Rail Transit Resilience: Understanding the impacts of outdoor tracks and weather conditions on subway system interruptions

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Submitted April 18, 2017 for publication in the International Journal of Sustainable Transportation.

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 IBM Canada, Cellint Traffic Solutions, Waterfront Toronto, the City of Toronto and the Region of Waterloo.

Report # 16-02-03-02

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING
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Rail Transit Resilience:
Understanding the impacts of outdoor tracks and weather conditions on subway system interruptions

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Paper submitted to the International Journal of Sustainable Transportation
submitted 18 April, 2017
Word Count: 5910 words, and 3 Tables + 3 Figures

ABSTRACT

One of the main challenges facing transit agencies is offering reliable service with minimum number of interruptions and ensuing delays. Although this issue has recently emerged as a top priority in many cities in order to contribute to their sustainable development, there has been little research effort to investigate issues surrounding service disruption. As a response to this gap, this study aims at understanding the impact of outdoor track segments (or open-air sectors) of the subway system and weather conditions on the number of service interruptions and the magnitude of resulting delays at the stop level. The study uses detailed subway system interruption data collected in 2013 by the TTC, the public transit provider in the City of Toronto, Canada. Descriptive statistics and statistical models are developed for the purpose of the study. The empirical investigation reveals that outdoor tracks have a statistically significant association with subway system's service interruptions. Longer outdoor track distances are linked to both higher frequencies and delays of service interruptions. Weather conditions, in terms of the amount of snow on the ground and rainfall interactions with outdoor tracks, have also a significant association with the frequency and duration of service interruptions. The paper results provide policy makers and planners with useful policy-relevant information related to the impact of outdoor tracks and weather conditions on the subway system interruptions that could be used to support higher capital investments when planning rail transit systems to achieve the system resilience.

Key words: Subway, System Interruption, Public Transit, Transit Resilience, Outdoor Tracks

1. INTRODUCTION

Transport infrastructure investments are central for the development of any city. Over the years, cities improve, build and expand their transport networks to meet the current and future needs of residents as well as visitors of a city. As can be observed across the globe, several cities are currently implementing or planning for expanding their subway systems in order to accommodate future population growth, stimulate local development and promote sustainability through reducing private automobiles trips and enhancing public health. For, example, Montreal and Toronto in Canada will receive considerable federal funding over the coming years to expand their current subway systems (Feith, 2016; Shum, 2016).

A sizable body of literature has developed around understanding the impacts and benefits of a new transport infrastructure on residents' mobility patterns, greenhouse gas emissions, and equity issues *(El-Geneidy, Manaugh, & van Lierop, 2014; Manaugh & El-Geneidy, 2012; Saxe, Cruickshank, & Miller, 2015).* This literature normally does not account for the provided quality of service by considering a consistent service with no service interruptions regardless of the kind of the transport investment. The truth, however, is that these transit systems are far from ideal, and in many cases they suffer from many operational, unexpected problems and incidents. These incidents and delays reduce the quality of service perceived by the public (Cirillo, Eboli, & Mazzulla, 2011), diminishing the system's ability to retain existing customers and attract new ones. Because commuters are distressed by the day-to-day variability in transit service performance, which affects their time-planning processes *(Bates, Polak, Jones, & Cook, 2001; Nam, Park, & Khamkongkhun, 2005; Noland & Polak, 2002)*. Thus, cities are currently interested in providing a resilient transport service with minimal number of disruptions and associated delays.

This study aims at understanding the impact of outdoor track segments (or open-air sectors) of the subway system and weather conditions on the frequency of service interruptions and the amount of delay caused by these interruptions at the stop-level of analysis. The study uses a detailed and comprehensive set of subway system interruption data collected in 2013 by the TTC, the public transit provider for the City of Toronto, Canada. It is important to note that the subway system configuration (in terms of outdoor or indoor tracks) is only one factor, among many, that should be taken into account when designing a new subway system, yet understanding its impacts is important in evaluating alternative locations and design policies in order to provide a resilient transport system. This information can be used to adjust future subway systems configuration as well as to provide a better understanding of where the shuttle service could be required prior to construction in order to reduce user delays due to un-expected service interruptions. The notion of transport system resilience is related to the system's capacity to absorb and minimize disruptions (Department of Transport, 2014).

2. LITERATURE REVIEW

Over the past few decades, the rapid expansion in city suburban areas and a more environmentally aware public have led cities to invest in various form of public transit to improve residents' mobility and reduce traffic congestion. Several studies assessed the impacts and benefits of these new transport infrastructures (Chen, 2015; El-Geneidy et al., 2014; Manaugh & El-Geneidy, 2012; Saxe et al., 2015). For example, Manaugh and El-Geneidy (Manaugh & El-Geneidy, 2012) assessed the potential effects of proposed transit infrastructure projects in the Montreal region transport plan. Saxe et al.(Saxe et al., 2015) measured the potential greenhouse gas impact of ridership on Sheppard Subway Line in Toronto. However, these studies did not assess the quality of service and the system's capacity to offer a consistent service with no service interruptions.

Several researchers focused on exploring the impact of weather conditions, mainly snow and rainfall precipitation, and indicated a negative impact of inclement conditions on service travel time and reliability (Diab & El-Geneidy, 2012, 2015; Mesbah, Lin, & Currie, 2015). For example, Diab and El-Geneidy (Diab & El-Geneidy, 2012, 2013), pointed out that meteorological factors, such as rainfall and snow on the ground, have a negative impact on bus transit operations, increasing the service running time and variation. Mesbah et al. (2015), investigated the effect of weather conditions on the tram service travel times and observed similar adverse effects of rainfall. However, none of the previous efforts has explored the impacts of weather conditions on transit system interruptions. This is because these studies largely utilized automatic vehicle location (AVL) system data sources, which are currently available for researchers, unlike detailed interruption data, which is harder to access. Therefore, the simple question of how weather conditions influence transit service interruption, more specifically subway service interruptions, is seldom tackled in literature.

