A Speed-Delay Study of Highway 401 in Toronto, Ontario

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ABSTRACT

Travel time is an important measure of performance for most traffic facilities. Unfortunately, obtaining accurate travel time information, using traditional floating car study methods, is often costly and time consuming. For freeway traffic management systems (FTMS), induction loop detectors can be used to measure spot speed, volume and occupancy at many locations simultaneously. These data could be used to compute trip travel times in a cost effective manner, but it is not clear if these estimates are sufficiently accurate. This paper describes a speed-delay study conducted on Highway 401 in Toronto, Canada in which a traditional floating car study was carried out over three days during June and August of 1992. Data for 37 eastbound and 40 westbound trips were collected. The trips encompassed the freeway section from Morningside Avenue to Eglinton Avenue, which represents a distance of approximately 35 km. Sampling of the peak commuting periods was ensured with trip departure times between 6 AM and 10 AM, and 3 PM and 7 PM. Free speed trip travel times were approximately 19 minutes while the longest observed trip time, on a Friday afternoon, was 54 minutes.

An analysis of the observed trip travel times was conducted using ANOVA and regression techniques. The results indicated that direction of travel and facility utilized (express or collector) are not significant factors in explaining the variations observed within the data. However, day of week and time of day were both found to be significant factors. A regression equation, calibrated to the AM data, is found to explain 71.5% of the variation within the observed AM data. A second regression, calibrated to the non-Friday PM data, is found to explain 82.4% of the observed variation in PM trip duration.

The observed trip travel times were compared with trip travel times estimated from FTMS detector data. The resulting correlation coefficient of 0.42 indicates that though there is some correlation between these different data sources, this correlation is too weak to accept trip travel times, which are estimated from FTMS detector data, as being representative of true field conditions.

Highway 401, which consists of separated express and collector facilities in both directions throughout Toronto, provides a unique opportunity to investigate travel times on two competing routes. If, as is usually assumed in most traffic assignment techniques, drivers route themselves in order to minimize their trip travel time, then the two competing routes that are utilized, should exhibit very similar travel times. An examination of data for Highway 401 indicated that the two competing routes have average differences in trip travel times that range from 5 to 8.5%.

The specific characteristics of Highway 401 are identified through the use of time-space diagrams. From these diagrams, congestion, such as that due to lane reductions at Keele Street in the eastbound collector lanes, is clearly identifiable.

INTRODUCTION

Background

Travel time is likely the single most important factor that drivers consider when evaluating the utility of alternative routes. In traffic assignment techniques, it has long been assumed that drivers select their routes in an attempt to minimize this travel time. Reductions in delay, or decreases in travel time, are also often used in benefit - cost analyses of proposed system improvements. In addition, trip or link travel times are often fundamental outputs of many traffic simulation models. However, despite the demonstrated wide use of travel time as a measure of performance, accurate travel time data are often difficult and/or costly to obtain, especially when such travel time data are know to vary significantly as a function of a trip's departure time.

The increased deployment of Freeway Traffic Management Systems (FTMS), which collect traffic volumes and speeds automatically, has increased the opportunity to obtain accurate estimates of travel times based on measured spot speeds.

This paper describes a travel time study conducted on Highway 401, a multi-lane freeway facility, in Toronto, Canada. This freeway forms the primary east-west commuting and through traffic corridor for the Greater Metropolitan Toronto Area. An FTMS, called COMPASS (Korpal, 1992), is currently operating on part of this freeway. A floating car study was carried out on this freeway on three separate days to collect travel time data. These data are examined to quantify the observed variations in trip duration. A comparison of observed travel times is made to those estimated from FTMS loop data. An analysis of the observed travel times is also made with respect to the effect of departure time, variations between days, and variations between competing routes (express vs. collector).

Study Objectives

The travel time study described in this paper was conducted primarily to obtain accurate measures of performance of the existing Highway 401 freeway system under varying peak and off-peak conditions. This information, in the form of trip durations and time-space trajectories, could be examined in order to satisfy a number of objectives, namely:

a. The travel time study measured a finite number of trip travel times. These data represent but a statistical sample of the entire true trip travel time distribution. The first objective then, is to quantify the variability that exists in total trip travel times for identical traffic conditions.

b. A second objective is to understand and quantify the variations in trip duration over different days and over different times during the day. This understanding is important, as any conclusions regarding travel time reductions, requires the analyst to first understand the existing variations in trip duration.

c. The freeway section used in this study is unique in that it consists of two separated facilities in each direction, an express and collector facility. These two facilities are connected by several transfer roadways providing routing alternatives for drivers (a more detailed description of the system appears later in this paper). If travel times on competing routes could be accurately determined, then some indication of how drivers were routing themselves could be obtained. This information on its own is useful as it provides some insight into how well drivers route themselves in comparison to the well known user optimal principles of Wardrop (1952). Based on these principles, it is consistently assumed that under equilibrium conditions, drivers will route themselves according to this user-optimal solution. Unfortunately, little empirical data exist indicating how well the user-optimal routing principles reflect reality, even in a network where the two competing routes are within view of each other along most of the length of the route. If user-optimal routing principles do not accurately reflect reality, then many of the simulation studies that are presently being conducted, may become suspect, particularly those involving any benefit-cost analysis of Intelligent Vehicle Highway Systems (IVHS).

   For Highway 401, the FTMS includes Changeable Message Signs (CMS) at several transfer roadways between the express and collector facilities. If the results of this study suggest that drivers are not routing themselves efficiently, then some additional capacity may exist in the system that could be utilized by using the CMS to more effectively influence the current driver routings.

d. A fourth objective is to determine if accurate trip durations can be derived indirectly from FTMS data. The observed speed-delay data from floating car runs could be compared to speed-delay data estimated from the FTMS detector volume, occupancy and spot speed data. Clearly, if the correlation between these two data sources is high, then speed-delay data estimated from FTMS data could be used confidently in the future.

e. The fifth objective is to identify system specific characteristics, such as bottlenecks, based on the time-space data collected. This information can be useful for the effective management of the system.

f. The last objective is to provide quantitative measures of performance of the system. A simulation study of the Highway 401 system through Toronto was carried out using the network traffic simulation model INTEGRATION (Rakha *et al.*, 1989; Van Aerde, 1985). To validate the simulation model's results, some accurate measure of the system's performance was required. The speed-delay information described in this paper were used to calibrate and evaluate the simulation model's results (Hellinga *et al.*, 1993; Hellinga and Van Aerde, 1994)

Description of Highway 401

The freeway site studied, which is illustrated in Figure 1, consists of a 35 km section of Highway 401 in Toronto, Canada. This highway is aligned in an east-west orientation and provides the primary transportation route for traffic traveling through Toronto, as well as for many commuting trips with one or both trip ends in Metropolitan Toronto. Highway 401, having an average annual daily traffic (AADT) of approximately 320,000 vehicles, is the second heaviest traveled section of roadway in North America. At one point, the freeway cross-section consists of 16 directional traffic lanes.

One unique feature of this freeway is that each direction consists of an express and collector facility. The collector facility provides primary access from and to the major arterial roads and other freeways connected to Highway 401. The express facility has limited access to and from the collector facility via high speed transfer roadways. The system of separated facilities provides drivers with routing alternatives. The system of express and collector facilities extended in 1992 from Neilson Road in the east to Islington Avenue in the west. Construction was underway at the time of the study to extend the express and collector system eastward. This extension is being completed in 1994.

