AGGREGATE ANALYSIS OF TRAVELLER ADAPTATION TO TRANSPORTATION NETWORK CHANGES - A STUDY OF THE IMPACT OF THE OPENING OF HIGHWAY 407

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ABSTRACT

The opening of Highway 407 in Toronto, and the subsequent introduction of tolls of this roadway, has provided an opportunity to examine the impact of extreme perturbations within an existing transportation system. This paper provides a quantitative analysis of aggregate traveller response. Specifically, 9 months of hourly volume count data from three locations on Highway 401, a major freeway facility that lies parallel to Highway 407, are examined. These data indicate that the opening of Highway 407 has had a statistically significant reduction of 4.9% on the average total daily cordon flows on Highway 401. However, the introduction of tolls on Highway 407, does not appear to have had a corresponding statistically significant impact. Seasonal variations in travel patterns were not explicitly considered within the analysis, with the result that the computed impacts may be underestimated. In addition to changes in total daily volumes, these perturbations also appear to have an impact on the temporal distribution of daily trips. The data do not permit conclusions to be made regarding the impact of changes in traveller's mode choices, or the extent to which demands are induced. It is recommended that an analysis method be developed by which the time required for the system to regain equilibrium can be determined.

KEYWORDS: traffic, freeway management, equilibrium, volume counts

INTRODUCTION

Substantial research and development efforts have been undertaken over the past 40 years to formulate models that capture travel behaviour. Traditionally, these models have attempted to quantify the number of trips undertaken, the origins and destinations of these trips, the transportation mode used for these trips, and the routes that drivers select. These models have typically relied on a number of assumptions, particularly the assumption that the system is at equilibrium. It is generally recognised by transportation engineers that the transportation system is never truly in equilibrium as the system is constantly perturbated by the impacts of incidents, weather, special events, road construction and maintenance, and variability in individuals travel needs. However, it is generally assumed that this amount of dis-equilibrium is not sufficient to invalidate the results of existing transportation models and methods, and is thus often ignored.

This paper examines extreme perturbations within a transportation system - namely the opening of Highway 407 in Toronto, in an attempt to provide a quantitative analysis of aggregate traveller response. Highway 407, a 6-lane limited access electronically tolled highway, traverses the northern edge of the Greater Toronto Area (GTA). This facility parallels Highway 401, the existing primary east-west transportation corridor. The first 36-kilometre section of Highway 407 opened on June 7, 1997, however, tolls were not implemented until October 14, 1997, providing two significant perturbations to the transportation system. The first perturbation occurred when Highway 407 opened, and the second occurred when tolls were implemented.

The impact of these perturbations on travel patterns is assessed by statistically examining loop data available from the COMPASS freeway traffic management system. Specifically, the analysis attempts to answer the following questions: How quickly do drivers reach a new state of equilibrium after the system is perturbated?; What are the characteristics of the system during this transition phase?; How does the provision of additional system capacity impact the temporal distribution of demand throughout the day?; and finally, Can this knowledge of traveller behaviour be used to improve traffic management measures?

It is expected that a better understanding of the response of travellers to changes in the transportation system will be useful not only with respect to large infrastructure changes, but also with respect to changes in traffic management policies, such as changing toll rates, implementing ramp metering, implementing high occupancy vehicle lanes, etc.

The following section of this introduction provides a description of the study network, and the approach taken within the analysis. Subsequently, the results of the analyses are presented. First, an assessment of the integrity of the COMPASS data is made. This is followed by a comparison between average non-holiday weekday total daily cordon volumes for each period. An assessment is also made of the presence of temporal shifts of traveller behaviour in each of the analysis periods. Finally, conclusions and recommendations are made.

Study approach

The opening of Highway 407, and the subsequent implementation of tolls, provides a unique opportunity for observing the reaction of travellers to large perturbations to the transportation system. In particular, the first perturbation occurred on June 8, 1997 when the first 36-km section of Highway 407 opened between Highway 410 in the West