Other studies focused on developing and testing different statistical models to predict or account for the impact of incidents on the transport system's delay duration (Louie, Shalaby, & Habib, 2016). These studies mainly focused on highway traffic only (Chung, 2010; Greibe, 2003; Li & Shang, 2014; Nam & Mannering, 2000; Valenti, Lelli, & Cucina, 2010), while only few recent studies focused on transit service interruptions (Louie et al., 2016; Weng, Zheng, Yan, & Meng, 2014). Regarding the transit related studies, Weng et al. (2014) tested different subway operational incident delay models and investigated the impacts of causal variables on subway delay duration, such as power and vehicle failures, and switch malfunction. They indicated that longer subway operation incident delays are highly correlated with power cable and signal cable failure, turnout communication disruption, and crashes involving a casualty, while vehicle failure makes the least impact. Another recent study done by Louie et al. (2016) expanded the previous work by investigating not only the impacts of causal variables, but also the non-causal variables, such as passenger related instances. Nevertheless, despite the previous efforts, it is rare to find studies that focus on investigating the impacts of outdoor tracks and their interactions with weather conditions on transit service interruptions and delays, which is quite an important issue for the decision making process for transit agencies when planning new subway systems. Furthermore, the effect of outdoor sectors must be considered and integrated by transit planners during various operation stages to add the appropriate amount of recovery time or to provide the appropriate amount of buses that can service as a shuttle service in case of severe interruptions.

3. STUDY CONTEXT

Toronto, Ontario, is the heart of the most populous metropolitan area in Canada with more than 2.8 million inhabitants in 2015. The city's population is expected to increase rapidly to reach 3.7 million in 2041 (Ontario Ministry of Finance, 2015), adding more stress on the current transit system. TTC operates the transit service within the city, covers around 640 km^2 and serves daily about 2.7 million passengers (American Public Transportation Association (APTA), 2013). It operates a multimodal transit service consisting of four subway lines, 11 streetcars lines, and 141 bus routes (TTC, 2013b). The TTC subway system extends to a total length of 68 km serving 69 stations. A total of 1.3 million passengers-trips per day were made using the subway system in 2013. The Yonge-University-Spadina (YUS) line, the yellow line in Figure 1-A, is the busiest subway line in Toronto with a total daily ridership of 730,00 passengers (TTC, 2013a). The Bloor-Danforth (BD) line, the green line in Figure 1-A, is the second busiest subway line in Toronto with a total daily ridership of 509,810 passengers in 2013, and the Sheppard and Scarborough lines have a total daily ridership of less than 90,000 passengers.

According to the TTC, around 94% of subway trains were on-time (within 0 to + 3 minutes of the scheduled headway) between March 2012 to February 2014, which is less than the target of 96% (TTC, 2014). In July 2012, the TTC introduced new subway trains, named Toronto Rocket (TR) trains, into the system to replace the TTC's oldest subway cars. The new trains, with open gangways between railcars, offer higher capacities and enable riders to move from one end of the train to the other (TTC, 2013b). In 2013, there were 47 TR trains out of 117 trains in operation throughout the system. However, these trains were the cause of many technical delays when they were first introduced (TTC, 2013b).