For this study, travel time data were observed from Morningside Avenue in the east, to Eglinton Avenue in the west. This portion encompassed the entire express and collector facility existing in 1992. This section of Highway 401 includes 22 interchanges with connecting arterial roads and other freeways. Table 1 provides the number of on and off ramps and transfer roadways that exist in each direction within the study area.

Description of COMPASS

Early in 1991, the Ontario Ministry of Transportation (MTO) began operation of a freeway traffic management system entitled COMPASS. A more detailed description of the COMPASS system is provided by Korpal (1992).

COMPASS maintains a complete record of incidents that occur on the system. Detection is facilitated by an incident detection algorithm and visual surveillance by the CCTV cameras. Incident log information includes incident start time, duration, location, and severity in terms of the number of lanes blocked. Only travel time data that were deemed to be unaffected by the logged incidents were used in the analysis.

The Highway 401 study area was coded into a network of directed links and nodes. Links were defined such that a single link existed for each existing FTMS detector station. Link boundaries were defined such that detector stations were positioned near the midpoint of the link. This permitted an association to be made between spot FTMS detector speed data and observed travel time, as detector speeds were assumed to remain constant for the entire link.

STUDY METHODOLOGY

The travel time study was carried out on three separate days: Monday, June 8; Thursday, August 6; and Friday, August 7, 1992. Weather conditions were favorable on all three days, precluding abnormal traffic behavior due to inclement weather.

Data were obtained through the use of floating cars. On June 8, two cars were used while on August 6 and 7, three vehicles were used. For all trips, each vehicle contained two people. One person drove the vehicle while the second person utilized a stop watch to record cumulative travel time as the vehicle passed pre-defined landmarks. The driver maintained average traffic stream speed by ensuring that, for the direction of travel, the vehicle passed as many vehicles as it was passed by (ITE, 1992; Box and Oppenlander, 1976).

On June 8, two vehicles operated independently, providing no correlation of trip departure times. On August 6 and 7 vehicle operations were correlated such that two of the three vehicles began their trips at the same time. Of these two vehicles, one traversed the study section using the express lanes. The other vehicle used the collector lanes for its entire trip. The third vehicle delayed its departure time by 5-10 minutes and utilized either the express or collector lanes for its entire trip.

The study consisted of acquiring travel times between successive on and off ramps on Highway 401 for both the eastbound and westbound express and collector lanes. The vehicles traversed the four possible routes throughout the day, ensuring that data were collected for the morning (6 AM to 10 AM) and afternoon (3 PM to 7 PM) commuting periods.

Paint lines were used as reference marks for timing. At on ramps, the bull nose created by converging paint lines represents the first instance when vehicles can make the transition onto the highway. Similarly, the bull nose created by diverging paint lines at off ramps represents the last instance when vehicles can safely exit the highway. All timings were made in relation to the first on ramp encountered in a given direction of travel. The stop watch was initialized at that time and then the time of each subsequent on ramp or off ramp occurrence was recorded.

Data collection forms listing all relevant locations at which cumulative times were to be recorded were constructed prior to the time of data collection. A different form for each direction and facility was required. Table 2 illustrates the data collection form for the express lanes of Highway 401 eastbound.

Raw travel time data were checked for anomalies and suspect trip data was discarded. Table 3 provides trip departure times and observed total trip travel times by day, direction and facility.

ANALYSIS OF RESULTS

Analysis of variation within the observed data

Transportation systems, such as Highway 401, often experience significant spatial and temporal variations in their operating characteristics. Countless other factors may influence how the system behaves, such as weather, location and severity of accidents, day of the week, time of day, construction, and special events, to list a few.

In this study, an attempt was made to control as many of these other factors as possible. Incident effects were removed, and adverse weather conditions were avoided. Construction impacts existed, but these remained constant for all three days during which the study was conducted. By minimizing these factors, it was possible to analyze variations in total trip travel time due to the day of the week and the time of day effects.

Four factors that impact trip duration were identified and explicitly examined in this study. These factors include; direction of travel (eastbound, westbound), facility used during trip (express, collector), day of the week (Monday, Thursday, Friday), and time of the day when the trip was started. Time of day was initially discretized into four classes; AM peak (7-9 AM), AM off-peak (prior to 7 AM or between 9 AM and 12 noon), PM peak (4-6 PM), and PM off-peak (between 12 noon and 4 PM or after 6 PM).

An analysis of variance (ANOVA) was carried out on the measured trip duration data to determine which of these four factors played a significant role in explaining the observed variation in the data. The results of this analysis are presented in Table 4. For each factor, the null hypothesis is that the duration of all trips come from the same distribution and that the mean trip duration is statistically the same for each category. If a 5% chance of an incorrect decision is accepted, then as indicated by the probabilities in Table 4 that exceed 0.05, the null hypothesis can not be rejected for the *Direction* and *Facility* factors. This indicates that *Direction* and *Facility* used were not found to be significant factors contributing to the observed variance in trip duration. However, as indicated in Table 4, the factors *Day* and *Time* were both found to be significant factors.

On the basis that *Day* and *Time* were the only significant factors in describing trip duration, a multiple linear regression model, having two binary variables, was fit to the 77 observed data points and found to explain 62.6% of the existing variance.

$$T = a + bZ_1 + cZ_2 \qquad [1]$$

where:

- T = regression estimate of trip duration (minutes)
- Z_1 = 1 if trip made on Monday or Thursday during the PM peak
- Z_2 = 1 if trip made on Friday during the PM peak
- a = 24.49 (minutes)
- b = 6.60 (minutes)
- c = 21.10 (minutes)

All three of the estimated coefficients were found to be statistically different from zero at the 95% confidence level (student t values: t_a = 5.31, t_b = 4.36, t_c = 10.68) and the standard error of the estimated trip duration was 4.6 minutes.

Regression equations provide an unbiased best estimate of the mean value of the dependent variable for given independent variables. However, for any given value(s) for the independent variable(s), there lies about the regression line a distribution of the dependent variable. In order to quantify this distribution of the trip duration, prediction intervals were computed.

The prediction interval for the conditional mean for small samples can be computed from Equation [2] while the prediction interval for an individual trip duration can be computed from Equation [3].

$$m_{T\cdot Z_i} = T \pm t_{a/2} S_{T\cdot Z_i} \sqrt{\frac{1}{n} + \frac{\left(Z_i - \bar{Z}\right)^2}{\sum Z^2 - \left(1/n\right)\left(\sum Z\right)^2}} \qquad [2]$$

where:

- $m_{T\cdot Z_i}$ = predicted interval estimate of the conditional mean trip duration (minutes)
- T = regression estimate of mean trip duration (minutes)
- $S_{T\cdot Z_i}$ = standard error of the estimated trip duration (minutes)
- n = number of observations in regression analysis
- $t_{a/2}$ = student t value for a total tail area of α ($t_{0.025} \approx 2.0$)
- Z = time at which observed trip departs (hours)
- $\bar{Z}$ = mean trip departure time (hours)

$$T_I = T \pm t_{a/2} S_{T\cdot Z_i} \sqrt{\frac{1}{n} + \frac{\left(Z - \bar{Z}\right)^2}{\sum Z^2 - \left(\frac{1}{n}\right)\left(\sum Z\right)^2} + 1} \qquad [3]$$

where:

- T_I = predicted interval estimate of an individual trip duration (minutes)

For samples having more than 30 observations, the term within the square root in Equations [2] and [3] becomes negligible and can be dropped from the calculation.

