Modelling of Transit Reliability and Speed Using AVL Data in the City of Toronto

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science in Transportation Engineering

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Abstract

The objective of this study is developing mathematical models to explain the relationships between transit reliability and speed and a variety of factors, including but not limited to service characteristics of bus lines, physical infrastructures, signal timings, traffic conditions and ridership, by using AVL data of bus lines that are representative of the entire bus network in the City of Toronto with special focus on examining the effect of transit signal priority (TSP). The coefficient of variation of run time is used as the indicator of transit reliability. The modelling results of linear regression at route and segment level suggest that the increase of service distance, signalized intersection density, stop density, volume of boarding and alighting passengers and vehicle volume significantly reduces both transit reliability and speed. TSP, involved as an independent variable in the segment level analysis, demonstrates beneficial influence on improving transit reliability and speed.
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1 Introduction

1.1 Overview

The modernization of municipalities has brought about a dramatic increase in the number of vehicles on the street network, which causes problems of pollution, noise and energy consumption. Popularizing public transit would be one of the solutions to these issues. However, in order to attract people from their private vehicles to buses, streetcars or subways, better transit performance is a prominent desire. Passengers choose public transit for the purposes of saving money, getting rid of the congestions on the roads, freeing their hands from steering wheels for other works, or trying to behave environmentally friendly as mentioned in *Transit Capacity and Quality of Service Manual 3rd Edition* (2013). They may also expect time savings by taking transit, especially for commute trips in peak hours. Overall, transit users want fast and reliable service.

The indicators designed for measuring the transit service quality have been widely studied. Various kinds of measures were proposed on the perspective of stakeholders and passengers, included in which reliability and speed always attracted a lot of attention. The transit operational speed as concretely defined to be the distance travelled in a unit of time can be straight used as an indicator. However, transit reliability, in contrast, has not been defined officially. Researchers explained it in a different way based on diverse focuses. There were measures emphasize the regularity of headways or travel times, as well as schedule adherence and wait times.

In regardless of what kind of reliability measure is used, transit planners are interested in knowing what factors cause unreliable service. Research studies on this topic were usually conducted in simulation software to test the effectiveness of newly innovated control strategies, such as holding control. The before-and-after study is also commonly applied for understanding such effect, during the process of which one strategy is investigated at a time. However, this approach is highly constrained by time, budget and policies. Therefore, simulation is a more popular choice, which is also capable of analysing the effect of one variable on transit reliability. This is done by examining the effect by altering the value of the factor of interest while maintaining the scenarios of the others. The joint effect of more than one variable has been rarely studied although it can be conducted in simulators as well. However, the research on combined
effect can be found on using field data of bus lines, but the data was restricted by the number of routes and the types of variables included.

As improving reliability and speed are the primary goals for the transit operators, there were abundant researches carried on finding new strategies to enhance transit performance. The one that is applied in the City of Toronto is transit signal priority (TSP). Once been deployed in 1970s, TSP has become a popular choice for transit planners to increase the running speed and facilitate the movements of transit vehicles by extending the green phase or shortening the red phase of traffic lights for transit vehicles approaching the intersections. The City of Toronto has increased the number of TSP equipped intersections continuously these years at the estimated cost of CAD20,000 per intersection (Currie and Shalaby, 2008). However, TSP has not been proved to have significant impact on transit reliability based on studies conducted in other cities (Diab and El-Geneidy, 2013; Kimpel, et al., 2005), even though a lot of guidebooks claimed that TSP is helpful in reducing variability.

Findings of previous researches are elaborate in more detail in the next chapter. These studies encourage a thorough investigation of a comprehensive list of factors that have potential impact on the transit reliability and speed by using automatic vehicle location (AVL) tracking data. Included in them, TSP as a control strategy applied in the City of Toronto to improve transit performance is of interest to determine if it is a worthwhile investment.

1.2 Thesis Statement

The objectives of this research work are to find a proper measure of reliability for the City of Toronto using AVL data, and explore the effect of a series of variables on transit reliability and speed at the route and segment level explained by mathematical functions. Special attention is drawn on TSP, because its contribution to transit reliability has rarely been proved and there exists controversial argument on its impact. The weekend operational data is excluded, because the transit reliability and speed on the weekdays are more critical to the users, especially during the peak hours.

The reliability and speed models in this thesis involve a large number of variables and a large amount of data. The research uses AVL data collected in the City of Toronto on its bus operational situations in November 2013, archived data on traffic conditions, signal timings,
weather as well as other information on physical infrastructures are also retrieved in the same time frame from the Toronto Transit Commission, the City of Toronto and Statistics Canada. Data on bus lines that are representative of the entire bus network in Toronto is obtained. As previous studies are constrained by a limited number of transit lines, they would not be able to reveal the characteristics of the entire network.

This research study consists the following approach. The first step is finding an appropriate measure of transit reliability as the dependent variable of models, for which literature review is conducted to categorize proposed indicators and understand their advantages and drawbacks. Based on the availability of data, ease of obtaining the values and the level of recognition by other researchers, the most feasible ones are selected. The next step is identifying the factors related to reliability and speed. Then the required data is collected from different sources and processed to convert them to the same format and scale. The last step is to develop statistical models that best fit the available data. The transit reliability and speed model proposed in this research is developed by using regression analysis. By judging the adjusted R square values, the significance of the explanatory variables and the transit operation theory, the best models are selected and presented in this thesis.

1.3 Thesis Organization

This thesis is aimed at finding the statistical relationships between various factors and transit reliability and speed. It provides a better knowledge of how the influential variables cause variations in transit service and reduce the speed, as well as how the beneficial attributes contribute to better service qualities. This thesis is organized into 7 chapters. The first chapter presents the background and motivation of the study and the objectives and scope of this thesis. The second chapter provides literature reviews on the definition of transit reliability, previously proposed reliability measures, potential influential factors, and improvement strategies for reliability and speed. The third chapter describes the methodologies and approaches used in the research process. The fourth chapter elaborates all kinds of data collected from multiple sources. The fifth chapter depicts the assumptions and methods used for data cleaning. The sixth chapter presents modelling results and explanations. The last chapter concludes the thesis and provides recommendations for future research.
2 Literature Review

The objective of this chapter is to review the literature in several subject areas related to transit reliability and speed. The first section outlines the definitions of transit reliability. The second section explains the importance of transit reliability and speed to the service providers and users. The third section lists the possible influencing factors. The fourth section briefly describes a variety of measures occurred in literatures on the measures of reliability. The fifth section points out several hot research topics on improving reliability and speed. The last section concludes limitations on existing research, which provides motivations for this thesis.

2.1 Definition of Transit Reliability

Transit reliability has always been cited by both transit agencies and passengers as one of the key indicators in assessing the quality of service. However, no agreement has been reached in defining it.

The transit reliability was most frequently found to be related to schedule adherence and consistency of service. Bowman and Turnquist (1981), Kimpel (2001), Levinson (1991), and Strathman et al. (1999) addressed the relationship of schedule adherence and transit reliability. While other researchers emphasized the regularity of service that involves consistent travel time and evenness of headways (Abkowitz, 1978; Polus, 1978; Lomax, et al., 2003; El-Geneidy, et al., 2011). A more comprehensive way to define transit reliability occurs when schedule adherence and consistency of service are both considered. For example, Turnquist and Blume (1980) mentioned that a reliable transit service system should have the ability to adhere to schedule or maintain regular headways and a consistent travel time. Similar statement also appears in Transit Capacity and Quality of Service Manual (TCQSM), “reliability includes both on-time performance and the evenness of headways between transit vehicles.”

There was also definition standing in the passenger’s position that referred transit reliability as the excess wait time at the stop (Transportation Research Board, 2010). As passengers expect transit vehicles to arrive at the scheduled time, this is another way to interpret schedule adherence.
2.2 Importance of Transit Reliability and Speed

The importance of transit service reliability has been addressed by both service providers and users. Providing reliable services is one of the basic service objectives that closely related to the ridership, and revenue consequently. As it was suggested in TCQSM and many other papers, reliable service is believed to have the benefit of attracting and retaining riders (Florida Department of Transportation, et al., 2008; Levinson, 2005). Obviously, higher ridership generates higher revenue. Moreover, reliability is essential to the operational cost (Abkowitz, 1978). It is also mentioned in TCQSM, service with high reliability reduces the likelihood of bunching and uneven passenger loadings.

For public transit users, reliability has a significant impact on their mode choices, as well as departure time choices so as to ensure on-time arrival at the destination (Abkowitz, 1978; Bhat and Sardesai, 2006; Camus, et al., 2005; Small, 1982). To be more specific, transit service reliability affects wait time at stops, transfer time and in-vehicle travel time. Passengers have to take all these variability into consideration when planning their trips. Therefore, transit reliability is frequently identified by transit users as one of the most influential factors, which contributes to the level of satisfaction of transit experience (Dowling, et al., 2004).

To summarize, unreliable service can easily lead to service disruptions, bunching, passenger overcrowding, longer travel time, and overall poor reputation for transit (Florida Department of Transportation, et al., 2008; Saberi, et al., 2013). These consequences directly increase the cost and reduce the benefit of passengers and transit providers.

The transit speed, as important as reliability, is one of the key indicators of service quality as mentioned in TCQSM. While speed is directly related to the travel time, it is always the key concern of passengers. Improved speed does not only save travel time and wait time, it also enhances comfort. Therefore, when travel time is a determinant for travellers, the speed would affect their mode choices.

In the perspective of transit companies, speed closely associates to the cost and revenue. If the demand does not vary, increasing speed can reduce the fleet size. Hence, the investment and operating cost is reduced. Since high-speed service attracts more passengers, it brings more revenue.
Increasing speed also brings about benefits to the communities, especially those adjacent to transit lines. Higher transit speed induces less congestion, noise and emissions. It also improves the mobility and sustainability (Vuchic, 2005).

2.3 Factors Influencing Transit Reliability and Speed

The transit service reliability and speed are related to a large number of factors covering static and real-time variables. Comprehensive lists of these influential attributes are outlined in TCQSM and by Diab and El-Geneidy (2013), which can be divided into the following categories:

- Traffic conditions: congestions (especially non-recurring ones), traffic incidents and parking manoeuvres;
- Road conditions: road constructions and maintenance, road width, number of lanes, pavement conditions, track maintenance, and line merges of rail systems;
- Vehicle related factors: number of vehicles available for each route, and quality of vehicles;
- Staff related factors: staff availability, and driving experience and skills;
- Passenger related factors: evenness of demand, and alighting and boarding characteristic;
- Operating conditions: amount of delay at start, number of actual stops made, and wheelchair and ramp usage;
- Route characteristics: length, number of stops, schedule achievability (layover time, headway, recovery time, etc.), and control strategies;
- Signal related factors: signal delays, transit priority, and number of signalized intersections;
- Environmental conditions;
- Time factors: period of day.

Among the above-mentioned factors, some can be easily monitored and improved which are the focuses of transit agencies. However, the others, like environmental conditions and time factors, are beyond human control.
2.4 Measures of Transit Reliability

Since there are a variety of definitions of transit reliability, abundant reliability indicators can be found in literatures from different perspectives. Researchers have kept proposing new measures to overcome the limitations of previous ones. The most common measures of transit reliability are given in TCQSM with calculation examples. These measures are simple and straightforward, which serve as the bases of many other forms of indicators developed later on.

Generally, existing reliability measures can be categorized into on-time performance, headway adherence (Saberi, et al., 2013), travel time variations, and wait time indicators (Gittens and Shalaby, 2015). The following sections provide sample indicators in each category.

2.4.1 On-Time Performance Measures

On-time performance measures concern about arriving stops at scheduled times. TCQSM defined “on-time” as being 1 minute early or up to 5 minutes late. However, from passengers’ perspective, an early bus is considered as a missed bus or being one headway late, especially when transit users time their arrivals at the stop. On-Time Performance (OTP) is calculated as the percentage of on-time trips over the total number of trips as described in TCQSM.

\[
OTP = \frac{\text{Number of On Time Trips}}{\text{Number of Trips}} \times 100\%
\]  

(2-1)

Hansen (1999) proposed Average Punctuality as a measure of departure time deviation of the timetable.

\[
p_l = \frac{\sum_{j}^{n_{i,j}} \sum_{i}^{n_{i,i}} |\bar{D}_{i,j}^{act} - \bar{D}_{i,j}^{sched}|}{n_{i,j} \cdot n_{i,i}}
\]  

(2-2)

where, \(p_l\) is the average punctuality on line \(l\), \(\bar{D}_{i,j}^{act}\) is the actual departure time of vehicle \(i\) on stop \(j\) on line \(l\), \(\bar{D}_{i,j}^{sched}\) is the scheduled departure time of vehicle \(i\) on stop \(j\) on line \(l\), \(n_{i,j}\) is the number of trips of line \(l\), and \(n_{i,j}\) is the number of stops of line \(l\).

Weighted Delay Index (WDI) used similar concept as Average Punctuality, but the average amount of delay is compared against the scheduled headway (Camus, et al., 2005).
\[ WDI = \frac{\sum_{k=t}^{H} k \cdot p(k)}{H} \]  

where, \( k \) is the amount of delay in minutes, \( p(k) \) is the probability of having \( k \) minutes delay, \( t \) is lower limit of delay, and \( H \) is the scheduled headway. Trips are not treated of being delayed until \( t \) minutes after the scheduled time. The upper limit is selected to be the length of the scheduled headway, because trips late for more than \( H \) minutes are considered as missed trips rather than delayed. The thresholds of time tolerance around the schedule can be selected according to requirements.

OTP and Average Punctuality do not differentiate being early and late. WDI only concerns about late trips. Moreover, OTP does not consider the amount of deviation from the schedule. Earliness Index (EI) is suggested as a complementary alternative that emphasizes situations of arriving before the scheduled time.

\[ EI = F(0) = P\{x \leq 0\} \]  

where, \( x \) is the amount of delay. In this case, EI presents the cumulative probability of the amount of delay being less than zero, which is the probability that all the observations are ahead of the schedule.

### 2.4.2 Headway Adherence Measures

The headway adherence describes the ability of transit vehicles to maintain constant headways according to the schedule. Headway indicators are often used to assess the reliability of high frequency lines, which, defined by TCQSM, is services with headways less than 10 minutes.

TCQSM used coefficient of variation of headway deviations \((c_{v,h})\) to interpret headway adherence, which is calculated as the standard deviation of headway deviations \((\sigma_h)\) over mean scheduled headways \((\mu_h)\):

\[ c_{v,h} = \frac{\sigma_h}{\mu_h} \]  

This approach does neither capture the extreme cases of unreliability, nor differentiate the cost of being late (Saberi, et al., 2013). To overcome these limitations, the Width Index (WI) is suggested, which utilizes the difference between the 95th and 5th percentile of headway deviations as the fraction for frequent services.
where $F^{-1}(p)$ is the inverse of the cumulative distribution function of headway deviations. When using WI for infrequent services, $F^{-1}(p)$ is the inverse of the cumulative distribution function of delays. Weighting factors ($\alpha, \beta$) can be added in front of $F^{-1}(p)$ to reveal the cost of being early and late (Equation 2-7).

$$WI = \frac{\alpha[F^{-1}(0.95)] - \beta[F^{-1}(0.05)]}{(Average\ Scheduled\ Headway)(\alpha + \beta)}$$  \hspace{1cm} (2-7)$$

where $F^{-1}(0.95)>0$, $F^{-1}(0.05)<0$, $\alpha$ is the cost of being late, and $\beta$ is the cost of being early.

