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Use of Automated Vehicle Location Data for Route- and Segment-Level Analyses of Bus Route Reliability and Speed

Wen Xun Hu and Amer Shalaby

Reliability and speed are arguably the most important indicators of surface transit performance for both operators and passengers. They can be influenced by a variety of factors, including service characteristics of bus routes, physical infrastructure, signal settings, traffic conditions and ridership patterns. These factors have often been analyzed individually for their impact on transit reliability or speed. Studies considering more than one factor tend to use one or two transit routes to explore their effects. The study that is the subject of this paper proposed an evaluation framework to guide the selection of an appropriate reliability measure. Regression analysis was applied subsequently to determine the factors that exhibit a statistically significant relationship with transit reliability and speed at both the route and segment levels. Automated vehicle location data of a bus route sample that is representative of the entire bus network in the City of Toronto, Ontario, Canada were used. Features significantly associated with reliability and speed were compared. The results showed that lower transit reliability and speed are significantly associated with the increase in service distance, signalized intersection density, stop density, volume of boarding and alighting passengers, and traffic volume. By segregating bus route segments on the basis of the presence of transit signal priority, the results of the segment-level model demonstrated the beneficial impact of transit signal priority on improving transit reliability.

Both transit agencies and users have the same prominent desire for reliable and fast transit service. For service providers, transit reliability and speed affect operational cost and ridership (*1, 2*). For passengers, who want to ensure on-time arrival at destinations and minimize the disutility of travel, reliability and speed are key factors that influence their mode choices (*2, 3*). Poor reliability of surface transit services can lead to bunching, passenger overcrowding, excessive travel time, and, ultimately, a poor image of transit (*1, 4*). Therefore, understanding the relationships of both transit reliability and speed with other factors in the operational context at the network scale is beneficial, both at the planning stage and during operation. However, previous studies have tended to analyze factors associated with reliability and speed individually. Although these factors exist in transit networks simultaneously, analysis performed to explore their relationship with reliability and speed jointly has been limited.

There are several ways to define transit reliability. Several studies have defined it in terms of adherence to schedule (*5, 6*), while others argued that transit reliability was related to service consistency as represented by constant travel time or evenness of headway (*2, 7*). A few studies proposed more encompassing definitions that addressed both schedule adherence and the ability to maintain regular headways and consistent travel time (*8, 9*). In addition, passenger wait time was also sometimes used as an important criterion of assessing transit reliability, especially for routes with low service frequencies (*10*).

The literature has shown a steady growth in the number and variety of transit reliability measures as research efforts over the past few decades have continued to propose new measures to overcome drawbacks of previous ones and to utilize new sources of data. Finding the most appropriate measure with which to monitor transit reliability is important for transit operators.

No matter which definition or measure of reliability is used, transit planners have always been interested in determining the factors that cause unreliable service and in devising effective countermeasures. Mitigating strategies, such as transit holding control, have been formulated and occasionally assessed for effectiveness in simulation studies (*11*). Also, before-and-after analyses have been applied to understand the effect of control strategies on reliability; these studies have typically focused on one strategy at a time (*12*).

A limited number of studies have investigated the impact of more than one factor on transit reliability but typically used data from one or two routes in their investigations. For instance, to study a cross-town route, El-Geneidy et al. developed regression models that used four different transit reliability indicators (*7*); the adjusted R^2 values ranged from .07 to .52. In another regression analysis, Diab and El-Geneidy developed a model (R^2 = .21) to understand the effect of strategies for improving reliability that use data from two routes (*12*).

In the same manner as reliability analysis, speed (or travel time) models have often utilized data from one or two transit routes. However, regression models of travel time have, on average, typically produced higher R^2 values than reliability models. For example, the run time model by El-Geneidy et al. had a higher R^2 value (.59) than its reliability models (*7*). Speed was used instead of travel time in the present study because multiple transit routes with different service lengths were covered.

Transit signal priority (TSP) is an important control strategy designed to reduce transit travel time by extending the green phase or

Department of Civil Engineering, University of Toronto, 35 Saint George Street, Toronto, Ontario M5S 1A4, Canada. Corresponding author: W. X. Hu, wenxun.hu@mail.utoronto.ca.

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shortening the red phase of traffic lights for transit vehicles approaching intersections. The City of Toronto, Ontario, Canada, has increased its number of TSP-equipped intersections continuously over the years. As of January 2015, Toronto had 405 signalized intersections equipped with TSP along four bus routes and seven streetcar routes (*13*). TSP was found to have brought about 5 to 9 s of reduction in delays for transit vehicles per direction at each intersection (*14*). Although TSP handbooks claim its beneficial effect in improving reliability (*15, 16*), a study in Montreal, Quebec, Canada, demonstrated a nonsignificant impact (*12*). In sum, investigation of whether TSP contributes to service reliability in Toronto is worthwhile.

In summary, although there have been several investigations of both transit reliability and travel time, comparisons of contributing factors have not been thoroughly made. Various models have utilized reliability indicators but made little effort to assess their adequacy and appropriateness. The number of transit routes and variety of factors covered in previous studies were limited. The effect of TSP on transit reliability was mixed. The present study established an evaluation framework to guide the selection of the most appropriate reliability measure. The criteria used can be modified to meet the specific needs of different transit agencies. The regression analysis utilized automated vehicle location (AVL) data from 13 Toronto Transit Commission (TTC) bus routes that are representative of the bus network in Toronto. A series of factors was investigated simultaneously to determine the factors' relative significance with respect to their relationship with bus reliability or speed. The criteria used for selecting the representative bus routes are discussed in the next section.