Based on the estimated regression equation, and Equations [2] and [3], mean trip duration estimates and upper and lower prediction intervals for both the mean and individual trip durations were computed. The resulting regression estimates and prediction intervals are illustrated in Figure 2 for PM peak trips excluding Friday trips.

Figure 2 illustrates that though the regression line explains 62.6% of the variation in the observed data, it is based on the premise that time can be discretized into peak and non-peak categories. As a result, trip duration is insensitive to departure time within each category. The observed data clearly indicate that trip duration increases in conjunction with the build up of the peak and then decreases again as the commuting period comes to an end. To be able to capture these dynamic changes in trip duration, a linear regression analysis was applied to the observed data treating time of departure as a continuous variable.

Due to the lack of observed data between the AM and PM commuting periods, data for the morning and afternoon periods were analyzed separately. As well, PM data from Friday, August 7, were not included in the analysis as it was clear from the ANOVA and previous regression results that these data are very different from the other weekday data.

The objectives for this regression analysis were;

a. Explain as much of the observed variance as possible.

b. Ensure that all coefficients estimated by the regression were statistically different from zero at the 95% level of confidence.

c. Formulate a regression model to estimate trip duration based solely on the time of day at which the trip was initiated.

Note that no explicit attempt was made to formulate a model structure for which a physical or simple causal explanation was available.

A series of model structures, including simple linear, polynomial, and gaussian were tested using the observed data. A linear transformation of the normal curve was found to best fit the 44 observed AM data points, explaining 71.5% of the observed variation in trip duration. Both of the estimated coefficients were found to be statistically different from zero at a 95% level of confidence (student t values: t_a = 59.1, t_b = 10.3). The standard error of the estimated trip duration was computed to be 1.88 minutes.

$$T = a + bF(t) \qquad [4]$$

where:

- a = 21.098
- b = 8.326
- $F(t)$ = $e^{-\left[\frac{(t-7.863)}{(0.519)}\right]^2}$
- t = trip departure time (hour of day)

Figure 3 depicts the regression curve and 95% prediction intervals along with the observed AM trip duration data.

A fourth order polynomial was fit to the 21 observed non-Friday PM data points. This model explained 82.4% of the variation in the observed data. All 5 estimated coefficients were found to be statistically different from zero at a 95% level of confidence (student t values: t_a = 2.31, t_b = -2.32, t_c = 2.32, t_d = -2.31, t_e = 2.30). The standard error of the estimated trip duration was determined to be 2.34 minutes.

$$T = a + bt + ct^2 + dt^3 + et^4 \qquad [5]$$

where:
a = 72840
b = -17900
c = 1643
d = -66.76
e = 1.012
t = trip departure time (hour of day)

Figure 4 depicts the regression curve and 95% prediction intervals along with the observed data. It is worth noting that since this regression model is a fourth order polynomial, three points of inflection exist. Only one inflection point, at approximately 5 PM, is clearly visible in Figure 4. The remaining two inflection points occur at 2:30 PM and 6:30 PM, at the extremities of the range of observed data. Using this equation to extrapolate beyond the range of observed data would result in a grossly over-estimated trip duration. Therefore, this regression equation should not be used to estimate trip durations for departure times outside of the range over which data were observed.

Comparison of competing route travel times

The common assumption made in most traffic assignment techniques is that users select routes which minimize their own personal travel times (Wardrop, 1952). This implies that all alternative routes between a given origin and destination, that are utilized by demand between this origin and destination, should have equal travel times. Highway 401 provides a unique opportunity to examine this assumption as the express/ collector system provides distinct but highly competitive alternative routes for drivers.

Figure 5 illustrates total trip time by route and by time of departure for the eastbound trips on August 6 and 7, while Figure 6 illustrates the comparable westbound trip travel times. From Figures 5a and 6a it can be seen that, during the morning commuting peaks of August 6 and 7, the express lanes provide marginally shorter trip travel times than do the collector lanes. However, as illustrated by Figures 5b and 6b, the collector lanes tend to provide shorter trip travel times during the afternoon commuting peaks. The data for June 8 are more difficult to interpret as vehicles using competing routes did not initiate their trips at the same time.

To quantify the difference in trip times on different routes, the mean route trip duration difference, expressed as a percent of the mean trip time on the two routes, can be computed from Equation [6] as illustrated in Table 5.

$$\overline{\Delta t} = \frac{100}{n}\sum_{i=1}^{n}\left[\left(t_e - t_c\right) \big/ \left(t_e + t_c\right)\right] \qquad [6]$$

where:
$\overline{\Delta t}$ = mean trip time difference (%)
n = number of trips observed to depart simultaneously
t_e = total trip time of trip using express facility (minutes) [1]
t_c = total trip time of trip using collector facility (minutes) [1]

[1] Note: In the case where two trips, using the same route, departed within 10 minutes of each other, the average of the total trip times of the two trips is used for t_e or t_c

It appears from Table 5, that for the morning period, the express lanes provided, on average, trip travel times which were 8% faster than those provided by the collector lanes. During the afternoon peak, the collector lanes provided trip travel times that were, on average, 8.5% faster than the express lanes for the eastbound direction, and 5% faster for the westbound direction.

While it is not clear why the identified trend occurred, Table 5 indicates, based on the limited number of observations, that drivers do not always route themselves in strict accordance with a user optimal assignment assumption based solely on time. It can potentially be argued, that as the system is never in a state of static equilibrium during the peak commuting periods, drivers may not have sufficiently dynamic information necessary to fully optimize their routes. Under these latter conditions, one might still expect an approximately equal number of drivers to incorrectly choose the collector vs. the express lanes as would choose the express vs. the collector lanes, such that the competing routes would still end up with nearly equal travel times. Such a conclusion was also not supported by the data.

The differences in trip times between routes, of on average less than 8.5%, could be due entirely to noise rather than some systematic driver bias, but this assertion was not tested.

Comparison of loop and floating car travel times

At the time of this study, the FTMS only existed west of Yonge Street. *Trips* for this portion of the analysis were therefore only analyzed for the portion of Highway 401 for which loop detectors were operating (between Yonge Street, in the middle of the study area, to Eglinton Ave at the west end of the study area).

Floating car trip durations were derived directly from the observer logs, while the total trip times from the June 8 FTMS detector data were converted from spot speed measurements made at each detector station.