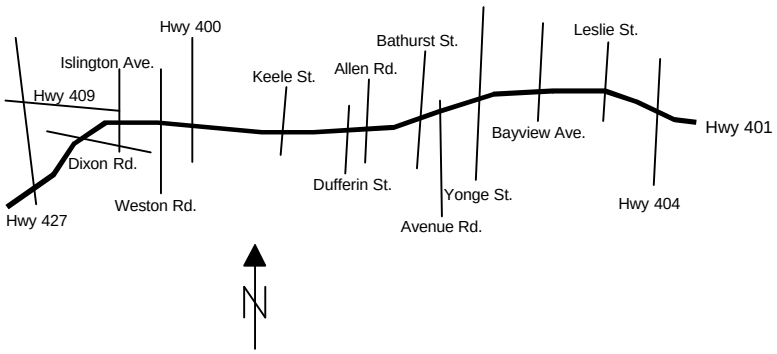

Figure 1: Highway 401 network in Toronto

and Highway 404 in the East. Tolls were not implemented on Highway 407 until October 14, 1997, at which time the second perturbation occurred. Thus, comparisons could be made between traveller behaviour prior to the opening of Highway 407 (this period is termed *Pre-407*), and when Highway 407 was open, but tolls were not charged (this period is termed *Pre-Tolls*). Comparisons could also be made between the period that Highway 407 was open without tolls, and the period following the implementation of tolls (this period is termed *Tolls*).

Since data were not available from Highway 407 directly, no direct analysis could be made of the change in traveller demand on Highway 407. However, the operation of COMPASS, a freeway traffic management system on Highway 401, provided loop detector data from Highway 401 (Figure 1), that could be analysed to assess changes in traveller behaviour between each of these three analysis periods.

The study approach consisted of three distinct phases. In the first phase, 1-hour aggregated loop detector volumes were examined to assess their reliability. Strategies were developed for addressing issues of missing data and data suspected of containing errors.

In the second phase, the data from each of the three analysis periods were assessed to determine if the total daily traveller demand on Highway 401 changed as a result of each of the perturbations.

Lastly, the data were examined to determine if traveller demands exhibited temporal shifts as a result of each of the perturbations.

Results from each of these study phases are presented in the following sections.

NOMENCLATURE

$DT_{F,D}$	=	daily total traffic volume for facility F, on day D (vph)
D	=	date
F	=	facility (i.e. EC, EE, WC, WE)
$AV_{t,w,F}$	=	average hourly volume computed from all 275 days (vph)
$V_{F,D,t}$	=	hourly volume
t	=	time of day (hours)
w	=	day of week (Sunday, Monday, Tuesday, ... Saturday)
$N_{w,nh}$	=	number of non-holiday days, of type w, in entire data set
$N_{P,nh}$	=	number of non-holiday weekday days in period P
N_F	=	number of lanes on facilities F at the location of interest
DCT_D	=	total non-holiday daily cordon volume for day D (vph)

$ADCT_P$ = average total non-holiday weekday cordon volume for period P (vph)
$SDCT_P$ = standard deviation of total non-holiday weekday cordon volume for period P (vph)

ANALYSIS OF RESULTS

Evaluation of Data Integrity

The Ontario Ministry of Transportation provided aggregated 1-hour volume data for 275 days, from April 1, 1997 through to December 31, 1997. Data were examined for three locations, namely Dixon Road, Keele Street, and Yonge Street. For each site, data were obtained for each facility and direction of travel. Thus, for the Keele Street and Yonge Street locations, data were obtained from the eastbound collector lanes (EC), eastbound express lanes (EE), westbound collector lanes (WC), and westbound express lanes (WE). At the Dixon Road location, the freeway is not divided into collector and express facilities, so data were available for only the eastbound direction and westbound direction.

Loop detector volumes are obtained from the field at 20-second intervals. These 20-second data are aggregated within the COMPASS software to provide 1-hour average volume data. As part of the internal data evaluation process, the COMPASS system attempts to distinguish between data that are considered reliable and those that are considered less reliable or *suspect*. If less than 95% of the 180 20-second counts that comprise the 1-hour average are available, then the hourly volume will be considered *suspect*. Suspect data are identified by reporting the volume as negative instead of positive.

It is the practice of MTO personnel to use the suspect data as valid data when the absolute value of the reported 1-hour volume is considered reasonable. However, as the definition of reasonable is often difficult to define, all suspect data encountered within this study were discarded.