METHODOLOGY

The objective of this study was to explore relationships between influential factors and transit reliability and speed by means of regression analysis. A sample of TTC bus routes was selected against predetermined criteria to ensure the routes were representative of the network. The most appropriate reliability measure for assessing TTC bus performance was chosen after the proposed evaluation framework. Factors were included in regression analyses as long as data were available. The performance of reliability and speed models was judged by the rationality and significance of independent variables and R^2 values.

Selection of Transit Routes

The first step in establishing transit reliability and speed models able to demonstrate the relationship between the transit performance and influential factors on a network scale was to determine a sample of bus routes representative of service characteristics of the entire TTC bus network. The criteria used to guide the selection process were

- Coverage of both downtown and noncentral areas,
- Inclusion of high-frequency and low-frequency routes,
- Inclusion of different route lengths,
- Inclusion of routes equipped with TSP, and
- Service provision in all time periods.

These criteria were proposed not only to ensure the representativeness of the overall route network but also to guarantee adequate variation in the values of each independent variable in the models. Detailed information on the 13 TTC bus routes selected is presented in Figure 1 and Table 1. Low-frequency routes were considered to be those with headways longer than 10 min, according to *TCRP Report 165: Transit Capacity and Quality of Service Manual, Third Edition* (TCQSM) (*9*). The workday time periods defined by TTC include morning peak (6 to 9 a.m.), midday (9 a.m. to 3 p.m.), afternoon peak (3 to 7 p.m.), early evening (7 to 10 p.m.), late evening (10 p.m. to 1 a.m.), and overnight (1:30 to 5:30 a.m.).

Transit Reliability Measures

Determining an appropriate reliability indicator as the dependent variable of the reliability model was the second step. As noted earlier, a variety of indicators that address diverse aspects of transit reliability can be found in the literature. They can be divided into five categories:

1. On-time performance measures. These measures, which are widely used, are concerned with the ability of buses to depart from service stops around the scheduled time and are most appropriate for low-frequency routes.
2. Headway adherence measures. These measures evaluate the ability to maintain consistent headways. This ability is frequently used to assess the reliability performance of high-frequency routes.
3. Travel time indicators. These measures capture the consistency of run time and are relevant to routes of both low- and high-service frequency.
4. Wait time measures. These measures emphasize the out-of-vehicle travel experience.
5. Composite indicators. These measures attempt to capture multiple aspects of reliability. One example is the customer journey time delay metric, which measures the difference between the actual trip duration and the passengers' expected duration (*17*).

This research investigated 19 transit reliability measures from the first four categories. These measures are displayed in Equation Boxes 1 through 4 (*18–26*). Indicators in the fifth category, composite indicators, are hardly used in practice; therefore, this category was excluded from this research.

Selection of Reliability Measures

An evaluation framework that included two stages of evaluation (Figure 2) was proposed to select the most appropriate reliability indicator among the 19 candidates. The first stage included a mandatory criterion that checked whether all data items required to compute the reliability measure were available. If a reliability measure met this mandatory criterion, it could enter the second stage of the evaluation.

The reliability measures were evaluated against four desirable criteria: data quality, cost of data retrieval (cost), recognition, and easiness of calculation (easiness). A weighted decision matrix was used to assess how well each measure satisfied each

