Subway service down again? Assessing the effects of subway service interruptions on local surface transit performance

Diab, Ehab and Amer Shalaby

iCity: Urban Informatics for Sustainable Metropolitan Growth

A project funded by the Ministry of Research and Innovation of Ontario through the ORF-RE07 Program and by partners Cellint Traffic Solutions, Esri Canada, IBM Canada, Waterfront Toronto, the City of Toronto and the Region of Waterloo.

Report #17-02-03-02

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING
Transportation Research Institute

UTTRI

Subway service down again?
Assessing the effects of subway service interruptions on local surface transit performance

Ehab Diab, Ph.D.*
Tel: 514-549-0093; Email: ehab.diab@utoronto.ca

Amer Shalaby, Ph.D., P.Eng*
Tel: 416-978-5907; Email: amer@ecf.utoronto.ca

***** University of Toronto, Department of Civil Engineering, 35 St. George Street, Toronto, Ontario M5S 1A4 Canada

Submission date: August 1st, 2017

Word Count: 5981, 5 Tables +1 Figure (1500) =7481

Paper Prepared for Presentation and Publication at the

Transportation Research Board 97th Annual Meeting

ABSTRACT

Cities around the world are keen to offer modern urban transit systems that connect various locations in an efficient and reliable manner with the highest degrees of riders' experience. These systems may consist of various modes such as buses, streetcars (or trams), and rapid transit systems (e.g., subways). In both research and practice, the quality of transit service has traditionally been measured and investigated on a mode-by-mode basis. Therefore, it is rare to find studies that investigated the impacts of poor performance or breakdown of one transit mode on other functioning modes in multi-modal integrated transit systems. This research aims at understanding the impact of subway service interruptions on the speed performance of surface transit in Toronto. In order to do that, a detailed dataset of subway service interruptions collected in 2013 by the TTC, the public transit provider in the City of Toronto, was used. In addition, another dataset was obtained from the TTC's Automatic Vehicle Location (AVL) system for 51 bus and streetcar routes that are within a short walking distance from some subway stations. Using two statistical models, the paper results indicate that subway service interruptions have a statistically significant negative impact on bus and streetcar service operations in terms of slower speeds, with more immediate and intense impacts on streetcar service. Findings from this research can be useful to transit planners and engineers as they highlight an important interaction between modes in a multi-modal transit environment.

Keywords: Subway system incidents, Bus service, Streetcar service, Service speed

INTRODUCTION

Cities around the world are keen to offer modern urban systems that connect various locations in an efficient and reliable manner with the highest degrees of riders' experience. These systems may consist of various modes such as buses, streetcars (or trams), and rapid transit systems (e.g., subways). A sizable body of literature has focused on understanding the impacts of general factors (e.g., weather conditions, route distance, demand, number of stops) or various transit improvement strategies (e.g., transit signal priority (TSP), reserved lanes) on transit service performance and reliability (*1-3*). These studies generally focused on one transit mode at a time such as the bus system (*1-3*), the streetcar system (*4-6*), or the subway system (*7; 8*) while ignoring the impacts of one system's disruption on the other systems in multi-modal networks. For example, Diab and El-Geneidy (*1; 9*), using bus data collected from the Automatic Vehicle Location (AVL) and Automatic Passenger Count (APC) systems in Montreal, tested the impact of a set of improvement strategies (e.g., TSP, articulated buses, bus lanes) on the bus service running time and variation. In another study, they investigated the impact of bus stop location on service quality (*10*). Mesbah et al. (*4*) explored the impacts of weather conditions on the tram system's travel times in Melbourne, Australia. Currie and Reynolds (*6*) investigated the impacts of two different fare collection methods on streetcar service performance, while Currie et al. (*5*) evaluated the impact of passenger crowding on tram dwell times. Regarding the subway related studies, Weng et al. (*8*) examined the impacts of causal variables on subway delay duration, such as power/vehicle failures and switch malfunction, while Louie et al. (*7*) investigated the impacts of both causal and non-causal variables, such as passenger related incidents.

Other researchers focused on understanding, modelling and proposing conceptual frameworks for rail (or subway) disruption management (i.e., emergency response plans), while testing different approaches or categorizing rail incidents according to some criteria (*11-14*). For example, Pender at al. (*15*) proposed a method to evaluate the economic viability of providing dedicated bus service reserved for bus bridging (i.e., shuttle service) purposes for rail system disruption. Darmanin at al. (*16*) and van der Hurk et al.(*17*) developed mathematical approaches with aim of minimizing commuter discomfort following a service disruption and estimating the required shuttle line frequencies, respectively.

Despite the previous efforts, it is rare to find studies that focused on understanding the impacts of service failures of one transit mode on the performance of other functioning transit modes in multi-modal integrated networks. An improved understating of the various causes behind the changes in transit system's performance that users experience on a daily basis would help transit agencies in developing more appropriate policies to maintain and improve transit systems' resilience and performance in the future. This research aims at understanding the impact of subway system's interruptions (due to incidents) on the speed performance of surface transit routes in Toronto. Using Toronto as a case study provides a unique opportunity to understand the effects of subway service interruptions on the service performance of both bus and streetcar lines in a highly integrated multi-modal transit system.

STUDY CONTEXT AND METHODOLOGY

Toronto, Ontario, is the most populous city in Canada with more than 2.8 million inhabitants in 2015 (*18*). The Toronto Transit Commission (TTC) operates the transit service within the City of Toronto, serving about 2.7 million passengers on a daily basis (*19*). It operates a multi-modal transit system, consisting of four subway lines, 11 streetcars lines, and 141 bus routes (*20*). The

TTC subway system extends to a total length of 68 km serving 69 stations. A total of 1.3 million passenger-trips per day were made using the subway system in 2013 (*21*).

Since the main aim of this study is to understand the impact of incident and interruption delays of Toronto's subway system on the performance of the surface transit system, it used two datasets. The first dataset includes a detailed subway system interruption data collected in 2013 by the TTC. In this dataset, each record includes the incident's date, time of day (in minutes), subway station, direction of travel, amount of delay (in minutes), vehicle number and type, as well as a brief description of the incident and a code representing the incident type. Around 12,000 subway incidents were reported at the stop level in 2013 along the two main subway lines (i.e., Yonge-University and Bloor–Danforth lines) operated by the TTC in Toronto (Figure 1-A). The incident causes, for example, included: debris/intrusions at track level, track circuit/track down, signal/switch/power problems, smoke/fire at the track, and disabled train/train body problems as well as incidents related to passengers' activity issues and security aspects (e.g., injuries, violence, suicide, police investigations etc.). A complete list of incident types at the stop level can be found at Louie et al. (*7*). The second dataset was acquired from the TTC's Automatic Vehicle Location (AVL) system for several bus and streetcar routes that are within a short walking distance from some subway stations. This dataset includes information about bus and streetcar locations (x- and y- coordinates) recorded every 20 seconds as well as other information related to the time of the record and route and run number.