On Highway 401, approximately 35% of the detector stations are dual loop stations, which can directly measure speeds, while the remaining single loop stations can not directly measure speed. For each single loop station, speeds are computed indirectly based on an average vehicle length that is computed from some nearby dual loop station every 20 seconds. While it is acknowledged that Equation [7], may yield biased estimates of speed over a portion of the range of operating conditions (Hall and Persaud, 1989), this equation is used within the FTMS logic.

$$\%occ = \frac{N\left(\overline{L}_v + L_D\right)}{10T\,\overline{m}_{sms}} \qquad [7]$$

where:

- N = number of vehicles detected during time T
- T = duration of observation period (hours)
- $\overline{m}_{sms}$ = average space mean speed (km/h)
- $\overline{L}_v$ = average vehicle length (meters)
- L_D = length of detection zone (meters)

For each trip carried out in the travel time study on June 8, the corresponding 15 minute average FTMS speed data were combined with the known link lengths, to compute a set of estimated link travel times. Total travel time was computed as simply the sum of all link travel times. In the event that a detector station was inoperative, a linear interpolation was performed between the speed estimates for the next valid upstream and downstream station.

The resulting trip travel times for the eastbound and westbound directions are plotted in Figure 7. Each observation point represents a single directional trip across the study area and a corresponding estimate of trip time based on FTMS detector speed data. The line of perfect correlation - where the trip times estimated from the FTMS detector data agree exactly with those observed by the floating cars, reveals that a perfect correlation did not exist for either direction.

In order to statistically quantify the above degree of correlation the sample correlation coefficient was computed using Equation [8].

$$r = \frac{S_{xy}}{S_x S_y} \qquad [8]$$

For the eastbound data, the correlation coefficient was computed to be 0.149. This indicates a relatively low correlation between the trip travel times estimated from FTMS detector speeds and those observed during the floating car study. For the westbound data, the correlation coefficient was found to be 0.562, indicating that there is a slightly stronger correlation between the FTMS travel time estimates and those observed. The correlation coefficient for the combined data was found to be 0.423.

Three factors can be identified which may explain why the correlation between the trip durations observed during the floating car study and those estimated from FTMS detector speed data was found to be rather poor.

a. The number of data used for this correlation analysis was relatively small. If trip times were estimated from FTMS detector speed data for the trips observed on August 6 and 7, the sample size could have increased substantially.

b. The observed trip times are but a sample of the entire trip time distribution from which the samples were taken. Even if the means of these distributions correlated exactly with the trip durations estimated from the FTMS detector data, samples of trip times from these distributions would vary somewhat about the mean, resulting in a computed correlation coefficient of < 1.0. In addition, as the FTMS speed data were aggregated into 15 minute averages, some of the deterministic variations inherent in the raw 20 second speed data may have been removed concurrently with the noise.

c. Only approximately 35% of the operating FTMS detector stations are dual loop stations, capable of measuring speed. The remaining 65% are single loop stations, which tend to provide very poor speed estimates, particularly at low levels of occupancy.

The low level of correlation demonstrated by these data would appear to suggest that the ability to estimate total trip travel time from FTMS detector data in 1992 may have been less for non-incident conditions than the calibrated regression models (Equations [4] and [5]).

Unfortunately, a correlation analysis between regression model estimates and FTMS data could not be carried out as the regression equations provided trip duration estimates for trips traversing the entire study section, not just that portion which was operating under FTMS surveillance.

System characteristics identified during study

This paper has so far, primarily analyzed trip duration data. However, much more can be discovered about the freeway system if the characteristics of each trip are investigated through the use of time-space diagrams.

Figures 8 and 9 illustrate time-space trajectories for selected eastbound and westbound trips respectively. The particular trips illustrated in these figures represent those trips that experienced delay indicative of at least moderate congestion. Examination of these figures leads to the following observations:

a. Eastbound collector trips, made during the morning period, experience significant delay due to the lane restrictions in effect at the construction sites just east of Keele Street. This delay is approximately 4 minutes, or 12% of the total trip duration.

b. Eastbound express trips, made during the evening period, experience significant delay prior to the point at which Highway 409 (5 km from west end of the study area) joins with Highway 401.

c. Considerable variation in speed (the inverse of the slope) for eastbound trips is observed from Eglinton Ave. to Keele Street, while east of Keele Street, speeds appear to be much more stable.

d. Westbound collector trips, made on Friday during the evening period, begin to experience considerable congestion just west of Highway 404. This congestion remains significant until the end of the study area.

e. Very little variation in speed for westbound trips is observed from Neilson Road until west of Highway 404.

f. As a significant portion of the afternoon commuting trips have a destination outside of the study area, the duration of trips observed during the floating car study may not reflect trips which continue beyond the study area. It appears from trips made during the PM peak that significant delay is incurred near the boundaries of the study area. It is also likely that significant additional delay is experienced by drivers continuing beyond the study area limits.

   Based on the observation that significant delay is experienced during the PM peak near the study area boundaries, it is probable that bottlenecks exist outside of the study area which cause congestion to spill-back into the study area. The presence of these bottlenecks will have significant effects on any simulation modeling attempts, as these bottlenecks yield congestion effects which affect trip travel times within the study area, while the actual cause of the congestion would not be modelled.

CONCLUSIONS

The acquisition of accurate trip travel time data, using traditional floating car methods, is costly and time consuming. Even based on moderate resources, it is still difficult to acquire sufficient data to make statistically reliable conclusions due to the large number of extraneous factors which affect trip duration such as the departure time, the day of week, the facility used, and the direction traveled.

Three regression equations were calibrated to the observed data. The first equation explained 62.6% of the observed variation in trip duration, but was based on discretizing time into 3 classes (non-Friday PM peak, Friday PM peak, Non-PM peak), and resulted in constant trip duration within each time class. Two further equations were obtained by treating trip departure time as a continuous variable. The regression equation calibrated using the AM data explained 71.5% of the observed variation in trip duration, while the equation fit to the PM data (excluding Friday data), was found to explain 82.4% of the observed variation. These equations permit the estimation of incident free trip duration based solely of the trip departure time.

At the time that the data used in this study were obtained, trip duration estimates made from FTMS speed data yielded a level of correlation between FTMS estimates and observed trip duration data of 0.42, which is significantly lower that the correlation between the regression model estimates and the observed data ($r = 0.85$ for AM data, $r = 0.91$ for non-Friday PM data).

Highway 401 provides alternative routes via the express and collector facilities. Comparison of travel times on these alternative routes indicated that a trend exists in which the express lanes provided a shorter trip duration during the morning peak than the collector lanes. During the afternoon period, the collector lanes tended to provide a shorter trip duration. This trend is interesting in that it may indicate that drivers are not routing themselves optimally. If this tend was found to be statistically significantly, based on additional observations, it would imply that there exists a potential opportunity to improve system-wide performance by assisting drivers to choose more optimal routes.

Trip duration was found to be dependent on the day of the week and the time of day, as trips beginning during the afternoon peak on Friday experience trip travel times that are as long as 53.8 minutes, which is 1.5 times as long as the longest trip duration observed on either Monday or Thursday.

Operational characteristics specific to Highway 401 were identified easily from time-space diagrams, such as the effect of lane restrictions in the eastbound collector lanes at Keele Street and the queue spill-back effects due to bottlenecks existing outside of the study area during the PM peak.

It is recommended for future floating car studies, that instantaneous vehicle speed be recorded at fixed locations - either every kilometer or at each timing station. Such direct measurements would circumvent the errors which arise in estimating link speeds from travel times when link lengths are not known precisely and when it is difficult for drivers to note exactly where link boundaries exist.