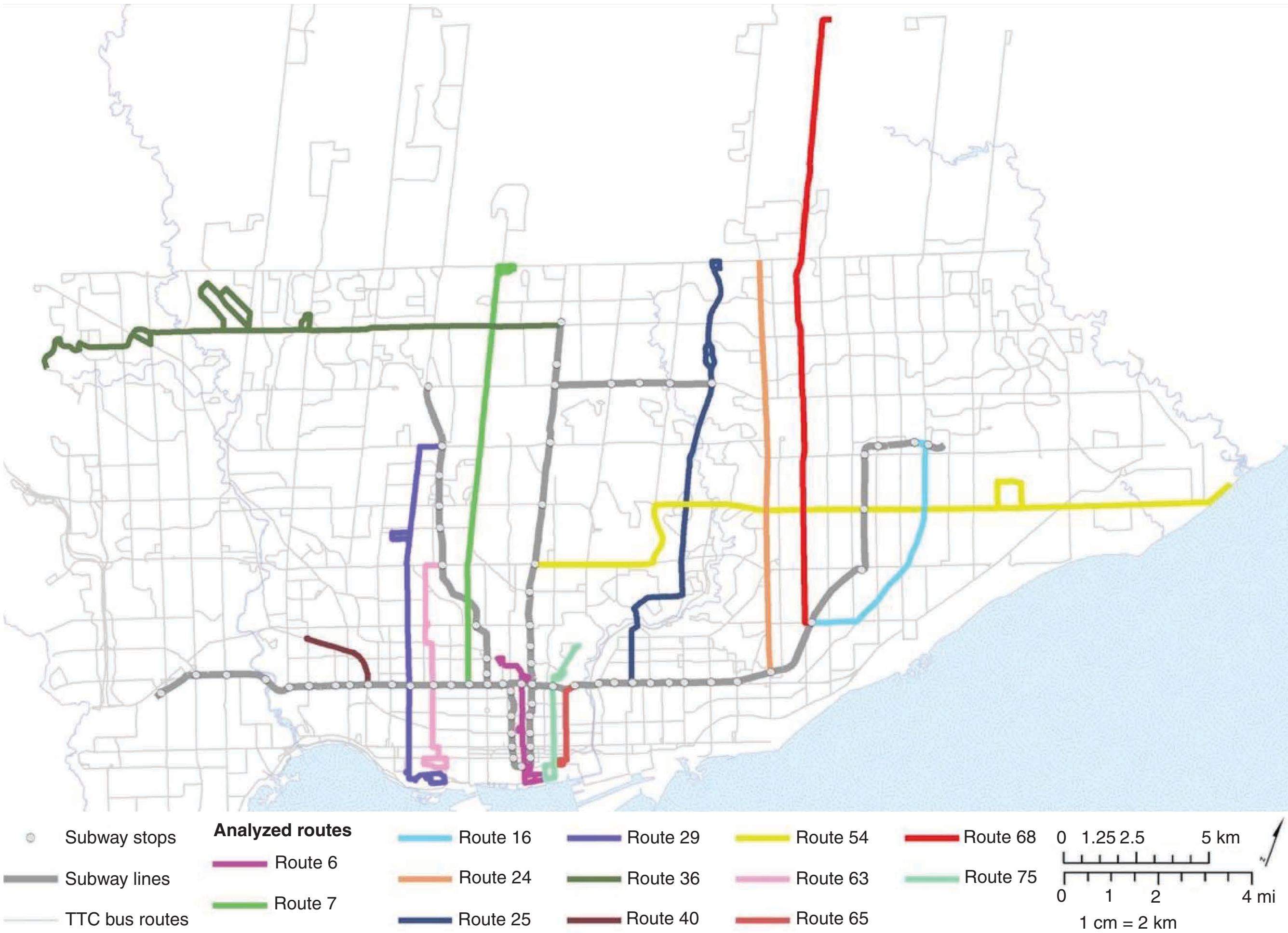

FIGURE 1 Map of selected bus routes. (Data source: City of Toronto, Statistics Canada, DMTI. Projection: NAD 1983 Ontario Lambert.)

TABLE 1 Service Characteristics Against Selection Criteria

Route	Service in Downtown	No. of Periods: High Frequency	No. of Periods: Low Frequency	Route Trip Length (km)	TSP	No. of Branches	No. of Service Periods	No. of Signalized Intersections
06 Bay	Yes	3	2	11.49	No	2	5	24
07 Bathurst	Yes	4	1	29.74	Yes	1	5	46
16 McCowan	No	2	3	18.33	No	1	5	19
24 Victoria Park	Yes	5	0	30.58	No	1	5	24
25 Don Mills	No	5	0	32.7	No	1	5	35
29 Dufferin	No	3	0	24.48	Yes	3	3	34
36 Finch West	No	5	0	39.97	Yes	5	5	41
40 Junction	No	3	2	6.03	No	1	5	8
54 Lawrence East	No	0	5	53.9	No	3	5	54
63 Ossington	No	4	1	21.46	No	2	5	18
65 Parliament	Yes	1	4	6.21	No	1	5	10
68 Warden	No	4	1	25.06	No	2	5	30
75 Sherbourne	Yes	3	1	8.59	Yes	2	4	13

EQUATION BOX 1 On-Time Performance Measures

On-time performance (OTP) (*9*)

$$\text{OTP} = \frac{\text{number of on-time trips}}{\text{number of trips}} \times 100\%$$

Average punctuality (*18*)

$$p_l = \frac{\sum_{j}^{n_{l,j}} \sum_{i}^{n_{l,i}} \left| \tilde{D}_{l,i,j}^{\text{act}} - \tilde{D}_{l,i,j}^{\text{sched}} \right|}{n_{l,j} \cdot n_{l,i}}$$

where

p_l = average punctuality on route l,
$\tilde{D}_{l,i,j}^{\text{act}}$ = actual departure time of vehicle i on stop j on route l,
$\tilde{D}_{l,i,j}^{\text{sched}}$ = scheduled departure time of vehicle i on stop j on route l,
$n_{l,j}$ = number of trips of route l, and
$n_{l,i}$ = number of stops of route l.

Weighted delay index (WDI) (*3*)

$$\text{WDI} = \frac{\sum_{k=t}^{H} k \cdot p(k)}{H}$$

where

k = amount of delay in minutes,
$p(k)$ = probability of having k minutes delay,
t = lower limit of delay, and
H = scheduled headway.

Earliness index (EI) (*4*)

$$\text{EI} = F(0) = P\{x \le 0\}$$

where x = amount of delay. In this case, EI presents the cumulative probability of the amount of delay being less than 0, which is the probability that all the observations are ahead of the schedule.

EQUATION BOX 2 Headway Measures

Coefficient of variation of headway deviations (*9*)

$$c_{v,h} = \frac{\sigma_h}{\mu_h}$$

where σ_h is the standard deviation of headway deviations and μ_h is mean scheduled headways.

Width index (WI) (*4*)

$$\text{WI} = \frac{F^{-1}(0.95) - F^{-1}(0.05)}{\text{average scheduled headway}}$$

where $F^{-1}(p)$ is the inverse of the cumulative distribution function of headway deviations.

Second-order stochastic dominance (*4*)

$$\text{SSDI} = \frac{\alpha \int_a^0 F(x)\,dx + \beta \int_0^b (1 - F(x))\,dx}{(\text{average scheduled headway})(\alpha + \beta)}$$

where

SSDI = second-order stochastic dominance index;
$F(x)$ = cumulative distribution function of headway or delay deviations of frequent or infrequent services, respectively;
α = cost of being late; and
β = cost of being early.

