhio.gc.ca/default.asp?lang=En&n=F837EFD4-1). See also Table A7-5, *Canada's Greenhouse Gas Inventory 1990-2002*, Environment Canada, August 2004, for detailed breakdown of CO_2 emission rates by vehicle, engine and technology type.

trip purpose impacts the costs of delay, because the value of time ($ / hour) varies by purpose. The trip purposes were determined from origin-destination travel survey data provided or developed by each urban authority.

Fuel costs reflected average gasoline fuel costs for each urban area, for the year represented by each model ($ / litre). Finally, GHG costs were estimated, per tonne of GHG. All monetary values were inflated to represent 2002 values. These values were retained for the current study, as were the estimated split by trip purpose for each urban area.

5.2 Delay Costs

This section presents the derivation of the non-recurrent and total costs of delay. Four tables summarize the results, as described below. Consistent with *The Costs of Urban Congestion* study, the tables follow the same format:

- All values reflect congestion for the auto-driver. They do not include the auto-passenger costs of congestion. This is because only some models could provide estimates of auto-passenger travel (whereas all models were able to estimate auto-driver travel).

- Costs are shown for three thresholds (50%, 60% and 70%).

- Two sets of values are shown for Hamilton and for Ottawa-Gatineau. The first figures represent the "base;" that is, the values for all expressways and arterials within the two urban areas. However, as detailed in *The Costs of Congestion* study, it was necessary to remove selected links in Hamilton, whose values clearly were outliers (due to the configuration of the network), and in Ottawa-Gatineau, where some links in the sparsely-populated rural areas similarly were treated as outliers. The resultant 'net' urban areas corresponded closely to the former (pre-amalgamation) boundaries of 'old' Hamilton and to the urbanized areas of Ottawa-Gatineau (which, again, correspond approximately to the pre-amalgamation limits of the urban area - it is noted that approximately 90% of the population lives in 10% of the area). Totals for all urban areas are provided according to both definitions.

The one difference is that the monetary values have been deflated to 2000 dollars, from the original study's 2002 dollars. All costs are expressed in millions of (2000) dollars.

The four tables are as follows:[34]

[34] It should be noted that the figures that comprise Tables 11 – 30, or from which percentages have been calculated in these tables, have been rounded for convenience. Thus, the figures may not be equal exactly to the totals listed in the given table.

- **Table 11** summarizes the costs of recurrent delay, as estimated in *The Costs of Urban Congestion in Canada* study.

- **Table 12** summarizes the costs of non-recurrent delay, calculated in the current research. The derivation of the delay costs for Calgary and Edmonton is explained below.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$355	$453	$556
Edmonton	$47	$59	$71
Calgary	$91	$107	$115
Winnipeg	$41	$65	$90
Hamilton	$5	$10	$14
Hamilton (old)	$4	$6	$9
Toronto	$741	$1,091	$1,437
Ottawa-Gatineau	$31	$51	$76
Ottawa-Gatineau (no rural)	$30	$50	$74
Montréal	$618	$758	$882
Québec City	$31	$43	$57
Total, base	$1,959	$2,636	$3,298
Total, Old Ham. / no rural Ottawa-Gat.	$1,957	$2,630	$3,291

Note: Totals may not add, due to rounding

Table 11. Costs of Recurrent Delay (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$327	$405	$459
Edmonton	$50	$57	$65
Calgary	$94	$104	$107
Winnipeg	$69	$88	$109
Hamilton	$11	$18	$30
Hamilton (old)	$10	$12	$18
Toronto	$934	$1,185	$1,440
Ottawa-Gatineau	$54	$97	$146
Ottawa-Gatineau (no rural)	$51	$93	$141
Montréal	$486	$551	$614
Québec City	$33	$48	$66
Total, base	$2,058	$2,552	$3,034
Total, Old Ham. / no rural Ottawa-Gat.	$2,054	$2,543	$3,018

Note: Totals may not add, due to rounding

Table 12. Costs of Non-recurrent Delay (2000 $m)

- **Table 13** summarizes the total costs of delay. This is the sum of recurrent and non-recurrent delay costs. It was calculated according to the steps described in Section 5.1, when the Modified Buffer Index factors were applied to the model outputs.

Accordingly, the costs of non-recurrent delay (**Table 12**) represent the difference between the total costs of delay (**Table 13**) and recurrent delay costs (**Table 11**).

- **Table 14** lists the costs of non-recurrent delay as a percentage of the total costs of delay. The costs for Calgary and Edmonton were estimated by applying the average proportion for the other urban areas to the recurrent delay for those two cities.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$681	$858	$1,014
Edmonton	$96	$116	$135
Calgary	$185	$211	$222
Winnipeg	$110	$152	$198
Hamilton	$17	$28	$44
Hamilton (old)	$13	$18	$27
Toronto	$1,675	$2,276	$2,877
Ottawa-Gatineau	$86	$148	$222
Ottawa-Gatineau (no rural)	$83	$143	$215
Montréal	$1,104	$1,308	$1,497
Québec City	$64	$91	$124
Total, base	$4,018	$5,187	$6,334
Total, Old Ham. / no rural Ottawa-Gat.	$4,011	$5,173	$6,310

Note: Totals may not add, due to rounding

Table 13. Costs of Total Delay (Recurrent + Non-recurrent) (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	48%	47%	45%
Edmonton	51%	49%	48%
Calgary	51%	49%	48%
Winnipeg	63%	58%	55%
Hamilton	67%	66%	67%
Hamilton (old)	71%	68%	68%
Toronto	56%	52%	50%
Ottawa-Gatineau	63%	66%	66%
Ottawa-Gatineau (no rural)	62%	65%	65%
Montréal	44%	42%	41%
Québec City	52%	53%	53%
Total, base	51%	49%	48%
Total, Old Ham. / no rural Ottawa-Gat.	51%	49%	48%

Note: Totals may not add, due to rounding

Table 14. Non-recurrent Delay Costs as % Total Delay Costs

The tables indicate the following:

- Non-recurrent and recurrent delay costs are approximately equal, with the non-recurrent delay costs representing 51% at the 50% threshold and recurrent delay costs representing 52% at the 70% threshold. In other words, non-recurrent delay costs double recurrent delay costs.