The study time frame of interest is all the weekdays of May 2013. This month was selected for analysis because it experienced the greatest number of incidents with the largest amount of delays and lowest standard deviations for both at the system level. This was done to capture the impacts of a good number of subway incidents with varying degrees of delays. On the other hand, other criteria were chosen to identify the subway stations to be included in the analysis. These criteria were based on generating a composite indicator (or index) for each subway station using the 2013 daily ridership data and TTC subway incident data to identify the most vulnerable stations in the subway system. This indicator consists of three equally weighted variables: daily ridership at the subway station, and total number of incidents and total amount of delay per weekdays of the month. Each variable was normalized using a z-score, then a total was generated by summing all three z-scores (Figure 1-B). This index was used to rank all the subway stations in May 2013. The results of this method helped identify the subway stations that suffered most from delays in May 2013. The majority of these stations were located along the Yonge-University-Spadina (YUS) Line, which travel north-south to serve the downtown area. Therefore, this study placed its focus on this line.

Furthermore, in order to achieve a good understanding of the impacts of subway incidents on the surface transit system, a subway station should satisfy the following conditions. It should be neither the first or last stations of the subway line nor a transfer station, where two subway lines are intersecting. This was done since delays in one subway line can encourage passengers to use the other line. Finally, the top ranked 24 subway stations along the YUS Line (out of 32 stations) were included in the analysis. This allowed for analyzing the impacts of around 388 incidents with total delay of 1702 minutes, ranging from two to 73-minute incidents. In addition, over 100 million individual observations were acquired from the TTC's AVL system for 41 bus routes and 10 streetcar routes for the weekdays between May 1, 2013 and May 31, 2013. These routes have stops within 200 metres from the selected subway stations, representing a viable option for subway users when a subway service interruption occurs. In fact, the focus on analyzing one subway line allowed us to dramatically decrease the number of analyzed routes.

The selected month had mild and clear weather with no reordered snow on the ground that could impact the bus and streetcar route operations.

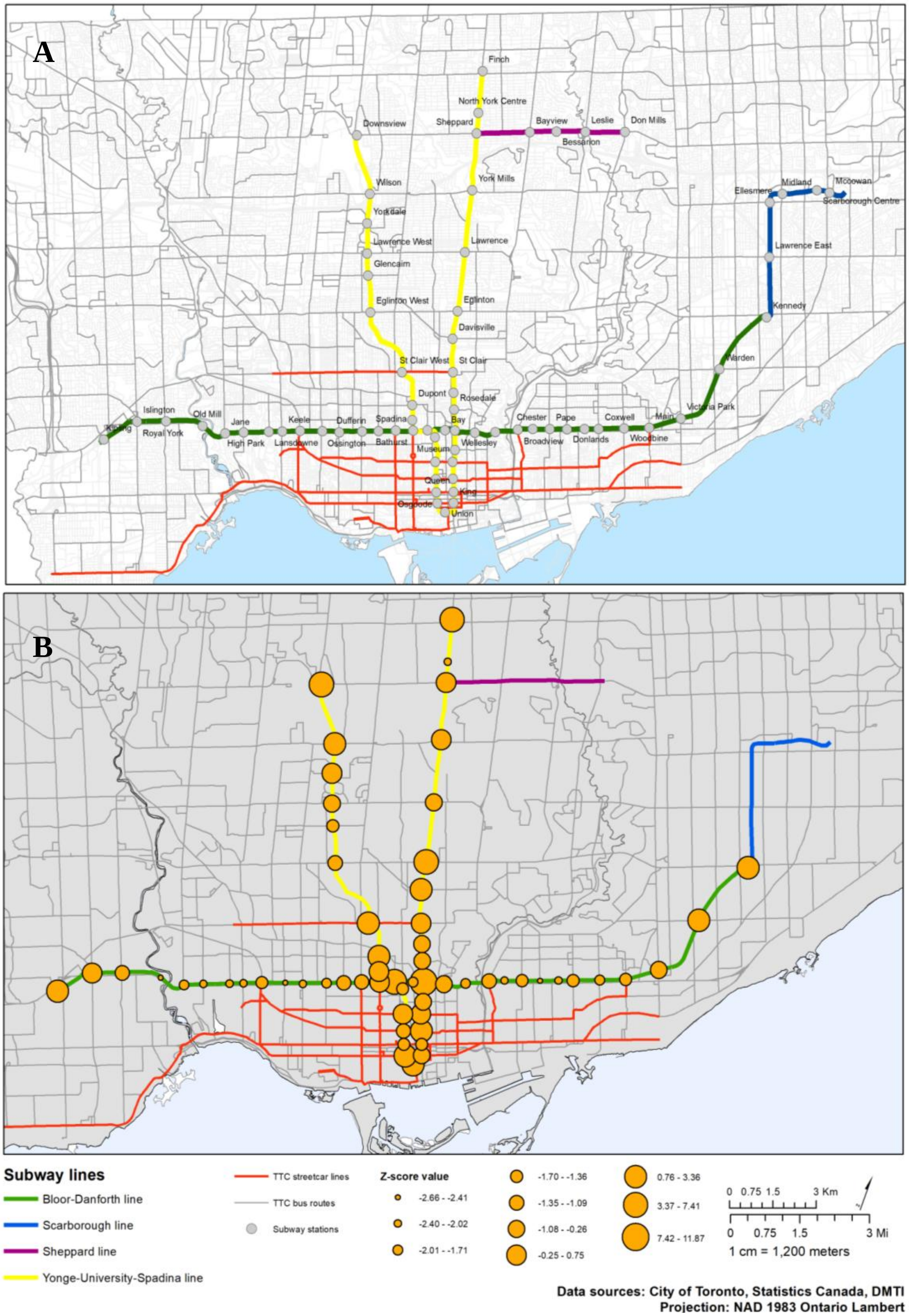

Figure 1: A- Toronto transit system, and B- subway system total z-score by subway station.

In order to isolate the effects of the subway service interruptions on surface transit performance, we developed two statistical models. They capture the impacts of subway service interruptions on the streetcar and bus service speeds, respectively, at the segment-level of analysis. The segment was defined as the route section between each two consecutive time points along a route. The time points are important locations for transit agencies schedule building and operational control (*22; 23*). Subsequently, all the variables in this study were defined according at the trip-segment level. For example, the average speed per trip-segment was computed as the average speed of all GPS points of a given trip within a given segment. In the analysis, we kept only trip-segments that start within a three kilometre straight-line distance buffer of the YUS Line to reduce the number of analyzed trip-segments. After processing the raw AVL data in ArcGIS by running an automated script written in Python, while removing system recording errors, duplicate records, holiday and weekend trips, the trip-segment's average speed, direction, starting time, and route and trip numbers were obtained.