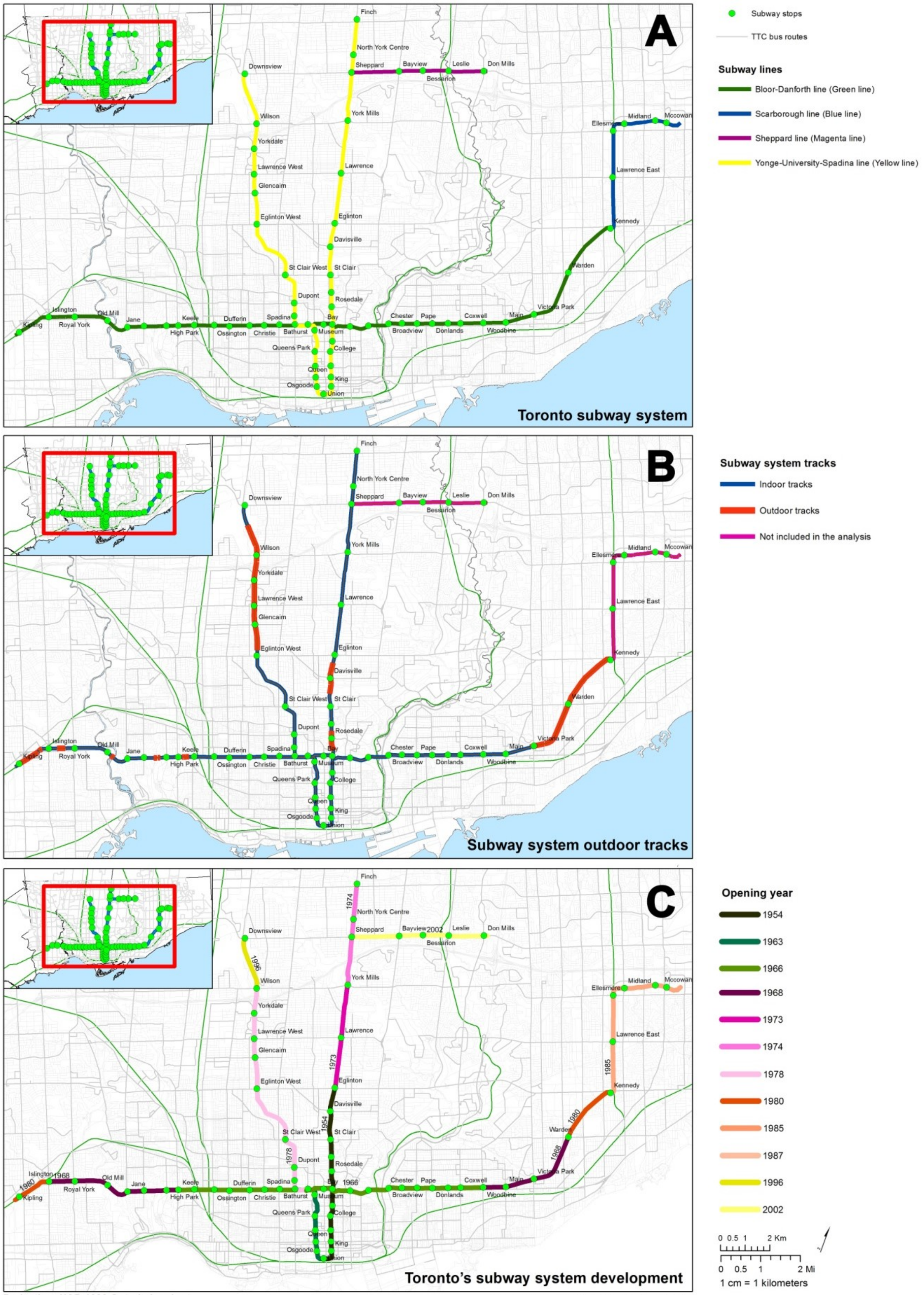
Figure 1-B shows the outdoor track segments within the TTC system, while Figure 1-C shows the TTC's subway system development. The TTC subway system construction started in 1949 in the Toronto downtown area and then expanded over time. The Yellow line extends to a total length of 23.3 km serving 32 stations, with an average distance of 720 m between stations. A total of 7.3 km within the line are outdoor tracks where subway trains need to travel to serve 12 stations. The Green line extends to a total length of 19.5 km serving 31 stations, with an average distance of 630 m between stations. A total of 7.1 km within the Green line are outdoor tracks that trains need to go through to reach 12 stations. This study focuses primarily on these two subway lines, since the TTC has provided interruption data for them. The TTC maintains the subway system on a regular basis, with much of the inspection and repair work done while the system is closed between 2 am and 5 am (Kalinowskir, 2016). In fact, a major upgrade project for the subway system is currently underway to improve the system performance (TTC, 2016) by replacing the current traditional block signal system with an automatic train control (ATC) system. This project started in 2014 and is expected to be completed by 2020 (Kalinowskir, 2014). It should be noted that the case study of TTC subway system and its outdoor track segments represent a unique case within the Canadian context. The other comparable subway system in Canada in terms of the size of the network and city weather conditions, namely the Montréal's subway system, is entirely indoors with no outdoor track segments.

4. METHODLOGY

This study uses detailed subway system interruption data collected in 2013 by the TTC. For each record, the dataset includes date, time of day, subway station, direction, amount of delay, gap in service, vehicle number and type, as well as a brief description of the incident and a code representing the incident type. A total of about 12,500 subway incidents were reported at the stop level of analysis in 2013 along the two main subway lines. The description field for each incident includes information about the exact source of the disruption. A number of codes were provided in the dataset to represent different incident causes; however, many of the incidents were not classifiable into these categories. This required us to explore the brief description of each incident along with its code to identify the type of incidents more accurately. A complete list of incident types can be find at Louie et al. (2016). In addition, around 80 records were reported an entire route (or a portion of route) service interruptions. These records were removed from the analysis because it was not possible to link them to a specific location along the subway lines.

Regarding the amount of delay caused by each incident, the TTC records any delay less than 2 minutes as zero delay. Thus, the smallest non-zero delay in the database was 2 minutes.

This is more rigorous than other transit agencies, such as MTA in New York City and the MTR in Hong Kong, who record only the incidents that exceed 5 minutes and above (Straphangers Campaign, 2014; Weng et al., 2014). Therefore, using the TTC incident data provides more sensitive estimation for the effects of outdoor tracks and weather conditions. Indeed, with a daily average headway of 3-4 minutes, short delays of even less than 2 minutes each can still have a noticeable effect on the subway system's quality (Schmöcker, Cooper, & Adeney, 2005). Therefore, to account for these short-term delays, a one minute delay was used instead of zero minutes to account for the impact of those very short incidents. The weather data was obtained from Environment Canada on an hourly and daily basis.



Projection: NAD 1983 Ontario Lambert

Data sources: City of Toronto, TTC, DMTI

Figure 1: A- TTC subway lines, B- indoors and outdoors tracks within the TTC system, and C- subway system development

Some incident types such as passenger related issues like medical emergencies, injuries, violence, and assault on employees needed to be removed from the analysis. Therefore, all incident types, codes and descriptions were reviewed and filtered in a systematic manner. In this process, a key word search for “track”, “signal”, “power”, and “switch” was performed within the description field to allocate those needed to be re-reviewed before elimination from the analysis in order to make sure that we are not missing any related incidents. This helped us keep only the incidents that may be related to whether or not tracks are protected from the elements and to the extent of weather conditions, with a total of 4,900 incidents. More specifically, the incident causes used in the analysis include: debris/intrusions at track level, signal and switch problems, track circuit/track down, smoke or fire at the track, speed control/emergency brakes applied, and disabled train due to traction problems and propulsion problems. Other incidents removed from the analysis were related to passengers’ activity issues (e.g., medical emergencies and injuries, violence, suicide, assault on employee, etc.), security aspects (e.g., bomb threats and police investigations), personal shortage and errors, work zones and offline in yard problems, and train body problems’ (e.g., door closing problems, fires on trains, etc.).