Considering the likelihood of having the curve of the cumulative distribution function entirely sitting on the right side (all the observations are late arrivals) or the left side (all the observations are early arrivals) of the y-axis, the weighted factors should be adjusted. Compared to Headway Adherence, WI captures more extreme values of a distribution.

Saberi, Feng and El-Geneidy (2013) also develop another index, Second-Order Stochastic Dominance (SSD), to further describe characteristics of the distribution of delays/headways deviations that helps differentiate distributions with similar width but different EI, as well as distributions with similar width and EI, but different curvatures.

$$SSDI = \frac{\alpha \int_a^0 F(x)dx + \beta \int_0^b (1 - F(x))dx}{(Average\ Scheduled\ Headway)(\alpha + \beta)}$$  \hspace{1cm} (2-8)$$

where F(x) is the cumulative distribution function of headway or delay deviations of frequent or infrequent services, respectively. $\alpha$ and $\beta$ are still cost of being late and early.

There was another rough estimate of Headway Regularity (HR) calculated as the proportion of trips with acceptable headways:

$$HR = \frac{Number\ of\ Trips\ with\ Acceptable\ Headways}{Number\ of\ Trips} \times 100\%$$  \hspace{1cm} (2-9)$$

Cramer, et al. (2009), who proposed this measure, defined “acceptable” as having headways within the range from 0.5 to 1.5 times the scheduled headways, or ±5 minutes, whichever is less.
Chen, et al. (2009) compared the difference between headways at stops to the dispatched headway to the predefined lower and upper limits, and calculated the probability of having the difference fall into this range as Deviation Index Based on Stops (DIS):

\[
DIS = P\{\theta_1 < H_s - H_0 < \theta_2\}
\]

(2-10)

where \(\theta_1\) and \(\theta_2\) are limits of acceptable headway deviation, \(H_s\) is the observed headway at stop \(s\), and \(H_0\) is the headway at which buses are dispatched.

### 2.4.3 Travel Time Measures

The travel time indicators, which are usually measured on route levels, concern about the run time of trips. While headway adherence is widely applied to routes with high service frequency, travel time is more popular for services with low frequency.

There were three similar indices proposed by the US Department of Transportation Federal Highway Administration (FHA, et al., 2004), Schrank and Lomax (2002), and Uniman, et al. (2010) separately. Reliability Buffer Index is suggested by FHA:

\[
\text{Reliability Buffer Index} = \frac{95\text{th Percentile Travel Time} - \text{Average Travel Time}}{\text{Average Travel Time}}
\]

(2-11)

If a passenger wants to be 95% sure that he or she can arrive at the destination on time, this is the percentage of extra time should be added to normal travel time.

The Buffer Index mentioned by Schrank and Lomax (2002) used very similar expression as Reliability Buffer Index, but they replaced average travel time with scheduled travel time:

\[
\text{Buffer Index} = \frac{95\text{th Percentile Travel Time} - \text{Mean Scheduled Travel Time}}{\text{Mean Scheduled Travel Time}} \times 100\%
\]

(2-12)

The Reliability Buffer Time Metric (RBT) also used 95th percentile travel time, but it was deducted by the median travel time in this case (Uniman, et al., 2010), which is given by:

\[
RBT = 95\text{th Percentile Travel Time} - \text{Median Travel Time}
\]

(2-13)
As coefficient of variation of headways reflects headway adherence, coefficient of variation of travel time is used as a travel time measure (Mazloumi, et al., 2008):

\[ C_{v,TT} = \frac{\sigma_{TT}}{\mu_{TT}} \]  

(2-14)

where \( \sigma_{TT,Obs} \) is the standard deviation of observed travel time, and \( \mu_{TT,Obs} \) is the mean observed travel time.

Using thresholds to confine the variation of travel time is another way to measure transit reliability. This range of reliability was defined to be 10\% of mean travel time by A Guidebook for Developing A Transit Performance-Measurement System (Kittelson & Associates, Inc., et al., 2003) and the Reliability Factor (RF) is given by:

\[ RF = \text{Percentage of Travel Times within 10\% of Mean} \]  

(2-15)

High value of RF means highly reliable service.

Chen, et al. (2009) set upper and lower limits of travel time deviations from schedule, and the Punctuality Index based on Routes (PIR) is calculated as:

\[ PIR = P\{\partial_1 < TT_{Actual} - TT_{Scheduled} < \partial_2\} \]  

(2-16)

where \( \partial_1 \) and \( \partial_2 \) are bounds of acceptable travel time deviation defined by the agency, \( TT_{Actual} \) is the actual travel time, and \( TT_{Scheduled} \) is the scheduled travel time. PIR is the probability of having travel time deviations within the predefined boundaries.

### 2.4.4 Wait Time Measures

The simplest wait time measure, Excess Wait Time (EWT), was given in TCQSM, which is calculated as:

\[ EWT = \text{Average Bus Departure Time} - \text{Scheduled Departure Time} \]  

(2-17)

Therefore, passengers have to wait longer for routes with low reliability. Similarly, Currie, et al. (2012) proposed another form of EWT:\'

\[ EWT' = \text{Actual Wait Time} - \text{Scheduled Wait Time} \]  

(2-18)

where, scheduled wait time (SWT) can be derived from:
\[ SWT = 0.5h_0(1 + c_{v,h}^2) \]  

(2-19)

where, \( h_0 \) is the mean scheduled headway. \( c_{v,h} \) is the coefficient of variation of headways. The formula of SWT is more applicable in calculating the scheduled headways of high frequency services. For long headways, passengers tend to time their arrival at the stop, and assumptions should be made before determining the formula.

Another wait time measure depicted in TCQSM is Budget Wait Time:

\[
\text{Budget Wait Time} = 95\text{th Percentile Departure Time} - 2\text{nd Percentile Departure Time}
\]

(2-20)

Low reliability results in a flat cumulative distribution curve and high budget wait time.

Wait Assessment (WA) utilized the percentage of observed headways within pre-set limits (\( H_{set} \)) to represent passenger wait time:

\[
WA = P\{\text{Headways} \leq H_{set}\}
\]

(2-21)

This form of expression is the same as Headway Regularity (HR) illustrated by Equation (2-9), but granted another name.

The Average Additional Waiting Time is a more complex way of deriving excess wait time compared to Equation (2-17) and (2-18). The additional wait time is calculated at stop level (Equation (2-22) and (2-23)), and then the weighted average is calculated along the line (Equation (2-24)) based on the number of passengers at all stops.

\[
\begin{align*}
\tau_{\text{Add,waiting}}^{i,j} & = H_{\text{sched}}^{i,j} & \text{if } d_{\text{departure}}^{i,j} \leq -\tau_{\text{early}} \\
\tau_{\text{Add,waiting}}^{i,j} & = 0 & \text{if } -\tau_{\text{early}} \leq d_{\text{departure}}^{i,j} \leq \tau_{\text{late}} \\
\tau_{\text{Add,waiting}}^{i,j} & = d_{\text{departure}}^{i,j} & \text{if } d_{\text{departure}}^{i,j} \geq \tau_{\text{late}}
\end{align*}
\]

(2-22)

\[
E\left(\tau_{\text{Add,waiting}}^{i,j}\right) = \frac{\sum_{i} E(\tau_{\text{Add,waiting}}^{i,j})}{n_{i,j}}
\]

(2-23)
\begin{equation}
E(\bar{T}_{l,i,j}^{\text{Add,waiting}}) = \sum_j (\alpha_{l,j} \cdot E(\bar{T}_{l,i,j}^{\text{Add,waiting}})) \quad \text{with} \sum_j \alpha_{l,j} = 1
\end{equation}

where, \( E(\bar{T}_{l,i,j}^{\text{Add,waiting}}) \) is the average additional waiting time per passenger due to unreliability of vehicle \( i \) of line \( l \) at stop \( j \), \( H_l^{\text{sched}} \) is the scheduled headway at line \( l \), \( d_{l,i,j}^{\text{departure}} \) is the departure deviation of vehicle \( i \) at stop \( j \) on line \( l \), \( \tau_{\text{early}} \) is the lower bound of arrival bandwidth of passengers at departure stop, \( \tau_{\text{late}} \) is the upper bound of arrival bandwidth of passengers at departure stop, \( n_{l,i} \) is the number of trips on line \( l \), and \( \alpha_{l,j} \) is the proportion of passengers of line \( l \) boarding at stop \( j \).

### 2.5 Improvement Strategies of Transit Reliability and Speed

As transit reliability is essential to both service providers and users, a variety of improvement strategies have been put forward to enhance this performance indicator. Methods range from driver training, planning, route design, and implementation of control actions to advance of infrastructures (El-Geneidy, et al., 2011). Among these strategies, holding control and signal priority has received most attention.

Planning usually aims at delivering achievable schedules that minimizes the possibility of variations. For example, adding enough slack times to the schedule, especially during peak hours and on critical routes that have high risks of delay helps produce more reliable service (Israeli and Ceder, 1996; Carey, 1998). However, this method induces longer travel time.

Route design strategies include using more independent lines than integrated lines (Vuchic and Musso, 1991). This method though increases the reliability; it brings up the transfer time. Shortening transit lines, increasing stop spacing, planning redundant service lines and adding shortcuts or bypasses also reduce variations (Tahmasseby and van Nes, 2010; van Oort and van Nes, 2008).

The control actions aiming at improving transit reliability usually involve route supervisors, holding and boarding limits. Reliability control usually requires real-time information of transit locations. For instance, real-time headway control requires AVL system that offers latitude and longitude of transit vehicles, which allows the prediction of arrival time at the next stop based on which the departure time can be adjusted (Ding and Chien, 2001). Later in 2008, the
effectiveness of using AVL information to aid route supervisors in the attempt of carrying out prefol holding strategies, which intend to make even headways of buses between their preceding and following buses, was proved by Pangilinan, et al. (2008). Cats, et al. (2010) test four holding strategies with AVL and APC data in a mesoscopic simulation model, BusMezzo. The four tested strategies are: 1) schedule-based holding strategy, 2) headway-based holding strategy with control of time interval from the preceding bus, 3) headway-based holding strategy to generate even headways on both sides (headways to preceding and following buses), 4) combined holding strategy of 2) and 3) that whichever generates a shorter holding time is used. The simulation results indicated that all of the above-mentioned strategies could improve service regularity, while the combined holding strategy was the most significant. Further research proved that headway-based holding control that regulates the headways of the preceding and the following bus is more effective than schedule-based mechanism (Cats, et al., 2012). However, van Oort, et al. (2010) indicated that schedule-based holding strategies are more effective for high-frequency lines, especially when a loose schedule is applied. In addition to AVL system, holding can be used together with limiting boarding to improve reliability which is most effective on the high passenger demand sections of high-frequency routes (Delgado, et al., 2012).

Advances of infrastructures emphasize providing priority to transit vehicles. Designing exclusive right of way is one of the common methods, which is effective but costly (Tahmasseby and van Nes, 2010). Another widely deployed strategy is transit signal priority. Both conditional and unconditional transit signal priority exert positive effect on service reliability based on results generated from microscopic simulation models (Chang, et al., 2003; Dion, et al., 2002). However, the field experiments did not suggest significant positive effects (Diab and El-Geneidy, 2013; Stevanovic, et al., 2013).

Among the above-mentioned strategies, a majority of them also help increase transit speed. To increase speed, focuses should be put on minimizing dwell time at stops, delay at intersections and on streets. To reduce dwell time at stops, it is common to suggest level boarding. Improvements on vehicle design, such as better interior circulation and wider doors, can speed up the boarding and alighting processes. Holding control and limitations on boarding at bus stops, proposed by Delgado, was proved to have positive effect on speed (Delgado, et al., 2012). The time wasted on fare collections cannot be ignored. Using smart card systems could be one solution to speed up this process.
Reducing delay at intersections can be achieved by applying transit signal priority or signal re-emption, which is believed to have ability to improve both reliability and speed (Smith, et al., 2005). Transit signal priority (TSP) is an operational strategy that extends the green phase or shortens the red phase of traffic lights for transit vehicles approaching an intersection to facilitate the movement of buses and streetcars. The working mechanism of TSP is described in Section 4.6. Smith et al. stated that TSP could save 15% travel time on average (2005). This also has been proved by case studies along various streetcar lines in Toronto that it was stated that TSP has reduced the signal delay and travel time of streetcars by an average of 24% and 8% respectively (Toronto Transit Commission, 1998). The City of Toronto also equipped some streetcar lines with special transit phase for the purpose of increasing speed. Besides, using queue-jump lane can shorten the wait time at intersections (Vuchic, 2005).

Commonly, transit vehicles spend most of their time on travelling on the streets in addition to dwell time and terminal time. The principle of increasing the speed for on-street travel is removing obstacles that may cause delay. Increasing stop spacing, using dedicated transit lanes, eliminating curb parking and alternating near-sided and far-sided stops at corridors with synchronized signals would be helpful (Vuchic, 2005). Better route planning, route supervisor and better performance of transit vehicles would reduce delays to some extent as well.

2.6 Limitations of Previous Research

Previous researches put a lot of effort in determining measures of reliability, as discussed in Section 2.4, as well as proposing control strategies and analysing their impact on transit reliability and speed. The effectiveness of newly suggested measures was often tested through simulations. For example, Chang, et al. used an integration simulation package to investigate the effect of TSP on service reliability (2003). Cats, et al. used a mesoscopic transit simulation model to test the effectiveness of real-time holding strategies on reliability (2010).

In terms of technologies for reliability improvement, TSP undoubtedly has received a lot of attention. There were studies that applied simulation (Ngan, et al., 2004) or utilized limited number of case studies (Albright and Figlioizzi, 2012) to investigate the impacts of several parameters on TSP effectiveness. However, the number of factors analysed and data source were restricted. The relationships between factors and effectiveness were not constructed to provide direct view on their interactions to guide TSP planning.
To summarize, the research on relationships between different factors and transit reliability and speed were always constrained by qualitative analysis, utilization of simulation software, and limited number of factors. Moreover, the constraints on the size of the dataset make it unable to transfer the analytical results to interpret the features of the entire transit network. This thesis proposes relatively comprehensive mathematical relationships by using AVL data to reveal the effect of a series factors on transit reliability and speed. As the bus lines used for this study are representative and greater in amount, the research result would be able to reflect the reliability and speed variations for the Toronto bus network.
3 Methodology and Approach

In addition to problem definition, literature review and problem clarification, the core steps of conducting this research include determination of dependent variables, preliminary independent variable selection, data collection, data processing and modelling. This chapter mainly depicts the approaches utilized in the latter four steps to finally develop the mathematical models of transit reliability and speed as functions of a series factors at route level and segment level by using real-time transit service data and traffic data in the City of Toronto. Overall, data collection and processing consumed the majority of time.

3.1 Determination of Dependent Variables

The measure of transit reliability, which is the dependent variable, has to be decided before starting the data collection. Section 2.4 has outlined a series of transit reliability measures proposed by different researchers. There are several important points to guide the selection the most appropriate measure.

1) Availability of required data,
2) Easiness, and
3) Wide recognition.

Every measure in Section 2.4 is given a score from 0 to 5 for every point listed above. If the data of all of the independent variables included in a measure are not available for Toronto transit system, 0 will be marked for availability. If all data can be found, 5 will be awarded. The score of easiness is graded under the assumption that all the data are available. Then, 0 is given to the most complex measures and 5 is given to the easiest ones. Wide recognition is judged by the number of citations in other papers, but this number is not precisely counted. The results are presented in Table 3-2.