- The total costs of delay range from $4.0 billion, at the 50% threshold, to $6.3 billion annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate.

5.3 Wasted Fuel

Adhering to the same format as the delay cost tables, the four tables below present the costs of wasted fuel. It should be noted that Calgary and Edmonton were not able to provide wasted fuel estimates in the original study. Accordingly, the non-recurrent costs for wasted fuel in the two cities were not calculated.

- **Table 15** summarizes the costs of recurrent fuel, as estimated in *The Costs of Urban Congestion in Canada* study.

- **Table 16** summarizes the costs of non-recurrent fuel, calculated in the current research.

- **Table 17** summarizes the total costs of fuel. This is the sum of recurrent and non-recurrent fuel costs. It was calculated according to the steps described in Section 5.1, when the Modified Buffer Index factors were applied to the model outputs. Accordingly, the costs of non-recurrent fuel (**Table 16**) represent the difference between the total costs of fuel (**Table 17**) and recurrent fuel costs (**Table 15**).

- **Table 18** lists the costs of non-recurrent fuel as a percentage of the total costs of fuel.

The tables indicate the following:

- Non-recurrent fuel costs represent approximately 40 - 42% of the total fuel costs. In other words, non-recurrent conditions increase recurrent fuel consumption by approximately 70%.

- The total costs of fuel range from $291 million, at the 50% threshold, to $340 million annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$24	$32	$36
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$5	$8	$8
Hamilton	$1	$1	$1
Hamilton (old)	$1	$1	$1
Toronto	$88	$96	$97
Ottawa-Gatineau	$5	$7	$7
Ottawa-Gatineau (no rural)	$5	$6	$7
Montréal	$42	$46	$47
Québec City	$4	$6	$7
Total, base	$168	$195	$202
Total, Old Ham. / no rural Ottawa-Gat.	$168	$194	$202

Note: Totals may not add, due to rounding

Table 15. Costs of Recurrent Fuel (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$22	$25	$24
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$6	$6	$7
Hamilton	$2	$3	$2
Hamilton (old)	$2	$3	$2
Toronto	$63	$68	$64
Ottawa-Gatineau	$7	$13	$13
Ottawa-Gatineau (no rural)	$7	$12	$12
Montréal	$20	$21	$21
Québec City	$4	$6	$6
Total, base	$123	$141	$136
Total, Old Ham. / no rural Ottawa-Gat.	$123	$140	$135

Note: Totals may not add, due to rounding

Table 16. Costs of Non-recurrent Fuel (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$46	$58	$60
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$10	$13	$15
Hamilton	$3	$5	$4
Hamilton (old)	$3	$4	$3
Toronto	$152	$164	$161
Ottawa-Gatineau	$12	$19	$20
Ottawa-Gatineau (no rural)	$11	$18	$19
Montréal	$61	$66	$68
Québec City	$8	$10	$12
Total, base	$291	$335	$340
Total, Old Ham. / no rural Ottawa-Gat.	$290	$334	$338

Note: Totals may not add, due to rounding

Table 17. Costs of Total Fuel (Recurrent + Non-recurrent) (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	48%	43%	40%
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	60%	43%	44%
Hamilton	67%	60%	50%
Hamilton (old)	67%	75%	67%
Toronto	42%	41%	40%
Ottawa-Gatineau	54%	70%	67%
Ottawa-Gatineau (no rural)	58%	68%	65%
Montréal	33%	32%	31%
Québec City	50%	55%	46%
Total, base	42%	42%	40%
Total, Old Ham. / no rural Ottawa-Gat.	42%	42%	40%

Note: Totals may not add, due to rounding

Table 18. Non-recurrent Fuel Costs as % Total Fuel Costs

5.4 Greenhouse Gases

The four tables below present the costs of GHGs (which, as noted, are calculated as a function of wasted fuel). As with wasted fuel estimates, it should be noted that Calgary and Edmonton were not able to provide GHG estimates in the original study. Accordingly, the non-recurrent costs for GHGs in the two cities were not calculated.

- **Table 19** summarizes the costs of recurrent GHGs, as estimated in *The Costs of Urban Congestion in Canada* study.

- **Table 20** summarizes the costs of non-recurrent GHGs, calculated in the current research.

- **Table 21** summarizes the total costs of GHGs. This is the sum of recurrent and non-recurrent GHG costs. It was calculated according to the steps described in Section 5.1, when the Modified Buffer Index factors were applied to the model outputs. Accordingly, the costs of non-recurrent GHGs (**Table 20**) represent the difference between the total costs of GHGs (**Table 21**) and recurrent GHG costs (**Table 19**).

- **Table 22** lists the costs of non-recurrent GHGs as a percentage of the total costs of GHGs.

The tables indicate the following:

- Non-recurrent GHG costs represent approximately 40 - 42% of the total GHG costs. In other words, non-recurrent conditions increase recurrent GHG consumption by approximately 70%.