After identifying the incidents that will be included in the analysis, the data was aggregated according to the following criteria: Subway line (Yellow line vs Green line), subway station unique id (e.g., Castle Frank station id =20, etc.), the presence of outdoor tracks (outdoor track vs. indoor track), and weather grouping factors (i.e., by season, snow level, or rainfall level). For example, all incidents that occurred along the Yellow line, at the Bloor/Yonge station, with the upstream tracks in the southbound direction being exposed to the elements (i.e., outdoor) that train will have to pass to reach the station, and during the Winter of 2013, are aggregated into one category in order to understand the total number of incidents and the total delay that occurred at that specific segment. To ensure robustness of the compiled data, the output of these categories were normalized by the number of days during a season; because not all of the seasons have the exact same number of days, some adjustments had to be made. This is particularly important in the context of Toronto, where the winter in 2013 starts early in November. Therefore, the winter in our analysis includes all the trips from the first of November till the end of March. This means that the winter season’s total number of incidents and total associated delay was divided by 120, while the corresponding data for the fall season was divided by 80. Other seasons where divided by 90 days. In addition, a category of 6 incidents per station, season, line and track type was used as a threshold for each category. Accordingly, categories showing 6 incidents or fewer were eliminated from the dataset. After the filtration process, 175 categories of incidents were used in the final analysis with an average of 25.9 incidents per category.

A similar process of aggregation was done using the average amount of snow on ground and rainfall per day, instead of using just the seasons of the year. Four snow groups were identified for this process: no snow on the ground, less than 7.5 cm of snow on the ground, 7.5-15 cm of snow on the ground, and more than 15 cm of snow. It should be noted that 15 cm of snow corresponds to Environment Canada’s warning threshold. This has been done in order to understand the impact of snow on the frequency and duration of service interruptions. Similar process was done using the amount of rainfall, by defining four levels: No rain, less than 12.5 mm of rain, 12.5-25 mm of rain, and more than 25 mm of rain. After this aggregation and the previously described filtration process, 157 and 140 categories with an average of 30.1 and 33.0 incidents were included in the final dataset for the snow and rainfall analysis, respectively. Afterwards several regression models (two models for each dataset) were generated, using the log of the number of incidents and log of the amount of delay for each category as the dependent variables. Logarithmic transformations were used to transform the number and duration of incidents to approach normal disruption.

In this research, we used descriptive statistics and six statistical models based on the incident data to capture and isolate the impact of outdoor tracks. Table 1 includes a detailed description of the variables incorporated in the analysis. Other variables were tested but eliminated from the study due to their non-significance, such as *transfer stations, frequency, platform location (central or side platform), and circuity (the ratio of network to Euclidean distance between stations) and age of infrastructure* (see Figure 1-C). The first two models are the seasonal linear regression models, which are developed to demonstrate the impact of the outdoor track segments and seasons on the number and duration of service interruptions. In these models, the two dependent variables are the log of number of incidents and the log of duration of delay per station, weather group (i.e., season), subway line, track type and day. Day was included only in the seasonal models to control the impacts of the different number of days associated with each season. Different control variables were used to isolate the impacts of outdoor track sections and seasons, which are expected to have an impact on service interruptions, including subway line number, layover station, and train type (Louie et al., 2016). Several dummy variables were used to understand the impact of seasons on operations as well as the seasonal interaction with the outdoor tracks. Only one interaction had a significant impact, namely the outdoor interaction with the winter season, which was kept in our analysis.

The second set of models is the snow models, using snow conditions as the weather grouping factor. These models use the log of number of incidents and duration of delay per station, amount of snow on ground, subway line and track type as dependent variables. These models include dummy variables for the amount of snow on ground as well as the interaction variables with the outdoor tracks, to capture the impact of snow conditions in correlation to the outdoor tracks on the frequency and duration of incidents. In these models, there was a missing category due to insufficient number of cases (i.e., *Snow more than 15*). The third set of models is the rainfall models, which uses the amount of rainfall as the weather grouping factor. These models also uses the log of number of incidents and duration of delay per station, amount of rainfall, subway line and track type as dependent variables. The models include dummy variables for the amount of rainfall as well as interaction variables with the outdoor tracks, to capture the impact of rainfall conditions in correlation to the outdoor tracks on the frequency and duration of incidents.

Table 1: Description of variables used in the regression models

Variable Name	Description
log of the number of incidents	The log of the total number of interruptions (or incidents) per station, weather group (i.e., season, snow, rainfall), subway line and track type (dependent variable).
log of the amount of delay	The log of the total amount of service interruption per station, weather group (i.e., season, snow rainfall), subway line and track type (dependent variable).
Yellow line	A dummy variable that equals 1 if the incidents occur on the Yonge-University line (Yellow line)
Layover station	A dummy variable that equals 1 if the incidents occur at a layover station (last station of a subway line).
Toronto rocket train	The total number of Toronto Rocket (TR) trains per category