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Table - 1: Number of ramps and transfer roadways within study area

Facility		Eastbound	Westbound
Ramps	ON	33	34
	OFF	18	21
Transfer Roadways	To Express	4	5
	To Collectors	5	4

Table - 2: Example of a blank data collection form for Highway 401 eastbound express lane floating car run

HIGHWAY 401 EASTBOUND EXPRESS LANES						
DATE :					SPEED:	
TIME :					DRIVER:	
WEATHER :					TIMER:	
NAME	**RAMP**	**MINUTES**	**SECONDS**	**TIME (SEC)**	**LINK TT (SEC)**	**COMMENTS**
DIXIE RD	on	0	0			
RENFORTH/427	off					
COLLECTOR TO EXPRESS	merge					
EGLINTON AVE	off					
CARLINGVIEW DR.	on					
H 427 NB	on					
DIXON RD	off					
DIXON RD	on					
DIXON RD	on					
EXPRESS TO COLLECTOR	diverge					
H 409	on					
WESTON RD		x	x			
H 400 NB	off					
EXPRESS TO COLLECTOR	off					
COLLECTOR TO EXPRESS	on					
KEELE ST.		x	x			
DUFFERIN ST./YORKDALE RD		x	x			
EXPRESS TO COLLECTOR	off					
ALLEN RD	on					
AVENUE RD		x	x			
COLLECTOR TO EXPRESS	on					
YONGE ST.		x	x			
BAYVIEW AVE		x	x			
EXPRESS TO COLLECTOR	off					
LESLIE ST.		x	x			
H 404 (DVP)	off					
COLLECTOR TO EXPRESS	on					
H 404 (DVP)	on					
VICTORIA PARK AVE		x	x			
WARDEN AVE		x	x			
EXPRESS TO COLLECTOR	off					
KENNEDY RD		x	x			
COLLECTOR TO EXPRESS	on					
McCOWAN RD		x	x			
EXPRESS TO COLLECTOR	off					
MARKHAM RD		x	x			
EXPRESS TO COLLECTOR	merge					
NEILSON RD	on					
MORNINGSIDE AVE	off					
TOTAL. TIME (sec)						Length : 34.5 km

Table - 3: Total trip durations observed during floating car study by date, time, direction, and route

	Eastbound				**Westbound**			
	Express		**Collector**		**Express**		**Collector**	
Date	Departure Time	Dur. (min.)	Departure Time	Dur. (min.)	Departure Time	Dur. (min.)	Departure Time	Dur. (min.)
Monday	7:20 AM	30.2	7:05 AM	24.7	6:35 AM	21.2	6:05 AM	22.1
June 8	8:35 AM	27.2	9:20 AM	21.8	7:45 AM	32.4	8:30 AM	23.4
1992	2:35 PM	20.3	9:50 AM	23.6	10:25 AM	21.4	9:20 AM	23.0
	5:00 PM	34.4	3:30 PM	27.1	3:00 PM	22.1	3:00 PM	23.1
			3:35 PM	32.2	4:20 PM	34.8	5:00 PM	35.9
			6:20 PM	20.3			5:50 PM	27.5
Number of trips		4		6		5		6
Thursday	7:50 AM	27.8	6:20 AM	20.4	7:00 AM	20.1	7:00 AM	22.0
Aug. 6	8:00 AM	26.7	7:55 AM	32.0	8:55 AM	20.9	8:50 AM	21.5
1992	9:30 AM	22.0	9:35 AM	21.9	10:10 AM	20.5	9:00 AM	22.0
	9:35 AM	22.1	2:40 PM	22.8	3:15 PM	27.2	10:15 AM	21.9
	2:35 PM	23.5	4:20 PM	33.9	3:25 PM	28.1	10:20 AM	21.9
	4:20 PM	32.2			5:20 PM	30.1	3:20 PM	25.5
	4:25 PM	33.5					5:15 PM	25.9
							5:25 PM	24.9
Number of trips		7		5		6		8
Friday	6:25 AM	19.4	6:30 AM	22.3	7:05 AM	21.9	7:10 AM	22.8
Aug. 7	6:30 AM	20.5	7:45 AM	27.3	7:15 AM	21.8	8:40 AM	25.6
1992	7:45 AM	27.9	7:55 AM	32.2	8:40 AM	20.9	8:45 AM	23.7
	9:20 AM	18.7	9:20 AM	21.1	10:00 AM	19.5	10:05 AM	23.0
	9:30 AM	20.9	3:00 PM	34.7	10:10 AM	22.7	2:05 PM	29.3
	3:05 PM	38.8	3:10 PM	33.6	2:10 PM	27.5	2:15 PM	29.8
	5:20 PM	41.6	5:20 PM	35.4	4:05 PM	53.8	4:05 PM	47.8
	5:30 PM	41.5			4:15 PM	53.6		
Number of trips		8		7		8		7
Sub Total		19		18		19		21
Total number of trips								**77**

Table - 4: ANOVA results for floating car trip times

Factor	**Categories**	**F-ratio**	**P**	**Accept H_0?**
Direction	(eastbound/westbound)	1.058	0.307	Yes
Facility	(express/collector)	0.015	0.901	Yes
Day	(Mon./ Thurs./ Fri.)	6.223	0.003	No
Time of Day	(AM peak/ AM off-peak/ PM peak/PM off-peak)	31.099	0.000	No

Table - 5: Comparison of travel times using alternate routes for floating car study

Direction	**Time**	$\bar{t}_e$ (min)	$\bar{t}_c$ (min)	$(\bar{t}_e - \bar{t}_c)$	$\overline{\Delta t}$ (%)[1]	**n**
Eastbound	AM	23.48	25.42	-1.94	-7.57	5
	PM	37.72	34.49	3.23	8.47	3
Westbound	AM	20.89	22.67	-1.78	-8.11	6
	PM	32.19	30.27	1.92	4.97	5