Headway regularity (HR) (*19*)

$$\text{HR} = \frac{\text{number of trips with acceptable headways}}{\text{number of trips}} \times 100\%$$

Acceptable headways is defined within the range of 0.5 to 1.5 times the scheduled headways, or ±5 min, whichever is less.

Deviation index based on stops (DIS) (*20*)

$$\text{DIS} = P\{\theta_1 \le H_s - H_0 \le \theta_2\}$$

where

θ_1 and θ_2 = limits of acceptable headway deviation,
H_s = observed headway at stop s, and
H_0 = headway at which buses are dispatched.

desirable criterion (Table 2). A score ranging from 0 to 5 was used for each criterion, with 0 designating no compliance and 5 full compliance. The data needed for reliability calculation were sourced mainly from the AVL system, which recorded real-time coordinates of transit vehicles every 20 s. These data could provide neither precise arrival and departure times at stops nor accurate headways after data cleaning. Therefore, on-time performance, headway, and wait time measures had lower scores than travel time measures with respect to data quality. In terms of data retrieval cost, a score of 5 was assigned to measures requiring data retrievable from online platforms; measures requiring data that needed to be collected individually from different departments were given lower scores. The recognition of a measure was judged by its number of citations. Easiness was scored on the basis of the estimated time and complexity of calculation.

Once all measures were scored against all desirable criteria, the score of each criterion was multiplied by the corresponding weight. In this study, 35%, 30%, 25% and 10% were assigned to data

EQUATION BOX 3 Travel Time Measures

Reliability buffer index (RBI) (*21*)

$$\text{RBI}(\%) = \frac{\text{95th percentile travel time} - \text{average travel time}}{\text{average travel time}}$$

Buffer index (BI) (*22*)

$$\text{BI} = \frac{\text{95th percentile travel speed} - \text{average travel speed}}{\text{average travel speed}} \times 100\%$$

Reliability buffer time (RBT) metric (*23*)

$$\text{RBT} = \begin{pmatrix}\text{95th percentile travel time} \\ - \text{ median travel time}\end{pmatrix}_{\text{O-D matrix}}$$

Coefficient of variation of travel time ($C_{v,\text{TT}}$) (*24*)

$$C_{v,\text{TT}} = \frac{\sigma_{\text{TT}}}{\mu_{\text{TT}}}$$

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

Reliability factor (RF) (*25*)

RF = percentage of travel times within 10% of mean

Punctuality index based on routes (PIR) (*20*)

$$\text{PIR} = P\{\partial_1 < \text{TT}_{\text{actual}} - \text{TT}_{\text{scheduled}} < \partial_2\}$$

where

∂_1 and ∂_2 = bounds of acceptable travel time deviation defined by the agency,
$\text{TT}_{\text{actual}}$ = actual travel time, and
$\text{TT}_{\text{scheduled}}$ = scheduled travel time.

EQUATION BOX 4 Wait Time Measures

Excess wait time (EWT) (*9*)

EWT = average departure time − scheduled departure time

Excess wait time (EWT) (*26*)

EWT′ = actual wait time − scheduled wait time

Budget wait time (BWT) (*9*)

BWT = 95th departure time − 2nd percentile departure time

Wait assessment (WA) (*19*)

$$\text{WA} = P\{\text{headways} \le H_{\text{set}}\}$$

H_{set} = preset upper limit of headway

quality, cost of data retrieval, recognition, and easiness of calculation, respectively, to reveal their relative importance. Data quality directly affects the performance of a model; therefore, it received the highest weight. Data acquisition, which involves intensive communication with multiple agencies, is usually the most time-consuming task. It markedly influences the overall speed of research. Recognition reflects, to some extent, the measure's appropriateness and acceptability in capturing service quality in terms of reliability. Easiness was the least important criterion because it influences only the time of calculation, which is not critical as compared with the time spent on data acquisition.

In the final step, the weighted total scores of the reliability measures were ranked from highest to lowest. The top-ranked reliability measure, coefficient of variation (CV) of travel time, was used as the dependent variable of the reliability models. The evaluation results are shown in Table 2. Travel time measures in general outperformed the other candidates, mainly because the selected bus routes included both low and high service frequencies. As noted earlier, travel time measures are relevant to both types of services, while other indicators are good for one type or the other.

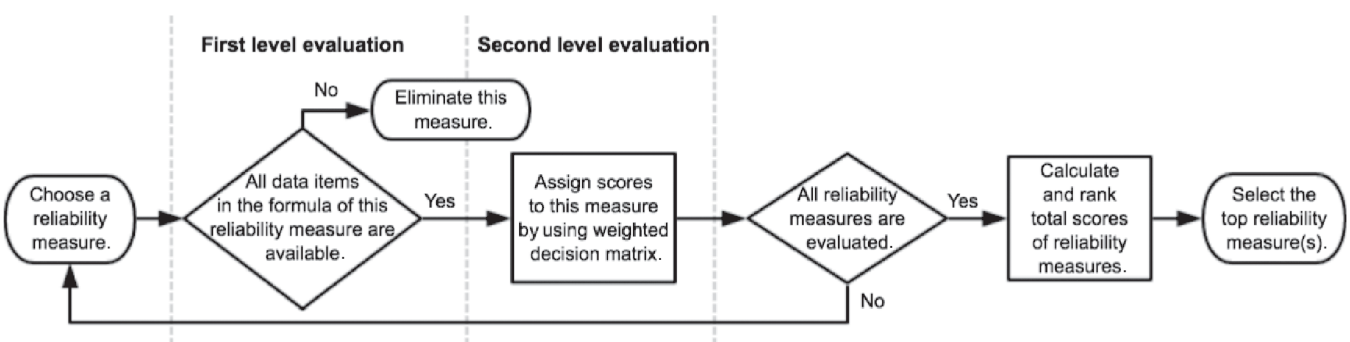

FIGURE 2 Framework of the selection of reliability measures.