Indoor track distance (KM)	The indoor distance of the track connecting this station with the upstream station in kilometer
Outdoor track distance (KM)	The outdoor distance of the track connecting this station with the upstream station in kilometer
Season Models	
Winter	A dummy variable that equals 1 if the incidents occur in the winter season, ranging from November to March; it equals zero otherwise
Spring	A dummy variable that equals 1 if the incidents occur in the spring season, ranging from March to June; it equals zero otherwise
Summer	A dummy variable that equals 1 if the incidents occur in the summer season, ranging from June to September; it equals zero otherwise.
Out* Winter	Interaction variable between outdoor tracks (dummy variable) and the winter season (dummy variable). This variable captures the combined effect of the existence of outdoor segments and winter conditions.
Snow Models	
Snow less than 7 cm	A dummy variable that equals 1 if the incidents occur on days that have less than 7.5 cm of snow on ground.
Snow less than 15 cm	A dummy variable that equals 1 if the incidents occur on days that have less than 15 cm of snow on ground.
Snow more than 15	A dummy variable that equals 1 if the incidents occur on days that includes 15 cm of snow on ground or more (Environment Canada's warning threshold).
Out* Snow less than 7 cm	Interaction variable between outdoor tracks and the less than 7.5 cm of snow variable
Out* Snow less than 15 cm	Interaction variable between outdoor tracks and the less than 15 cm of snow on ground variable.
Out* Snow more than 15 cm	Interaction variable between outdoor tracks and the more than 15 cm of snow on ground variable.
Rain Models	
Rain less than 12 mm	A dummy variable that equals 1 if the incidents occur on days that have less than 12.5 mm of rainfall.
Rain less than 25 mm	A dummy variable that equals 1 if the incidents occur on days that have less than 25 mm rainfall.
Rain more than 25 mm	A dummy variable that equals 1 if the incidents occur on days that includes 25 mm of rainfall or more (Environment Canada's warning threshold).
Out* Rain less than 12 mm	Interaction variable between outdoor tracks and less than 12.5 mm of rain variables,
Out * Rain less than 25 mm	Interaction variable between outdoor tracks and less than 25 mm of rain variables
Out* Rain more than 25 mm	Interaction variable between outdoor tracks and more than 25 mm of rain variables

5. RESULTS

5.1 Descriptive statistics

Table 2 shows the number of incidents and total delay per subway line, track type and distance. As seen in the table, a total of 1227 incidents occurred along the subway green line causing a total delay of 4671 minutes (77 hours). A total of 497 incidents occurred along the indoor tracks, while 730 incidents occurred along the outdoor tracks. This suggests a total of 25 incidents per kilometer along the indoor tracks and a 102 incidents per kilometer along the outdoor tracks. These incidents caused a total delay of 4671 minutes (77 hours) along the green line. About 29% of the delay (1345 / 4671) occurred along the indoor tracks, while about 71% of the delay (3326/ 4671) occurred along the outdoor tracks. The average amount of total delay is 68 minutes per kilometer along the indoor tracks, while it is 466 minutes per kilometer along the outdoor tracks. Furthermore, a total of 4.5 minutes of delay by incident (3326/730) can be observed along the outdoor tracks, while only 2.7 minutes of delay by incident (1345/497) can be observed along the indoor tracks. This suggests not only more frequent incidents along the outdoor tracks, but also lengthier delays.

Similar trends can be observed along the Yellow line. A total of 3652 incidents occurred along the subway line causing a total delay of 7742 minutes (129 hours). Along this line, more incidents (1925 incidents) occurred at the indoor tracks than the outdoor tracks (1727 incidents). However, the total amount of delay was split almost equally between the two track types. Nevertheless, the total number of incidents and total delay per kilometer paint a different picture, where a total of 82 incidents with a delay of 167 minutes per kilometer can be observed along the indoor tracks, compared to a total of 237 incidents with a delay of 528 minutes per kilometer can be observed along the outdoor tracks. A total of 2.0 and 2.2 minutes of delay by incident can be observed along the indoor and outdoor tracks, respectively. This suggests a similar trend to the one found along the green subway line.

Table 2: Number of incidents and total delay per kilometer of track

Row Labels	Number of incidents	Total delay (minutes)	Total distance (Km)	Number of incidents per kilometer	Amount of delay per kilometer (minutes)
Green line - Indoor track	497	1345	19.52	25.46	68.89
Green line - Outdoor track	730	3326	7.13	102.33	466.22
Yellow line - Indoor track	1925	3895	23.26	82.76	167.45
Yellow line - Outdoor track	1727	3847	7.28	237.10	528.15
Total	4,879	12,413	57.2		

Figure 2 breaks down spatially the number of incidents and amount of delay by station name and track type. As seen in the figure, stations with indoor tracks experienced an average of 47.5 incidents per station, with a standard deviation of 56.9. In contrast, a higher average of 107 incidents per station, with a lower standard deviation (compared to the mean) of 96, can be observed along the outdoor tracks. This observation indicates higher and more consistent delays occurring at stations with outdoor tracks. A stronger pattern can be observed for the magnitude of delay at the stations with outdoor track segments. The figure shows an average of 102 and 312 minutes of delay per station, with standard deviations of 106 and 287, along the indoor and outdoor tracks, respectively. However, it appears that the stations with the greatest number of incidents are not necessarily those with the largest amount of delay. This suggests that more frequent delays do not necessarily lead to lengthier delays at the station level of analysis, thus calling for other factors to be explored.