- The total costs of GHGs range from $64 million, at the 50% threshold, to $73 million annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$5	$7	$8
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$1	$2	$2
Hamilton	$0	$0	$0
Hamilton (old)	$0	$0	$0
Toronto	$19	$20	$21
Ottawa-Gatineau	$1	$1	$2
Ottawa-Gatineau (no rural)	$1	$1	$1
Montréal	$10	$10	$10
Québec City	$1	$1	$1
Total, base	$36	$41	$44
Total, Old Ham. / no rural Ottawa-Gat.	$36	$41	$43

Note: Totals may not add, due to rounding

Table 19. Costs of Recurrent GHGs (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$5	$5	$5
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$1	$1	$2
Hamilton	$0	$1	$1
Hamilton (old)	$0	$1	$0
Toronto	$13	$14	$13
Ottawa-Gatineau	$2	$3	$3
Ottawa-Gatineau (no rural)	$2	$3	$3
Montréal	$5	$5	$5
Québec City	$1	$1	$1
Total, base	$27	$30	$30
Total, Old Ham. / no rural Ottawa-Gat.	$27	$30	$29

Note: Totals may not add, due to rounding

Table 20. Costs of Non-recurrent GHGs (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$10	$12	$12
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	$2	$3	$3
Hamilton	$1	$1	$1
Hamilton (old)	$1	$1	$1
Toronto	$32	$35	$34
Ottawa-Gatineau	$3	$4	$5
Ottawa-Gatineau (no rural)	$3	$4	$4
Montréal	$14	$15	$15
Québec City	$2	$2	$3
Total, base	$64	$72	$73
Total, Old Ham. / no rural Ottawa-Gat.	$64	$72	$72

Note: Totals may not add, due to rounding

Table 21. Costs of Total GHGs (Recurrent + Non-recurrent) (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	50%	38%	38%
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	50%	33%	67%
Hamilton	0%	100%	100%
Hamilton (old)	0%	100%	0%
Toronto	41%	41%	39%
Ottawa-Gatineau	67%	75%	60%
Ottawa-Gatineau (no rural)	67%	75%	75%
Montréal	33%	31%	31%
Québec City	50%	50%	33%
Total, base	42%	41%	40%
Total, Old Ham. / no rural Ottawa-Gat.	42%	41%	39%

Note: Totals may not add, due to rounding

Table 22. Non-recurrent GHG Costs as % Total GHG Costs

5.5 Total Costs

This section presents the total costs of congestion; that is, for recurrent and non-recurrent delay, fuel and GHGs combined. As before, the tables adhere to the format established in *The Costs of Urban Congestion* study. There are five tables:

- **Table 23** summarizes the total costs of recurrent delay, fuel and GHGs, as estimated in *The Costs of Urban Congestion in Canada* study.

- **Table 24** summarizes the total costs of non-recurrent delay, fuel and GHGs, calculated in the current research.

- **Table 25** summarizes the total costs of recurrent and non-recurrent delay, fuel and GHGs. This is the sum of the aforementioned recurrent and non-recurrent costs. As before, it was calculated according to the steps described in Section 5.1, when the Modified Buffer Index factors were applied to the model outputs. Accordingly, the non-recurrent costs (**Table 24**) represent the difference between the total costs (**Table 25**) and total recurrent costs (**Table 23**).

- **Table 26** expresses total non-recurrent costs as a percentage of the total costs.

- **Table 27** expresses delay costs as a percentage of the total costs.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$384	$493	$599
Edmonton	$47	$59	$71
Calgary	$91	$107	$115
Winnipeg	$46	$73	$99
Hamilton	$7	$10	$16
Hamilton (old)	$5	$8	$10
Toronto	$848	$1,207	$1,555
Ottawa-Gatineau	$38	$58	$85
Ottawa-Gatineau (no rural)	$36	$56	$82
Montréal	$669	$814	$941
Québec City	$35	$50	$65
Total, base	$2,164	$2,871	$3,546
Total, Old Ham. / no rural Ottawa-Gat.	$2,160	$2,867	$3,538

Note: Totals may not add, due to rounding

Table 23. Total Costs of Recurrent Congestion (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$354	$435	$488
Edmonton	$50	$57	$65
Calgary	$94	$104	$107
Winnipeg	$75	$95	$117
Hamilton	$14	$22	$31
Hamilton (old)	$11	$15	$20
Toronto	$1,011	$1,267	$1,517
Ottawa-Gatineau	$63	$112	$162
Ottawa-Gatineau (no rural)	$60	$109	$156
Montréal	$511	$577	$640
Québec City	$37	$53	$73
Total, base	$2,209	$2,722	$3,201
Total, Old Ham. / no rural Ottawa-Gat.	$2,203	$2,711	$3,184

Note: Totals may not add, due to rounding

Table 24. Total Costs of Non-recurrent Congestion (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$737	$927	$1,087
Edmonton	$96	$116	$135
Calgary	$185	$211	$222
Winnipeg	$121	$169	$216
Hamilton	$20	$33	$48
Hamilton (old)	$17	$23	$30
Toronto	$1,858	$2,474	$3,072
Ottawa-Gatineau	$100	$172	$246
Ottawa-Gatineau (no rural)	$97	$166	$238
Montréal	$1,179	$1,390	$1,580
Québec City	$73	$104	$138
Total, base	$4,370	$5,596	$6,745
Total, Old Ham. / no rural Ottawa-Gat.	$4,364	$5,580	$6,721

Note: Totals may not add, due to rounding

Table 25. Total Costs, Recurrent + Non-Recurrent Congestion (2000 $m)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	48%	47%	45%
Edmonton	51%	49%	48%
Calgary	51%	49%	48%
Winnipeg	62%	56%	54%
Hamilton	68%	66%	66%
Hamilton (old)	67%	67%	66%
Toronto	54%	51%	49%
Ottawa-Gatineau	63%	66%	66%
Ottawa-Gatineau (no rural)	62%	66%	66%
Montréal	43%	41%	41%
Québec City	51%	51%	53%
Total, base	51%	49%	47%
Total, Old Ham. / no rural Ottawa-Gat.	50%	49%	47%