Table 2 includes a list of variables incorporated in the statistical analysis with a detailed description. The squared terms of some independent variables are used to account for a possible non-linear relationship between each and the dependent variable. Other variables have been tested but eliminated from the study due to their insignificance and/or correlation with other used variables (with a Pearson coefficient greater than 0.80) such as *bus/streetcar headway*, *express routes* and *total number of nearby bus/streetcar lines*. According to previous studies, the general factors affecting bus and streetcar travel times include stop sequence along a trip, time of day (morning peak, off-peak, afternoon peak), segment distance and number of stops (23-25).

Regarding the control variables, dummy variables for the direction of travel and time of the day were included in the models to isolate the impacts of traffic congestion on the service performance. A dummy variable, *Adjacent segment*, was included in the analysis to control for the trip-segments that start within 200 metres from a subway station. These segments are expected to have lower speeds due to higher passenger activity at these locations. It should be noted that in a few cases the time-point segments start before the 200-metre buffer; however, they were distinguished as within 200 metres, if they had a stop that serve passengers at subway locations. Also, in order to fully capture the impacts of subway system on bus/streetcar performance, time-point segments that start immediately at subway stations were extended by 30 metres at the expense of one stop before. This was done to capture the total impact of passenger activity (boarding and alighting passengers) at subway stations as well as to eliminate stopping errors (e.g., cases where bus/streetcar stopped a few metres before the stop location to serve passengers). Another variable that was used in the models is the distance between Union Station and the segment in question. Union Station, the country's largest intermodal transit hub, is located in the heart of downtown Toronto.

Several variables were included in the models to examine the potential effect of subway service interruptions on surface transit speed. The first is a set of dummy variables that capture whether a trip has taken place after the occurrence of a subway service incident along a bus/streetcar time-point segment located within 200 metres of a subway station (from the created *Adjacent segment* variable). These dummy variables were utilized to capture both the spatial and temporal connections between the subway incidents and the neighbouring bus and streetcar segments. These dummy variables were categorized into six groups, namely trips starting within 0-5, 5-10, 10-20, 20-30, and 30-60 minutes of an incident, as well as trips starting 60 minutes after an incident. Theses dummy variables represent trips that have started after a subway incident starting time, while the incident is still taking place or within a 30-minute buffer after the incident clearance time. These 30 minutes were considered as the maximum recovery time for the system to return to its normal operation. Accordingly, another variable, *Trips starting after a cleared incident time (minutes)*, representing the difference between the trip's starting time and the incident clearance time was used to control for the changes in speed of trips that start after the incidents' clearance time and within the 30-minute buffer. Another variable was used to understand in more detail the spatial and temporal impacts of subway system interruptions. This variable, *trip-segment downstream a segment adjacent to interruption,* distinguishes the trip-segments downstream of a trip-segment adjacent to the location of subway service interruption. In other words, this variable captures the change in speed along the bus/streetcar segments that are not immediately adjacent to the subway but lie within the three-kilometre buffer of the YUS Line). It is important to note that the TTC' subway service interruption data are recorded at the station level, indicating the type and amount of delay, with no clear information about the extent of its spatial effect in terms of other subway stations that had also experienced no service. Therefore, another cleaning step was done. This step was based on removing all the segments that are within the interruption impact window (incident duration + 30 minutes of recovery time) and within 200 metres from subway stations adjacent to the subway station reported in the data. This was done to make sure that we are capturing the subway service interruptions impact at only one location (i.e., the first location).

In this paper, we used two models to reveal the potential effects of the subway service interruptions. The first is a streetcar speed model, which uses the streetcar speed (measured in km/hour) over a segment (i.e., time-point segment) as the dependent variable. A negative value for the coefficient in the model means that a streetcar had a slower speed. In this model, in addition to the route number dummy variables (10 dummy variables in total), additional variables are used to control for the type of vehicles. This was done because the TTC uses more than one type of vehicle along each single streetcar route, including the short Canadian Light Rail Vehicle (CLRV) and the long Articulated Light Rail Vehicle (ALRV). Furthermore, in 2014, the TTC began introducing new low-floor and articulated streetcar vehicles, named *Flexity Outlook*, to offer more capacity (*26*). Also, sometimes and due to the shortage streetcar service capacity, the TTC uses regular buses on streetcar routes to provide a supplementary service alongside the streetcar service. The second model is the bus speed model, which uses the bus speed over a segment as the dependent variable. In this model, 41 dummy variables of the bus route numbers were generated to isolate the unique impacts of each individual bus route on service speed.

TABLE 1: Description of variables used in the model

Variable Name	Description
Trip speed (km/h)	Trip speed over a segment. The segment is defined as the route section between two consecutive time points along a route (dependent variable).
Segment sequence	A number that represents the sequence of the time-point segment along a trip calculated from the terminal
Number of scheduled stops	Number of scheduled stops within a time-point segment
Adjacent segment	A dummy variable equals one if the segment is within 200 metres from subway station
Segment with a layover	A dummy variable equals one if the segment includes a layover stop