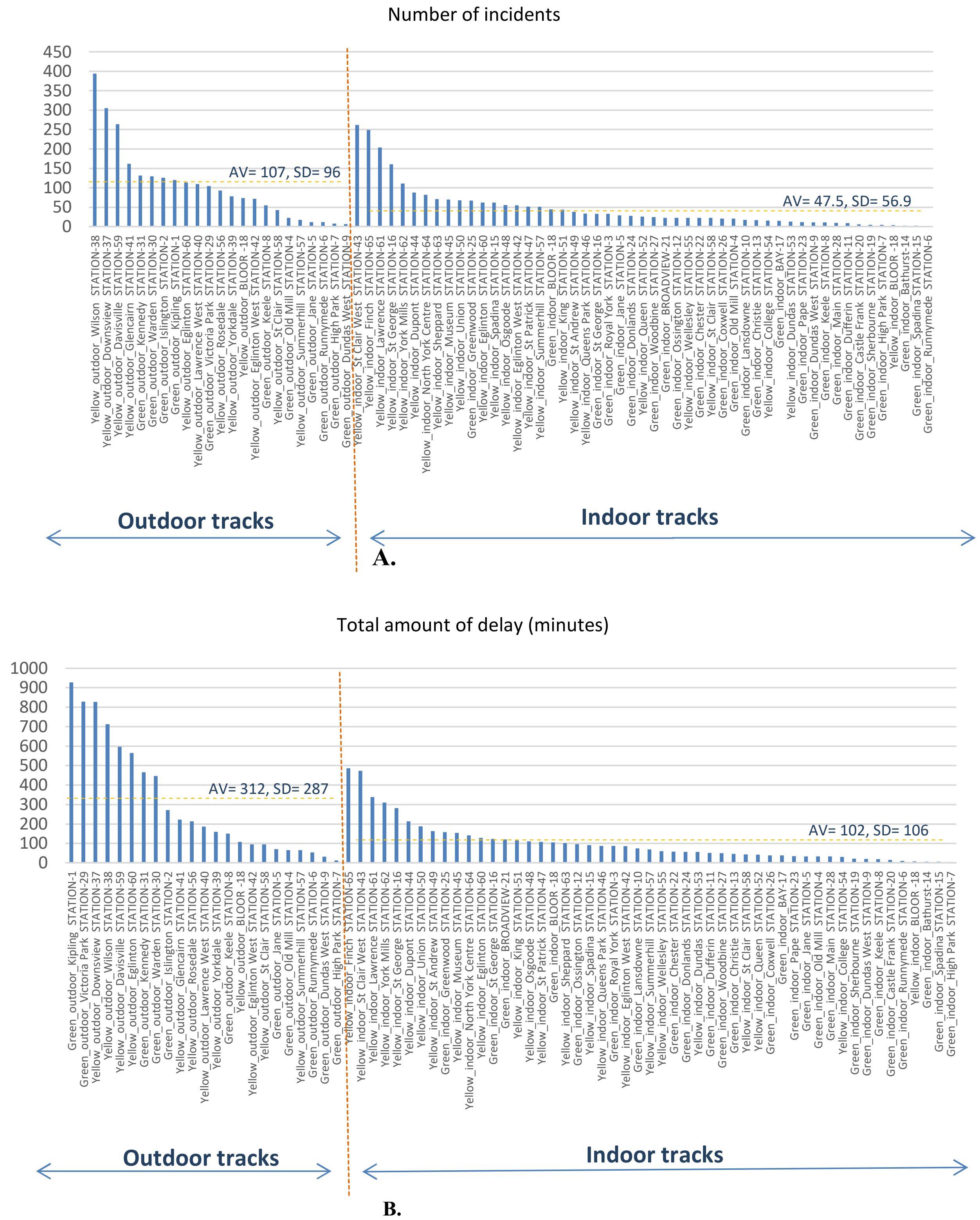
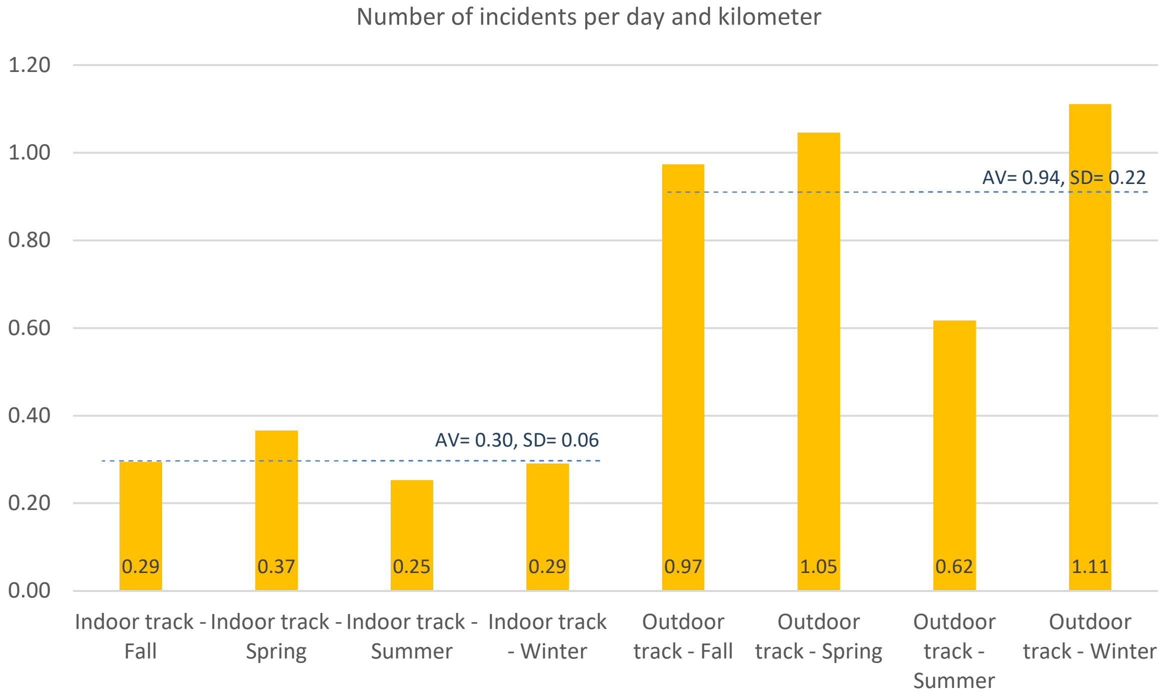