Note: Totals may not add, due to rounding

Table 26. Total Non-recurrent Costs as % Total Costs

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	92%	92%	93%
Edmonton	--	--	--
Calgary	--	--	--
Winnipeg	90%	91%	92%
Hamilton	82%	84%	91%
Hamilton (old)	82%	81%	88%
Toronto	90%	92%	94%
Ottawa-Gatineau	85%	86%	90%
Ottawa-Gatineau (no rural)	85%	86%	90%
Montréal	94%	94%	95%
Québec City	88%	87%	89%
Total, base	92%	93%	94%
Total, Old Ham. / no rural Ottawa-Gat.	92%	93%	94%

Note: Totals may not add, due to rounding

Table 27. Delay Costs as % of Total Costs

The tables indicate the following:

- Delay dominates the costs of congestion, at 92% to 94% of the total costs of congestion (see **Table 27**). This is slightly higher than the proportion of delay in total recurrent costs, at 91% - 93%; and reflects the impact of the 93% - 95% proportion of total non-recurrent costs.

- Non-recurrent and recurrent costs are approximately equal, with the non-recurrent costs representing 51% at the 50% threshold and recurrent costs representing 53% at the 70% threshold. In other words, non-recurrent costs double recurrent costs.

- The total costs of delay range from $4.4 billion, at the 50% threshold, to $6.7 billion annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate.

5.6 Costs per VKT

This section expresses the total recurrent and non-recurrent costs of congestion, developed in Section 5.5, in terms of costs per vehicle-kilometre travelled (VKT) – a measure of vehicle activity. **Tables 28**, **29** and **30** summarize, respectively, the peak hour VKT for the urban areas, under conditions of recurrent, non-recurrent and total (recurrent plus non-recurrent) congestion. This is calculated from outputs of the urban models, by summing the multiple of modelled peak hour volume (i.e., the peak hour assignment outputs from each model) and link length for all links whose speeds are below the particular threshold. Thus, the VKT changes according to threshold; that is, because only those links that are operating under congestion at the given threshold are summed. Because the relevant data were not available for the Edmonton and Calgary models, the tables reflect only the other seven urban areas.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	583,859	878,418	1,259,027
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	115,636	195,926	259,757
Hamilton	106,399	156,363	180,103
Hamilton (old)	33,805	83,769	107,509
Toronto	2,425,695	3,289,401	4,350,136
Ottawa-Gatineau	141,255	271,469	465,116
Ottawa-Gatineau (no rural)	140,023	262,500	452,425
Montréal	1,155,359	1,466,859	1,785,695
Québec City	100,600	154,042	246,997
Total, base	4,628,803	6,412,478	8,546,831
Total, Old Ham. / no rural Ottawa-Gat.	4,554,978	6,330,915	8,461,547

Note: Totals may not add, due to rounding

Table 28. Total Peak Hour VKT - Recurrent Congestion

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	533,512	709,630	657,840
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	130,403	156,303	252,326
Hamilton	68,860	125,602	331,063
Hamilton (old)	68,860	125,602	321,475
Toronto	1,581,646	2,306,816	3,194,705
Ottawa-Gatineau	223,153	588,016	819,376
Ottawa-Gatineau (no rural)	213,962	550,970	594,375
Montréal	504,748	688,027	928,414
Québec City	82,158	179,442	279,558
Total, base	3,124,480	4,753,836	6,463,282
Total, Old Ham. / no rural Ottawa-Gat.	3,115,290	4,716,790	6,228,693

Note: Totals may not add, due to rounding

Table 29. Total Peak Hour VKT – Non-recurrent Congestion

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	1,117,371	1,588,048	1,916,868
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	246,039	352,229	512,084
Hamilton	175,259	281,965	511,165
Hamilton (old)	102,665	209,371	428,984
Toronto	4,007,341	5,596,217	7,544,841
Ottawa-Gatineau	364,407	859,485	1,284,492
Ottawa-Gatineau (no rural)	353,985	813,470	1,046,800
Montréal	1,660,108	2,154,886	2,714,109
Québec City	182,758	333,484	526,555
Total, base	7,753,284	11,166,314	15,010,113
Total, Old Ham. / no rural Ottawa-Gat.	7,670,268	11,047,705	14,690,240

Note: Totals may not add, due to rounding

Table 30. Total Peak Hour VKT - Recurrent + Non-recurrent Congestion

Consistent with *The Costs of Urban Congestion Study*, congestion was assumed to occur only for the two peak periods, and equally throughout each period. This assumption reflected the availability of data outside the peak period (except for Edmonton and Calgary). Therefore, to develop annual estimates of VKT under congestion, the peak *hour* VKTs (as noted, calculated as the product of the assigned [modelled] peak hour link volumes and the link lengths) were factored first to reflect peak *period* values (by 2.0, 2.5 or 3.0, depending on the duration of the peak period: see **Table 31** for the factors for each urban area). Next, the peak *period* VKTs were doubled to represent the two peak periods (i.e., daily values). These daily values were then factored by 250 working days per year, to yield annual totals.

Location	**Factor**
Vancouver	2.50
Edmonton	-
Calgary	-
Winnipeg	2.00
Hamilton	2.00
Toronto	3.00
Ottawa-Gatineau	2.50
Montréal	3.00
Québec City	2.50

Table 31. Peak Hour to Peak Period Conversion Factor

The total costs for recurrent, non-recurrent and total congestion (**Tables 23**, **24** and **25**, respectively) were divided by the respective total annual VKTs. The resultant total costs per VKT are summarized for recurrent, non-recurrent and total congestion, in **Tables 32**, **33** and **34**, respectively.