Variable Name	Description
Segment distance (km)	Segment length between the two consecutive time-points
Distance to Union Station (km)	Distance measured from the Union Station to the nearest point of the time-point segment
Distance to Union Station (KM)^2	Distance to Union Station squared. The squared term is used to account for the observed non-linear relationship between the variable and the dependent variable.
Morning peak	A dummy variable equals one if the trip over a time-point segment started between 6:00 am to 9:00 am and zero otherwise
Afternoon peak	A dummy variable equals one if the trip over a time-point segment started between 3:00 pm to 7:00 pm and zero otherwise
Early evening	A dummy variable equals one if the trip over a time-point segment started between 7:00 pm to 10:00 pm and zero otherwise
Late evening	A dummy variable equals one if the trip over a time-point segment started between 10:00 pm to 1:00 am and zero otherwise.
Subway station ridership (000s)	Daily ridership of the subway station.
Subway station ridership^2	Subway station daily ridership squared.
Trips starting within 5 minutes of an incident	A dummy variable equals one if the trip started between 0 to 5 minutes after a nearby subway service interruption took place
Trips starting within 5-10 minutes of an incident	A dummy variable equals one if the trip started between 5 to 10 minutes after a nearby subway service interruption took place
Trips starting within 10-20 minutes of an incident	A dummy variable equals one if the trip started between 10 to 20 minutes after a nearby subway service interruption took place
Trips starting within 20-30 minutes of an incident	A dummy variable equals one if the trip started between 20 to 30 minutes after a nearby subway service interruption took place
Trips starting within 30-60 minutes of an incident	A dummy variable equals one if the trip-segment started between 30 to 60 minutes after a nearby subway service interruption took place
Trips starting within 60+ minutes of an incident	A dummy variable equals one if the trip-segment started 60 minutes or more after a nearby subway service interruption took place.
Trips starting after a cleared incident time (minutes)	Time between the trip starting time (after an incident was cleared) and the incident clearance time. This time should range between 1 to 30 minutes (i.e., within the 30-mintue recovery buffer).
Trip-segment downstream a segment adjacent to interruption	A dummy variable equals one if the trip-segment was downstream of a trip-segment adjacent to the location of subway service interruption.
Bus line *i*	A dummy variable that equals to 1 when the trip-segment is done along bus line *i*, where *i* represents a bus line; it equals zero otherwise.
Streetcar—Bus	A dummy variable equals 1 if the trip-segment is done using buses along the streetcar routes
Streetcar—CLRV	A dummy variable equals 1 if the trip-segment is done using a Canadian Light Rail Vehicle (CLRV)
Streetcar—ALRV	A dummy variable equals 1 if the trip-segment is done using an Articulated Light Rail Vehicle (ALRV)
Streetcar—Flexity	A dummy variable equals 1 if the trip-segment is done using a Flexity Outlook
Streetcar line *i*	A dummy variable that equals 1 when the trip-segment is done along streetcar line *i*, where *i* represents a streetcar line; it equals zero otherwise.

ANALYSIS

Descriptive Statistics

Table 2 presents the summary statistics of the variables used in the streetcar and bus models. The results are differentiated according to the subway service operations: trips during subway service normal operations and trips during subway service interruptions. For the streetcar system, a total of 753,820 records were included in the analysis, with about 2,800 records occurring after a subway incident and within 200 metres from the subway station. In contrast, a total of 1,074,497 records were included in the bus model, with about 10,300 records occurring after a subway incident took place and within 200 metres from the subject subway station.

As observed in the table, the overall speed of all streetcar trips during normal operations was about 12.8 km/h with a standard deviation of 5.5 km/h, while the average speed of streetcar trips that occurred after a subway service interruption was 9.6 km/h with a standard deviation of 3.9 km/h. For the bus routes, a similar pattern can be observed regarding the difference between trips occurring after a subway incident and those taking place during normal subway service operations. The overall bus average speed was 18.6 km/h with a standard deviation of 9.3 km/h under normal operations and 14.2 km/h with a standard deviation of 9.6 km/h after a subway system incident. Nevertheless, in order to better understand how subway service interruptions impact surface transit operations while controlling a set of relevant variables, two statistical models are presented in the following section.

TABLE 2: Streetcar and bus route descriptive statistics

	Streetcar segments				**Bus segments**			
	Subway normal operations		**After subway incident**		**Subway normal operations**		**After subway incidents**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Segment average speed (KM/H)	12.81	5.55	9.64	3.92	18.56	9.26	14.23	9.56
Outbound direction	0.50	0.50	0.54	0.50	0.50	0.50	0.51	0.50
Time-point sequence	5.73	3.35	6.61	1.54	6.24	4.23	6.60	5.26
Number of scheduled stops	4.78	9.76	3.51	2.87	3.63	2.48	3.07	2.51
Adjacent segment	0.18	0.38	1.00	0.00	0.23	0.42	1.00	0.00
Segment with a layover	0.19	0.49	0.13	0.39	0.16	0.37	0.29	0.45
Segment distance (KM)	1.00	0.64	0.88	0.41	1.20	0.79	1.27	0.92
Streetcar—Bus	0.10	0.30	0.06	0.23	0.00	0.00	0.00	0.00
Streetcar—CLRV	0.79	0.41	0.86	0.35	0.00	0.00	0.00	0.00
Streetcar—ALRV	0.11	0.31	0.09	0.28	0.00	0.00	0.00	0.00
Streetcar—Flexity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average headway	3.84	1.61	3.89	2.02	7.00	5.77	7.19	6.12
Distance to Union Station (KM)	2.22	1.48	1.95	1.85	7.91	3.35	8.22	2.82
Distance to Union Station (KM)^2	7.11	9.82	7.22	10.2	73.7	54.1	75.4	40.6
Morning peak	0.18	0.39	0.23	0.42	0.20	0.40	0.29	0.45
Afternoon peak	0.24	0.42	0.25	0.43	0.23	0.42	0.37	0.48
Early evening	0.13	0.34	0.15	0.35	0.13	0.34	0.08	0.26
Late evening	0.13	0.33	0.06	0.23	0.13	0.33	0.06	0.24

Trips starting within 5 minutes of an incident	0.00	0.00	0.14	0.35	0.00	0.00	0.15	0.36
Trips starting within 5-10 minutes of an incident	0.00	0.00	0.15	0.36	0.00	0.00	0.16	0.37
Trips starting within 10-20 minutes of an incident	0.00	0.00	0.30	0.46	0.00	0.00	0.30	0.46
Trips starting within 20-30 minutes of an incident	0.00	0.00	0.27	0.44	0.00	0.00	0.29	0.45
Trips starting within 30-60 minutes of an incident	0.00	0.00	0.12	0.33	0.00	0.00	0.10	0.30
Trips starting within 60+ minutes of an incident	0.00	0.00	0.01	0.10	0.00	0.00	0.00	0.03
Trips starting after a cleared incident time (minutes)	0.00	0.00	12.63	9.56	0.00	0.00	13.34	9.42
Trip-segment downstream a segment adjacent to interruption	0.03	0.17	0.00	0.00	0.03	0.18	0.00	0.00
Number of records	**751,016**		**2,804**		**1,064,197**		**10,300**	

Streetcar Speed Model

A linear regression model was developed using streetcar speed per trip-segment in kilometre/hour as the dependent variable. The output of this model is reported in Table 3. Only significant variables were kept in the model. The t-statistics and the statistical significance are reported in the table along with their coefficients. The model contains 753,820 observations and explains 32% of the variation in speed. As seen in the table, generally, the key policy variables, *Trips starting within (…) minutes of an incident*, accounting for the trip's starting time after the occurrence of a subway service interruption and before resumption of subway service, have negative significant coefficients. While, this indicates a general negative impact of subway incidents on the streetcar speed, the impacts vary according to when the trip starts relative to the incident's start time. More specifically, trips starting within 0-5 minutes from a subway incident that has not been cleared yet, do not suffer any significant change in their speed. This indicates that there is no immediate impact of subway incidents on streetcar performance within the first 5 minutes. Nevertheless, streetcar trips starting within 5-10 minutes from a subway incident that is still persisting start to see some delays, experiencing a reduction in speed by 0.68 km/h. This may be reflecting the combined effect of people coming to use the subway only to learn the service was interrupted and deciding to use the streetcar lines instead and subway users off-loaded from the interrupted subway trains and deciding immediately to use the nearby streetcar lines instead of waiting for the resumption of subway service.