[1] negative indicates that express route is faster than collector

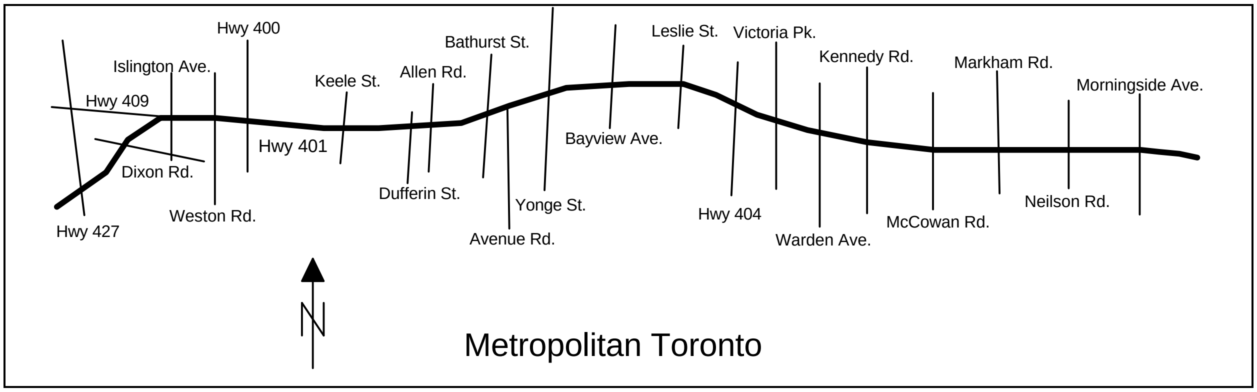

Figure - 1: Location of major interchanges within the Highway 401 study site

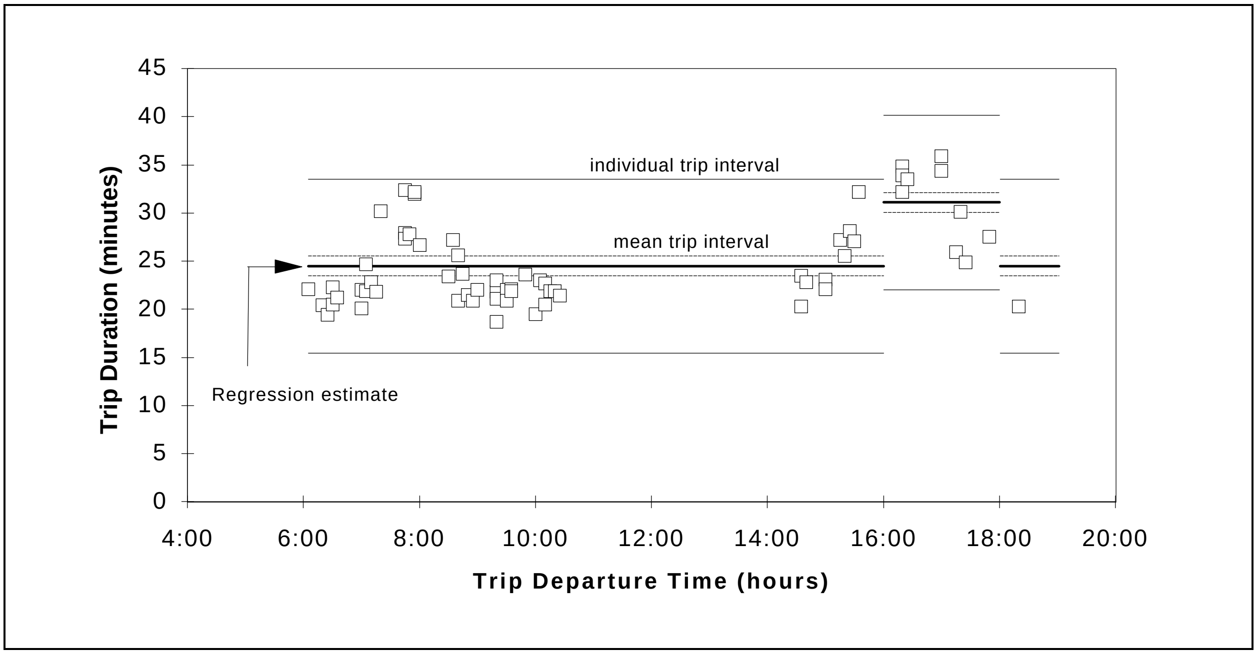

Figure - 2: Estimated trip duration and 95% prediction intervals for multiple linear regression model based on discretizing departure time

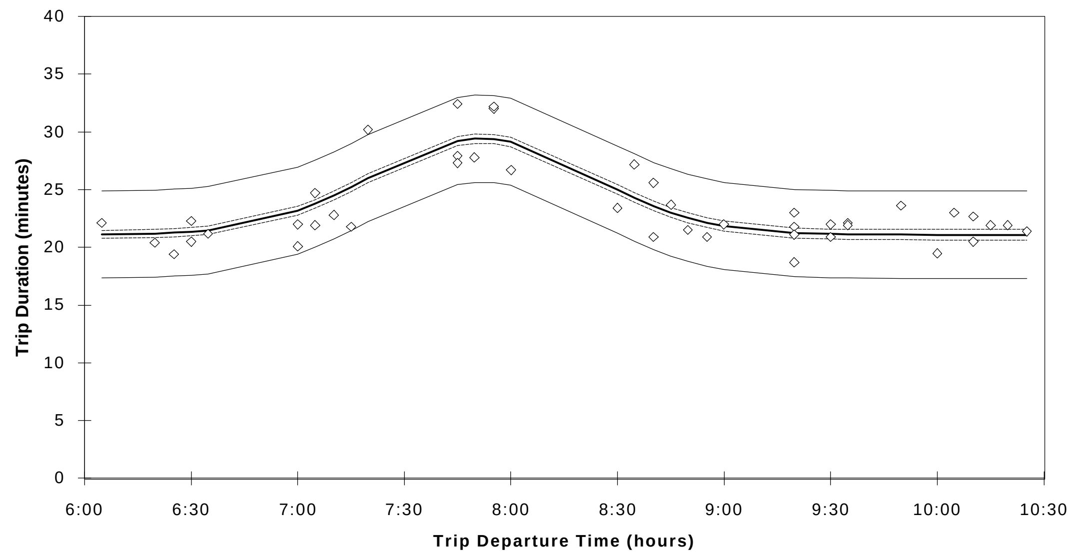

Figure - 3: Observed and estimated trip duration and 95% prediction intervals for the linear regression model based on continuous departure time (AM trips only)

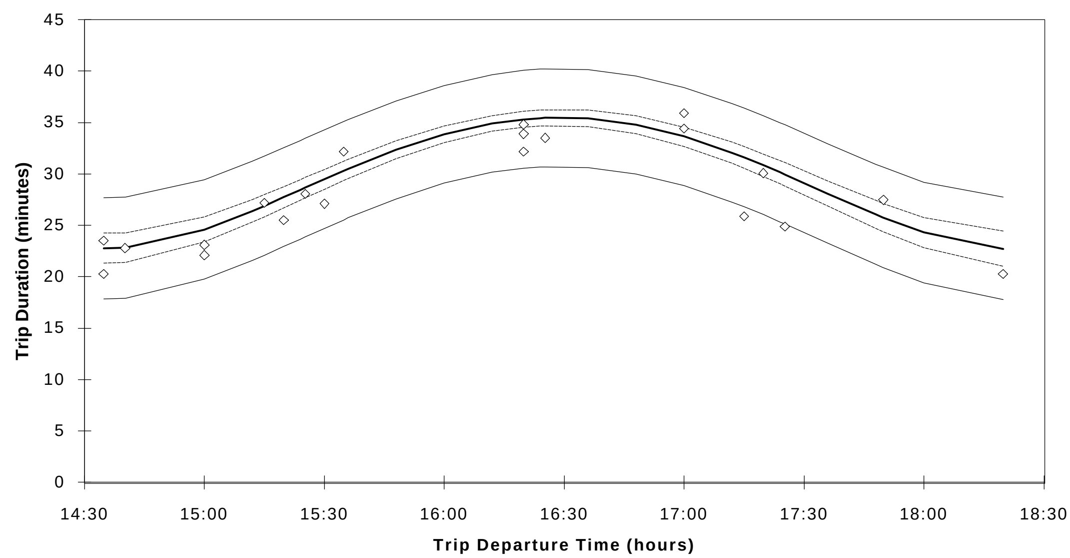

Figure - 4: Observed and estimated trip duration and 95% prediction intervals for the linear regression model based on continuous departure time (PM trips excluding Friday data only)