Figure 2 illustrates the proportion of the 1-hour volume data observed in the eastbound

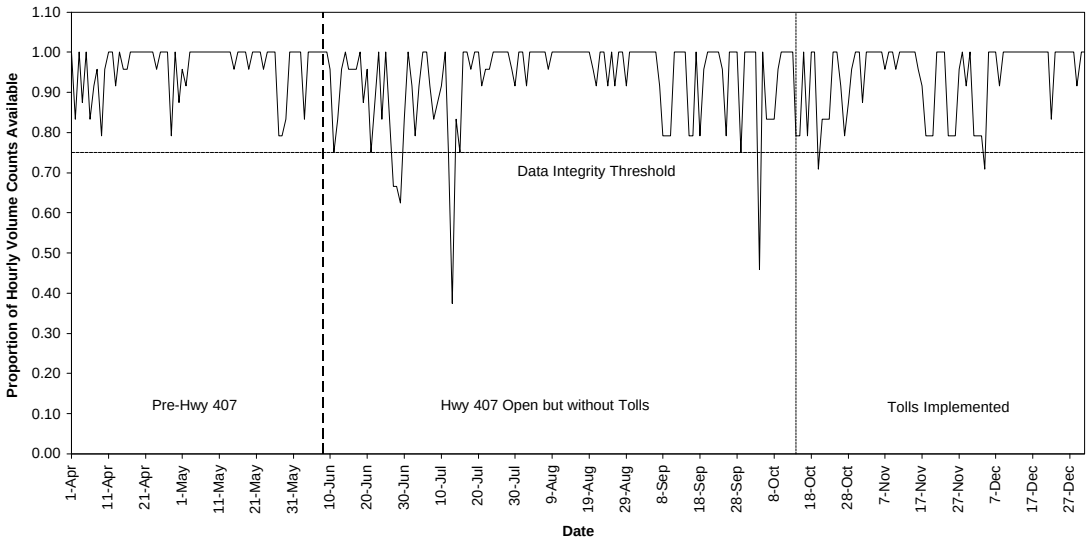

Figure 2: Proportion of hourly traffic volumes available for each day from the Eastbound Collector lanes at Keele Street

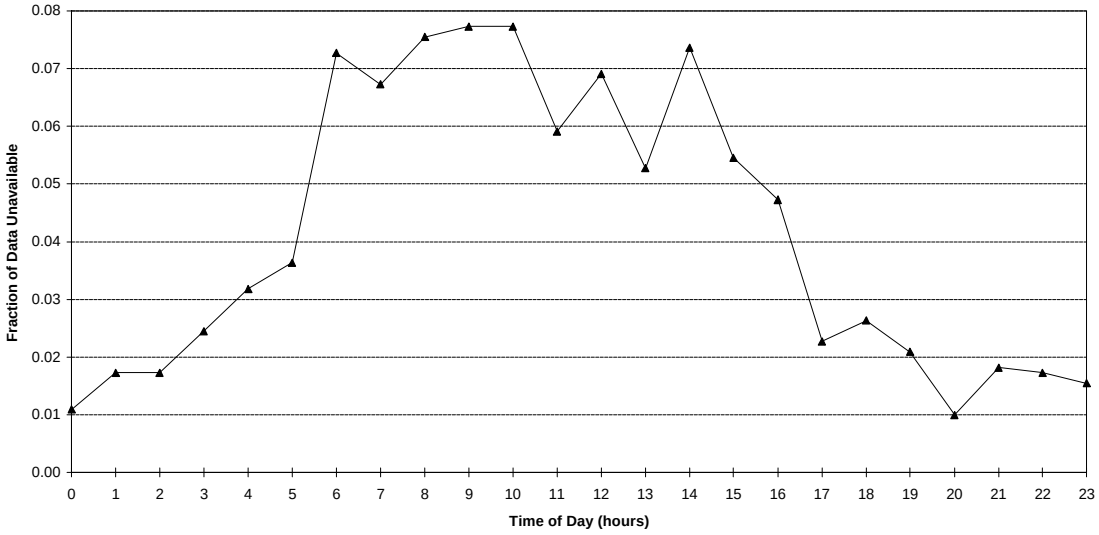

Figure 3: Average distribution of unavailable data by time of day for Keele Street (computed on basis of all days between April 1 and Dec. 31, 1997)

collector lanes at Keele Street that were available during each day between April 1 and December 21, 1997. It is clear from Figure 2, that while the proportion of data available varies substantially, for all but a few days, data were available for more than 75% of the 24-hour period (i.e. 18 1-hour periods).