The speed reduction persists at about 0.57 km/h when the streetcar trip starts in 10-20 minutes after a subway incident start time and while it is still in effect. The trips starting within 20-30 minutes from a subway incident that is still taking place suffer a reduction of 0.83 km/h in speed. The decrease in speed grows to reach 1.01 km/h and 1.47 km/h for trips starting within 30-60 minutes and more than 60 minutes of an incident, respectively. This means that more delays and lower speeds are expected for streetcar trips starting while longer subway incidents are persistent, while keeping all other variables at their mean values. This can be due to the current policies followed by TTC of providing fewer shuttle buses at disrupted subway locations served by nearby streetcar service in downtown Toronto (*27*). Therefore, transit agencies should provide more resources and different disruption management strategies in responding to subway incidents in downtown areas in order to reduce the adverse impacts on nearby surface transit which are typically characterized with overcrowding issues. After the incident clearance time, every minute difference between the streetcar trip's starting time and the incident's clearance time is expected to improve the streetcar service speed by 0.035 km/h. This indicates that trips starting after 10 minutes of the subway incident clearance time could expect about 0.35 km/h recovery in their average speed, while trips starting after 20 and 30 minutes could expect a 0.70

and 1.05 km/h recovery in their average speed. This indicates (with comparison to the model's coefficients in Table 3) that most of the trips will recover within the 30-minute window to their original speed, except for the trips that start at 60 minutes or later of an incident that is still taking place. However, this window still represents a good recovery approximation, since the longest subway incident duration in our sample is 73 minutes.

In accordance with previous work (*23; 24; 28; 29*), the remaining control variables in the model perform as expected with regard to the expected sign and significance. Trips during the afternoon peak were slower by 0.7 km/h than mid-day trips, while trips made during other time periods were faster than mid-day trips. This is not particular to the context of Toronto, and it has been observed in other cities in the literature (*9; 24; 28*), and it was explained by the higher level of congestion and demand during this period of time. Segment distance, which reflects the distance of streetcar route section between two consecutive time points, increases the service speed. For every additional kilometre, streetcar speed is expected to increase by 2.85 km/h. This suggests that longer distances between time-point stops can improve the service speed, which is consistent with previous research (*24*). Distance to downtown, represented by Union Station, increases streetcar service speed. For every additional kilometre in distance to downtown the streetcar speed is expected to increase by 0.13 km/h. This is expected due to less traffic congestion and demand at locations that are farther from downtown. Nevertheless, the distance to Union Station square term (which is used to account for the observed non-linear relationship) had a statistically significant positive association with the speed, indicating that after a certain distance no negative association between the distance to Union Station and streetcar speed can be expected.

Route speed also varies by direction, likely resulting from traffic conditions and other unseen factors not explained by the model's variables, which can be found in previous operational models (*30-32*). The increase in the segment sequence within a trip is expected to increase the streetcar operational speed slightly by 0.006 km/h for every additional segment. The number of scheduled stops within a segment is expected to decrease the speed by 0.03 for every additional stop, which is expected due to passenger activity and streetcar acceleration and deceleration at stops. Any segment within 200 metres from a subway station and any segment that includes a layover stop are slower by 2.85 and 1.9 km/h compared to other segments, respectively. This is expected due to the high volume of passengers at these locations. In addition, the subway station's daily ridership has a negative impact on streetcar service speed. For every additional one thousand passengers per subway station the streetcar service speed starting at segments that are within 200 metres is expected to be slower by 0.05 km/h. Nevertheless, the subway ridership square term shows that after a certain ridership level, no decrease in speed can be expected. Finally, the type of streetcar vehicles and route number also have an impact on streetcar average speed, which can be related to the vehicle offered capacity and specifications, traffic conditions, route lengths, and TTC scheduling and route management practices.

Table 3: Streetcar segment speed model

	Coeff.	Z	95% Conf. Interval	
			Lower Bound	**Upper Bound**
(Constant)	**9.73**	**288.4*** **	**9.67**	**9.80**
Outbound direction	**-0.40**	**-37.4*** **	**-0.42**	**-0.38**
Time-point sequence	**0.01**	**2.68*** **	**0.00**	**0.01**
Number of scheduled stops	**-0.03**	**-44.35*** **	**-0.03**	**-0.03**
Adjacent segment	**-2.85**	**-152.8*** **	**-2.89**	**-2.81**
Segment with a layover	**-1.90**	**-146.5*** **	**-1.93**	**-1.88**
Segment distance (KM)	**2.24**	**213.8*** **	**2.22**	**2.26**
Streetcar bus	**-0.06**	**-1.73*** **	**-0.13**	**0.01**
Streetcar ALRV	**-0.19**	**-4.58*** **	**-0.28**	**-0.11**
Streetcar Flexity	0.42	0.20	-3.60	4.43
Distance to Union Station (KM)	**1.30**	**76.5*** **	**1.27**	**1.33**
Distance to Union Station (KM)^2	**-0.18**	**-57.1*** **	**-0.18**	**-0.17**
Morning peak	**1.51**	**96.8*** **	**1.48**	**1.54**
Afternoon peak	**-0.72**	**-50.6*** **	**-0.75**	**-0.70**
Early evening	**1.16**	**67.6*** **	**1.13**	**1.20**
Late evening	**4.00**	**226.9*** **	**3.96**	**4.03**
Subway station ridership	**-0.05**	**-17.54*** **	**-0.05**	**-0.04**
Subway station ridership^2	**0.00**	**18.55*** **	**0.00**	**0.00**
Trips starting within 5 minutes of an incident	0.07	0.28	-0.40	0.53
Trips starting within 5-10 minutes of an incident	**-0.68**	**-2.83*** **	**-1.16**	**-0.21**
Trips starting within 10-20 minutes of an incident	**-0.57**	**-2.36** **	**-1.05**	**-0.10**
Trips starting within 20-30 minutes of an incident	**-0.81**	**-2.23** **	**-1.53**	**-0.10**
Trips starting within 30-60 minutes of an incident	**-1.01**	**-2.37** **	**-1.84**	**-0.18**
Trips starting within 60+ minutes of an incident	**-1.47**	**-1.74* **	**-3.12**	**0.19**
Trips starting after a cleared incident time (minutes)	**0.035**	**2.23** **	**0.00**	**0.06**
Route 501	**-0.69**	**-15.10*** **	**-0.78**	**-0.60**
Route 502	**-0.66**	**-13.41*** **	**-0.76**	**-0.56**
Route 503	-0.10	-1.33	-0.24	0.05
Route 504	**0.07**	**3.72*** **	**0.03**	**0.11**
Route 506	**0.15**	**6.94*** **	**0.11**	**0.20**
Route 509	**1.23**	**25.45*** **	**1.14**	**1.33**
Route 510	**-2.75**	**-107.6*** **	**-2.80**	**-2.70**
Route 511	**-1.51**	**-54.77*** **	**-1.56**	**-1.45**
Route 512	**1.07**	**20.84*** **	**0.97**	**1.17**
N	753,820			
Adjusted R Square	0.32			
F statistics	(34, 753819) 10430			
F significance (Prob > F)	0			