As shown in Table 3-1, the coefficient of variation of headway (Equation 2-5) and the coefficient of variation of run time (Equation 2-14) proposed by TCQSM prevail. TCQSM is one of the most widely acknowledged manual for transit planning practitioners, even though these two indicators have their own drawbacks, as mentioned in Section 2.4, they have still been frequently cited and studied. The measure of transit speed is straightforward compared to reliability, which equals the distance travelled over travel time.
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<th>Wide Recognition</th>
<th>Total Score</th>
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</tbody>
</table>

Table 3-1 Comparison of Transit Reliability Measures

Equation (2-5) and (2-14) while focusing on different features of transit reliability would both been used as dependent variables. Thus, two reliability models would be developed for the coefficient of variation of headway and coefficient of variation of run time. However, before conducting the modelling process, it is unable to tell if they were feasible. The final reliability model will be the one with the best performance. If none of them worked, other indicators would be applied. At this stage, it is assumed that at least one measure, either Equation (2-5) or (2-14) would function. Therefore, the actual headway, scheduled headway, actual run time and scheduled run time have to be collected.
3.2 Preliminary Selection of Independent Variables

The transit reliability and speed can be affected by many factors, including real-time and stationary ones. They have to be wisely selected to produce satisfying models with high predictability, to clearly illustrate the impact of explanatory variables, and to facilitate future analyzing processes by using factors that can be easily obtained with low cost (Guyon and Elisseeff, 2003). The preliminary selection of variables considers all possible factors that have an influence on transit reliability or speed. This step determines what types of data are to be collected.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Variables</th>
</tr>
</thead>
</table>
| Bus Service Characteristics | 1. One-way route length  
                      | 2. Total number of stops  
                      | 3. Stop density  
                      | 4. Scheduled headway (or scheduled frequency)  
                      | 5. Total number of boarding/alighting passengers  
                      | 6. Time period of day  
                      | 7. Day of week  
                      | 8. Terminal time  
                      | 9. Scheduled Speed  
                      | 10. Vehicle type  |
| Physical Infrastructures | 1. Number of non-signalized intersection  
                      | 2. Number of signalized intersection  
                      | 3. Total number of far-sided stops  
                      | 4. Total number of near-sided stops  
                      | 5. Vehicle volume  
                      | 6. Pedestrian volume  
                      | 7. Dedicated Transit Lane  
                      | 8. Number of 4-Leg Intersections  
                      | 9. Number of 3-Leg Intersections  
                      | 10. Number of 2-Leg Intersections  |
| Signals                | 1. Green  
                      | 2. Cycle time  
                      | 3. Utilization of transit phase  
                      | 4. Number of type 1 TSP-equipped intersections  
                      | 5. Number of type 2 TSP-equipped intersections  
                      | 6. Number of type 3 TSP-equipped intersections  |
| Other                  | 1. Weather |

Table 3-2 Preliminary Set of Independent Variables
Literature review was conducted to attain a comprehensive list of the influential elements as mentioned in Section 2.3. No matter a variable was stated to have significant impact on the transit reliability or not, it would be added to the preliminary list of variables. As Toronto uses transit signal priority as a mean to improve transit performance, its effect on the quality of service is one of the emphases of this research. Thus, variables associated with the characteristics of TSP were carefully studied. The situation of the installment of TSP in the City of Toronto was also investigated, so as to design specific variables for the city. Despite of TSP, there are other strategies applied around the world to enhance transit service, such as holding control, but they are not utilized in Toronto, hence not considered in this research. The preliminary set of independent variables after literature review is listed in Table 3-2. They can be further converted to other variables reflecting features that may play a part in transit reliability and speed. For example, the number of far-sided and near-sided stops can be used to obtain a ratio between these two values.

3.3 Data Collection

Data collection was the most time-consuming part, which required frequent communication with multiple agencies. The basic principle of data collection is finding as much as possible data from online sources. The City of Toronto provides freely accessible open data in various catalogues to the public. The most relevant areas include transportation, and locations and mapping. Some other information, such as weather, can be derived from Statistics Canada. The TTC Service Summary is also available online. General information regarding bus service can be found on the TTC website as well.

After searching the Internet, data remained unknown were to be retrieved from related departments. Any information on bus service, such as tracking data, was requested from Service Planning Department of Toronto Transit Commission (TTC). The time frame of interest was set to be 5 consecutive workdays in the fall of 2013. The specific time frame was left for the department to decide. The data request sent to TTC is illustrated in Figure 3-1.

The headways, run time and speed listed in Part 1 of Figure 3-1 were able to be obtained from the tracking data through further treatment to extract the values. Delays at bus stops were only available at time points where TTC schedules the departure time. The detailed pedestrian and
vehicle volume data at intersections were later obtained from an online service platform from Ryerson University (Section 4.7). The stop locations and their relative locations to intersections (far-side, midblock or near-sided) were provided by TTC. The right of way and data about intersections were not available, which were later obtained from searching Google Maps. The Service Planning Department did not have TSP information.

**Data Request - TTC**

- 24-hour data for one week in Fall 2013 (or any data available around this time) on route basis.
- The Service Summary (includes data like route numbers, No. of vehicles, scheduled headways, scheduled run time, average speed) in the time periods during which real-time data is to be provided.
- AVL data
- Archived Schedules in Fall 2013 (current schedules can be helpful if the historical ones are not available)
- For transit routes:  
  Bus lines:  
  - 6 Bay (Dundas - Queens Quay & Sherbourne)  
  - 7 Bathurst (Bathurst Bln - Steeles)  
  - 16 McGee (Warden Bln - Scarborough Centre Brn)  
  - 24 Victoria Park (Victoria Park Bln - Steeles)  
  - 25 Don Mills (Pape Bln - Steeles)  
  - 26 Dupont (St. George Bln - Jane Bln)  
  - 22C Eglinton West (Eglinton Bln - Jane & Lawrence via Trethewey)  
  - 32C Jane (Jane Bln - Steeles)  
  - 36B Finch West (Finch Bln - Humberwood)  
  - 35C Finch East (Finch Bln - Neilson)  
  - 40 Junction (Dundas West Bln - Runnymede)  
  - 52 Lawrence West (Lawrence Bln - Martin Grove)  
  - 53B Steeles East (Finch Bln - Markham Rd)  
  - 54 Lawrence East (Eglinton Bln - Orton Park)  
  - 54A Lawrence East (Eglinton Bln - St. Pumpers Blvd)  
  - 65 Parliament (Castle Frank Bln - express lane)  
  - 68 Warden (Warden Bln - Steeles)  
  - 72 Pace (Pape Bln - Eastern)  
  - 72A Pace (Pape Bln - Union Bln)  
  - 75 Sherbourne (South Drive - Queens Quay)

PART 1

**REAL-TIME DATA OF THE TRANSIT LINES**

1. Record Time:  
   - Time/Day/Month/Year
2. Passenger Volume:  
   - Number of boarding and alighting passengers at stops

**Figure 3-1 Data Request Sent to TTC**

Since the signal timing data was not available at TTC. Another piece of request was sent to the Traffic Management Centre of City of Toronto. The first set of data received were timing cards, which included comprehensive information on phase splits as well as TSP. The details of timing cards are described in Section 4.6. After careful study of the timing cards, another issue was discovered. The TSP systems installed at some of the signalized intersections were disabled due to the update of signal control systems, which would not be enabled until field tests were carried out. However, the timing cards did not indicate whether the TSP at an intersection was enabled.
or not during the analytical time period. Thus, a second request was sent to the Traffic Management Centre for this information.

After collecting data from online sources, TTC and the City of Toronto, all the information needed for conducting the research was ready. The next step would be preparing the data for modelling.

### 3.4 Data Processing

The data processing was done by using Microsoft Excel and MATLAB. Section 5.9 gives detailed explanation of how tracking data was processed in MATLAB. Any other data that vary with time were disaggregated or aggregated to the level of time periods in MS Excel, because the dependent variables (coefficient of variation of headway deviations, coefficient of variation of run time, and the period average speed) are computed at the period level. Another reason for doing so is many independent variables, such as service frequency, only change with time periods. Besides, the passenger, vehicle and pedestrian volume can only be disaggregated down to the period level. As certain degree of variations has to be ensured in the values of every independent variable, the lowest time level for analysis was chosen to be time period. If the unit was selected to be an hour a lot of unscientific assumptions have to be made, such as even distribution of passengers in each hour.

### 3.5 Modelling

Very few researches considered building mathematical models to reveal relationships between transit reliability and influential factors. There was one investigated variables of one transit route including distance, number of stops, direction, peak hour, number of alighting passengers, passenger load and driver experience and their effect on the run time by developing a regression model (El-Geneidy, et al., 2011). Therefore, regression model was the first to try. Besides, when the relationships were not clear, linear regression should be applied first as long as the assumptions of this modelling approach would not be issues of this research.

To begin the linear regression modelling, the correlation coefficients of all possible pairs of dependent and independent variables were computed to check the extent to which the two variables would change together. The ones with very high correlation coefficients (greater than
or equal to 0.7) cannot be included in the same model at a time. The correlation coefficients between dependent and independent variables also helps rank the latter one. As MS Excel can only include 16 independent variables to its maximum, the ranking process would assist in preparing the factors for the initial trial. Those independent variables having high correlation coefficients with dependent variables were given priority to be included in the model because they are more likely to be significant factors.

The general selection method applied was backward elimination. The measurement variables having higher correlation coefficients with dependent variables were first considered. Those highly correlated variables were grouped, only one of them would be chosen at a time for modelling. The alternatives in the same group were included one by one for each trial. Different combinations were also made for alternatives across different groups to yield the best model.

The models on the segment-level were constructed after the route-level ones. Therefore, it was easier to do the segment-level analysis when the effect of a major proportion of independent variables has been investigated. Thus, variables in the initial trial for segment-level modelling consisted all the factors in the final route-level model and the new ones designed for segment-level modelling.

### 3.6 Statistical Analysis

The selection of the models with the best performance was based on the magnitude of the adjusted R² values. Furthermore, the explanatory variables should be statistically significant with signs of coefficients following the transit operation theory. The forms of the dependent variables may be altered to generate models with higher goodness-of-fit. For example, the lognormal formulation was tested at the segment level for coefficient of variation of run time. The delta speed which was the difference between the actual speed and the scheduled speed was utilized as the dependent variable of the segment level average speed model.

Since backward elimination was the basic method deployed for selecting the independent variables, the first criteria of excluding certain independent variables was analysing the signs of their coefficients. The sign of the coefficient must follow the transit operation theory to maintain a variable in the model. For example, the traffic volume would have a positive sign in the coefficient of variation of run time model, which indicates that high traffic volume would result
in low reliability. If the sign of traffic volume was negative, it did not follow the theory. After the signs were checked, the magnitude of t-statistics was judged at the confidence level of 90%. If the t-statistics of a variable is lower than 1.645 it would be excluded, because one was uncertain if this variable has a significant effect on the dependent variable at 90% confidence level. There were a few exceptions that explanatory variables with low t-statistics were remained in the model due to their importance of providing information on their impact on transit reliability and speed. The overall performance of the models was then judged by the adjusted coefficient of determination (R²) values that the higher the adjusted R² the better the models.
4 Data

This chapter describes the whole set of data obtained from online sources and different agencies. Descriptions are provided on bus lines, service data of buses, physical infrastructures, tracking data, riding counts, signal timings, vehicle and pedestrian volume and weather. The data sources are defined for every piece of data. When it is necessary, samples of data are illustrated for better understanding. The raw data usually came in different format and levels, they have to be scaled and cleaned before modelling.

4.1 Bus lines

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<th>No. of Low Frequency Periods</th>
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<td>Yes</td>
<td>1</td>
<td>4</td>
<td>6.21</td>
<td>No</td>
<td>1</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>68</td>
<td>No</td>
<td>4</td>
<td>1</td>
<td>25.06</td>
<td>No</td>
<td>2</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>75</td>
<td>Yes</td>
<td>3</td>
<td>1</td>
<td>8.59</td>
<td>Yes</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4-1 Bus Line Information of Selection Criteria

13 TTC bus lines are used for research analysis in total, while 11 of them are investigated in both directions. These lines are primarily selected based on the following criteria:

1) Covering downtown and non-central areas,
2) Having high-frequency and low-frequency lines,
3) Having different lengths,
4) Including lines equipped with TSP,
5) Having as fewer as possible branches,
6) Providing service in all time periods, and
7) Minimizing the amount of data request from the City of Toronto.

Most importantly, the selection criteria should guarantee adequate variations among the independent variables, so as to facilitate the modelling process. Minimizing the number of branches was aimed at reducing the complexity of cleaning the tracking data. Trade-offs need to be made among the criteria in order to have an overall best performance. These criteria ensure that the selected routes are representative for the TTC bus network. Table 4-1 outlines the basic information about the selected bus lines according to these criteria. TTC provides service in five time periods of a day (details in Table 4-2). According to the passenger demand, investment and operational cost, service frequencies vary from periods to periods.

### 4.2 Service Data of Buses

The service data provided by TTC in *Toronto Transit Commission Service Summary* (2013) provides information of all service routes in six time periods (Table 4-2) about their names, round-trip distance, vehicle type, number of transit units, headway, round-trip driving time, total terminal time, average speed, and service hours.

<table>
<thead>
<tr>
<th>MONDAY TO FRIDAY</th>
<th>SATURDAY AND SUNDAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning peak period</td>
<td>06:00 – 09:00</td>
</tr>
<tr>
<td>Midday</td>
<td>09:00 – 15:00</td>
</tr>
<tr>
<td>Afternoon peak period</td>
<td>15:00 – 19:00</td>
</tr>
<tr>
<td>Early evening</td>
<td>19:00 – 22:00</td>
</tr>
<tr>
<td>Late evening</td>
<td>22:00 – 01:00</td>
</tr>
<tr>
<td>Overnight</td>
<td>01:30 – 05:30</td>
</tr>
</tbody>
</table>

Table 4-2 Definition of Time Periods

The information on the stops was retrieved from three sources. The TTC website provides lists of stops in sequence for entire routes, including different branches, from which the numerical stop IDs and stop names of branches were obtained. The City of Toronto Open Data offers locations (latitudes and longitudes) of stops in the city. The *Stop List* retrieved from TTC also contains the latitudes and longitudes information. In addition, it records the “on street” and “at street” of stops. The on street direction, on street location (near-sided, mid-block, far-sided), and accessibility of stops are recorded in this file as well.
4.3 Physical Infrastructures

The data on physical infrastructures mainly contains information of intersections and lanes. The list of intersections of bus routes was manually collected by using Google Maps. The location information of signalized intersections is available on the City of Toronto Open Data, which also involves activation date of signals and configuration of intersections.

The dedicated bus lanes in the City of Toronto are marked by white diamonds. Very few routes have segments with dedicated lane. This information can be derived by observations and searching on Google Maps.

4.4 Tracking Data

The historical bus tracking data of totally 13 lines from November 23 to 27, 2013 (Monday to Friday) were provided by the Strategy and Service Planning Department of Toronto Transit Commission (TTC). Basically, TTC’s AVL data is collected by the Communication and Information System (CIS) conceived in 1970s in the City of Toronto that records real-time coordinates of service vehicles every 20 seconds. This system is also used for communications between operators and the control centre.