It was also of interest to determine if, on average, data were uniformly available throughout the day. Figure 3 illustrates the average proportion of data not available for each hour of the day at Keele Street. The average proportion is computed on the basis of all 275 days of data. It is evident from Figure 3 that the distribution of data availability is not uniform throughout the day. This implies that an average scaling factor is not appropriate when attempting to determine the daily total volume, as 1-hour volumes during the period from 6 AM to 4 PM are more likely to be unavailable, and these volumes are also larger in magnitude than the volumes from 4 PM to 6 AM.

Assessment of Changes in Average Total Daily Travel

It was desired to determine when the introduction of Highway 407 without tolls and then later with tolls had a statistically significant impact on the total daily travel experienced on Highway 401. To address this question, it was necessary to compute the mean and standard deviation of the total daily cordon volume for each analysis period, at each of the three locations. To avoid biases, only data from non-holiday weekdays were used. A total of 8 holidays were identified within the period from April 1 through December 31, 1997, including Victoria Day (Monday, May 19), Canada Day (Tuesday, July 1), Civic Holiday (Monday, August 4), Labour Day (Monday, September 1), Thanksgiving Day (Monday, October 13), Remembrance Day (Tuesday, November 11), Christmas Day (Thursday, December 25), and Boxing Day (Friday, December 26).

Equation 1 was used to determine the total daily volume associated with each facility for each day. However, in many instances, the hourly volume ($V_{F,D,t}$) was not available. In order to enable the estimation of the daily total volume, the average hourly volume ($AV_{t,w,F}$) was computed on the basis of all non-holiday data using Equation 2. Then, when

the hourly volume ($V_{F,D,t}$) was not available, the average daily volume ($AV_{t,w,F}$) was used in Equation 1 instead.

To limit the amount of error that might be introduced through the use of average hourly volumes in place of observed volumes, daily total volumes were only computed if a minimum of 75% of the 24 1-hour observed volumes ($V_{F,D,t}$) were available. If less than 75% of the 1-hour volumes were available, no daily total was computed for that facility and day.

$$DT_{F,D} = \sum_{t=1}^{24} V_{F,D,t} \quad [1]$$

$$AV_{t,w,F} = \frac{1}{N_{w,nh}} \sum_{D=1}^{N_{w,nh}} V_{F,D,t} \quad [2]$$

As indicated in Equation 3, the total non-holiday daily cordon volume was computed as the summation of the individual facility daily volumes. Daily cordon traffic volumes were only computed for those days for which daily traffic volumes ($DT_{F,D}$) were computed for all facilities.

$$DCT_D = \sum_{F=1}^{N_F} DT_{F,D} \quad [3]$$

Figure 4 illustrates the total daily cordon traffic volumes resulting from the application of Equation 3 to the data from the Dixon Road, Keele Street, and Yonge Street locations. Several observations can be made:

First, the Dixon Road location experiences total cordon volumes that are approximately 70% of the cordon volumes observed at Keele Street and Yonge Street. Second, there are a number of days for which total cordon volumes could not be computed. This is