Bold indicates statistical significance
*** Significant at 99% ** Significant at 95% * Significant at 90%

Bus Speed Model

A linear regression model was also developed using bus speed per trip-segment in km/h as the dependent variable. The output of this model is reported in Table 4. Only the significant variables were kept in the model. The t-statistics and the statistical significance are also reported in the table along with their coefficients. The model contains 1,074,496 observations and explains 37% of the variation in bus service's speed. As seen in the table, a different pattern can be observed with respect to the variable signs and magnitude of coefficients in comparison to the previous model. The key policy variables, *Trips starting within (…) minutes of an incident*, have a negative significant coefficient for only two cases, namely for trips starting within 20-30 minutes and within 30-60 minutes after a subway incident start time. More specifically, trips starting within 20-30 and 30-60 minutes of a subway incident while it is still in effect suffer a reduction of 0.25 km/h and 0.53 km/h in their speed, respectively.

Nevertheless, the observed reductions in speed are relatively minor compared to the previous model, particularly considering that bus speeds are normally higher than streetcar speeds. Therefore, the following section presents a sensitivity analysis to better understand the relative impacts on both systems. Bus trips starting more than 60 minutes after a subway incident do not suffer a statistically significant reduction in their service speed. This indicates an improved situation, which can be related to the TTC's practice of employing shuttle buses at these locations, relieving the impacts of subway incidents. On the other hand, bus speeds over the same trip's segments following an impacted segment by the subway service interruption is expected to be slower by 0.47 km/h, which could be explained by induced passenger activity along these segments and/or by traffic conditions along the bus corridor.

Regarding the other remaining control variables in the model, it is clear that the model coefficients follow the same signs and magnitude as the previous model. Afternoon peak trips are slower than all other trips during the day. Distance to Union Station increases the bus service speed up to a certain point, beyond which no positive impact is observed. The segment distance and segment sequence have a positive impact on speed, while the number of stops within a segment, trips that are within 200 metres from a subway station, and trips with layovers have negative impacts on bus speed. Finally, the route direction and route number (40 dummy variables but not reported in Table 4) also showed a significant impact on bus speeds, which can be attributed to each route specifications, traffic conditions, and scheduling.

TABLE 4: Bus segment speed model

	Coeff.	Z	95% Conf. Interval Lower Bound	95% Conf. Interval Upper Bound
(Constant)	**13.11**	**150.6*** **	**12.9**	**13.3**
Outbound direction	**0.28**	**19.24*** **	**0.25**	**0.30**
Time-point sequence	**0.02**	**6.92*** **	**0.02**	**0.03**
Number of scheduled stops	**-0.21**	**-47.0*** **	**-0.22**	**-0.20**
Adjacent segment	**-3.98**	**-208.5*** **	**-4.02**	**-3.94**
Segment with a layover	**-7.13**	**-295.2*** **	**-7.18**	**-7.09**
Segment distance (KM)	**2.85**	**195.8*** **	**2.82**	**2.88**
Distance to Union Station (KM)	**0.42**	**29.63*** **	**0.39**	**0.45**
Distance to Union Station (KM)^2	**-0.01**	**-18.36*** **	**-0.02**	**-0.01**
Morning peak	**0.55**	**26.49*** **	**0.51**	**0.59**
Afternoon peak	**-2.11**	**-108.0*** **	**-2.15**	**-2.07**
Early evening	**2.00**	**85.68*** **	**1.96**	**2.05**
Late evening	**6.42**	**266.4*** **	**6.37**	**6.46**
Subway station ridership	**-0.04**	**-12.39*** **	**-0.05**	**-0.03**
Subway station ridership^2	**0.001**	**13.63*** **	**0.00**	**0.00**
Trips starting within 5 minutes of an incident	0.13	0.66	-0.25	0.51
Trips starting within 5-10 minutes of an incident	0.19	0.98	-0.19	0.56
Trips starting within 10-20 minutes of an incident	0.07	0.52	-0.21	0.35
Trips starting within 20-30 minutes of an incident	**-0.25**	**-1.70* **	**-0.53**	**0.04**
Trips starting within 30-60 minutes of an incident	**-0.53**	**-2.28** **	**-0.98**	**-0.07**
Trips starting within 60+ minutes of an incident	-2.98	-1.14	-8.07	2.12
Trip-segment downstream a segment adjacent to interruption	**-0.47**	**-11.7*** **	**-0.55**	**-0.39**
***** 40 dummy variables to control for the route number*				
N	1074496			
Adjusted R Square	0.37			
F statistics	(62, 1074495)10220			
F significance (Prob > F)	0			

Bold indicates statistical significance
*** Significant at 99% ** Significant at 95% * Significant at 90%

Sensitivity Analysis

A sensitivity analysis is conducted in order to explore the relative impacts of subway incidents on streetcar and bus systems speed while keeping all variables constant at their mean values. Table 5 shows the expected average speed for streetcars and buses during the different time periods of the day. For the streetcar system, the speed estimates were made for the eastbound trips of Route 501 and using CLRVs. While for the bus system, the speed estimates were made for the westbound trips of Route 96. Both routes included in the sensitivity analysis operate at the median speed of their respective systems. In Table 5, the percentage of change in average speed due to subway service interruptions compared to normal operations is reported.

As shown in the table, the average speed for streetcars over an adjacent segment within 200 metres from a subway station and during normal operations is 10.7 km/h. This average decreases by 6.5% for trips starting in 5-10 minutes after a subway incident start time and while it is still in effect. The reduction in speed remains at about 5.5% for trips that start within 10-20 minutes after a subway incident's start time. Afterwards, the speeds further decline gradually by 7.7%, 9.6 %, and 13.9 % for trips starting within 20-30, 30-60 and more than 60 minutes of an incident, respectively. This reflects a higher magnitude of impact of longer subway incidents on the streetcar service speed. The maximum delay for streetcars occurs during the afternoon peak period, with a 16.6% reduction in speed for trips starting more than 60 minutes of an incident while the service interruption is still in effect. This highlights a challenge during this time period that requires more attention from the transit agency.