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$0.53	$0.45	$0.38
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	$0.40	$0.37	$0.38
Hamilton	$0.06	$0.07	$0.09
Hamilton (old)	$0.14	$0.09	$0.10
Toronto	$0.23	$0.24	$0.24
Ottawa-Gatineau	$0.22	$0.17	$0.15
Ottawa-Gatineau (no rural)	$0.21	$0.17	$0.14
Montréal	$0.39	$0.37	$0.35
Québec City	$0.28	$0.26	$0.21

Table 32. Total Annual Recurrent Congestion Costs / VKT (2000 $)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$0.53	$0.49	$0.59
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	$0.58	$0.61	$0.46
Hamilton	$0.21	$0.17	$0.09
Hamilton (old)	$0.17	$0.12	$0.06
Toronto	$0.43	$0.37	$0.32
Ottawa-Gatineau	$0.23	$0.15	$0.16
Ottawa-Gatineau (no rural)	$0.22	$0.16	$0.21
Montréal	$0.67	$0.56	$0.46
Québec City	$0.36	$0.24	$0.21

Table 33. Total Annual Non-Recurrent Congestion Costs / VKT (2000 $)

	Threshold		
Location	**50%**	**60%**	**70%**
Vancouver	$0.53	$0.47	$0.45
Edmonton	-	-	-
Calgary	-	-	-
Winnipeg	$0.49	$0.48	$0.42
Hamilton	$0.11	$0.12	$0.09
Hamilton (old)	$0.17	$0.11	$0.07
Toronto	$0.31	$0.29	$0.27
Ottawa-Gatineau	$0.22	$0.16	$0.15
Ottawa-Gatineau (no rural)	$0.22	$0.16	$0.18
Montréal	$0.47	$0.43	$0.39
Québec City	$0.32	$0.25	$0.21

Table 34. Total Annual Recurrent + Non-Recurrent Congestion Costs / VKT (2000 $)

6. SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Summary

This research has estimated the costs of non-recurrent congestion in Canada's nine largest urban areas. The method built upon that developed in Transport Canada's study of *The Costs of Urban Congestion in Canada* for recurrent congestion. It did so by applying a modified version of the Buffer Index, which measures travel time reliability, to the average peak hour volumes and speeds as modelled by the various urban areas. Using travel time data provided by some of the urban authorities, the consultant developed Modified Buffer Index values of 127% for expressways and 134% for arterials. From these, estimates of the costs of non-recurrent congestion were developed for the nine urban areas, for the three impacts calculated in *The Costs of Urban Congestion in Canada* study: delay, wasted fuel and greenhouse gas emissions.

The key findings are as follows:

- Non-recurrent and recurrent costs are approximately equal, with the non-recurrent costs representing 51% at the 50% threshold and recurrent costs representing 53% at the 70% threshold. In other words, non-recurrent costs double recurrent costs.

- The total costs of delay range from $4.4 billion, at the 50% threshold, to $6.7 billion annually (70%). As with the original study results, it is important to note that these costs must be considered as a conservative estimate. This is because the estimates for both studies reflect the time losses that accrue to auto drivers (but not to auto passengers, or to passengers of transit or other modes) and only peak period travel conditions. These constraints reflect the available data and the time periods simulated in the models. In addition, congestion that occurs during the off-peak periods is not quantified – due to data and modelling limitations. Nor are the congestion impacts and costs to trucks or commercial vehicles, or to the value of the good being carried, quantified; again due to data and modelling limitations.

6.2 Applicability of the Modified Buffer Index

An underlying theme throughout the course of this research was the relative paucity of data; specifically, travel time and traffic volume surveys. This was the critical reason for developing a 'modified' version of the Buffer Index, which – according to the literature – was found to be the most practical and proven method for estimating the impact of non-recurrent conditions on congestion and its costs. Although acceptable for the purposes of this (economic) analysis, this means that from a traffic operational (engineering) point of view, the reasons for using the Modified Buffer Index – and the associated cautions - are important to understand:

- The Buffer Index could *not* be used, because of the lack of travel time data. Accordingly, for the reason of practicality – there being no other suitable method in practical use, according to the literature – it was necessary to modify the relationship, in order to base it on speed. This retained the three critical attributes of the original Buffer Index: first, a basis in travel time or speed (where speed = distance / time) is maintained; and, second, the values are normalized (weighted); and, third, the 95th (5th) percentile limit is maintained.

- It is fundamental to understand that a proper and thorough treatment of the Buffer Index – which, to our knowledge, had not been applied in Canada prior to this study – is required, in order to provide a method that can be used for engineering and modelling studies. Critically, we note a general paucity of data (the brief of this research was to use such data as were available, caveated as appropriate); and such extensive data sources as are available from Montréal and Ottawa-Gatineau require extensive processing, well beyond the mandate and need of the current research.

- An important side-benefit of this research is the exploration of some methodological considerations, which we were able to make within the constraints of the study's scope: the recognition that the method is not applicable to non-congested conditions (such as those exhibited by the Hamilton expressways); the need for a better treatment of arterials (none exists in the literature: this is likely a first application); the need to understand differences between AM and PM peak periods (as in Ottawa-Gatineau). These provide fundamental stepping stones for possible future methodological research.

- It has been pointed out that the Buffer Index as applied to several American cities has resulted in values ranging between 27% and 64%, for weekday peak period conditions. However, it is important to note that these results are not at all comparable with the application of this study, for several fundamental reasons: They are based on expressways only (our analysis required the treatment also of arterials); they were developed for specific sections of expressways (then extrapolated to represent other sections: a fundamentally different methodological approach than the model base used here); the American studies had available travel time *and* volume data (we had only time data); data were collected in the same way in all the cities (not the case in Canada); and, we did not always have critical information, such as distance.