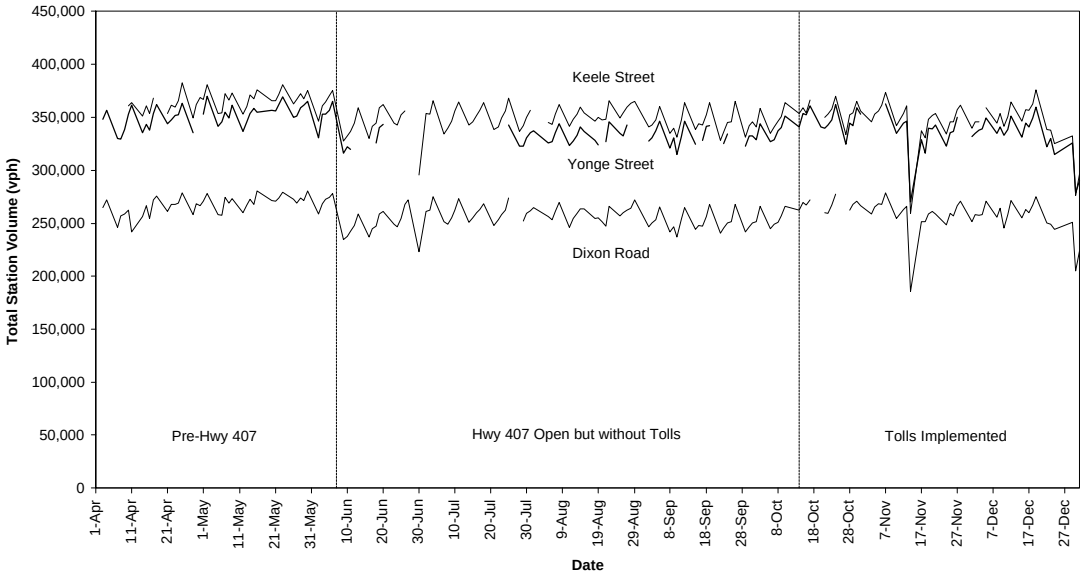

Figure 4: Total non-holiday weekday daily cordon volume observed at Dixon Road, Keele Street, and Yonge Street

particularly evident for the Yonge Street location between June 23 and July 24. Third, there appears to be substantial variation in total cordon volume by day. Fourth, there appears to be several days in December that experience total cordon volumes that are noticeably lower than expected. It is suspected that the lower volumes during the Christmas season are seasonal effects rather than erroneous data.

In order to test for an impact of the opening of Highway 407, or the imposition of tolls, on the average demand on Highway 401, the average total non-holiday weekday daily cordon volume was computed for each period using Equation 4, and the standard deviation of total daily cordon volume was computed using Equation 5. The standard approach for testing differences of means was used. The null hypothesis for all tests was that the average daily cordon volumes from both periods were obtained from the same underlying population. All tests were conducted at the 95% level of significance. The pooled standard deviation was computed using Equation 6. If the absolute value of the difference in means was less than 1.96 $\times$ the pooled standard deviation, then there existed no evidence to reject the hypothesis. Table 1 provides the results for each of the three locations.

$$ADCT_P = \frac{1}{N_{P,nh}} \sum_{D=1}^{N_{P,nh}} DT_{F,D} \quad [4]$$

$$SDCT_P = \frac{1}{N_{P,nh}-1} \sum_{D=1}^{N_{P,nh}} \left(DCT_D - ADCT_P\right)^2 \quad [5]$$

$$\hat{S} = \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \quad [6]$$

It is evident from Table 1, that at the cordon level, the average non-holiday total

Table 1: Results from hypothesis testing of difference of mean average daily volumes

Location	Comparison	Facility				
		EC	EE	WC	WE	Cordon
Dixon Road[1]	Pre-407 vs. Pre-Tolls		R		R	R
	Pre-Tolls vs. Tolls		A		R	A
	Pre-407 vs. Tolls		R		R	R
Keele Street	Pre-407 vs. Pre-Tolls	R	R	A	R	R
	Pre-Tolls vs. Tolls	A	A	A	A	A
	Pre-407 vs. Tolls	R	R	R	R	R
Yonge Street	Pre-407 vs. Pre-Tolls	R	R	R	R	R
	Pre-Tolls vs. Tolls	A	R	A	R	A
	Pre-407 vs. Tolls	R	R	R	R	R

[1] Only a single facility exists for each direction of travel at Dixon Road

Notes:

H_0 = average non-holiday weekday total daily volumes observed in two periods result from the same population mean

A = accept hypothesis; R = do not accept hypothesis

Testing conducted at 95% level of significance

Table 2: Percent change in mean average daily volumes

Location	Comparison	Facility [2]				
		EC	EE	WC	WE	Cordon
Dixon Road[1]	Pre-407 vs. Pre-Tolls	-1.6%		-7.5%		-4.8%
	Pre-Tolls vs. Tolls	-0.4%		+2.8%		+1.3%
	Pre-407 vs. Tolls	-2.0%		-5.2%		-3.7%
Keele Street	Pre-407 vs. Pre-Tolls	-5.7%	-5.9%	-2.1%	-1.9%	-4.7%
	Pre-Tolls vs. Tolls	-0.4%	+0.3%	-1.3%	0.0%	-0.3%
	Pre-407 vs. Tolls	-6.4%	-6.0%	-3.4%	-2.0%	-5.2%
Yonge Street	Pre-407 vs. Pre-Tolls	-3.6%	-7.2%	-3.2%	-6.3%	-5.3%
	Pre-Tolls vs. Tolls	-0.6%	+3.3%	-0.9%	+3.0%	+1.4%
	Pre-407 vs. Tolls	-4.3%	-4.3%	-4.2%	-3.6%	-4.2%

[1] Only a single facility exists for each direction of travel at Dixon Road

[2] Percent Change computed as $\Delta = \frac{\left(\overline{V}_2 - \overline{V}_1\right)}{\overline{V}_1} \times 100\%$

weekday daily volumes can be considered to be statistically different prior to Highway 407 opening from those during the period when Highway 407 was open but without tolls, as well as different from those during the period when tolls were imposed. However, there is no statistical evidence to state at the 95% confidence level that the average non-holiday total weekday daily volumes during the period when Highway 407 is open but without tolls are different from those during the period when tolls are imposed.