The City of Toronto has signposts installed throughout the city. Transit vehicles receive signals from these white poles through the CIS units on-board when passing them and update the signpost reference. As transit vehicles move on, the odometer calculates their distances to the last recorded signpost every 20 seconds based on pre-set background information on route and run number which provides a pool of possible locations. The relative distances to the signposts are further converted to coordinates and recorded as vehicle tracking data. Once a vehicle reaches a new signpost, the system updates the reference and makes correction to the previous records of locations when necessary.

The CIS monitoring system has a few limitations. First, it relies on the background information about route schedules and path. If a vehicle goes off its scheduled route, the system would not be able to determine its correct location. Second, the system usually assumes that the vehicle is travelling straight along a street. When it makes left/right turns and U-turns, the system could not define these actions until the vehicle reaches a signpost in another direction. The current system
has a program developed for tackling this problem, but still cannot cover all the critical points. Third, the tracking records of one transit line are easily interfered by other adjacent lines that records belong to one route are always found to be mixed with trajectory of another as illustrated in Figure 4-1. Fourth, when either signposts or odometers does not function correctly, the coordinates would possibly appear anywhere in the city even in the middle of Lake Ontario.

The AVL data provided by TTC is an Excel file sorted by date and time, which includes five columns, namely Message Date and Time, Route Number, Vehicle Number, Latitude and Longitude (Table 4-3). This table only shows one format of date and time, but the data extracted from TTC’s program also contains another format, which randomly appears in the spreadsheet and cannot be easily converted to the standard format. These data are recorded by locations of time instead of time of locations. If each row is referred as a tracking “data point,” then it contains information of date, time, route number, vehicle number, latitude and longitude. This concept will be used in the later sections (e.g. Section 5.9).

<table>
<thead>
<tr>
<th>Message Date and Time</th>
<th>Route Number</th>
<th>Vehicle Number</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-NOV-13 06:30:00</td>
<td>40</td>
<td>7316</td>
<td>43.656967</td>
<td>-79.453163</td>
</tr>
<tr>
<td>18-NOV-13 06:30:00</td>
<td>40</td>
<td>7310</td>
<td>43.651165</td>
<td>-79.52652</td>
</tr>
<tr>
<td>18-NOV-13 06:30:00</td>
<td>40</td>
<td>7317</td>
<td>43.665932</td>
<td>-79.482536</td>
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<td>43.653149</td>
<td>-79.52475</td>
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<td>7316</td>
<td>43.656967</td>
<td>-79.453163</td>
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<tr>
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<td>7317</td>
<td>43.66555</td>
<td>-79.481796</td>
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<td>43.656967</td>
<td>-79.453163</td>
</tr>
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<td>7316</td>
<td>43.656967</td>
<td>-79.453163</td>
</tr>
<tr>
<td>18-NOV-13 06:31:00</td>
<td>40</td>
<td>7310</td>
<td>43.656898</td>
<td>-79.520332</td>
</tr>
<tr>
<td>18-NOV-13 06:31:00</td>
<td>40</td>
<td>7317</td>
<td>43.665535</td>
<td>-79.47863</td>
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<td>18-NOV-13 06:31:20</td>
<td>40</td>
<td>7310</td>
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<td>-79.516068</td>
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<tr>
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<td>7316</td>
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<td>-79.453163</td>
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<tr>
<td>18-NOV-13 06:31:40</td>
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<td>7317</td>
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<td>40</td>
<td>7317</td>
<td>43.665482</td>
<td>-79.473549</td>
</tr>
</tbody>
</table>

Table 4-3 Sample TTC Tracking Data of Route 40
4.5 Riding Count

TTC regularly counts the passenger volumes of service lines manually from the start of service till the end. A scan of sample riding count of line 505 eastbound is presented in Figure 4-2. The summary reports of riding count provided by TTC include the accumulative number of boarding (ONs) and alighting (OFFs) passengers at each stop over five time periods of a day, namely, morning peak, mid-day, afternoon peak, early evening and late evening. The time frame of each time period is shown in Figure 4-2. This report does not differentiate passengers using different branches, so each “ONS” or “OFFS” at a stop is defined as:
\[ \text{ONs} = \int_{t_1}^{t_2} \sum_{i=1}^{b} \text{number of passengers boarding at stop } i \]  \hspace{1cm} (4-1)

\[ \text{OFFs} = \int_{t_1}^{t_2} \sum_{i=1}^{b} \text{number of passengers alighting at stop } i \]  \hspace{1cm} (4-2)

where, \( t_1 \) is the start time of a time period, \( t_2 \) is the end time of a time period, \( b \) is the total number of branches serving stop \( i \). That is to say, on January 15, 2014, if a person stood at the first stop (Dundas West at Outer Platform) of 505 eastbound counting passengers getting on to all branches of line 505 from 9:00 to 14:59, he or she would get 444 “ONs” in total. Because of counting errors, the summations of “ONs” and “OFFs” over all stops do not equal to each other.

Signal timing data was retrieved from Traffic Management Centre of the City of Toronto for signalized intersections along 6 bus lines. There are mainly four types of signal control systems implemented in Toronto, namely, MTSS, TransSuite, SCOOT or UTC/SCOOT, and Econolite Aries, where the first two are most widely used.

MTSS, short for Main Traffic Control System, was the oldest system in Toronto. It usually consists three pre-determined timing plans in am peak on workdays, pm peak on workdays and off peak. Some of the MTSS intersections are equipped with transit pre-emptions. This traffic control system has a series of limitations and requires frequent maintenance that has started...
being replaced by TransSuite about ten years ago to ensure signal coordination and the overall function of transportation system.

TransSuite Traffic Control System (TCS) is a more reliable integrated traffic management system that overcomes the existing weaknesses of MTSS. TransSuite TCS can provide a lot of features according to customer requirements including support for multiple controllers, fully compliant NTCIP communication, support for advanced local controller features, multiple control modes including traffic responsive, real-time communications and error checking, IP communications support including wireless, advanced controller database management tools with efficient parameter upload/download access, relational database for easy data import/export, flexible and full-featured event scheduler, and highly configurable searchable event log (TransCore, 2015). It is now the most widely installed computer system in Toronto.

Urban Traffic Control (UTC)/Split Cycle Offset Optimization Technique (SCOOT) consists of predetermined timing plans (UTC) used when SCOOT is not available and an adaptive signal control system (SCOOT) that offers timing plans based on real-time traffic demand. This is also a relative old system that comes to the end of its service life.

Aries is a closed-loop traffic management system implemented at eight intersections along Queens Quay to grant priority to streetcars once they are detected by the sensor located within the streetcar track (City of Toronto, 2015). Aries is capable of providing back-up coordination in reaction of actual traffic conditions (Econolite, 2015), but this function has never been used in Toronto. This system will also be replaced by TransSuite shortly.

The timing cards of signalized intersections provided by the City of Toronto include general information (location, computer system and implementation date), and the length of each phase (walk, flash don’t walk, amber, all red, green) for different patterns (timing plans) during a day. Additional descriptions about TSP, turn restrictions and extended push activation, etc. are provided when applicable.

In the City of Toronto, 10 bus lines and all streetcar lines (11 in total) have TSP equipped on route. If a transit vehicle checks in at the request loop upstream of an intersection when the green phase is operating, the TSP system will be activated and if the bus is still in the priority operating zone at the decision point which is usually when the regular Walk phase terminates, TSP starts to
provide green extensions at 2-second increments up to its predetermined maximum value or until the vehicle checks out at the cancel loop (Figure 4-3). If a bus arrives at the check-in loop during a red phase, the TSP system would react to reduce the length of red signal.

If obstacles exist on the street that obstacles exist to prevent the check-in detection loop from being installed at the right position (Position 1), the loop has be to move backwards to a location further upstream to the intersection (Position 2). In this case, “delay time” should be given to cater the time needed for a bus to travel from Position 2 to Position 1. The “delay time” is set based on the average scheduled speed of buses. Therefore, if it takes 18 seconds for a bus to run from Position 2 to Position 1, when a bus checks in at Position 2 the TSP will not be activated until 18 seconds later.

The TSP system in the City of Toronto deals conflict of transit request based on the principle of “first come, first serve,” and minimizing net wait time of buses. Most of time, TSP gives priority to the first bus that passes a request loop, and it only provides priority to one vehicle in a cycle. However, if a bus on the side street arrives at its red phase at first and another bus arrives immediately later on the main street in its green phase, instead of truncate the red phase, the priority is granted to the one on the main street to minimize the net wait time.

There are four types of TSP green extension algorithms in the City of Toronto. The first algorithm provides green extension during the Green/Walk phase up to 30 seconds. The second extends the green phase during Green/Solid Don’t Walk up to 16 seconds. The third one gives extension during Green/Walk up to 14 seconds and Green/Solid Don’t Walk up to 16 seconds of 30 seconds in total. The details of the operating mechanism of the third algorithm are illustrated in Figure 4-4. The fourth mode has two detection zones per direction that offers extensions during Green/Walk up to 14 seconds and/or Green/Solid Don’t Walk up to 16 seconds. This is the most complex algorithm, and it is presented in Figure 4-5.
Figure 4-3 Configuration of Intersection with Green Extension Algorithm 1

Figure 4-4 Green Extension Algorithm 3 (Source: City of Toronto)
4.7 Vehicle and Pedestrian Volume

Two types of traffic volume data were retrieved from the City of Toronto and Ryerson University. The first one, available on the City Hall Open Data, contains 8-hour and 24-hour vehicle and pedestrian volumes at all signalized intersections in the city. The record dates range from 2007 to 2011 and different for each intersection. A proportion of signalized intersections also have data collected on days in 2012 or 2013. 8-hour volume was collected approximately from 7:30 to 18:30 with breaks. 24-hour counts are simply twice the 8-hour volumes.
The second piece of data is Traffic Turning Movement Count measured at a 15-minute interval from 7:45 to 18:00 obtained from an online service platform operated by Ryerson University. This data contains through, right-turn and left-turn traffic and pedestrian volumes in all directions at signalized intersections. The 15-minute counts are further summarized to report a.m. peak, average off-peak and p.m. peak vehicle and pedestrian volumes. This detailed measurement has not been taken at all intersections in the city.

4.8 Weather

The weather data is derived from Statistics Canada. There are 7 weather-monitoring stations near the City of Toronto, namely, Toronto, Toronto City Centre, Toronto East York Dustan, Toronto North York, Toronto International Airport, Toronto Buttonville Airport, and Richmond Hill. These stations record weather data every hour, and usually contain monitoring items like weather, temperature, dew point temperature, relative humidity, wind direction, wind speed, visibility, station pressure and wind chill. Some other items may or may not be reported by the stations are evaporation, extreme maximum temperature, extreme minimum temperature, precipitation, saturation point, snow depth, soil temperature, solar radiation and vapour pressure.
5 Data Processing

This chapter depicts the formulas and methods used for processing all types of data. In order to investigate as many independent variables as possible, the data were obtained from multiple sources in a variety of formats. Basically, the data originally at route level were disaggregated for conducting analysis at the segment level. Similarly, aggregation requires to be done for route level modelling if the data were at intersection or stop level, such as vehicle volume and number of alighting passengers. Specific treatments are needed for TTC tracking data and riding counts.

5.1 Line Length

The line length is the actual distance travelled by a transit unit from the origin terminal to the destination terminal and returns back to the origin terminal, which is the length of a round trip. In this thesis, line length is broken down into the directional length, because factors, such as stop configuration and through traffic volume, are not the same in different directions of a line.

The TTC Service Summary only provides distance for round trips. In most cases, the directional length can be simply calculated as half of the round-trip distance, when the origin and the destination of one direction are the destination and origin of the other. In the meantime, the buses should travel on the same streets while only in the opposite directions. TTC has some bus lines that do not follow this criterion. These lines have one service direction shorter than the other. If \( \Delta d \) is used to present the sum of distance that is served by one direction but not in the other, the length of the long direction and the short direction can be calculated as:

\[
\begin{align*}
  d_l &= \frac{d}{2} \\
  d_s &= \frac{d}{2} - \Delta d
\end{align*}
\]

where, \( d_l \) is the length of the long direction, \( d \) is the round-trip distance, and \( d_s \) is the length of the short direction. When knowing the latitude and longitude of the start and end of both directions, \( \Delta d \) can be obtained from Google Maps or the “Distance” function in MATLAB. The segment lengths are obtained from Google Maps as well.
5.2 Frequency of Service and Terminal Time

The service frequency is the number of transit units that pass a point on a line in an hour. This value can be derived if the headway is given.

\[ f = \frac{60}{h} \]  

(5-3)

where, \( f \) is the frequency, \( h \) is the headway in the unit of minute. TTC Service Summary and the TTC website both contain information on service intervals, which usually differ in different time periods. A majority of TTC bus lines have higher frequency in peak periods. It is most common to use 10 minutes as the boundary of low- and high-frequency service.

The terminal time is the time a transit vehicle spent at terminal. It is less than 5 minutes for most TTC bus lines. Similar to the service frequency, terminal time does not require any aggregation or disaggregation for analysis.

5.3 Scheduled Speed and Driving Time

The average scheduled speed that is given in TTC Service Summary, which is the calculated as the round-trip driving time over the round-trip distance. That is to say, the design speed includes the dwell time at stops, but exclude terminal time. This speed is the average of the entire route, but it has a lot of variations from segment to segment. The design speed in two directions of a line is assumed to be the same in this thesis.

The run time provided in TTC Service Summary is the round-trip driving time, excluding terminal time. By assuming that the travel time remains constant when the travel distance does not change, the run time of one-way trip is:

\[ t_l = \frac{d}{2v} \]  

(5-4)

\[ t_s = \frac{d - \Delta d}{2v} \]  

(5-5)

where, \( t_l \) is the run time of the long direction, \( t_s \) is the run time of the short direction, and \( v \) is the scheduled speed. \( \Delta d \) is 0 when two directions have the same length. Thus, \( t_l = t_s \). When conducting the segment analysis, the scheduled run time is:
\[ t_{seg} = \frac{d_{seg}}{v} \quad (5-6) \]

where, \( t_{seg} \) is the scheduled run time of a segment, \( d_{seg} \) is the length of a segment, \( v \) is the scheduled speed given in \textit{TTC Service Summary}.

5.4 Service Hours

The duration of service hours in five time periods vary from line to line. The lengths of the periods between the first and last periods are constant. If a bus line provides service in five time periods every day, the second (midday), third (afternoon peak), and fourth (early evening) period have fixed duration of 6, 4 and 3 hours, respectively. Attention should be paid on bus lines with service in inconsecutive periods, that the lengths of the above mentioned time periods are not constant anymore. The lengths of time periods are used in calculating the number of alighting and boarding passengers per hour in Section 5.5.

5.5 Riding Count

The riding count data obtained from TTC as discussed in Section 4.5, is the sum of the total number of boarding/alighting passengers in a time period from all branches at a stop. In order to know the number of users for each branch, these values should be disaggregated.