The average speed for buses over an adjacent segment within 200 metres from a subway station and during normal operations is 19.4 km/h. This average decreases slightly by 1.3% and 2.8% for trips starting in 20-30 and 30-60 minutes after a subway incident's start time and while it is still in effect, respectively. Similar to the streetcar system, the peak delay occurs during the afternoon peak period, with a 3.3% reduction in speed for trips starting 30-60 minutes after a subway incident's start time. This highlights a maximum of 13.3% of additional delay for streetcars due to subway service interruptions in comparison with buses. This delay means an increased waiting time, travel time and overcrowding experienced by the streetcar's users, which would have a direct negative effect on their perceptions of the service quality. Therefore, developing more appropriate policies to maintain and improve the streetcar systems' resilience and performance during these situations is highly recommended.

Table 5: Streetcar and bus service speed (in km/h) sensitivity analysis

	Morning peak		Midday		Afternoon peak		Early evening		Late evening		Overall
Streetcar service speed											
During normal operations	**11.0**		**9.6**		**8.8**		**10.7**		**13.6**		**10.7**
During subway disruption	Speed	%	Speed	%	Speed	%	Speed	%	Speed	%	%
Trips starting within 5 minutes of an incident	11.0	**0.0%**	9.6	**0.0%**	8.8	**0.0%**	10.7	**0.0%**	13.6	**0.0%**	**0.0%**
Trips starting within 5-10 minutes of an incident	10.3	**-6.2%**	8.9	**-7.2%**	8.1	**-7.8%**	10.0	**-6.4%**	12.8	**-5.0%**	**-6.5%**
Trips starting within 10-20 minutes of an incident	10.5	**-5.2%**	8.9	**-6.0%**	8.2	**-6.5%**	10.1	**-5.4%**	12.9	**-4.2%**	**-5.5%**
Trips starting within 20-30 minutes of an incident	10.2	**-7.4%**	8.7	**-8.5%**	8.0	**-9.2%**	9.9	**-7.6%**	12.7	**-6.0%**	**-7.7%**
Trips starting within 30-60 minutes of an incident	10.0	**-9.1%**	8.5	**-10.6%**	7.8	**-11.4%**	9.7	**-9.4%**	12.5	**-7.5%**	**-9.6%**
Trips starting within 60+ minutes of an incident	9.60	**-13.3%**	8.1	**-15.4%**	7.3	**-16.6%**	9.2	**-13.7%**	12.1	**-10.8%**	**-13.9%**
Bus service speed											
During normal operations	**16.5**		**17.0**		**15.9**		**21.0**		**26.4**		19.4

During subway disruption	Speed	%	Speed	%	Speed	%	Speed	%	Speed	%	%
Trips starting within 5 minutes of an incident	16.5	**0.0%**	17.0	**0.0%**	15.9	**0.0%**	21.0	**0.0%**	26.4	**0.0%**	**0.0%**
Trips starting within 5-10 minutes of an incident	16.5	**0.0%**	17.0	**0.0%**	15.9	**0.0%**	21.0	**0.0%**	26.4	**0.0%**	**0.0%**
Trips starting within 10-20 minutes of an incident	16.5	**0.0%**	17.0	**0.0%**	15.9	**0.0%**	21.0	**0.0%**	26.4	**0.0%**	**0.0%**
Trips starting within 20-30 minutes of an incident	16.3	**-1.5%**	16.7	**-1.4%**	15.6	**-1.6%**	20.7	**-1.2%**	26.1	**-0.9%**	**-1.3%**
Trips starting within 30-60 minutes of an incident	16.0	**-3.2%**	16.4	**-3.1%**	15.3	**-3.3%**	20.4	**-2.5%**	25.8	**-2.0%**	**-2.8%**
Trips starting within 60+ minutes of an incident	16.5	**0.0%**	17.0	0.0%	15.9	0.0%	21.0	0.0%	26.4	**0.0%**	**0.0%**

% refers to the percentage of change in speed = (trip speed during an incident category - trip speed during normal operations)/ trip speed during normal operations

CONCLUSION

The objective of this study is to evaluate the impact of subway system's interruptions on surface transit system's performance in Toronto. In order to do that, the study mainly used two datasets obtained from the TTC. The first dataset included detailed subway system interruption data collected in 2013, while the second dataset was acquired from the TTC's AVL system for all the weekdays of May 2013 for 51 transit routes (i.e., 41 bus routes and 10 streetcar routes) within a short walking distance from a subway station (i.e., < 200 metres). The selection of subway stations to be included in the analysis was based on a composite indicator generated to identify the most vulnerable stations in the subway system and to capture the exceptional events of subway interruptions. Two models were utilized using bus and streetcar speeds at the disaggregate level of time-point segment and trip as the dependent variable.

The models indicate that subway service interruptions have a statistically significant impact on streetcar and bus operations, contributing to longer passengers' waiting times at downstream locations and in-vehicle passengers' total travel time. Nevertheless, the intensity of delay varies according to the mode and the starting time of the trip category in comparison with the starting time of the incident. More specifically, subway incidents have more immediate and long lasting negative impacts on the streetcar service speed. This reduction in speed ranged between 5.5% and 13.9% of the average speed during normal operations. In contrast to the streetcar service, the bus service experienced less significant delays in its operational speed due to subway service interruptions. This reduction in speed ranged only between 1.3% and 2.8% of the average speed during incident-free operations.

This difference in impacts between the two systems may reflect the TTC's use of disruption management protocols for dealing with subway service disruptions. These protocols mainly deploy fewer shuttle buses along the southern section of the subway system (U-shaped section) where nearby streetcar service is available, which could very well be the reason for the sharper decline in streetcar service speed. Therefore, a detailed investigation regarding the shuttle service level of employment that is required to minimize the subway incidents' impact on local streetcar service is recommended, which we were not able to investigate here due to missing accurate information about shuttle service arrival and departure times during our study period.

Since it is rare to find studies in the literature that explore the impact of one public transport mode failure on other public transport modes in a multi-modal environment, one of the key contributions of this research is developing a methodology that can be used by other agencies and researchers to understand these impacts at different setups and locations. While this research explores the impact of subway system interruptions on the neighbouring bus and streetcar systems, it is recommended to expand this study to cover the impact of other system interruptions such as commuter rail systems on surface transit quality.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Kenny Ling and Francis Li from the Toronto Transit Commission (TTC) for providing the data used in the paper and for their feedback and comments that helped in improving this study. This research was funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Research Fund (ORF). The ideas and findings presented in this paper represent the authors' views in an academic exercise.