6.3 Recommendations for Future Research

In sum, although the immediate analytical purposes of this study have been met, clearly further research is needed to better understand the phenomenon of non-recurrent congestion in Canada. This study has provided an important 'first-step' in addressing the phenomenon on a topic that is of fundamental importance to transportation economists and engineers alike; however – as with the first *Costs of Urban Congestion in Canada* – it is only a first step. We note that an improved analytical treatment would benefit the practice of transportation engineering and modelling as well as the practice and understanding of transportation pricing and policy. We would consider such improvements to be essential.

The research succeeded in developing practical and supportable estimates of non-recurrent congestion, appropriate to the level of analysis. However, from the more detailed perspective of traffic operational analysis, more detail would be beneficial; and in turn would enhance any subsequent analysis at this (planning) level. Accordingly, it is worth noting several methodological observations, which both identify important qualifications to the analysis and point to potential further research:

- Expressways that were operating at or close to the posted or free-flow speeds were not appropriate for consideration in this analysis; that is, because they were not operating under congestion.

- There were clear distinctions in the probability distributions between the congested and less-congested directions of a given section of expressway or arterial. Thus, the ability to distinguish data in this manner is important. However, it was not always possible with the given data; and the question arises as to how to address inconsistencies from section to section.

- A subsequent analysis should consider a further categorization of facilities, by location within the urban area - urban, suburban, fringe – in order to see if causal relationships could be identified. There are sizable quantities of data for Montréal and Ottawa-Gatineau; however, the analysis of all these data was beyond the resources and timing available for this study, and data from other urban areas should be developed to complement these. The Montréal data provide the opportunity to assess seasonal variations.

- A similar analysis should be developed for arterial data, in order to develop a more detailed categorization according to posted speed, cross section, side ‘friction,’ etc. However, compared with expressways, the existing data are somewhat sparse (Ottawa-Gatineau excepted). Therefore, significantly more arterial data would be required.

- Together, these categorized analyses for expressways and arterials, and the availability of supporting data, should be assembled into a technical guide for further application by the relevant authorities.

- An analysis of the AM and PM peak directional data for the same expressway sections in Ottawa-Gatineau found that the distributions and mean speeds were similar, but with greater variability (i.e., a higher Modified Buffer Index) in the PM peak period. For predictive purposes, it would be worthwhile to understand how, or if, these findings are associated with the differences in trip purposes and peaking characteristics that are associated with the two peaks, through the collection and analysis of similar data in other urban areas.

- As planning models evolve and are integrated with network micro-simulation models (which simulate the dynamics of traffic operations), it would be appropriate to investigate further and make more precise the methods to estimate non-recurrent congestion. However, this depends on the development of appropriate network micro-simulation models in different urban areas and, again, on the availability of the relevant data.

- As a final note, the approach and method used in this research were based upon those developed in and for the United States. That is, they are based upon observed traffic conditions, i.e. of travel times, speeds and traffic volumes. Thus, they provide quantitative tools that can be applied directly to actual data. In contrast, the European approach incorporates travellers' perceptions of the impact on their journey times of non-recurrent congestion. Although European practitioners and researchers recognize that a more quantitative approach is required (taking into account the American approach), we recommend that further development of the two approaches, *in combination*, be considered for Canada. The reason is that although the quantitative approach necessarily provides the analytical basis, the eventual implementation of, and the public's acceptance of, congestion mitigation measures requires an understanding of travellers' perceptions. The two go hand in hand; and – in fact – this point was established in MTQ's incorporation of local perceptions of when congestion begins into the choice of quantitative thresholds.

7. BIBLIOGRAPHY

No author given. *ATLANTIC – Proceedings of International Workshops on ITS Benefits, Evaluation and Costs at the 9th ITS World Congress, Chicago*. European Commission Directorate General Information Society. October 2002.

No author given. *Congestion charging impacts monitoring second annual report (Part 2 – congestion)*. Transport for London, London. 2004.

No author given. *Performance Indicators for the Road Sector: Summary of the Field Tests*. Organisation for Economic Cooperation and Development, Paris. 2001.

No author given. *Perceptions of and attitudes to congestion* (survey). United Kingdom Department for Transport, London. 2001.

Battelle Memorial Institute. *Time methods to support mobility performance monitoring – Otay Mesa Site Report*. Federal Highway Administration, Washington, DC. 2002.

Bell, K. *Valuing Emissions from Germiston Generating Project*. Convergence Research, Seattle. 1994.

Bullock, P., Jiang, Q. and Stopher, P.R. *Using GPS technology to measure on-time running of schedules bus services.* Journal of Public Transportation, Vol. 8, No. 1, 2005.

Cambridge Systematics et al. *Performance Measures and Targets for Transportation Asset Management*. NCHRP Report 551. Transportation Research Board, Washington, DC. 2006.

Fina, M.H. *Urban Spatial Structure and Household Travel Time*. (Chapter 5) Unpublished PhD. dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University, Blacksburg, VA. 2001.

Gourvil, L. and F. Joubert. Évaluation de la congestion routière dans la région de Montréal. Ministère des transports du Québec, Montréal. 2004.

Hallenbeck, M.E., McCormack, E., Nee, J. and Wright, D. *Freight data from intelligent transportation system devices.* Washington State Transportation Centre, Seattle, WA. 2003.

Jones, C., Murray, D. and Short, J. *Methods of travel time measurement in freight-significant corridors.* American Transportation Research Institute, Alexandria, VA. 2005.