The test results for the individual facilities are predominately consistent with the results obtained for the cordons. Interestingly, at Yonge Street, the null hypothesis is rejected for both express facilities (i.e. WE and EE) when comparing *Pre-Tolls* to *Tolls*.

While the results in Table 1 demonstrate that the opening of Highway 407 had a statistically significant impact on the average total volumes observed on Highway 401, these results do not provide any insight as to the magnitude or direction of these impacts. Table 2 provides the percent change in the average non-holiday total weekday daily volumes for each of the locations and analysis periods.

At the cordon level, when Highway 407 opened without tolls, the total cordon volumes at Dixon Road, Keele Street, and Yonge Street were reduced by 4.8%, 4.7%, and 5.3% respectively. This trend is consistent with expectation, as many of the drivers that had been using Highway 401, would have altered their routes to use Highway 407, once this facility was opened. When tolls are imposed on Highway 407, the cordon volumes at Dixon Road increase by 1.3%, are further reduced at Keele Street by 0.3% and are increased at Yonge Street by 1.4%. On the basis of the results provided in Table 1, it is clear that these changes are not statistically significant.

Since volume data were not available for Highway 407, it is not possible to estimate the proportion of these changes that results from simple route switching by existing drivers, and the proportion that results from switches in mode and/or induced demand.

It must be noted that the analysis has not considered the impact of seasonal fluctuations in travel patterns. It is generally observed that travel volumes peak during the summer months. While this impact has not be considered, it is anticipated that this seasonal variation in demand may have reduced the computed impact that the opening of Highway 407 and the subsequent introduction of tolls, had on flows on Highway 401.

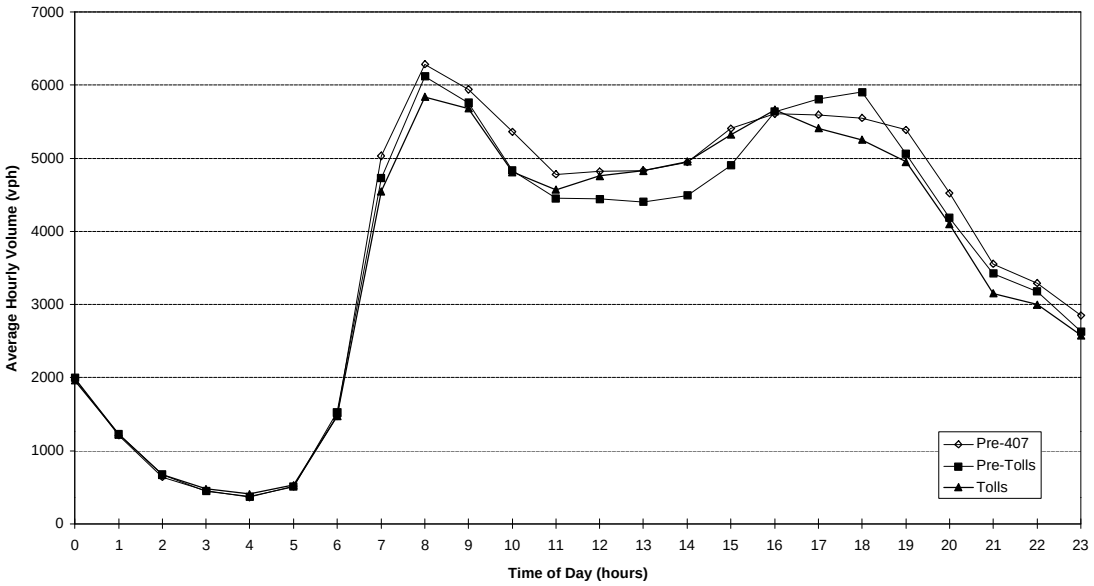

Figure 5: Average cordon hourly volumes for Wednesdays during each analysis period at Keele Street

Assessment of Changes in Demand by Time of Day

Having established the average total daily impact of the opening of Highway 407 and the subsequent imposition of tolls, it is desirable to determine if these events also had an influence on the daily temporal distribution of demand.