Selection of Independent Variables

This study attempted to investigate as many relevant factors as possible. These factors had to be carefully selected to produce models that would be robust, policy sensitive, and practical. On the basis of the set of factors that can potentially influence transit reliability and speed [as mentioned in the TCQSM (*9*) and Diab and El-Geneidy (*12*)] and the availability of data, this study considered the independent variables listed in Table 3. Additional independent variables were also formulated by combining some of the listed variables, such as the ratio of the number of farside to nearside stops and the number of TSP-equipped intersections with nearside stops.

Regression Analysis

Linear regression analysis was employed in developing reliability and speed models following data collection and processing. First, the Pearson product-moment correlation coefficients (r) of all possible pairs of dependent and independent variables were calculated to check how they would change with one another. The highly correlated independent variables with r greater than .7 were grouped and were not included in a single model at the same time.

In general, backward elimination was applied such that all candidate explanatory variables not in the same category were included at the start. The alternatives in the same category were included one by one for each trial. Different combinations were also made for alternatives across different groups to yield the best model. The performance of models was evaluated by the adjusted R^2 values. The t-statistics of explanatory variables were used to check their statistical significance at the 90% confidence level. The signs of the variables should also conform to prior expectation and common knowledge of transit operations.

DATA

Bus Service Data

For each bus route and service period, the data acquired from TTC included round-trip distance, bus type, number of buses, scheduled headway, scheduled round-trip driving time, scheduled total terminal time, average scheduled speed, and service hours. Additionally, the stop sequence and coordinates of stops and their on-street locations (i.e., nearside, midblock, and farside) were provided by TTC.

Road Infrastructure

The number of intersections along each bus route, the latitude and longitude of each intersection, and the geometric configurations of roads and intersections were gathered from the City of Toronto.

TABLE 2 Evaluation Results of Reliability Measures

		Desirable Criterion					
Measure	Data Availability	Data Quality (35%)	Cost (30%)	Recognition (25%)	Easiness (10%)	Weighted Total	Rank
On-Time Performance Measures							
OTP	Pass	4	4	1	5	3.35	8
p_l	Pass	3	1	1	4	2	17
WDI	Pass	3	0	1	3	1.6	18
EI	Pass	4	2	1	5	2.75	11
Headway Measures							
$c_{v,h}$	Pass	2	3	5	4	3.25	10
WI	Pass	2	3	3	3	2.65	13
SSDI	Pass	3	3	2	2	2.65	13
HR	Pass	2	2	1	5	2.05	16
DIS	Pass	3	3	1	5	2.7	12
Travel Time Measures							
RBI	Pass	5	5	3	3	4.3	2
BI	Pass	5	4	2	3	3.75	5
RBT	No	na	na	na	na	na	na
$C_{v,\mathrm{TT}}$	Pass	5	4	5	4	4.6	1
RF	Pass	5	5	1	5	4	3
PIR	Pass	5	4	1	5	3.7	6
Wait Time Measures							
EWT	Pass	3	2	1	5	2.4	15
EWT′	No	na	na	na	na	na	na
BWT	Pass	4	4	2	5	3.6	7
WA	Pass	3	5	1	5	3.3	9

NOTE: na = not applicable.

TABLE 3 Independent Variables

Independent Variable	Minimum	Maximum	Average
Bus Service Characteristics			
Directional route length per segment length (km)[a]	3.02	26.95	11.59
Scheduled headway (scheduled frequency)[b]	3 min 10 s	30 min	10 min 6 s
Hourly volume of boarding and alighting passengers	11	1,839	415
Time period of day	na	na	na
Day of week	na	na	na
Terminal (layover) time (min)[b]	0	7	1.86
Scheduled speed (km/h)	10.30	15.30	13.32
Number of connections to subway stations	1	2	na
Road Infrastructure			
Number of nonsignalized intersections	15	89	46
Number of signalized intersections	8	54	27
Total number of intersections	27	135	71
Intersection density per kilometer	3.90	10.63	7.25
Stop density (stop spacing) per kilometer[b]	3.40	5.15	4.02
Number of timed stops per direction	3	31	13
Total number of stops in each direction	14	92	44
Total number of farside stops	1	28	10
Total number of nearside stops	12	55	13
Presence of dedicated transit lane	0	1	na
Number of right-turn prohibitions per segment	0	3	1.16
Signals			
Length of green phase (s)	24	56	34.93
Signal cycle length (s)	56	92	68.20
Utilization of transit phase	na	na	na
Length of maximum TSP green extension available	16	30	na
Traffic			
8-h traffic volume per intersection[c]	2,770	11,501	6,652
8-h pedestrian volume per intersection	205	6,411	1,081

NOTE: na = not applicable.
[a]Route length and segment length were used for route- and segment-level analysis, respectively.
[b]Variable in the parentheses is the alternative.
[c]8-h volumes are counts taken at intersection approximately from 7:30 a.m. to 6:30 p.m.