Kouwenhoven, M., de Jong, G. and Rietveld, P. *Reliability Ratios voor het Goederenvervoer – Eindrapport / Reliability ratios for freight movements – Working Paper*. RAND Europe, The Hague. 2005.

Kriger, D., M. Baker, F. Joubert and G. Joubert. *Costs of Urban Congestion in Canada*. Final Report. Transport Canada, Ottawa. 2005.

Kriger, D. and Molloy, S. *Methods to Estimate Non-Recurrent Congestion in Canada*,. Transport Canada, Ottawa. 2005.

Li, R. *Examining travel time variability using AVI data.* Institute of Transport Studies, The Australian Key Centre in Transport Management, Victoria, Australia. 2004.

Lomax, T., S. Turner, G. Shunk, H.S. Levinson, R.H. Pratt, P.N. Bay and G.B. Douglas. *Quantifying Congestion*. *NCHRP Report 398*. TRB, National Research Council, Washington, DC. 1997.

Lomax, T., Schrank, D., Turner, S. and Margiotta, R. *Selecting Travel Reliability Measures.* Texas Transportation Institute, College Station, TX. 2003.

Lu, J., Ban X., Qiu, Z. Yang, F., and Ran, B. *Robust route guidance model based on advanced traveler information systems.* Transportation Research Board Annual Meetings, Washington, DC. 2005.

Medley, S. and Demetsky, M. *Development of Congestion Performance Measures Using ITS Information*, Final Report. Virginia Transportation Research Council, Charlottesville, VA. 2003.

National Cooperative Highway Research Program. *National Highway Cooperative Research Program: Current State of Research.* Transportation Research Board, Washington, DC. 2003.

Schrank, D. and Lomax, T. *The 2005 Urban Mobility Report.* Texas Transportation Institute and Texas A&M University System, College Station, TX. 2005.

Texas Transportation Institute et al. *International Border Crossing Truck Travel Time for 2001.* US Federal Highway Administration, Washington, DC. 2002.

Tu, H., van Lint, H. and van Zuylen, H. *Real-time modelling travel time reliability on freeways*. Consiglio Nzionale delle Richerche IASI. Rome, 2005.

Van Lint, J.W.C., Van Zuylen, H.J. *Monitoring and predicting freeway travel time reliability.* Transportation Research Board Annual Meetings, Washington, DC. 2005.

Warffemius, P. *Using the standard deviation of the travel time distribution as an indicator for valuing the reliability of travel time*. Transport Research Centre, Dutch Ministry of Transport, Public Works and Water Management, The Hague. 2005.

Weisbrod, G., D. Vary and G. Treyz. Economic Implications of Congestion. *NCHRP Report 463*. TRB, National Research Council, Washington DC. 2001.

Appendix A
Derivation of Skew-Normal Distribution

This exercise has been performed to see if a skew-normal distribution is a reasonable model of the distribution of travel time data.

The following information has been taken from http://tango.stat.unipd.it/SN/Intro/intro.html *A very brief introduction to the skew-normal distribution.* On the statistical side, the skew-normal distribution is often useful to fit observed data with "normal-like" shape of the empirical distribution but with lack of symmetry.

First, let us describe the skewed normal distribution. The component alpha is called the shape parameter because it regulates the shape of the density function. The following graphs show the shape parameter equal to 2, 5, and –5 (**Figures A-1, A-2** and **A-3**, respectively). A shape parameter equal to 0 is the normal distribution.