To illustrate, consider Figure 5, which depicts the average hourly cordon traffic volume at Keele Street for each of the three analysis periods. The average cordon volumes are computed for all non-holiday Wednesdays in each period.

It appears from Figure 5 that there is very little difference in the average hourly cordon volumes between the three analysis periods prior to 6 AM and after 8 PM. During the AM Peak period (6AM to 10 AM) the *Pre-407* volumes appear to be the largest, while the *Tolls* volumes are the smallest. During the PM Peak period (4 PM to 8 PM) *Pre-Tolls* volumes appear to be the largest, while the *Tolls* volumes are again the smallest. During the Off-Peak period the *Pre-Tolls* volumes are the smallest and the *Pre-407* volumes are the largest.

The same analysis procedure used for testing the significance of the mean cordon volumes, which was described in the previous section, was used to test the significance of the hourly volumes. The average hourly volume for each day of the week at each location was tested. The results of these tests are summarised in Figure 6, which illustrates the proportion of the test results indicating that the null hypothesis (i.e. that the hourly volumes in each analysis period were drawn from the same population) was rejected.

Figure 6 indicates that the largest proportions of hourly volumes that are significantly different are observed during the mid-day off-peak periods. Greater than 80% of the *Pre-407* mean mid-day off-peak hourly volumes are statistically different from those observed in the *Pre-Tolls* period. For this same comparison, only 20% of the AM Peak volumes and between 8% and 45% of the PM-Peak volumes are statistically different.

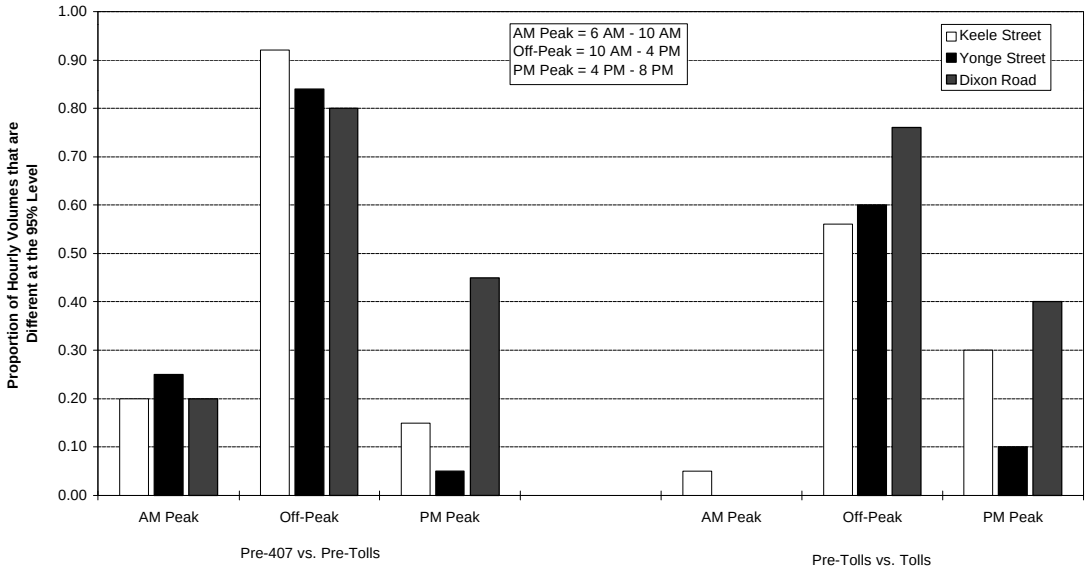

Figure 6: Temporal distribution of mean hourly cordon traffic counts that are different between periods at the 95% level

From these results, it would appear that the greatest changes in hourly volumes occurred during the mid-day off-peak period. However, these test results must be interpreted carefully. These results reflect comparisons between the magnitude of observed mean and standard deviation of hourly volumes. However, it has already been established that the mean total daily volumes have also changed. Thus, it could be expected that even if the relative distribution of total daily traffic throughout the day remained the same, there might be a statistically significant difference between the observed hourly volumes. Thus, it may be more appropriate to compare the **proportion** of the total daily volume observed during each hour, rather than the actual observed volume. While the results of such a statistical comparison are not presented within this paper, Figure 7 illustrates this