Three routes had segments with dedicated bus lanes. The number and locations of dedicated bus lanes was provided by TTC.

AVL Data

The AVL data of the selected bus routes were provided by TTC and were later processed in MATLAB to calculate travel times of individual segments and end-to-end trips in each direction. The AVL data were saved separately for different routes as Excel files sorted by date and time, and they included five columns: date and time, route number, vehicle number, latitude, and longitude. The records in each file represent the individual locations of buses recorded by the AVL system every 20 s. For the route-level analysis and when a route had multiple branches, this research considered the branch with the highest passenger volume and longest duration of service.

The AVL data of this study were collected on five weekdays, from November 23 to 27, 2013. Data were acquired for all trips made by all transit vehicles operated on the selected routes from the start of the service to the end. TTC overnight service has special service patterns and was thus excluded from the study. Two evening periods that lacked data on traffic and pedestrian volume were not utilized in the analysis. Weekends were excluded because of lower demand and lack of passenger and traffic data.

Riding Counts

The summary reports of riding counts provided by TTC included the cumulative number of boarding passengers ($\mathrm{ON}s_p$) and alighting passengers ($\mathrm{OFF}s_p$) at each stop during each time period p. The data covered the five time periods from the morning peak to late evening. The TTC report does not differentiate between passengers using different branches. The number of boarding and alighting passengers of a branch at a stop per hour, denoted respectively by V_b and V_a, was calculated as

$$V_b = \frac{\mathrm{ON}s_p \cdot f_{p1}}{\sum_{i=1}^{b} f_{pi} \cdot t_{p1}} \tag{1}$$

$$V_a = \frac{\text{OFF}s_p \cdot f_{p1}}{\sum_{i=1}^{b} f_{pi} \cdot t_{p1}} \qquad (2)$$

where

f_{p1} = service frequency of the branch of interest,
f_{pi} = frequency of branch i,
t_{p1} = service duration in time period p of the branch of interest, and
b = total number of branches serving the stop.

If a stop is served by a single branch, then $V_b = \text{ON}s$ and $V_a = \text{OFF}s$.

The reason for converting the riding counts to hourly volumes is to make them consistent across different routes. The total hourly boarding and alighting passengers used as an explanatory variable is the sum of V_b and V_a at all stops along the route or within a segment.

$$\text{total hourly boarding and alighting passengers} = \sum_{i=1}^{s} (V_b + V_a) \qquad (3)$$

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

Signal Timings

The signal timing plans at intersections along the selected bus routes, which included detailed information on phase splits and TSP settings, were acquired from the Traffic Management Centre of the City of Toronto. The signal settings varied by time period. Any independent variable related to signal timing was included in the segment model only. The cycle lengths are usually similar at intersections along a corridor and vary in different time periods. The average cycle length of signalized intersections along the entire bus route or within a segment was used as an independent variable.

Vehicle and Pedestrian Volumes

The 8-h traffic and pedestrian volumes covering the period from 7:30 a.m. to 6:30 p.m. for all intersections along the selected routes were acquired from the City of Toronto. The vehicle volume used for modeling was the volume in the direction of the transit unit movement, which was the sum of left-turn, through, and right-turn traffic. The average vehicle and pedestrian volumes of the entire route and the segments were computed.

DISCUSSION OF MODELING RESULTS

Route-Level Reliability Model and Average Speed Model

The regression analysis at the route and segment levels considered 45 different forms of independent variables in total. The categories of variables are outlined in Table 3. The specific variables included in the models are explained later in this paper. The dependent variable chosen for the reliability models was the CV of travel time, which was computed for different time periods in both directions. The CV of travel time equals the standard deviation of observed travel time divided by the scheduled travel time.

$$\text{CV of travel time}^{\text{period}} = \frac{\sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(t_{a_{jp}} - \overline{t_{ap}}\right)^2}}{t_{s_{tp}}} \qquad (4)$$

where

$t_{a_{jp}}$ = actual end-to-end directional travel time of trip j in time period p,
$\overline{t_{ap}}$ = average end-to-end directional travel time during the time period p,
$t_{s_{tp}}$ = corresponding scheduled travel time of the time period p, and
M = total number of directional trips during time period p.

Figure 3 shows one example of the temporal distribution of route travel times, specifically, that of Route 6 in the southbound direction. The blue dots represent the actual trip travel times, while the black solid line depicts the average actual travel time in the five time periods of the five weekdays. The dashed red lines separate the different days. The scheduled travel times from the morning peak period to the late evening period were 30, 35, 35, 30 and 24 min, respectively.