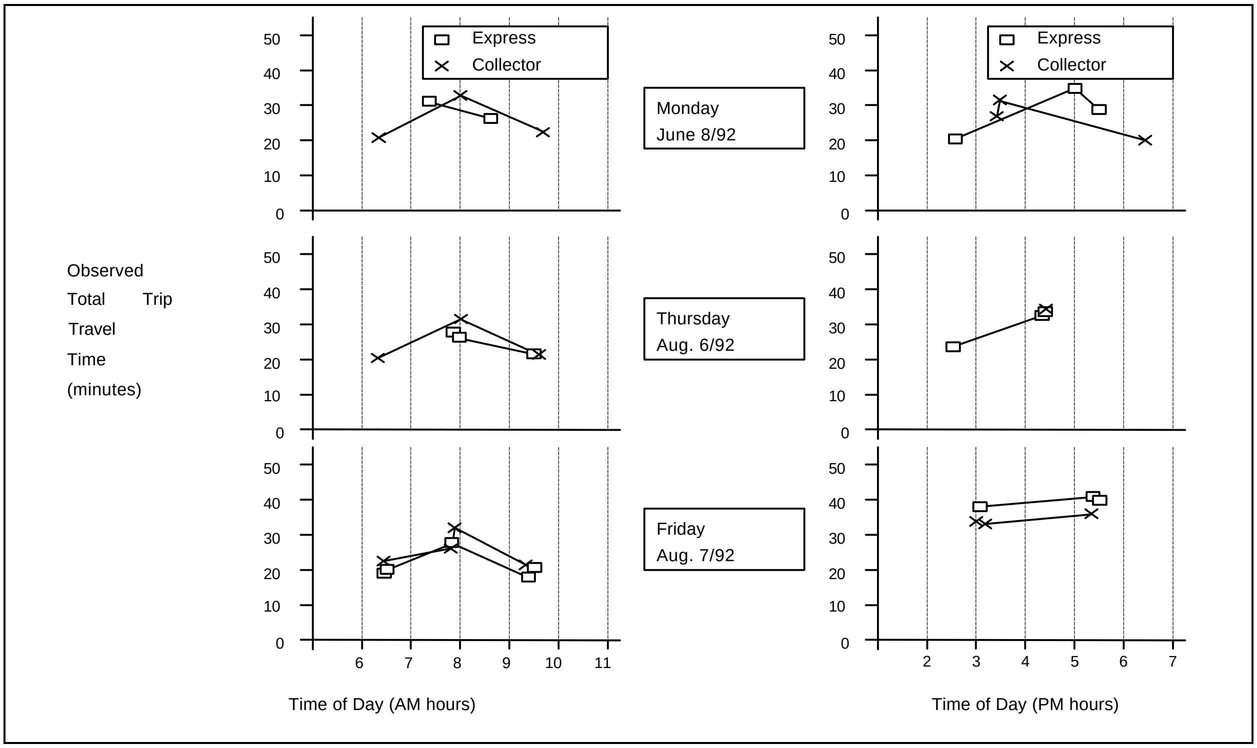

Figure - 5 (a and b): Total eastbound trip duration by facility and time of day from floating car runs

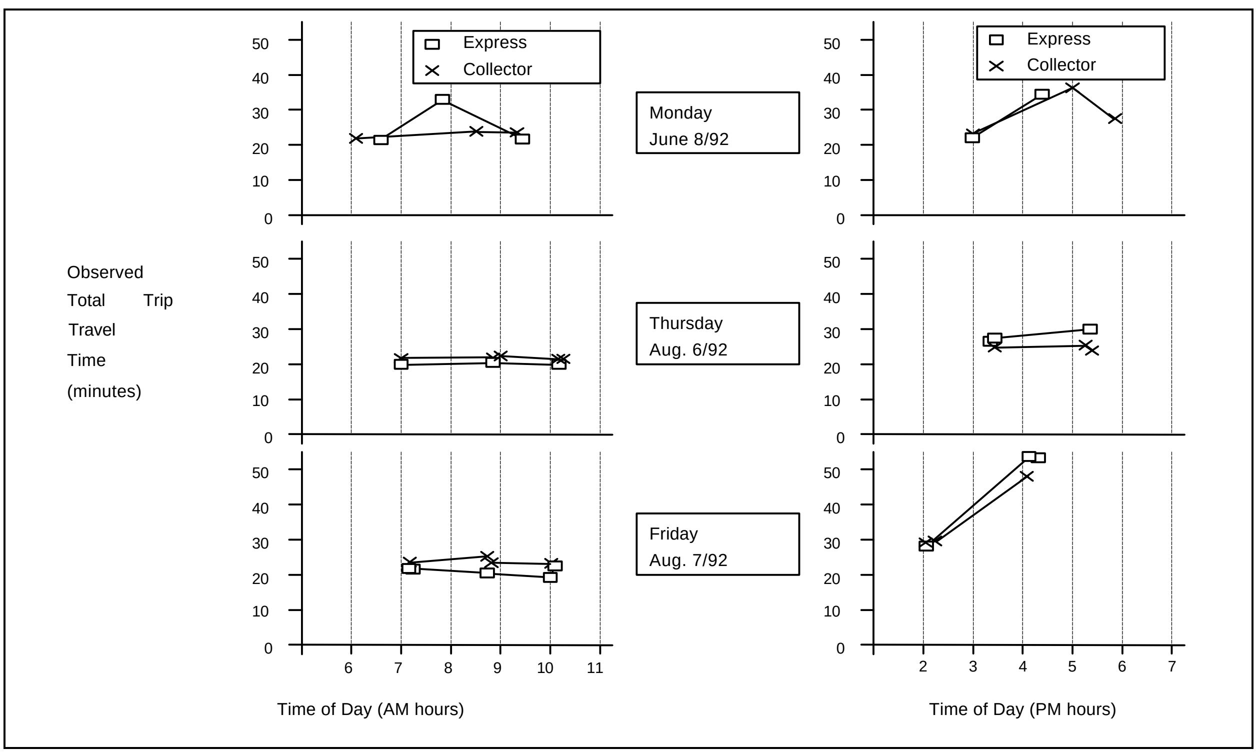

Figure - 6 (a and b): Total westbound trip duration by facility and time of day from floating car runs