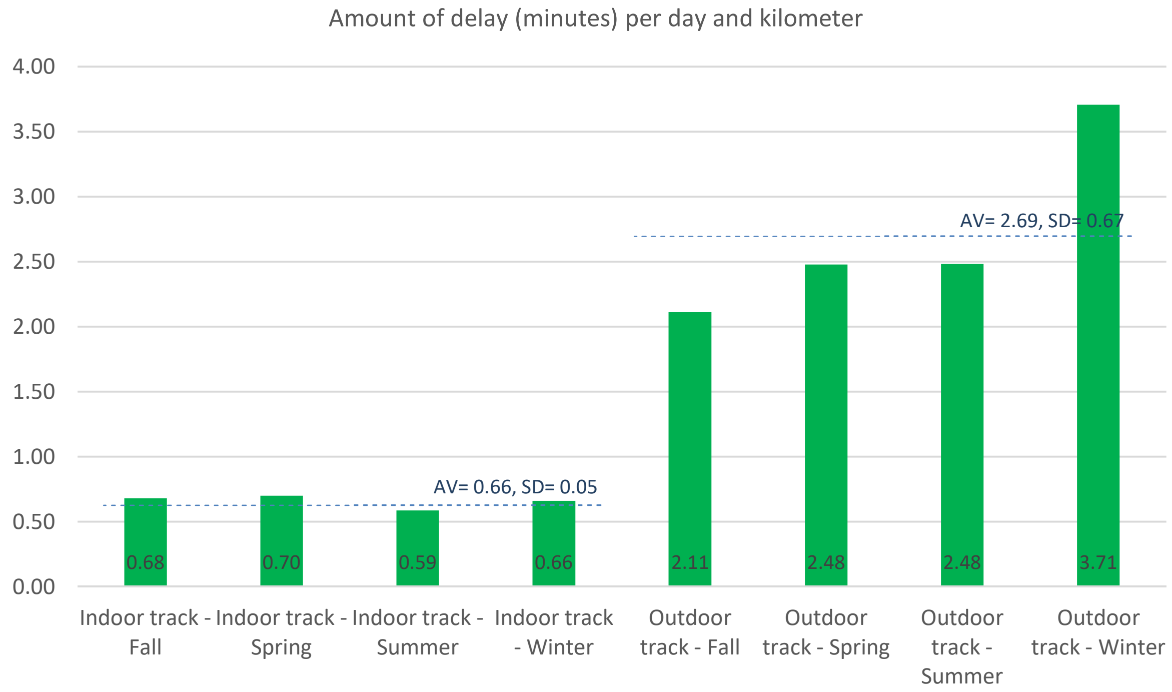
Figure 2: A- Total number of incidents by station and track type, and B. Total delay by stop and track type

Figure 3 shows the number of incidents and amount of delay per day per kilometer by season and track type. This figure illustrates the temporal differences in number of incidents and delays across the yearly seasons. As shown, an average of 0.30 incidents per km-day can be observed along the indoor tracks for all seasons of the year, with a standard deviation of 0.06. The highest average of incidents per km-day can be observed during the spring season (0.37), while the lowest average can be observed during the summer season (0.25). In contrast, a higher average of incidents per km-day can be observed along the outdoor tracks (0.94 incidents), with noticeable differences between seasons (standard deviation of =0.22). The largest amount of incidents per km-day can be observed during the winter season (1.11), while the summer season has the lowest average of incidents (0.62). This shows a higher amount of incidents per km-day, with larger differences between seasons, occurring along the outdoor tracks compared to the indoor tracks, which might be attributed to changes in weather conditions across seasons of the year and their relation to the presence of outdoor tracks.

With respect to the amount of delay, an average of 0.66 minutes of delay per km-day can be observed along the indoor tracks throughout the seasons, with a standard deviation of 0.05 minutes. The largest amount of delay per km-day can be observed during the spring season (0.70 minutes), while the smallest amount of delay can be observed during the summer season (0.59 minutes). In contrast, along the outdoor tracks, an average of 2.69 minutes of delay per km-day can be observed along the outdoor tracks throughout the year seasons. The largest amount of delay can be observed during the winter season (3.71 minutes), while the fall season has the smallest amount of delay (2.11 minutes). These observations suggest that during the winter season outdoor tracks suffer considerably lengthier service interruptions than any other season. To better understand these findings, while controlling for influential variables, several statistical models are introduced in the following section.



A.



B.

Figure 3: A- Number of incidents per day per kilometer by season and track type, and B- amount of delay per day per kilometer by season and track type

5.2 Regression analysis

Several regression models have been developed using the log of the number of incidents and log of the amount of delay as the dependent variables. Table 3-A presents the results of the seasonal models, while table 3-B and table 3-C present the results of the snow and rainfall models, respectively. All the models explain well the variation in the log of the number of incidents and amount of delay. For example, the seasonal models contain 175 records and explain 68% and 52% of the variation in the log of the number of incidents and amount of delay, respectively. As seen in Table 3-A.1 for the number of incidents, the key policy variable, *Outdoor track distance (KM)*, accounting for the outdoor tracks distance between stations that a subway train has to go through, has a positive significant coefficient. This indicates that an increase in the number of incidents is associated with an increase in the outdoor track distance. In contrast, *Indoor Track Distance* variable, which account for the indoor tracks distance, has a positive coefficient but is not significant. This suggests that using indoor tracks for future subway extensions can reduce the number of unexpected incidents, thus increasing the system resilience.

The winter season has no significant impact on the frequency of service interruptions, compared to the fall, while the summer and spring seasons have a negative coefficient, indicating a lower number of incidents. This can be attributed to the availability of resources to better maintain the service for the transit agency during these times of year. The model includes an interaction variable of *Out * Winter* to capture the combined effects of the existence of outdoor segments and winter conditions on the number of incidents. This interaction variable has a positive significant coefficient, which suggests that the frequency of service interruptions is expected to be higher during the winter season along the outdoor tracks. With regard to the control variables, Yellow line has no significant relationship with the frequency of service interruptions in comparison with Green line. Nevertheless, the use of Toronto Rocket (TR) trains, which were mainly operating along the Yellow line, had a positive relationship with the number of incidents. This is understandable since these trains were the cause of many problems when they were first introduced (TTC, 2013b). Layover stations compared to other stations had a higher number of incidents. This is expected due to the non-revenue activities that take place at these stations during the repositioning and switching of trains from one direction to another.