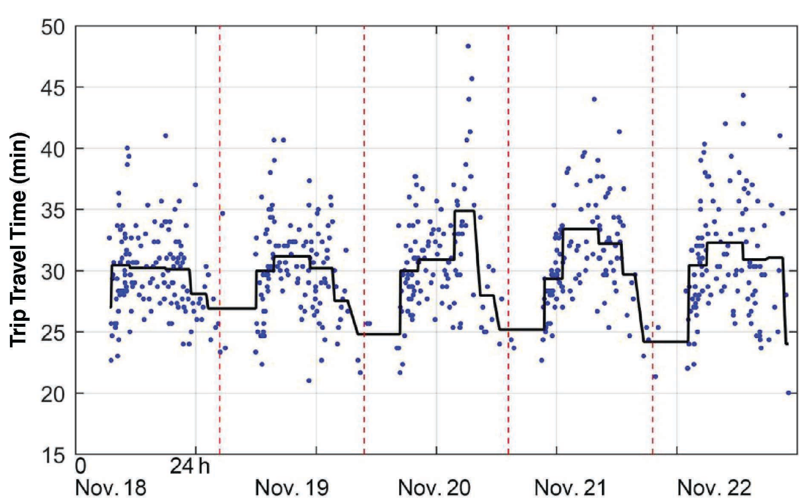

FIGURE 3 Trip travel times of Bus Route 6 southbound in November 2013.

The observed period averages fluctuated around the scheduled values with discrepancies smaller than 5 min. However, the figure shows a wide spread of travel times around the average.

Variables related to signal timings were excluded in the route level analysis because of the difficulty of aggregation along individual corridors. Highly correlated variables were not added simultaneously in the model. The analyses covered the morning peak, midday, and afternoon peak periods. The northbound direction of Routes 24 and 68 and both directions of all the other routes were included.

The final linear regression models of transit reliability and speed are presented in Table 4. The significance of variables was assessed by *t*-statistics at the confidence level of 90%. In the transit reliability model, explanatory variables with positive coefficients had a negative impact on travel time regularity, as they increased the value of the CV of travel time. In the speed model, all variables negatively influenced the transit speed.

Transit reliability and speed were negatively associated with the intersection density and ratio of signalized intersections to nonsignalized intersections, which is an expected result, as these factors inflict delays on bus service. Reliability and speed were also shown to have lower values along routes that had more connections with the subway system, likely because of the remarkably high number of transfer passengers at such connecting stops. The model results also showed that route reliability and speed were negatively related to route traffic volume. Peak period operation was captured in the model by a dummy variable, with 1 representing the morning and afternoon peak periods and 0 otherwise. This variable points to the role of various peak period factors that were not represented explicitly in the model, such as road traffic restrictions and higher traffic congestion. However, this dummy variable and the average route volume were statistically significant in the speed model but not in the reliability model, which shows the difference between speed and reliability with respect to their relationship with these factors.

The presence of a dedicated bus lane was represented by a dummy variable. The model results showed a positive relationship between route reliability and the presence of a dedicated lane, but no significant relationship was found with speed—likely because most dedicated lanes in this study are implemented in suburban areas. Even without dedicated lanes, bus speeds are slightly affected by the general traffic in suburban areas.

Higher variation of travel time was observed on longer routes, probably because of delay propagation along the trip. No significant relationship with route speed was detected. The number of boarding and alighting passengers was negatively related to bus reliability, as higher values are expected to have a disproportionate effect on dwell times. High pedestrian volumes also corresponded to high variations. Because signal phases for pedestrian crossing at some intersections were given upon request, more pedestrians meant a longer bus wait time at signalized intersections. On the other hand, the CV of travel time was higher when the ratio of farside to nearside stops was lower, likely because farside stops save deceleration time and provide gaps for buses to merge back into the traffic stream (*27*).

Lower speeds were found to be accompanied by higher stop density, owing to the time spent in frequent acceleration and

TABLE 4 Route- and Segment-Level Models

	Route-Level Models		Segment-Level Models	
	Reliability Model	Average Speed Model (km/h)	Reliability Model	Speed Deviation Model (km/h)
Independent Variable	Coefficient (10^{-3})	Coefficient	Coefficient	Coefficient
Intercept	−5.292 (−5.68)	44.117 (39.51)	−1.637 (−4.93)	44.413 (10.65)
Intersection density (number of intersections per kilometer)	0.434 (7.46)	−1.295 (−14.09)	na	na
Ratio of signalized to nonsignalized intersections	2.283 (5.06)	−6.038 (−11.02)	na	na
Number of connections to subway stations	0.589 (2.78)	−2.389 (−11.20)	na	na
Peak/off-peak (dummy variable)	0.148 (1.33)*	−0.857 (−7.70)	na	na
Average 8-h vehicle volume (10^3)	0.160 (0.64)*	−0.639 (−1.77)	0.533 (4.02)	na
Route or segment length (kilometer)	0.199 (14.46)	na	0.324 (3.65)	−4.427 (−4.94)
Dedicated lane (dummy variable)	−1.389 (−7.00)	na		
Total hourly boarding and alighting passengers (10^3)	0.578 (3.14)	na	0.381 (2.84)	−11.047 (−6.27)
Average 8-h pedestrian volume (10^3)	0.570 (3.44)	na	na	na
Ratio of farside to nearside stops	−1.012 (−1.86)	na	−0.363 (−3.15)	na
Stop density (number of stops per kilometer)	na	−1.545 (−0.11)	0.043 (1.43)*	−5.446 (−12.07)
Service frequency (number of vehicles per hour)	na	−0.247 (−8.63)	na	−0.287 (−3.27)
Number of stops upstream of the segment	na	na	0.002 (1.25)*	−0.172 (−5.68)
Signalized intersection density (number of intersection per kilometer)	na	na	0.154 (5.37)	−0.751 (−2.05)
Percentage of intersections with right-turn prohibitions	na	na	−0.304 (−2.35)	7.455 (3.86)
Implementation of TSP systems (dummy variable)	na	na	−0.193 (2.84)	0.900 (1.01)*
Average signal cycle (s)	na	na	0.008 (3.05)	na
Adjusted R^2	0.57	0.81	0.55	0.75
Number of observations	334	334	105	105

NOTE: *t*-statistics are provided in parentheses.
*Not significant at 90% confidence level.

deceleration. High service frequency, usually associated with peak hours and high passenger demand, was found to be negatively associated with speed. The percentage of time points along transit routes was also investigated but did not show a significant effect.