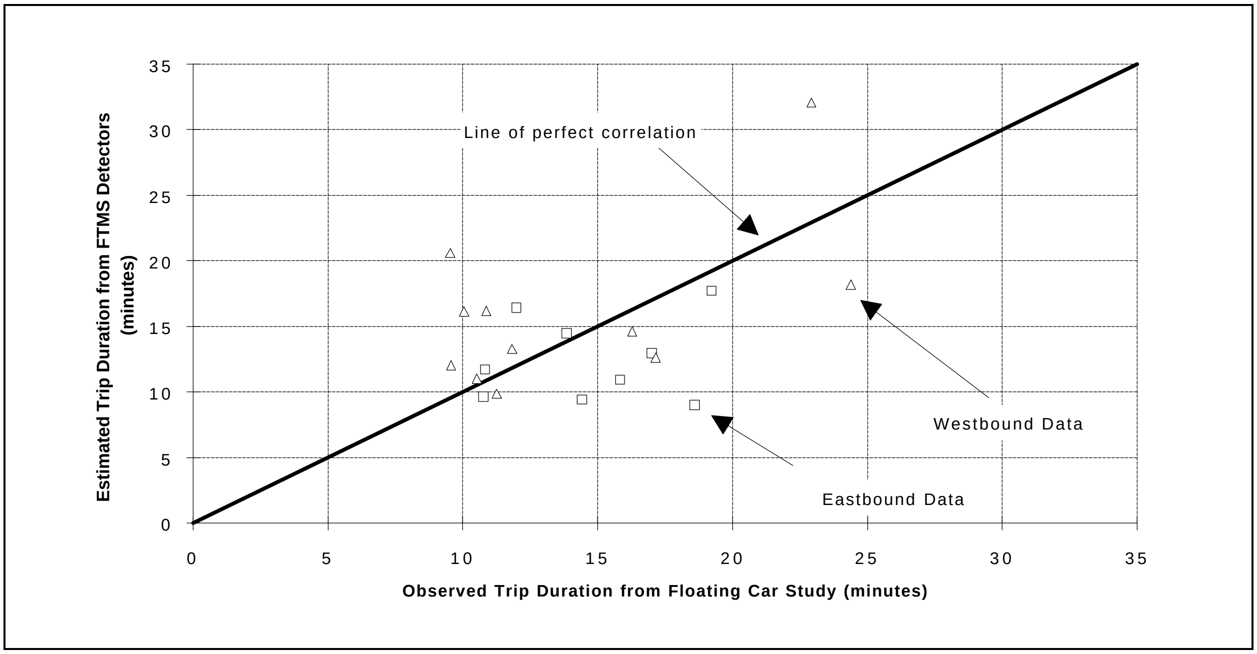

Figure - 7: Correlation between observed and FTMS estimated trip duration data

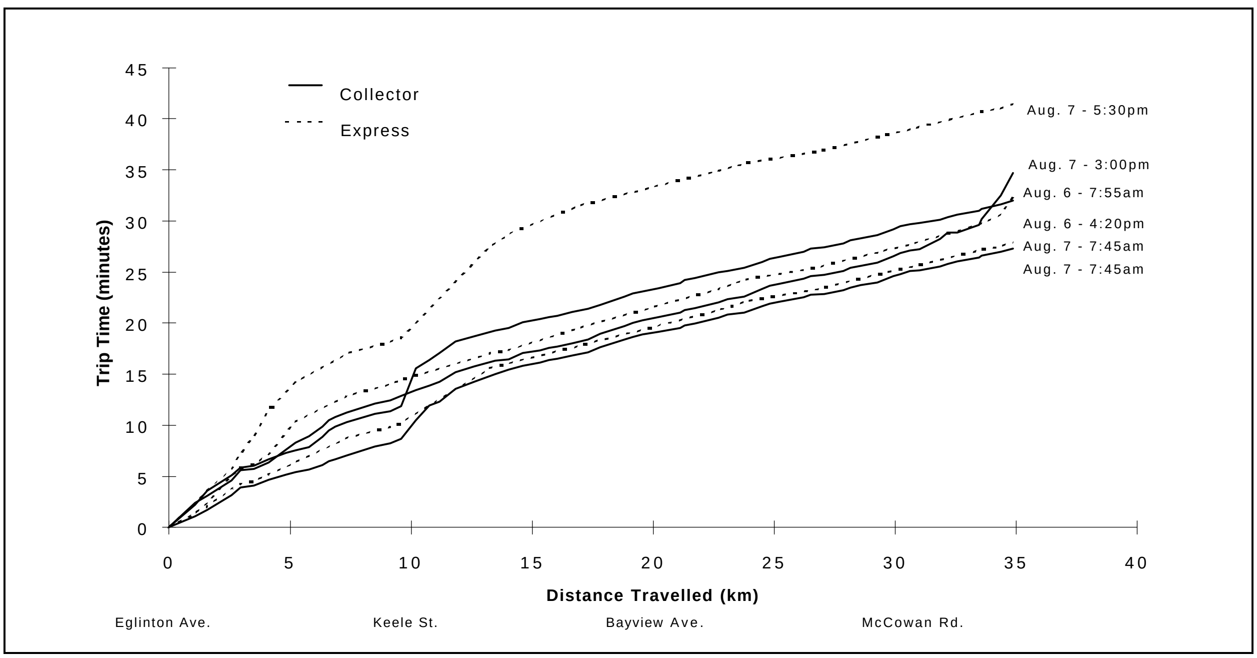

Figure - 8: Selected observed space-time trajectories for eastbound trips

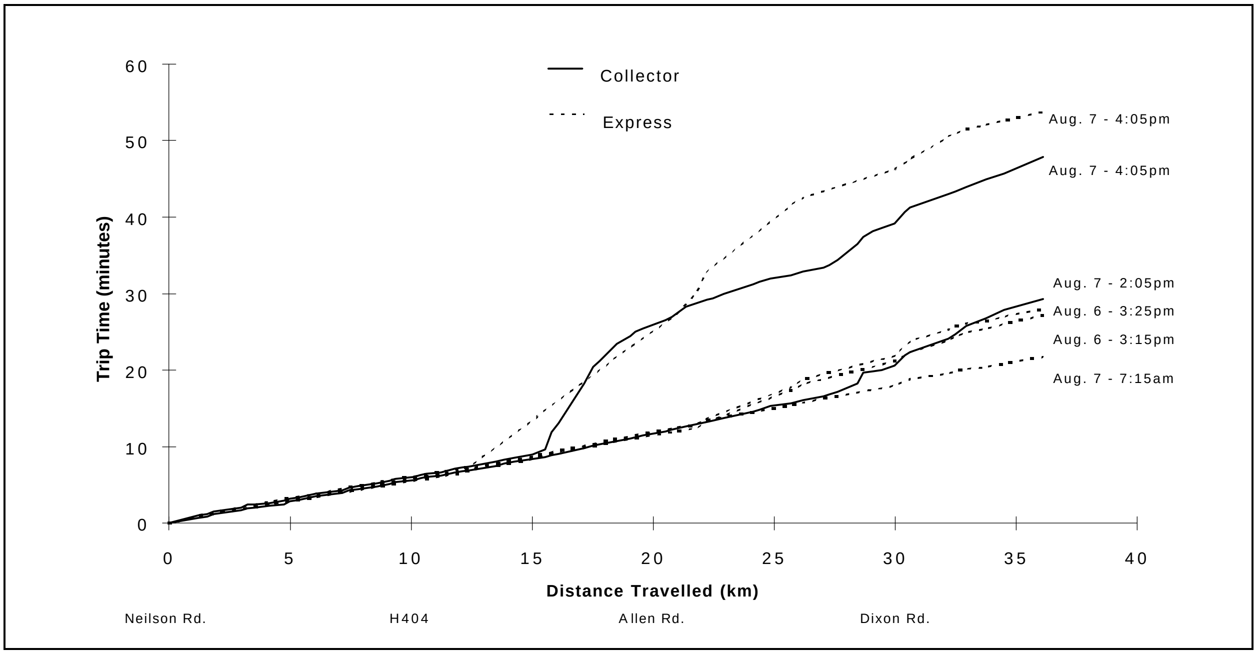

Figure - 9: Selected observed space-time trajectories for westbound trips