In order to obtain the hourly boarding/alighting passengers volumes \((V_b/V_a)\) of a particular branch, the following information is required: the start and end time of each time period, the service frequency and the service stops of all branches. With the assumption that the number of boarding and alighting passengers are evenly distributed and proportional to the service frequencies and the lengths of service time of each branch, the number of boarding and alighting passengers at a stop during a time period is calculated as:

\[
V_b = \frac{ONs \cdot f_1 \cdot t_{p1}}{\sum_{i=1}^{b} f_i \cdot \sum_{i=1}^{b} t_{pi}}
\]

\[
V_a = \frac{OFFs \cdot f_1 \cdot t_{p1}}{\sum_{i=1}^{b} f_i \cdot \sum_{i=1}^{b} t_{pi}}
\]

where, \( f_1 \) is the service frequency of the branch of interest, \( f_i \) is the frequency of branch \( i \), \( t_{p1} \) is the duration of service in time period \( p \) of the branch of interest, \( t_{pi} \) is the duration of service in
time period p of branch i, b is the total number of branches serving the stop. The number of boarding and alighting passengers of a branch at a stop per hour is calculated as:

\[ V_b' = \frac{ONs \cdot f_i}{\sum_{i=1}^{b} f_i \cdot \sum_{i=1}^{b} t_{pi}} \]  
(5-9)

\[ V_a' = \frac{OFFs \cdot f_i}{\sum_{i=1}^{b} f_i \cdot \sum_{i=1}^{b} t_{pi}} \]  
(5-10)

If a stop is served by a single branch, then

\[ V_b = ONs \]  
(5-11)

\[ V_a = OFFs \]  
(5-12)

The reason for converting the riding counts to hourly volumes is making them comparable across different lines. To illustrate, without the conversion, 1000 alighting passengers in the morning peak for a line starts its service at 6 a.m. is not comparable to another line with 800 alighting passengers that starts at 8 p.m. The “total ONs and OFFs” used as an explanatory variable is the sum of ONs and OFFs at all stops along the route or within a segment.

\[ Total \ ONs \ OFFs = \sum_{i=1}^{s} (V_b' + V_a') \]  
(5-13)

where, s is the total number of stops of the branch or within the segment.

### 5.6 Stops and Intersections

The stop density and the intersection density are calculated as the number of stops/intersections per unit length (km). Other factors considered for intersections are the ratio of the number of signalized intersections to the non-signalized intersections, and their density.

The location of stops in relation to their downstream intersections is an important factor as well. The ratio of far-sided stops to near-sided stops is calculated. The number of mid-block stops is always 0, so it does not affect this ratio in most cases. However, considering its features, the mid-block stops are treated as far-sided stops.
Geographic layout of the stops and intersections on the streets is also investigated to understand their relative locations. This step is done for the segment analysis. Based on the latitude and longitude information, the stops and intersections can be plotted on the same map. As a bus moves along its scheduled route, one would be able to tell the stops and intersections it passes in sequence from this map.

5.7 Signal Timings

The first variable considered about signal timings is the cycle length, which usually remains constant along a corridor and varies in time periods. The average value of the cycle length of signalized intersections along the entire bus route or segment is computed.

\[ C = \frac{\sum_{i=1}^{n} C_i}{n} \]  

(5-14)

where, \( C \) is the average cycle length, \( C_i \) is the cycle time of the \( i^{th} \) intersection, and \( n \) is the total number of signalized intersections.

The second variable is the ratio of the length of green phase to the cycle time, denoted by \( G/C \).

\[ G/C = \frac{\sum_{i=1}^{n} G_i/C_i}{n} \]  

(5-15)

where, \( G_i \) is the length of green phase at the \( i^{th} \) intersection.

The third variable is the average length of green extensions, which is the extra green phase given to transit vehicles approaching an intersection (Equation 5-16). This is a parameter associated with TSP control, which usually equals to 16 seconds when the side street is a major street and 30 seconds when the side street is minor.

\[ G_{ext} = \frac{\sum_{j=1}^{m} G_{ext_j}}{n} \]  

(5-16)

where, \( G_{ext} \) is the average length of green extension, \( G_{ext_j} \) is the length of extension at the \( j^{th} \) intersection, \( m \) is the total number of intersections with TSP or with green extension, and \( n \) is the total number of signalized intersections.
5.8 Vehicle and Pedestrian Volume

The vehicle volume used for modelling is the volume in the direction of the transit unit movement, which is the sum of the left-turn, through and right-turn traffic. The maximum and average vehicle volume of the entire route and the segments are computed.

\[
\bar{V}_{veh} = \frac{\sum_{i=1}^{n} V_{veh_i}}{n} \quad (5-17)
\]

Where, \( \bar{V}_{veh} \) is the average vehicle volume, \( n \) is the total number of intersections with vehicle volume data, and \( V_{veh_i} \) is the vehicle volume at the \( i^{th} \) intersection. Similarly, the average pedestrian volume is calculated using Equation 5-18.

\[
\bar{V}_{ped} = \frac{\sum_{i=1}^{n} V_{ped_i}}{n} \quad (5-18)
\]

Where, \( \bar{V}_{ped} \) is the average pedestrian volume, and \( V_{ped_i} \) is the pedestrian volume at the \( i^{th} \) intersection. The maximum pedestrian volume is also considered when developing the models.

The number of vehicle turning right at an intersection may block bus stops, especially near-sided stops. Therefore, the average volume of right-turn vehicles needs to be known. However, not all intersections have right-turn traffic. T-intersections and those with right-turn prohibited would have zero traffic turning right. Thus,

\[
\bar{V}_{right} = \frac{\sum_{i=1}^{r} V_{right_i}}{n} \quad (5-19)
\]

where, \( \bar{V}_{right} \) is the number of average right-turn vehicles of the entire route or segment, \( V_{right_i} \) is the number of average right-turn vehicles at the \( i^{th} \) intersection, and \( r \) is the total number of intersections that have right-turn traffic.

5.9 Tracking Data

The tracking data obtained from TTC is the most important and time-consuming data in the entire processing part. The overall purpose is finding out the arrival and departure time at the stops for the runs made by selected branches. The following assumptions are made when writing the MATLAB program.
1) If a bus departs from the origin terminal, it begins a trip (or run). When this bus reaches the terminal in the other end of its designed route, this trip (or run) ends. Since AVL saves bus locations every 20 seconds, there were a lot of data points of a trip, they may have locations around the stops, in the midblock, or at the intersections. The arrival time at stop i is assumed to be the time associated with the data point that has the shortest distance to stop i among all data points of a trip. Since the CIS system records bus locations every 20 seconds, even there was no record taken at a stop, the maximum error can be only 10 seconds, which can be ignored.

2) If the shortest distance to a stop is associated with more than one data points in a trip, it indicates that the bus dwells at this location for more than 20 seconds. Then, the earliest data point is considered to be the arrival time and the latest is the departure time.

3) If only one shortest distance is observed, this data point is used as both arrival and departure time.

4) Commonly, there are more than one data points with the shortest distance to the terminals, because vehicles usually dwell at the terminals for more than 1 minute, even if there is no terminal time assigned in the schedule. The start of a trip is selected as the latest data point that has the shortest distance to the origin terminal, which is the departure time.

5) The end of a trip is the earliest data point that has the shortest distance to the destination terminal, which is the arrival time.

6) If the shortest distance to the origin or destination terminal is related to only one data point, then this point is the departure time from the origin or arrival time at the destination.

This research only deals with one branch of each transit line, even if there exists more than one. To better understand the situations of branches, bus lines are categorized into four classes as shown in Table 5-1. Lines in Class 1 and 2 do not require special processing code. To explain, bus lines in Class 2 have branches that either start at the same location with the selected branch but end earlier, or start later but terminate at the same location. Therefore, if a group of data lack data points adjacent to the origin but travels till the end, or miss points around the destination but begins from the start, will be automatically filtered out. However, bus routes in Class 3 (Figure 5-1) and 4 need to have codes to eliminating the trips made by the longer branches. This is done
by adding location information of their origin or destination terminals, whichever is different from the selected branch.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Type of the Extra Branches</th>
<th>Bus Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Only one branch is present</td>
<td>None</td>
<td>7, 16, 25, 40 and 65</td>
</tr>
<tr>
<td>2</td>
<td>Other branches lie within the service region of the selected branch</td>
<td>a. Begins at the same origin terminal with the selected branch, but ends at a stop upstream of the destination of the selected branch</td>
<td>36 and 54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Begins at a stop downstream of the origin of the selected branch, but ends at the destination of the selected branch</td>
<td>6, 54, 63 and 75</td>
</tr>
<tr>
<td>3</td>
<td>Having other branches provide service beyond the service region of the selected branch</td>
<td>a. Begins at the same origin terminal with the selected branch, but ends at a stop downstream of the destination of the selected branch</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Begins at a stop upstream of the origin of the selected branch, but ends at the destination of the selected branch</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>Having branches that fall in Class 2 and Class 3</td>
<td>a. Having 2a and 3a</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Having 2a, 2b and 3a</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 5-1 Classes of Bus Lines Based on Situations of Branches

5.9.1 Part 1 MATLAB CODE

The general steps of processing the tracking data are presented in Figure 5-2. As described in Section 4.4, the date and time stored in the tracking data needs to be separated, after which the tracking data is imported to MATLAB for further processing. The MATLAB program consists of three major components. The first one deals with cleaning up the tracking data and obtaining the arrival and departure time at stops, which involves the following steps.

1) Deleting data points outside the predetermined boundaries of the service region of the target bus line. This region should cover all branches. As shown in Figure 5-1, the branch of interest (B1) lies in Region B (serves stop 3 to 7). Another branch (B2) of this line serves stops 1 to 7, which is a Class 3b line. If the boundaries set for cleaning data is between X2 and X3, and Y1 and Y2, data points in Region A will be deleted. Since B2
covers all stops in Region B, if data points in Region A are deleted, the data points which belongs to B2 but fall in Region B would be considered to be points of B1.

2) Clearing data points outside the service periods. Step 1) and 2) are designed for reducing the computational complexity.

3) Sorting data points by vehicle number, then date, and then time.

4) Calculating the distance (BusDis) from every data point to every stop of the branch of interest. In total there will be \(d \times s\) distances, where \(d\) is the number of data points and \(s\) is the number of stops.

5) After step 4), every data point should have \(s\) BusDis associated with the stops along the branch, from which the shortest distance is selected and the corresponding stop is allocated to the data point.

6) Since data points are sorted in step 3), the ones belong to the same trip should be in adjacent cells. This step is designed to find the data points of the origin and destination terminals. The data points in between them are pertain to the same trip.

7) Within data points of the same vehicle numbers, searching the first origin terminal, and continues to search data points one by one until the destination terminal is found.
   a. If another group of origin terminal is observed before finding a destination, which indicates a Type 2a branch. All data points between these two origins will be deleted.
   b. The data points of Type 2b branches will automatically be ignored, because the origin terminal cannot be found.
   c. For lines with Type 3a branches, the latitude and longitude of the terminal of the extra branch (denoted by Terminal\(_{e}\)) that lies beyond the service region of the selected branch are imported to the MATLAB program. Codes are developed for picking out the extra terminal. If the destination of selected branch is denoted by Terminal\(_{s}\), the program will find Terminal\(_{s}\) before Terminal\(_{e}\) after the origin. Therefore, if after discovering a group of data points with origin terminals assigned, the program finds a Terminal\(_{e}\). When it continues to search, a Terminal\(_{e}\) exists after Terminal\(_{s}\) before another origin terminal is found. Then, these data points between the origin and Terminal\(_{e}\) belong to Type 3a branch and will be deleted.
d. The Type 2a and 2b branches of Class 4 lines will be filtered out following the criteria depicts in 7) a and 7) b.

e. The Type 3a branches of Class 4 lines will be deleted following the rule in 7) c.

8) Giving every trip a numerical code and assigning them to data points.

After Part 1, the raw tracking data is converted to Table 5-2. Since every data point is allocated to a stop, every stop corresponds to a series of data points. As TTC raw tracking data contains a significant portion of data errors, the Part 1 code cannot treat all of them. For example, the data in the second line of Trip Number 120 demonstrated in Table 5-2 is pertained to Stop 11, which should be Stop 1 theoretically. Therefore, Part 2 code is designed to deal with all sources of errors remained.

Figure 5-1 Example of Class 3 Bus Lines
Table 5-2 Sample Tracking Data after Part 1 Code

5.9.2 Part 2 MATLAB Code

The second part of the MATLAB program mainly focuses on preparing the final list of arrival and departure times at the stops of the trips made by the selected branch. The steps are elaborated as follows.

1) The only data points that need to be saved for modelling are the arrival and departure time at stops, so these points must be found in the group of data points that belong to the
same stops. Following Rule (2), (3), (4), (5) and (6) elaborated on page 41, the start and end time of a trip, arrival and departure time at stops can be found.

2) There are two situations that stops appear at wrong places. In the first case, a series of data points belong to the $i^{th}$ stop are mixed with a group of data points belong to the $j^{th}$ stop. In the order of time, this situation can be presented as: $j, j, i, i, j, j$. The second case contains groups of stops not in order. For example, a part of the stop list of a trip may be $3, 3, 8, 8, 4, 4, 5, 5, 6, 6, ...$ To tackle both situations, the following logic is used.

   a. After finding the departure time from origin terminal, this data point is saved in a new matrix, called “LIST.”

   b. Searching ($s-8$) data points following the origin data point that has been save in “LIST.” In ($s-8$) data points, group every 2 data points that is the 2$^{nd}$ and 3$^{rd}$, 4$^{th}$ and 5$^{th}$, 6$^{th}$ and 7$^{th}$, and 8$^{th}$ and 9$^{th}$ data points. Every 2 data points in the same group are data points of the same stop. Finding the group with the smallest stop number greater than 1 and save two data points in this group in “LIST” following the origin data point. Where $s$ represent the total number of stops of the selected branch.

   c. After saving the arrival and departure time of Stop 2 in “LIST,”” repeat the logic outlined in step b above until the data point of the destination terminal appears in the four comparison groups. Since only one data point of the end terminal is present, involve this single data point in a group instead of two points.

   d. Terminate a trip when the destination terminal is saved in “LIST.”

   e. Beginning to search data of another trip, repeat step a to d.

3) In some of the trips, a few stops may be found to have no data points. In these times, data points of these missing stops are added to “LIST” with the missing stop number assigned. However, no time, latitude or longitude would be given to these data points.

At the end of Part 2 program, the list of critical data points of trips from Monday to Friday is saved in “LIST” and ready for the final check.

5.9.3 Part 3 MATLAB Code

Part 3 MATLAB program aims at finalize the data and prepare it for headway, run time and average speed calculation. This is the shortest program with the following steps.
1) Checking if the stop number of the $i^{th}$ data point equals the stop number of the $(i+1)^{th}$ data point or equals to the stop number of the $(i+1)^{th}$ data point plus 1.

2) If the above criterion were not met, the program would display an error warning and locate the error.

3) Since Part 2 code largely guarantees the correctness of the data points in “LIST,” very few errors would occur. Any stops not in order can be manually corrected.

4) After the data are finalized, they will be sorted in the unit of trips by the departure time from the origin terminal. The final data are still saved in “LIST.”

5.9.4 Part 4 MATLAB Code

The fourth part prepares data of dependent variables for modelling, including coefficient of variation of headway, coefficient of variation of run time and average speed. The formulas and processing steps are illustrated as follows.

5.9.4.1 Coefficient of Variation of Headway Deviations

1) Compare the number of data points in “LIST” of every branch of interest. The theoretical number of data points are calculated as the number of scheduled trips per day times the number of stops times five days times two.