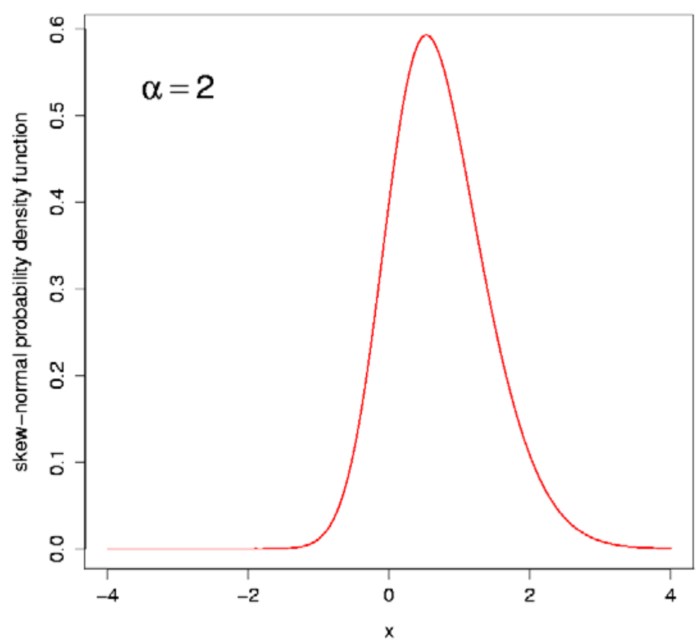

Figure A-1. Skew-Normal Distribution: Alpha = 2

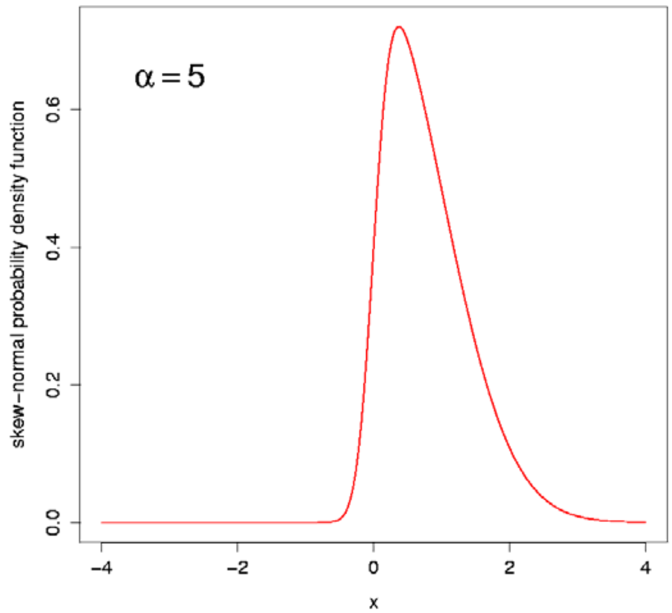

Figure A-2. Skew-Normal Distribution: Alpha = 5

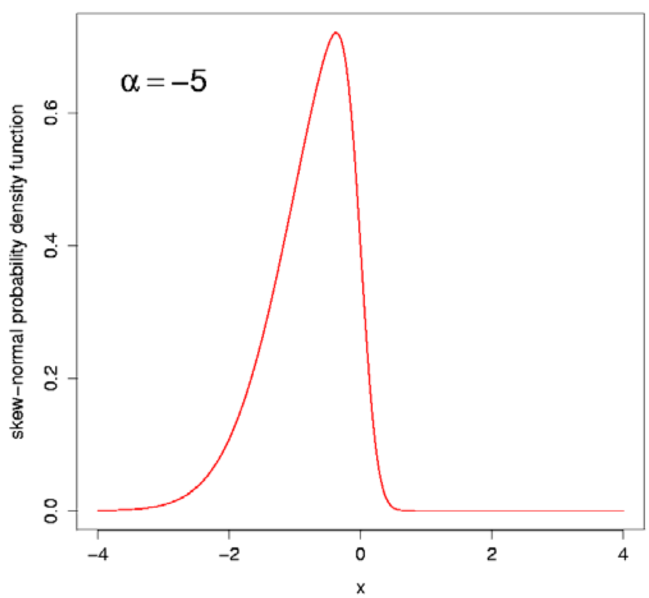

Figure A-3. Skew-Normal Distribution: Alpha = -5

In addition to the shape parameter, there is the *location* parameter which describes where on the x-axis the distribution appears, and there is the *scale* parameter which describes the size of the distribution. An online program allows one to play with the parameters to see how the distribution varies at http://azzalini.stat.unipd.it/SN/plot-SN1.html.

Travel time data are expected to have a normal distribution with a lack of symmetry. The shortest travel time is bounded by the operating speed limits of the road, whereas the longest travel times may be vary quite a bit depending upon the circumstance. The mean travel time is expected to be larger than the median travel time.

As a sample test, data were tested from 38 runs from Newmarket to Richmond Hill – both northern suburbs of the Greater Toronto Area - along Highway 404, an expressway. Each run is the same distance travelled, at roughly the same time of day, but on 38 different days (not consecutive days).

The raw data in seconds per run are listed in **Table A-1**. The mean time for the travel time is about 15 minutes.

Table A-1. Time in seconds for travel time.

Total Sec
2017
1870
1798
1482
1386
1385
1183
1177
1151
1137
1043
1030
1016
989
987
895
881
854
849

823
811
743
742
669
664
651
592
581
566
565
557
555
553
551
549
537
534
534

The data were then entered into an online modeling of the skew-normal distribution at http://azzalini.stat.unipd.it/SN/sn-fit.html . The data are plotted in **Figure A-4** as the histogram in yellow. The skew-normal distribution fitted to the data is shown as the blue line. Based upon a visual inspection of the data and model, a skew-normal distribution appears to be a reasonable fitting model.

Parameter estimates and standard errors are listed below:

	estimate	**s.e.**
location	533.0077	22.497
scale	541.6982	64.676
shape	33.4885	42.728

Request from 64.229.207.164 at 2006-07-12,04:04:21
This output has been produced by R in association with its packages 'CGIwithR','xtable' and 'sn'

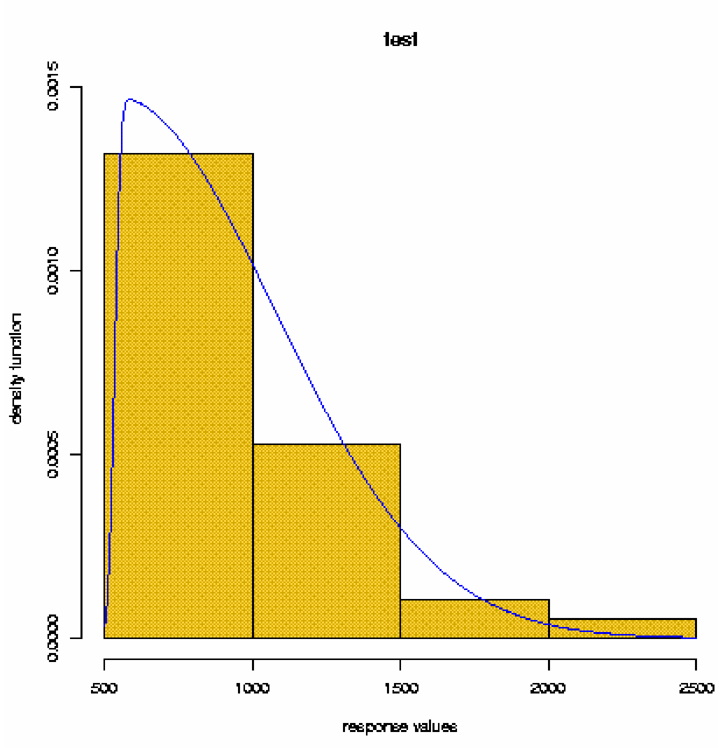

Figure A-4. Distribution of 38 *iTREC*® Runs (Sample Size: 38)

Appendix B

Calculation of Non-Recurrent Congestion and Costs *(spreadsheet)*