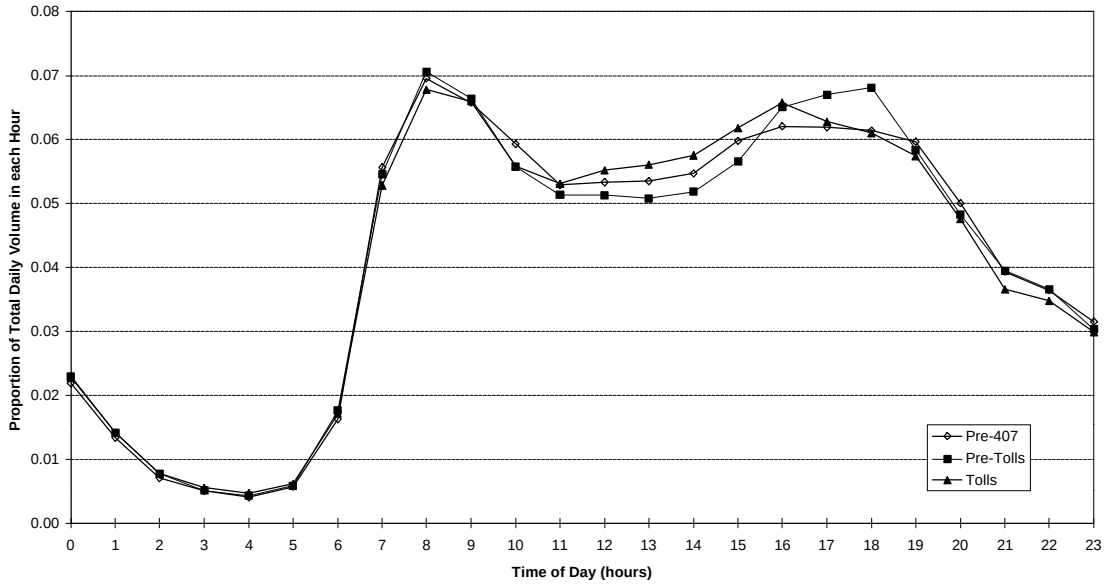

Figure 7: Average proportion of total daily cordon volume observed in each hour on Wednesdays at Keele Street

comparison for Wednesday data collected at Keele Street.

CONCLUSIONS AND RECOMMENDATIONS

The opening of Highway 407 in Toronto, and the later introduction of tolls on Highway 407, are observed to act as significant perturbations to the transportation system in Toronto. The impact of these perturbations has been assessed on the basis of 9 months of hourly volume data from three locations (Dixon Road, Keele Street, and Yonge Street) on Highway 401.

The opening of Highway 407 on June 8, 1997 is observed to have had a statistically significant impact on the average total daily cordon volume experienced on Highway 401 at all three locations analysed. On average, across all three locations, a decrease of 4.9% in average total daily cordon traffic was observed.

The implementation of tolls of Highway 407 on October 14, 1997 does not appear to have had a statistically significant impact on the average total daily cordon volume experienced on Highway 401. On average, across all three locations, an increase of 0.8% in average total daily cordon traffic was observed.

The observed impact of the opening of Highway 407 and of the subsequent introduction of tolls may have been mitigated by the impact of seasonal travel demand trends. Typically, travel volumes are at their peak during the summer months, and are substantially reduced during the Christmas season. It is recommended that the analysis be extended to explicitly consider these seasonal variations.

The available data do not support an investigation of the extent to which mode shift occurred or the amount of traffic demand that was induced by the addition of highway capacity.

The analysis of temporal distribution of daily traffic indicated that few changes in peak period hourly volumes were observed, but that substantial changes in mid-day off-peak hourly volumes were observed. These results may be biased by the type of analysis conducted, and it is recommended that a further analysis be undertaken in which the hourly proportions of total daily traffic be compared, rather than the observed average volumes.

The data analysed did not exhibit any obvious trends that would indicate the length of time required for the system to regain a state of equilibrium after each perturbation. It had been speculated that the observed changes in the variance of volume over time could be used as a measure of dis-equilibrium, however this analysis has not yet been completed. It is recommended that further work be conducted to develop an analysis methodology for assessing the time required by the system to regain equilibrium.

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