Total theoretical number of data points on 5 weekdays

$$\sum_{i=1}^{5} \frac{Duration \ of \ period_i}{Scheduled \ headway_i} \cdot (Number \ of \ stops) \cdot 5 \cdot 2$$

(5-20)

where, $i$ is the number of time periods, 5 after $(Number\ of\ stops)$ stands for 5 weekdays, and 2 stands for 2 data points (arrival and departure) associated with every stop. Ideally, the number of data points saved in “LIST” should equal to the total theoretical number of data points. However, the CIS tracking data contain more errors than expected that reduce the number of data points remained after the cleaning process. Therefore, any branch with more than 90% of the theoretical value stored in “LIST” is eligible for headway analysis. Otherwise, with too many missing values, the headway at stops would be increased by several times.

2) Sort data in “LIST” by stop number, then date and time. For data points with the same stop number, use the departure time of the $(i+1)^{th}$ data point minus the $i^{th}$ to derive the
headway at stops. Thresholds are set to cater the gap between the first trip of a day and the last trip of the previous day.

3) Sort data by trip number, then date and time.

4) Compute the coefficient of variation of headway (headway adherence) among trips for route level analysis, which is the standard deviation of headway deviations over the scheduled headway.

\[
COV_{\text{Headway}^{\text{trip}}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [(h_{a_i} - h_{S_t}) - (\bar{h}_a - h_{S_t})]^2} \tag{5-21}
\]

where, \(N\) is the total number of stops along the selected branch, \(h_{a_i}\) is the actual (measured) headway at stop \(i\), and \(h_{S_t}\) is the scheduled headway based on departure time at first stop (scheduled headways are different during different time periods of a day. The departure time from the origin terminal is used to determine to which time period this trip belongs).

\[
\bar{h}_a = \frac{1}{N} \sum_{i=1}^{N} h_{a_i} \tag{5-22}
\]

where, \(\bar{h}_a\) is the average actual headway of a trip.

Then, taking the time period average of \(COV_{\text{Headway}^{\text{trip}}}\).

For segment level analysis, the coefficient of variation of headway of time period is calculated as:

\[
COV_{\text{Headway}^{\text{seg}}} = \sqrt{\frac{1}{NM} \sum_{j=1}^{M} \sum_{i=1}^{N} [(h'_{a_i} - h_{S_t}) - (\bar{h}_a - h_{S_t})]^2} \tag{5-23}
\]

where, \(N\) is the total number of stops in the segment, \(M\) is the total number of trips during a time period, \(h'_{a_i}\) is the actual (measured) headway at stop \(i\) in the segment, and \(h_{S_t}\) is the scheduled headway of the time period. The average actual headway of a segment over a time period is:

\[
\bar{h}_a = \frac{1}{NM} \sum_{j=1}^{M} \sum_{i=1}^{N} h'_{a_i} \tag{5-24}
\]
5) Save COV of headways, their corresponding time period and date.

5.9.4.2 Coefficient of Variation of Run Time

1) Sort data in the unit of trips by the departure time from the origin terminal.

2) Calculate travel time of every trip.

\[
\text{Run time} = \text{Arrival time at destination terminal} - \text{Departure time from origin terminal}
\]  
\[\text{(5-25)}\]

The run time obtained from Equation (5-25) is used for route level analysis. At the segment level, the run time of segment \(i\) is defined to be the travel time from the last stop in the \((i-1)^{th}\) segment to the last stop of the \(i^{th}\) segment when \(i \geq 2\). The run time of the 1\(^{st}\) segment is the travel time between the first stop and the last stop in this segment. For example, the run time of the 2\(^{nd}\) segment equals to the arrival time at the last stop of the 2\(^{nd}\) segment minus the arrival time at the last stop of the 1\(^{st}\) segment.

3) Calculate the coefficient of variation of run time over the time periods, which for the route level analysis is the standard deviation of observed travel time over the scheduled run time.

\[
COV \text{ of Run Time}_{\text{period}} = \frac{\sqrt{\frac{1}{M} \sum_{j=1}^{M} (t_{aj} - \bar{t}_a)^2}}{t_{st}}
\]  
\[\text{(5-26)}\]

where, \(t_{aj}\) is the actual run time of trip \(j\), \(t_{st}\) is the scheduled run time, and \(\bar{t}_a\) is the average run time during the time period.

The coefficient of variation of run time over the time period for segment level is calculated as,

\[
COV \text{ of Run Time}_{\text{seg}} = \frac{\sqrt{\frac{1}{M} \sum_{j=1}^{M} (t'_{aj} - \bar{t}'_a)^2}}{t'_{st}}
\]  
\[\text{(5-27)}\]

where, \(t'_{aj}\) is the run time of a segment of the \(j^{th}\) trip in a time period, \(t'_st\) is the scheduled run time of the road segment, and \(\bar{t}'_a\) is the average run time of a segment during a time period.
The scheduled run time of a segment is calculated as:

\[ t'_{st} = \frac{Segment \ length}{Scheduled \ speed} \]  \hspace{1cm} (5-28)

where, \textit{scheduled speed} is different for each time period. In Equation (5-28), to which period it belongs to is determined based on the departure time from the origin terminal of the trip.

4) Save COV of run time, their corresponding date and time period.

5.9.4.3 Average Speed

The average speed is also calculated over the time periods, which defined as the distance travelled over the travel time. Since the distance and travel time are derived from the previous steps, the period average speed can be easily computed.

\[ v_{\text{avg}} = \frac{length}{Actual \ run \ time} \]  \hspace{1cm} (5-29)

The average speed and its corresponding time periods and date are saved.

5.9.5 Part 5 MATLAB Code

All the explanatory variables are categorized into period-dependent and route-dependent variables. Every bus line provides service in five time periods every day, the period-dependent variables differ in bus lines and time period. For instance, period-dependent variables include service frequencies, vehicle volume, and passenger volume. Route-dependent factors only vary from line to line. Number of stops, route length, number of connections to subway stations, et al, are route-dependent variables. When doing segment level analysis, the values of all route-dependent variables need to be re-calculated. This part of MATLAB program is developed to integrate all the data of dependent and independent variables into one spreadsheet. There are two dataset arrays for route and segment level analysis separately, but the processing programs are similar. In regards to the types of data, the process of data integration involves the following steps.

1) Divide explanatory variables into period-dependent and route-dependent ones and write them in Microsoft Excel. Since the vehicle and pedestrian volume are only available in the morning peak, midday and afternoon peak, the dataset for modelling only contains three time periods.
2) Import period-dependent variables that the first and second column of the data array is route number and the code of time periods, respectively, followed by the values of variables. Thus, every bus line has 3 rows of data. The first, second and third columns of the segment dataset, is route number, segment number and code of time periods, respectively. If the selected branch of a bus line is divided into 6 segments, it has 18 (6 segments times 3 time periods) rows of data.

3) Import route-dependent (segment-dependent) variables and add them in the data columns right to the period-dependent variables. Since these numbers are not affected by time periods, they keep the same in different time periods of the same bus line.

4) Add columns of dependent variables, all of which are period-dependent. Therefore, they vary in routes, segments and time periods.

5) Export dataset array to Microsoft Excel.
Figure 5-2 Flow Chart of Tracking Code
6 Results and Discussion

This chapter depicts the variations in headways and travel time of bus lines on the weekdays and explains the modelling results of transit reliability and speed at route and segment level. Factors presented in the models and their impact on transit reliability and speed are discussed. Findings discovered in the process of modelling are also included. The reliability and speed models presented in this chapter have relatively high goodness-of-fit explained by significant factors with the signs of coefficients following the transit operation theory.

6.1 Variations of Headways

To ensure the data after processing is feasible for headway analysis, the period average headways are computed and compared to the scheduled values. Figure 6-1 shows an example of headway variations on the weekdays from November 18, 2013 to November 22, 2013 of route No.6. The vertical lines represent average trip headways, which are calculated as,

$$\bar{H}_{trip} = \frac{\sum_{i=1}^{n} H_i}{n}$$

(6-1)

where, $H_i$ is the headway measured at stop i, and n is the total number of stops. The horizontal line segments indicate the average trip headways in different time periods.

The theoretical number of data points for line 6 accumulated on five weekdays is 31,050. The processed tracking data points are 33,306, which is 7.3% more than the theoretical values. As we set ±10% to be the acceptable range, line No.6 meets this requirement. It is apparent in Figure 6-1 that the amounts of fluctuations of headways vary in trips, time periods and days. Specifically, Thursday has the most significant variation. The scheduled headways in time periods from morning peak to late evening are 6.5, 10, 10, 15 and 24 minutes. The actual morning peak average headways are around 5 minutes. The midday headways on Monday, Tuesday and Wednesday are 10 minutes, while longer intervals observed on Thursday and Friday. The afternoon peaks and evenings experience higher deviations from the schedule. By comparing the actual average headways in time periods and the scheduled values, one would be able to tell if the tracking data has been properly processed or not. When the differences between the scheduled values and the actual ones are beyond a predetermined threshold, there might be data points unexpectedly deleted during the treatment process.
The fluctuations of headways are observed for all the other bus lines but the pattern differs in details. Even though the headways of line 6 suggest larger variations on Thursdays and Fridays, this may or may not be true for other bus lines. The shorter bus line No.40, from Dundas West Station to Runnymede, has more stable period average headways as shown in Figure 6-2. The general patterns of variations in different time periods are very similar from Monday to Thursday. Only Friday afternoon and evening produces higher variations. This can be explained by the increased number of people going out for activities after work. The headway modelling process would be able to generate more convincible results that better captures the feature of the entire bus network.

![Figure 6-1 Headway of Line #6](image1)

![Figure 6-2 Headway of Line #40](image2)
6.2 Factors Influencing Coefficient of Variation of Headway

The bus lines with sufficient data maintained after treatment are line number 6, 16, 40, 54 and 63. Tracking data in both directions of these 5 lines are utilized for modelling. Theoretically, the opposite operating directions of a single bus line can be regarded as two different lines as they do not share a series of variables, like bus stops, directional vehicle volume, pedestrian volume and ridership. The variables investigated for route-level headway variations are listed in Table 6-1.

The modelling results indicate that the vehicle volume has the highest influence on the coefficient of variation of headway, which deteriorates the headway regularities. Vehicles moving in the same direction with transit units may cause congestions or block the bus stops, and consequently result in transit delays or bus bunching. The second most significant factor is time of day. As shown in Figure 6-1 and Figure 6-2, afternoon peaks tend to bear higher headway variations, especially on Friday. The third factor that raises the coefficient of variation of headway is the number of boarding and alighting passengers, which mainly lengthens the dwell time at stops. The terminal time is found to exert positive effect on reliability. Longer terminal time is able to absorb deviations from the schedule and guarantee on-time dispatch to some extent.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Day of week</td>
<td>Monday=1, Tuesday=2, Wednesday=3, Thursday=4 and Friday=5</td>
<td>Peak/off peak (peak=1, off peak=0)</td>
</tr>
<tr>
<td>2. Time of day</td>
<td>Morning peak=1, midday=2, afternoon peak=3</td>
<td></td>
</tr>
<tr>
<td>3. Length</td>
<td>The directional travel distance in kilometres between the origin terminal and the destination terminal</td>
<td></td>
</tr>
<tr>
<td>4. Number of Stops</td>
<td>The total number of scheduled stops along the transit line in one direction</td>
<td></td>
</tr>
<tr>
<td>5. Number of far-sided stops</td>
<td>The total number of stops located immediately after an intersection</td>
<td>Percentage of far-sided stops among total number of stops</td>
</tr>
<tr>
<td>6. Number of near-sided stops</td>
<td>The total number of stops located immediately before an intersection</td>
<td>Percentage of near-sided stops among total number of stops</td>
</tr>
<tr>
<td>7. Number of mid-</td>
<td>The total number of stops located in the</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>block stops</td>
<td>middle between two intersections</td>
<td></td>
</tr>
<tr>
<td>8. Far-sided/near-sided stops</td>
<td>The ratio of the number of far-sided stops along the transit line to the number of near-sided stops</td>
<td></td>
</tr>
<tr>
<td>9. Number of intersections</td>
<td>The total number of intersections along the transit route in one direction, including signalized and non-signalized intersections</td>
<td></td>
</tr>
<tr>
<td>10. Number of signalized intersections</td>
<td>The total number of signalized intersections along the transit route in one direction</td>
<td></td>
</tr>
<tr>
<td>11. Number of non-signalized intersections</td>
<td>The total number of non-signalized intersections along the transit route in one direction</td>
<td></td>
</tr>
<tr>
<td>12. Presence of dedicated lane</td>
<td>The presence of dedicated bus lanes in some of the road segments along the transit route No dedicated lane=0, having dedicated lane=1</td>
<td></td>
</tr>
<tr>
<td>13. Service frequency</td>
<td>The scheduled number of vehicles serving a bus line per hour</td>
<td></td>
</tr>
<tr>
<td>14. Terminal time</td>
<td>The total time a bus spends at the terminals in both ends</td>
<td></td>
</tr>
<tr>
<td>15. Number of boarding and alighting passengers</td>
<td>The hourly sum of the number of passengers getting on and off at all the stops along the transit line</td>
<td></td>
</tr>
<tr>
<td>16. Total vehicle volume</td>
<td>The total hourly number of vehicles travelling in the direction of the transit movement recorded at the intersections along the transit line</td>
<td></td>
</tr>
<tr>
<td>17. Total pedestrian volume</td>
<td>The total hourly number of pedestrians recorded at the intersections along the transit line in different time periods</td>
<td></td>
</tr>
<tr>
<td>18. Weather</td>
<td>The weather reported at Centre Toronto (numerical values used to represent different weathers)</td>
<td></td>
</tr>
</tbody>
</table>

Percentage of signalized intersections among total number of intersections
Percentage of non-signalized intersections among total number of intersections

Table 6-1 Variables for Route-Level Headway Analysis
6.3 Variations of Run Time

The directional run time is computed as the time duration between the arrival time at the destination terminal and the departure time from the origin terminal. The travel time can be calculated for every bus line no matter there are sufficient data remained after processing or not. As long as the time of dispatch and arrival at the terminals in the two ends are known, travel time can be obtained. In the contrary, the average headway of trips can only be determined for lines having more than 90% and less than 110% of the scheduled data points after being processed to ensure the accuracy of the computed headways.

Similar to headway plots demonstrated in Figure 6-1 and Figure 6-2, the travel time of trips is indicated by the vertical lines fluctuating up and down. The horizontal lines are the period average travel time. Comparisons are also made between the actual and scheduled travel times. The scheduled directional run times in five time periods from morning peak to late evening are 30, 35, 35, 30 and 24 minutes. In the meantime, the observed average values in these time periods are fluctuating around the scheduled length with discrepancies smaller than 5 minutes. The patterns of run time of line 40 are more stable from day to day than line 6, which is analogous to the situation of headway variations. An increase of travel time on Friday afternoon peak is observed while the headway in this period is also higher than its counterparts due to higher demand of transportation.

These figures of headways and run times of trips give visual tools for us to understand how they vary across service runs. They also serve as testing tools for figuring out problems of the processed tracking data and discovering special phenomenon with higher variations. Whenever outliers of travel time is observed, these values would be deleted from the dataset for computing the coefficient of variation of run time.
Figure 6-3 Run Time of Line #6

Figure 6-4 Run Time of Line #40
6.4 Route-Level Modelling

The route-level modelling takes the entire transit line from the origin terminal to the destination terminal into account. Two models with relatively high goodness-of-fit are developed for coefficient of variation of run time and average speed. These two models share several attributes in common, which adversely influence the transit reliability and speed in a similar way. The models are presented in the sections below.