REFERENCES

[1] Diab, E., and A. El-Geneidy. Variation in bus transit service: understanding the impacts of various improvement strategies on transit service reliability. *Public Transport,* Vol. 4, No. 3, 2013, pp. 209-231.

[2] Yetiskul, E., and M. Senbil. Public bus transit travel-time variability in Ankara (Turkey). *Transport Policy*, Vol. 23, No. 0, 2012, pp. 50-59.

[3] Kimpel, T., J. Strathman, R. Bertini, P. Bender, and S. Callas. Analysis of transit signal priority using archived TriMet bus dispatch system data. *Transportation Research Record*, No. 1925, 2005, pp. 156-166.

[4] Mesbah, M., J. Lin, and G. Currie. "Weather" transit is reliable? Using AVL data to explore tram performance in Melbourne, Australia. *Journal of Traffic and Transportation Engineering (English Edition)*, Vol. 2, No. 3, 2015, pp. 125-135.

[5] Currie, G., A. Delbosc, S. Harrison, and M. Sarvi. Impact of crowding on streetcar dwell time. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2353, No. 2353, 2013, pp. 100-106.

[6] Currie, G., and J. Reynolds. Evaluating pay-on-entry versus proof-of-payment ticketing in light rail transit. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2540, 2016, pp. 39-45.

[7] Louie, J., A. Shalaby, and K. Habib. Modelling disruption duration for Toronto's subway system: An empirical investigation using lognormal regression and hazard models In *The Transportation Research Board 95th Annual Meeting*, Washington, D.C., 2016.

[8] Weng, J., Y. Zheng, X. Yan, and Q. Meng. Development of a subway operation incident delay model using accelerated failure time approaches. *Accident Analysis & Prevention*, Vol. 73, 2014, pp. 12-19.

[9] Diab, E., and A. El-Geneidy. Understanding the impacts of a combination of service improvement strategies on bus running time and passenger's perception. *Transportation Research Part A: Policy and Practice*, Vol. 46, No. 3, 2012, pp. 614-625.

[10] ---. The farside story: Measuring the benefits of bus stop location on transit performance. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2538, 2015, pp. 1-10.

[11] Schmöcker, J., S. Cooper, and W. Adeney. Metro service delay recovery: Comparison of strategies and constraints across systems. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 1930, 2005, pp. 30-37.
[12] Kepaptsoglou, K., and M. Karlaftis. The bus bridging problem in metro operations: conceptual framework, models and algorithms. *Public Transport,* Vol. 1, No. 4, 2009, pp. 275-297.
[13] Wang, Y., J. Guo, G. Currie, W. Dong, and B. Pender. Bus bridging disruption in rail services with frustrated and impatient passengers. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 15, No. 5, 2014, pp. 2014-2023.
[14] Codina, E., and A. Marin. A design model for the bus bridging problem.In *World Conference on Transport Research Society*, Lyons, France, 2010.
[15] Pender, B., G. Currie, N. Shiwakoti, and A. Delbosc. Economic viability of bus bridging reserves for fast response to unplanned passenger rail disruption. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2537, 2015, pp. 13-22.
[16] Darmanin, T., C. Lim, and H. Gan. Public railway disruption recovery planning: A New recovery strategy for Metro Train Melbourne.In *The 11th Asia Pacific Industrial Engineering and Management Systems Conference; The 14th Asia Pacific Regional Meeting of International Foundation for Production Research*, Melaka, 2010.
[17] van der Hurk, E., H. Koutsopoulos, N. Wilson, L. Kroon, and G. Maróti. Shuttle planning for link closures in urban public transport networks. *Transportation Science,* Vol. 0, No. 0, 2016, p. null.
[18] Ontario Ministry of Finance. *Ontario population projections update, 2015–2041*. Ontario Ministry of Finance,, Torotno, Canada. http://www.fin.gov.on.ca/en/economy/demographics/projections/. Accessed 24 July 2016, 2016.
[19] American Public Transportation Association (APTA). APTA transit ridership report, Second Quarter, 2013.In, American Public Transportation Association (APTA), Washington, D.C., 2013.
[20] TTC. *TTC Operating Statistics 2013*, Toronto, Canada. https://www.ttc.ca/About_the_TTC/Operating_Statistics/2013.jsp. Accessed May 2nd, 2016.
[21] ---. Toronto Transit Commission subway ridership, 2012-2013.In, Toronto Transit Commission (TTC), Toronto, Canada, 2013.
[22] Vuchic, V. *Urban transit: operations, planning, and economics*. 2005.
[23] Kimpel, T. Time point-level analysis of transit service reliability and passenger demand.In *Urban Studies and Planning, No. Doctor of Philosophy*, Portland State University, Portland, OR, 2001. p. 154.
[24] El-Geneidy, A., J. Horning, and K. Krizek. Analyzing transit service reliability using detailed data from automatic vehicular locator systems. *Journal of Advanced Transportation,* Vol. 45, No. 1, 2011, pp. 66-79.
[25] Figliozzi, M., W. Feng, and G. Lafferriere. A Study of headway maintenance for bus routes: Causes and effects of "bus bunching" in extensive and congested service areas.In *Civil and Environmental Engineering Faculty Publications and Presentations, No. Paper 96*, Portland, Oregon, 2012.
[26] TTC. *New streetcars.* TTC, Toronto, Canada. http://www.ttc.ca/About_the_TTC/Projects/New_Vehicles/New_Streetcars/index.jsp. Accessed July 16, 2017.

[27] Diab, E., W. Feng, and A. Shalaby. Breaking into emergency shuttle service: Aspects and impacts of retracting buses from existing scheduled bus services.In *Transportation Research Board 96th Annual Meeting*, Washington DC, 2017.
[28] Strathman, J., K. Dueker, T. Kimpel, R. Gerhart, K. Turner, P. Taylor, S. Callas, D. Griffin, and J. Hopper. Automated bus dispatching, operations control, and service reliability: Baseline analysis. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1666, 1999, pp. 28-36.
[29] Strathman, J., T. Kimpel, and S. Callas. Headway deviation effects on bus passenger loads: analysis of Tri-Met's archived AVL-APC data.In, Center for Urban Studies, College of Urban and Public Affairs, Portland State University, Seattle, WA, 2003.
[30] Fletcher, G., and A. El-Geneidy. Effects of fare payment types and crowding on dwell time. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2351, No. -1, 2013, pp. 124-132.
[31] El-Geneidy, A., and N. Vijayakumar. The effects of articulated buses on dwell and running times. *Journal of Public Transportation*, Vol. 14, No. 3, 2011, pp. 63-86.
[32] Dueker, K. J., T. J. Kimpel, J. G. Strathman, and S. Callas. Determinants of bus dwell time. *Journal of Public Transportation*, Vol. 7, No. 1, 2004, pp. 21-40.