Segment-Level Reliability Model and Speed Deviation Model

The segment-level analysis focused mainly on assessing the effect of TSP on transit reliability and speed. Two bus routes with TSP installed at some intersections (Routes 29 and 75) were investigated. The route segmentation was aimed at combining adjacent signalized intersections equipped with TSP. Therefore, the data set included segments with all intersections equipped with TSP and segments without TSP. Each segment begins and ends with a bus stop and usually consists of about five intersections. The CV of travel time over the time period for the segment model was calculated in the same way as for the route model, but all travel times were disaggregated to the segment level. Instead of average speed, the speed deviation was applied for the segment level model because of higher variations of speed observed within short lengths, which is the actual speed minus the scheduled speed. The linear regression results at the segment level are presented in Table 4.

The negative relationships between signalized intersections and reliability and speed remained significant in the segment analysis. Low reliability and speed were observed when the volumes of boarding and alighting passengers were high. Low reliability and speed were also associated with long segment length and high stop density. The latter segments of a route showed lower speed, but no significant pattern for reliability could be detected.

As expected, right-turn prohibition was positively related to reliability and speed, as it prevents right-turning traffic from blocking the curb lane, particularly where nearside stops exist. Segments with TSP-equipped intersections had low variability in bus travel time. Speed was positively related to the implementation of TSP, although the parameter was not significant at the 90% confidence interval. A possible explanation is that the likely saving at the intersection level does not manifest to a degree that results in significant difference in travel time at segments with and without TSP.

In agreement with the route-level model, the ratio of the number of farside to nearside stops and the average vehicle volume were negatively related to transit reliability. The scheduled service frequency, which had higher values in peak hours, was negatively related to transit speed. This finding is also in accordance with the route level analysis.

SUMMARY AND CONCLUSIONS

This research developed a framework for evaluating transit reliability measures and selecting an appropriate one for this study. Transit reliability and speed models were developed by using the AVL data of TTC buses in the City of Toronto to investigate the significant factors related to travel time variability and speed at the route and segment levels. Some of the factors mentioned in the paper but not included in the models were not found to be significant. This study is distinct from previous studies on the topic because it

- Developed an evaluation framework to guide the selection of the most appropriate reliability measure,
- Considered a wider transit network,
- Covered a broad list of factors related to speed and reliability,
- Estimated models with relatively higher values of adjusted coefficient of determination (compared with previous studies),
- Included TSP in the segment-level model and showed its significant impact on improving service reliability, and
- Compared the factors affecting transit reliability and speed.

The route-level analysis provided insight into the factors that are significantly related to poor transit performance and that warrant special attention when bus routes are being planned. These factors include the density of signalized intersections, the number of transfer stops to subway stations, peak hours and traffic volumes. Although transit agencies cannot control the last two factors, mitigating measures, such as dedicated bus lanes, could improve transit performance under such conditions. Routes with densely located signalized intersections experience frequent stops and cause delays for buses. At corridors with high intersection density, the introduction of mitigating measures to counteract adverse impacts might be prudent. Subway stations with high volumes of passengers transferring to the bus system bring lengthy and unpredictable variations in dwell times. As some bus routes are intentionally designed to connect with subway stations, buses may require more flexible schedules during peak hours to accommodate variations and delays.

The segment-level models investigated factors at a relatively disaggregated level. Lower speed and reliability were observed on segments with higher signalized intersection density, boarding and alighting passengers, segment length, stop density, and segments toward the end of routes. Higher passenger demand results in longer dwell times. The density of stops influences speed and travel time variability in a way similar to intersection density. Service length is also related to travel time variability at the route level. Therefore, the relationship between the length of bus routes and bus reliability and speed should be considered at the planning stage. Slack time can be slightly increased at time points in the middle of bus paths to absorb delays and recover from variations. More reliable service was observed on segments with right-turn prohibitions and TSP. Restricting right turns is particularly important to nearside stops, which can be severely affected by vehicle queues at intersections. Therefore, improvements in reliability could be achieved if right turns were prohibited on critical road segments that have nearside stops during the peak hours. TSP, one of the major transit control strategies applied in Toronto, demonstrated a positive relationship with transit reliability.

Both route- and segment-level models indicated the importance of the on-street location of bus stops in travel time variability. Better performance was observed on routes or segments with a higher proportion of farside stops. However, of 10,000 surface transit stops (for buses and streetcars) in Toronto, approximately 67% are nearside, while only 22% and 11% are farside and midblock, respectively. As TSP also functions more effectively at intersections with farside stops, a proportion of nearside stops can be altered to farside within a reasonable budget limit.

To conclude, at the transit planning stage, attention should be paid to the route length, passenger demand, stop locations, and the coordination of bus and subway routes. City planning in favor of transit systems needs to consider the locations of intersections, especially those equipped with traffic signals. In regard to reliability, farside stops are preferred. TSP and right-turn prohibitions are possible effective solutions for improving service reliability and speed. Dedicated lanes can also be considered as a means, but they generate capital investment and maintenance cost and are highly constrained by available space.

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