6.4.1 Coefficient of Variation of Run Time Model

The coefficient of variation of run time (COV of run time) is calculated as the standard deviation of run time deviations over the scheduled run time among time periods. The final dataset used for route-level COV of run time modelling includes line 6, 7, 16, 25, 29, 36, 40, 54, 63, 65 and 75 in both directions, and 24 and 68 in one direction. These lines cover service regions within and outside downtown, consist high and low frequencies ranging from 20 to 2 transit units per hour. Their directional route lengths scattered between 3 and 27 kilometres as shown in Figure 6-5. Line No.7 and No.29 have transit-priority traffic signals on route. Based on the service features of the selected lines, they are representative of the bus network in Toronto.

Figure 6-5 Directional Route Length of Bus Lines
### Table 6-2 Additional Variables for Route-Level Run Time Analysis

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stop density</td>
<td>The number of stops over the route length</td>
</tr>
<tr>
<td>2. Percentage of timed stops</td>
<td>The number of scheduled timed stops over the total number of scheduled stops</td>
</tr>
<tr>
<td>3. Intersection density</td>
<td>The number of intersections (including signalized and non-signalized) over the route length</td>
</tr>
<tr>
<td>4. Signalized/ non-signalized intersections</td>
<td>The ratio of the number of the signalized intersections to non-signalized intersections</td>
</tr>
<tr>
<td>5. Number of connections to subway stations</td>
<td>The number of subway stations directly connected to the bus line</td>
</tr>
<tr>
<td>6. Presence of TSP</td>
<td>No=0, yes=1</td>
</tr>
<tr>
<td>7. Maximum vehicle volume</td>
<td>The vehicle volume at the intersection along the transit line with the maximum volume detected in the moving direction of the transit units</td>
</tr>
<tr>
<td>8. Average vehicle volume</td>
<td>The total vehicle volume accumulated at all the intersections along the transit line in an hour over the total number of intersections</td>
</tr>
<tr>
<td>9. Maximum pedestrian volume</td>
<td>The pedestrian volume at the intersection along the transit line with the maximum volume detected</td>
</tr>
<tr>
<td>10. Average pedestrian volume</td>
<td>The total pedestrian volume accumulated at all the intersections along the transit line in an hour over the total number of intersections</td>
</tr>
</tbody>
</table>

In addition to the variables outlined in Table 6-1, more factors are involved in the modelling of COV of run time (Table 6-2). The correlation coefficients of the variables, which are between -1 and 1, are first computed to measure how strongly two variables are dependent on each other as:

\[
\text{Correl}(X,Y) = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}
\]  

(6-2)

where, \(\bar{x}\) and \(\bar{y}\) are the sample means of \(x\) and \(y\). When the absolute value of the correlation coefficient is greater than 0.7, the two variables have very strong relationship. These independent variables are listed in Table 6-3 as groups. The second column shows the factors that are highly correlated with the variable in the first column.

Apparently, the total vehicle volume is dependent on many variables. However, its alternatives, such as average vehicle volume and maximum vehicle volume, are more independent. Similarly,
the number of far-sided and the number of near-sided stops appear in the second column several times, but the ratio of them only occurs once as highly correlated variables to % far-sided stops. Thus, considering of capturing the features of stop locations, the ratio of near-sided to far-sided stops should be carried in the model instead of the number or percentage of far-sided and near-sided stops. In these case, the alternatives are more favourable for modelling. Some other elements, like number of stops, length, number of intersections, etc., are strongly correlated. Therefore, only one factor amongst them should be included at a time in the modelling procedure.

The final result of the linear regression analysis produces a model with adjusted R square value equals to 0.573. This indicates that 57.3% of the data can be explained by the regression equation.

\[
R_{\text{adjusted}}^2 = 1 - \frac{(1 - R^2)(n - 1)}{n - k - 1}
\]

\[
R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2}
\]

where, n is the number of data points, k is the number of independent variables, \(y_i\) is the observed value of dependent variables (COV run time), \(\hat{y}_i\) is the fitted value, and \(\bar{y}\) is the mean. The regression result is demonstrated in Table 6-4.

As indicated from the modelling result, peak hour, longer service length, higher intersection density, more signalized intersections, higher number of connections to subway stations, higher passenger volumes, and higher vehicle and pedestrian volumes all contribute to headway variations that they have positive coefficients. Among these factors, length is the most significant one. Longer distance makes a transit stay in an environment full of various kinds of causes of delays for a longer duration. When a bus fails to absorb the delays while moving forward to its destination, the delays accumulate and become progressively severer. However, long route length also provides more chances to absorb the delay. When situation allows, the amount of time saved while a bus travelling towards its destination can also accumulate to produce significant savings. Hence, long service length increases the probability of running significantly behind and ahead of the schedule that both lead to dramatic variation.

The second factor comes to our attention is the intersection density. Obviously, intersections trigger delays no matter they are equipped with signals or not. At signalized intersections, delays
of through and left-turn traffic are caused by waiting for red lights. The delay occurs for right-turn and at non-signalized intersections is brought by yield to the right of way of pedestrians and traffic. However, signalized intersections introduce more variations to the travel time compared to non-signalized ones as revealed by the term “sig/non-sig.”

The hourly average pedestrian volume in time periods also has a negative effect on travel time regularity. Since signal phases for pedestrian crossing at some of the intersections are given upon request, more pedestrian means longer red phase. Another typical situation in Toronto is the time provided for pedestrian crossing is just about enough. If there were a lot of pedestrians, some of them may still be in the middle of the intersection when time is out. At this time, the vehicles need to wait even if the green phase is granted.

The “Hourly Ons and Offs” stands for the total number of passengers getting on and off the bus in an hour at all stops along the transit line averaged in the time periods. More passengers boarding and alighting would make the bus to stop more frequently and dwell at stops for longer time. The number of connections to subway stations influences the travel time in a similar way. Usually, subway stations have significantly higher passenger demand than other stops that more connections to subway stations means longer time spent on dwelling at these stations.

The term of peak hour and average vehicle volume are not as significant as the other variables, but they are presented in the model to provide information on their impact. Peak hour does not affect the COV of run time itself, but it is a proxy for many hidden factors that are related to the variation of run time. Higher service frequency, probability of traffic congestion and a series of elements that would deteriorate the service regularity can be observed in peak hours. These variables themselves were not found to be significant individually, but peak hour as a representative of them all shows its effect.

There are two factors noticed to be able to remediate run time variations. The presence of dedicated bus lane gives priorities to the transit units and set them away from the general traffic. Hence, buses are protected from being trapped in traffic jams. Another factor relates to the locations of stops. More far-sided stops than near-sided stops help achieve regular travel time. The far-sided stop has been proved to be beneficial to bus service in previous research. It saves time for deceleration and provides gaps for buses to meander back into the traffic stream (Bolton, et al., 2013). Besides, it benefits the street network for not blocking the intersection for right turn.
### Independent Variable

<table>
<thead>
<tr>
<th>Route length</th>
<th>Number of stops</th>
<th>Number of far-sided stops</th>
<th>Number of near-sided stops</th>
<th>Number of mid-block stops</th>
<th>% Far-sided stops</th>
<th>Number of intersections</th>
<th>Number of signalized intersections</th>
<th>Number of connections To Subway</th>
<th>Dedicated Lane</th>
<th>Hourly Ons and Offs</th>
<th>Average Vehicle Volume</th>
<th>Average Pedestrian Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly Correlated Variables</td>
<td>Number of far-sided stops, number of near-sided stops, number of mid-block stops, number of intersections, number of signalized intersections, and total vehicle volume</td>
<td>Number of far-sided stops, number of near-sided stops, number of mid-block stops, number of intersections, number of signalized intersections, and total vehicle volume</td>
<td>Number of far-sided stops, % far-sided stops, %near-sided stops, number of intersections, number of signalized intersections, and total vehicle volume</td>
<td>Number of intersections, number of signalized intersections, and total vehicle volume</td>
<td>% Mid-block stops, and total vehicle number</td>
<td>Near-sided/far-sided stops</td>
<td>Number of non-signalized intersections, number of signalized intersections, and total vehicle volume</td>
<td>Total vehicle volume</td>
<td>Average vehicle volume</td>
<td>Average pedestrian volume</td>
<td>Average pedestrian volume</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 6-3 Correlation Analysis Result of Route-Level Run Time Variables

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Coefficients</th>
<th>Standard Deviation</th>
<th>t-Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-0.005292</td>
<td>0.00093</td>
<td>-5.6829</td>
</tr>
<tr>
<td>Peak/Off-peak</td>
<td>0.000148</td>
<td>0.00012</td>
<td>1.3253</td>
</tr>
<tr>
<td>Route Length</td>
<td>0.000199</td>
<td>1.379E-05</td>
<td>14.463</td>
</tr>
<tr>
<td>Far/near-sided stops</td>
<td>-0.001012</td>
<td>0.00054</td>
<td>-1.8626</td>
</tr>
<tr>
<td>Intersection Density</td>
<td>0.000434</td>
<td>5.825E-05</td>
<td>7.4563</td>
</tr>
<tr>
<td>Signalized/non-Sig Intersections</td>
<td>0.002283</td>
<td>0.00045</td>
<td>5.0569</td>
</tr>
<tr>
<td>Number of Connections To Subway</td>
<td>0.000589</td>
<td>0.00021</td>
<td>2.7759</td>
</tr>
<tr>
<td>Dedicated Lane</td>
<td>-0.001389</td>
<td>0.00020</td>
<td>-7.0041</td>
</tr>
<tr>
<td>Hourly Ons and Offs</td>
<td>5.782E-07</td>
<td>1.843E-07</td>
<td>3.1374</td>
</tr>
<tr>
<td>Average Vehicle Volume</td>
<td>1.596E-07</td>
<td>2.5113E-07</td>
<td>0.6355</td>
</tr>
<tr>
<td>Average Pedestrian Volume</td>
<td>5.704E-07</td>
<td>1.6590E-07</td>
<td>3.4386</td>
</tr>
</tbody>
</table>

#### Table 6-4 Route-Level COV Run Time Model
6.4.2 Average Speed Model

The average speed is the speed of trips averaged over the time periods. The independent variables studied for speed modelling is identical to COV of run time, so the matrix of the correlation coefficients of the traits is the same. The linear regression model of the average speed has an adjusted R square value of 0.81, which stands for a very good fit of the model to the data. The final expression of the average speed model is:

\[
\text{Average Speed} = 44.12 - 0.86 \times \text{(period of day)} - 1.55 \times \text{(stop density)} - 1.29 \times \text{(intersection density)} - 6.04 \times \text{(signalized/non-signalized intersection)} - 2.39 \times \text{(number of connections to subway stations)} - 0.25 \times \text{(scheduled headway)} - 6.34 \times 10^{-4} \times \text{(average vehicle volume)}
\]

All factors included in the model exert negative effect on run time adherence. The intersection density has the most significant adverse impact. Waiting for red phase, acceleration, deceleration and yielding to traffic and pedestrians at intersections decrease the speed. The signalized intersections generate severer delays than non-signalized intersections. Buses usually spend long time at stops connects to subway stations because of high passenger volume. Therefore, the speed reduces with the increase of the number of connections to subways. The stop density influences transit speed in a way analogous to intersection density that buses waste time on deceleration, stop and acceleration.

An interesting finding is that long headway is associated with low speed. If we take a closer look at the schedule, it is easy to figure out that during the daytime, the periods with longer scheduled headway are always assigned with lower average scheduled speed. The design of scheduled speed takes traffic conditions and number of transit units required into consideration. Therefore, when the design speed is low, the real conditions on the roads does not allow transit vehicles move at high speed or they tend to slow down deliberately to maintain schedule adherence. In general, the actual speed is lowered in either case. The dummy variable represent peak or off-peak in the model suggest that transit vehicles move slower in the peak hours. This can be easily explained by higher volume of general traffic and more pedestrians and passengers, while the average vehicle volume is included in the model itself.
### Table 6-5 Route-Level Average Speed Model

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Coefficients</th>
<th>Standard Deviation</th>
<th>t Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>44.11656761</td>
<td>1.116513019</td>
<td>39.51281076</td>
</tr>
<tr>
<td>Peak/off-peak</td>
<td>-0.85729475</td>
<td>0.111282753</td>
<td>-7.703752195</td>
</tr>
<tr>
<td>Stop Density</td>
<td>-1.545260039</td>
<td>0.169647789</td>
<td>-9.108636501</td>
</tr>
<tr>
<td>Intersection Density</td>
<td>-1.294787652</td>
<td>0.091923101</td>
<td>-14.08555236</td>
</tr>
<tr>
<td>Signalized/non-Sig Intersections</td>
<td>-6.037844021</td>
<td>0.548092973</td>
<td>-11.01609456</td>
</tr>
<tr>
<td>Number of Connections to Subway</td>
<td>-2.389227369</td>
<td>0.213336987</td>
<td>-11.19931148</td>
</tr>
<tr>
<td>Scheduled Headway</td>
<td>-0.246645736</td>
<td>0.028574174</td>
<td>-8.631771423</td>
</tr>
<tr>
<td>Average Vehicle Volume</td>
<td>-0.000639355</td>
<td>0.000360935</td>
<td>-1.771385172</td>
</tr>
</tbody>
</table>

#### 6.5 Segment Level Modelling

The segment level modelling mainly focuses on finding the effect of signal timings and TSP on transit reliability and speed. The segmentation is mainly based on the number of intersections, while also constrained by the availability of vehicle turning movement count at the intersections. Usually, a segment consists of five intersections, but this value may vary depend on the availability of the other data. It has to be ensured that every segment has more than one intersection with turning movement count data available. The variables used for segment level modelling in addition to Table 6-1 and Table 6-2 are outlined in Table 6-6. Any route-level variables in the previous two tables should be converted to segment level. For example, the number of stops for route level analysis should be the number of stops within the segment under investigation. The modelling results are elaborated in Section 6.5.1 and 0.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Highly Correlated Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Presence of TSP</td>
<td>No=0, yes=1</td>
</tr>
<tr>
<td>2. Average green extension of TSP</td>
<td>The total length of maximum green extension over the number of intersections equipped with TSP in the segment</td>
</tr>
<tr>
<td>3. Number of TSP</td>
<td>The number intersections with TSP in the segment</td>
</tr>
<tr>
<td>4. # of TSP/# of intersections</td>
<td>The total number of intersections equipped with TSP over the total number of signalized intersections</td>
</tr>
<tr>
<td>5. # of near-sided with TSP</td>
<td>The number of near-sided stops having its downstream intersections equipped with TSP</td>
</tr>
<tr>
<td>6. # of far-sided with TSP</td>
<td>The number of far-sided stops having its downstream intersections equipped with TSP</td>
</tr>
</tbody>
</table>
7. Average cycle time  
The segment average cycle length
8. Average G/C  
The segment average green time over the cycle time
9. Maximum G/C  
The maximum green time over the cycle time value in the segment
10. Average right-turn vehicle volume  
The segment average number of vehicles turning right at the intersections
11. # of right-turn prohibitions  
The number of intersections prohibited right-turn in the segment
12. % right-turn prohibitions  
The percentage of intersections prohibited right-turn in the segment
13. Scheduled speed  
The scheduled speed for the specific time period
14. Number of stops upstream  
The number of stops on the transit line upstream of the segment under investigation
15. Segment length  
The distance from the last stop of previous segment to the last stop in the segment under investigation

Table 6-6 Additional Variables for Segment-Level Run Time Analysis

6.5.1 Coefficient of Variation of Run Time

When conducting the modelling analysis at the segment level, the lognormal formulation and the common one as the previous models are tested, because the log form of COV of run time follows the normal distribution curve better. The values of adjusted R square are very close that the lognormal formulation is 0.54 and the other one is 0.55. The predictor variables contained in these two models are also the same. The regression results are demonstrated in Table 6-7 and Table 6-8.

The lognormal formulation shown in Table 6-7 and the “common formulation” in Table 6-8 have ten explanatory variables, included in which three are beneficial to the transit reliability. Beginning with the one with the most significant positive effect on maintaining regular travel time within the segments, TSP facilitates transit movement through the intersections by granting priority to them. TSP is represented by a dummy variable here that with and without TSP installed at the intersections within the segment is denoted by 1 and 0, respectively. When dividing the route into segments, special attention has been paid on grouping together the intersections with TSP next to each other. Therefore, the dataset includes segments with 100% and none intersections with TSP. The second positive factor is the ratio of the number of far-sided and near-sided stops. As discussed in the previous sections, far-sided stops can smooth traffic movement although most stops in Toronto are near-sided. When act jointly with TSP, far-
sided stops would bring much more profitable effect than near-sided stops which has been stated in several research papers (Feng, 2014; Figliozzi and Feng, 2014). This modelling result further proves the truthiness of this statement. The third one is the percentage of the number of intersections having prohibitions on right turn. Right turning vehicles may block near-sided stops when vehicles are queued for waiting traffic and pedestrians. The term “average G/C” is also found to have a positive impact on run time regularity, but is not very significant compared to these ones included in the model and is not presented.

In terms of the independent variables that decrease the travel time regularity, most of which has occurred in the previous route level COV of run time model and will not be discussed for a second time. The average cycle length, a factor related to signal timings, is the new one involved in this model. This finding is in consistency with the saying that longer cycle time causes higher variations in speed and longer delays (National Association of City Transportation Officials, 2015).

To compare these two models, the “common formulation” has a slightly higher adjusted R square value (0.55), and lower standard error (0.14). Besides, the explanatory variables carried in both are identical. Hence, the “common formulation” is selected to depict the relationships between the attributes and the coefficient of variation of run time at the segment level.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>-7.174320456</td>
<td>0.936618911</td>
<td>-7.659807392</td>
</tr>
<tr>
<td>Segment Length</td>
<td>0.96156167</td>
<td>0.250194462</td>
<td>3.843257217</td>
</tr>
<tr>
<td>Number of Stops Upstream</td>
<td>0.007092726</td>
<td>0.005235104</td>
<td>1.354839631</td>
</tr>
<tr>
<td>Stop Density</td>
<td>0.152902083</td>
<td>0.084708568</td>
<td>1.805036797</td>
</tr>
<tr>
<td>Far-sided/Near-sided Stops</td>
<td>-1.20390208</td>
<td>0.325429475</td>
<td>-3.699425445</td>
</tr>
<tr>
<td>Signalized Intersection Density</td>
<td>0.38785452</td>
<td>0.080714591</td>
<td>4.805259071</td>
</tr>
<tr>
<td>Segment Total Ons Offs</td>
<td>0.001195954</td>
<td>0.000377897</td>
<td>3.164760948</td>
</tr>
<tr>
<td>Average Vehicle Ons Offs</td>
<td>0.001826712</td>
<td>0.000373029</td>
<td>4.89696796</td>
</tr>
<tr>
<td>% Right Turn Prohibitions</td>
<td>-0.373317189</td>
<td>0.365161361</td>
<td>-1.022334859</td>
</tr>
<tr>
<td>Average Cycle Time</td>
<td>0.025589229</td>
<td>0.007582195</td>
<td>3.374910261</td>
</tr>
<tr>
<td>TSP (dummy)</td>
<td>-0.740348249</td>
<td>0.191569918</td>
<td>-3.864637293</td>
</tr>
</tbody>
</table>

Table 6-7 Segment Level COV of Run Time Lognormal Formulation Model
Independent Variables | Coefficients | Standard Error | t Stat
---|---|---|---
Intercept | -1.636892913 | 0.332331285 | -4.925485468
Segment Length | 0.324139982 | 0.088774042 | 3.65129235
Number of Stops Upstream | 0.002316505 | 0.001857521 | 1.247095385
Stop Density | 0.042963552 | 0.030056309 | 1.429435391
Far-Sided/ Near-Sided Stops | -0.36327777 | 0.115468943 | -3.146108046
Signalized Intersection Density | 0.153753351 | 0.028639165 | 5.368639432
Segment Total Ons Offs | 0.000380578 | 0.000134086 | 2.838321865
Average Vehicle Volume | 0.000532659 | 0.000132358 | 4.024368737
% Right Turn Prohibitions | -0.303985296 | 0.129566618 | -2.346169878
Average Cycle Time | 0.008192458 | 0.002690316 | 3.045165998
TSP (dummy) | -0.193222978 | 0.067972872 | -2.842648449

Table 6-8 Segment Level COV of Run Time Model

6.5.2 Average Speed

The dependent variable of average speed modelling at the segment level is altered to “delta speed” which is the difference between the actual speed and the scheduled speed. It is noticeable that the actual average speed is utilized as the dependent variable at the route level analysis. This is because the scheduled speed designed by TTC is on a route basis according to the experience of operational service. Even though buses experience high deviations at different segments, the overall averaged speed usually does not deviate from the scheduled value very much. Therefore, simply using the average speed at the left hand of the function is adequate enough to generate a model with high goodness-of-fit. However, as segments are much finer units for studying the speed, it bears higher variations. The difference of speed is introduced in such situations to obtain a model with larger adjusted R square (0.75).

As outlined in Table 6-9, two variables help increase transit speed. The first one is percentage of intersections with right turn prohibitions. This constraint keeps the right most lanes for through traffic only and prevents it from blocking by right-turning vehicles. The existence of TSP also assists in achieving faster speed. Although its t-stat is not as significant as the others, it is retained in the model for its importance of providing knowledge on its contributions.

In agreement with the route level model, route length (segment length), stop density and signalized intersections decrease transit speed. The number of boarding and alighting passengers that consumes time for dwelling at the stops lowers the speed undoubtedly. It is interesting to
find that the number of stops upstream of the investigated intersection displays negative effect, which means the latter sections of a transit line have lower speed. Comparing to the beginning part, the middle section always has higher traffic volume and more complex traffic conditions which result in a speed reduction. This is also true in the situations that the TTC bus lines always end on minor streets, that the transit units travel slowly to make turn-around.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>44.41316619</td>
<td>4.170489253</td>
<td>10.64938991</td>
</tr>
<tr>
<td>Frequency</td>
<td>-0.286967153</td>
<td>0.08765605</td>
<td>-3.273786028</td>
</tr>
<tr>
<td>Segment Length</td>
<td>-4.426843427</td>
<td>0.895464904</td>
<td>-4.943625829</td>
</tr>
<tr>
<td>Number of Stops Upstream</td>
<td>-0.172357167</td>
<td>0.030324305</td>
<td>-5.683796035</td>
</tr>
<tr>
<td>Stop Density</td>
<td>-5.445729603</td>
<td>0.451274187</td>
<td>-12.06745204</td>
</tr>
<tr>
<td>Signalized Intersection Density</td>
<td>-0.750558559</td>
<td>0.366504676</td>
<td>-2.047882625</td>
</tr>
<tr>
<td>Segment Total Ons Offs</td>
<td>-0.011046763</td>
<td>0.001760481</td>
<td>-6.274854975</td>
</tr>
<tr>
<td>% Right Turn Prohibitions</td>
<td>7.454717192</td>
<td>1.93283326</td>
<td>3.856885819</td>
</tr>
<tr>
<td>TSP (dummy)</td>
<td>0.899862509</td>
<td>0.891813345</td>
<td>1.009025615</td>
</tr>
</tbody>
</table>

Table 6-9 Segment Level Delta Speed Model
7 Summary, Discussion and Conclusions

The objectives of this study are the development of:

- Route-level transit reliability model,
- Route-level average speed model,
- Segment-level transit reliability model, and
- Segment-level average speed model.

This chapter is divided into three sections. The first section is the summary of work performed in this research study. The second section discusses the modelling results, the utilization and the significance of this study. The last section presents limitations of this research and provides recommendations for future research.

7.1 Summary

As the transit reliability and speed are core indicators of service qualities, knowledge on their relationships with factors in the operational context would be helpful in understanding their interactions and guide the plan of fast and reliable service. The regression models proposed in this research would help.

The literature review provided the basis for selecting explanatory variables and feasible reliability measures for the TTC and Toronto data. After being processed in MS Excel and MATLAB, the data were utilized for developing the reliability and speed models at route and segment levels. The measure of coefficient of variation of headway was proved not applicable to represent the variations of TTC data, because of the errors included in the raw tracking data and the aggregation of the variations of headways from stops level to the level of time period. Therefore, for both route and segment level, regression models of the coefficient of variation of run time were constructed to explain how the independent variables affect transit reliability. In terms of average speed models, the period average speed was used at the route level, while the difference between the actual speed and the scheduled speed is used at the segment level.
7.2 Discussion

7.2.1 Route-Level Models

At the route level analysis, transit reliability and speed were both found to be reduced in rush hours and on lines where there were more connecting stops to the subway stations and when the general traffic volume was high and the intersections were densely located, especially the signalized intersections. The intersection density is usually fixed. Some of the bus lines are designed specifically for connecting major subway stations. A proper way to improve transit reliability and speed is proposing more flexible schedules in peak hours. For example, adding longer slack time may be beneficial.

It can be noticed that the percentage of timed stops, at which points the bus operators should time their departures, is not shown to be helpful for reliability. Theoretically, the variability can be reduced if drivers check their on-time performance with higher frequency. However, this is not true in Toronto. There are two explanations of this situation. First, drivers do check the departure time at these points, but they have no means to adhere to the schedule. In this case, flexible schedules should be worked out for peak hour services. Second, drivers do not endeavour to be on time. If this applies, better training of the transit operators is necessary.

In addition, introducing dedicated bus lanes can enhance reliability as demonstrated by the route level COV of run time model. However, this generates capital investment and maintenance cost. It is also constrained by available space. For instance, in downtown Toronto, implementing dedicated bus lanes without affecting the general traffic flow, which means building extra lanes for buses, would not be possible even in the next few decades. Relocating bus stops to the points immediately after intersections would also increase transit reliability. However, this do not profit transit speed as indicated by this research study.

7.2.2 Segment-Level Models

The segment level models investigated transit movements at a relatively micro level. The results suggest that both transit reliability and speed decrease with the increase of segment length, stop density, signalized intersection density, number of stops upstream and the total number of
boarding and alighting passengers per hour. The later sections of a transit line are more critical and suffer from higher variation.

The segment length and signalized intersection density cannot be easily improved. The stop density is confined in certain range to provide appropriate walking distance for nearby transit users. However, if the passengers can be evenly distributed throughout the network, the number of passengers accumulated at certain stops can be reduced, so the dwell time is decreased consequently. In this way, the run time regularity and speed can both be enhanced.

It is indicated by the COV of run time and speed model that prohibitions on right-turn and installation of TSP can promote transit performance. These findings are very important. It is possible to prohibit right turns on critical road segments having near-sided stops during the peak hours so as to enhance transit performance in these periods. The effectiveness of TSP has long been discussed in research studies, but the findings using real data in research papers indicated that TSP had no impact on service variation as mentioned in Chapter 2, while simulation results insisted its benefit to schedule adherence and transit reliability. The result of this research clearly demonstrates the effectiveness of TSP on reducing run time variability.

7.2.3 Route-Level and Segment-Level Models

Taking all the models proposed in this thesis for analysis, it can be indicated that length, density of signalized intersections, stop density, the number of boarding and alighting passengers and the average vehicle volume are the most important factors that reduce both transit reliability and speed either on the route level or on the segment level. If only reliability models are investigated, length, ratio of far-sided and near-sided stops, signalized intersection density, number of boarding and alighting passengers and average vehicle volume are found to be influential at both levels. In regards to the speed models, stop density, and signalized intersection density are the common terms discovered at both levels.

It is noticeable that some of the variables included in the list never appeared in any model, despite the ones who have alternatives that represent similar characteristics, such as the number of near-sided stops and the number of far-sided stops whose effect are explained by the ratio of them. The terminal time was found to have positive impact on transit reliability at the route level, but it was not significant. The day of week, as shown in Figure 6-1 to Figure 6-4, had influence
on the variations of headway and run time that Friday afternoons tend to suffer higher variations. However, as day of week was represented by numerical numbers from 1 to 5, when the magnitude of variations from 1 to 4 did not differ from each other very much, the linear regression model would not be able to explain the deviations occur on Fridays. Besides, only Friday afternoons demonstrated unique patterns of variation, the “day of week” term may not be able to describe it without combing with the “time of day” term. Weather was another factor excluded in all the models. This is because the weather did not change very much in the time frame selected. It was usually cloudy to clear, except that it rained for short periods of time on Thursday midnight and Friday noon.

7.3 Conclusions

Regression models of the coefficient of variation of run time and average speed were developed at the route and segment level in this study. The models revealed the relationship between a series of variables and the transit reliability and speed. More variations and lower speed can be expected on routes with longer length, higher density of signalized intersections, higher stop density, more boarding and alighting passengers and higher volume of average vehicles. TSP and right-turn prohibitions are possible solutions to unreliable service. TSP can be also implemented to increase transit speed.

There are few limitations of this research study that can be improved. First, data were aggregated to the level of time period even though some of them are available in hours. This aggregation processed induces errors while assumptions were made. Therefore, if finer data can be obtained, the modelling results would be more accurate. For example, the ridership data provided by TTC did not differ branches and intersections, which were accumulated volumes during time periods. If automated passenger counter (APC) can be installed on a representative portion of TTC buses, more accurate data can be collected.

Second, before-and-after study would be more powerful to capture the effectiveness of TSP rather than the cross-sectional studies applied in this research, because it minimizes the effect of the variation of the other variables. As discussed previously, before-and-after study is time-consuming and expensive. However, it can be done in Toronto. The city has been working on updating the computer system of the signal several years that TSP was usually disabled immediately after the system has been updated. TSP would be enabled until a field test is run to
check its compatibility with the new system. If the time frame during which the TSP was
disabled and enabled can be obtained, it would be possible to carry out a before-and-after study
to examine how TSP affected the transit system and the general traffic.

Third, there are still factors not involved in this research study but may exert impact on bus
service. For example, traffic incidents can induce significant delays of buses. The influence of
weather, although is not discovered in this research, may become significant if data are collected
throughout a longer time frame in different seasons.

Fourth, the regression models presented in this thesis have some drawbacks. To begin with, they
did not consider joint effect of multiple factors. This can be done by using multiplications of two
or more factors as variables. Another limitation is the assumption that the independent and
dependent variables are linearly related. This formulation does not have a peak point, but
assumes that the dependent variables would increase or decrease continuously with the increase
or decrease of independent variables. Without limits of explanatory variables, the coefficient of
variation of run time may drop below zero, which cannot happen in real case. Even though the
independent variables have natural constraints that limit the magnitude of their values, it is
unable to guarantee that the values of dependent variables would lie within a reasonable range.
Therefore, the models in this research are developed for revealing relationships instead of
prediction. However, future research is encouraged to apply more complicated formulations to
explain the interactions.
References


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