Regarding the amount of delay model (Model 3-A.2), similar trends can be observed in terms of the direction and significance. Outdoor track distance has a positive significant coefficient, suggesting that as this distance increases so does service interruption delay, while indoor distance displays no significant correlation with the length of service interruption. This suggests that outdoor tracks not only have higher frequency of incidents (Model 3-A.1), but also longer delays (Model 3-A.2). Therefore, planning for subway extensions should account for the negative impacts of outdoor tracks on service when estimating the cost-benefit of alternative options and designs. In addition, the winter interaction with the outdoor track variable has a positive significant coefficient, indicating longer service interruptions during the winter season along the outdoor tracks. The remaining control variables in the model perform as expected.

Table 3: Regression models

Variable	Coeff.	Z	95% Conf. Interval		Coeff.	Z	95% Conf. Interval	
			Lower Bound	Upper Bound			Lower Bound	Upper Bound
A. Seasonal linear regression models								
	A.1 Log of the number of incidents				**A.2 Log of the amount of delay**			
Constant	**-0.86**	**-19.0*****	**-0.95**	**-0.77**	**-0.44**	**-6.70*****	**-0.57**	**-0.31**
Yellow line	0.00	-0.01	-0.07	0.07	**-0.14**	**-2.69*****	**-0.25**	**-0.04**
Layover station	**0.14**	**2.71*****	**0.04**	**0.24**	**0.26**	**3.44*****	**0.11**	**0.41**
Toronto rocket train	**0.02**	**12.0*****	**0.02**	**0.02**	**0.02**	**8.14*****	**0.01**	**0.02**
Indoor track distance (KM)	0.03	1.28	-0.02	0.09	0.01	0.16	-0.07	0.08
Outdoor track distance (KM)	**0.18**	**6.23*****	**0.13**	**0.24**	**0.19**	**4.32*****	**0.1**	**0.27**
Winter	-0.07	-1.62	-0.17	0.02	-0.02	-0.35	-0.16	0.11
Spring	**-0.10**	**-2.67****	**-0.18**	**-0.03**	**-0.10**	**-1.70***	**-0.21**	**0.02**
Summer	**-0.14**	**-3.62*****	**-0.22**	**-0.06**	-0.09	-1.50	-0.20	0.03
Interactions								
Out * Winter	**0.12**	**2.00****	**0.00**	**0.24**	**0.19**	**2.19****	**0.02**	**0.37**
N	175				175			
Adjusted R Square	0.68				0.52			
F statistics/significance	(9, 165) 42.7 / 0.00				(9, 165) 22.1 / 0.00			
B. Snow linear regression models								
	B.1 Log of the number of incidents				**B.2 Log of the amount of delay**			
Constant	**1.06**	**20.8*****	**0.96**	**1.16**	**1.51**	**22.4*****	**1.38**	**1.64**
Yellow line	**0.21**	**4.20*****	**0.11**	**0.31**	0.06	0.85	-0.08	0.19
Layover station	**0.16**	**1.87****	**-0.01**	**0.32**	**0.27**	**2.49****	**0.06**	**0.49**
Toronto rocket train	**0.01**	**6.71*****	**0.01**	**0.01**	**0.01**	**4.66*****	**0.01**	**0.01**
Indoor track distance (KM)	**0.10**	**2.44****	**0.02**	**0.19**	**0.11**	**2.03****	**0.01**	**0.22**
Outdoor track distance (KM)	**0.28**	**5.73*****	**0.19**	**0.38**	**0.31**	**4.76*****	**0.18**	**0.44**
Snow less than 7 cm	0.08	1.05	-0.07	0.22	0.01	0.15	-0.17	0.2
Snow less than 15 cm	**-0.47**	**-6.91*****	**-0.6**	**-0.34**	**-0.47**	**-5.18*****	**-0.64**	**-0.29**
Interactions								
Out* Snow less than 7 cm	-0.08	-0.77	-0.3	0.13	0.03	0.20	-0.26	0.32
Out * Snow less than 15 cm	**1.00**	**6.40*****	**0.69**	**1.31**	**1.12**	**5.44*****	**0.72**	**1.53**
Out * Snow above 15 cm	**-0.88**	**-6.27*****	**-1.16**	**-0.6**	**-1.00**	**-5.39*****	**-1.37**	**-0.64**
N	157				157			
Adjusted R Square	0.69				0.56			
F statistics/significance	(10, 146) 34.9 / 0.00				(10, 146) 20.7 / 0.00			
C. Rainfall linear regression models								
	C.1 Log of the number of incidents				**C.2 Log of the amount of delay**			
Constant	**1.03**	**21.4*****	**0.93**	**1.12**	**1.51**	**22.3*****	**1.37**	**1.64**
Yellow line	**0.11**	**2.42****	**0.02**	**0.21**	-0.08	-1.26	-0.22	0.05
Layover station	0.11	1.57	-0.03	0.24	0.22	2.29	0.03	0.41
Toronto rocket train	**0.01**	**8.79*****	**0.01**	**0.02**	**0.01**	**6.52*****	**0.01**	**0.02**
Indoor track distance (KM)	0.05	1.22	-0.03	0.13	0.02	0.3	-0.10	0.13
Outdoor track distance (KM)	**0.26**	**5.88*****	**0.17**	**0.35**	**0.24**	**3.77*****	**0.11**	**0.36**
Rain less than 12 mm	**0.35**	**3.31*****	**0.14**	**0.56**	**0.39**	**2.65****	**0.1**	**0.68**
Rain less than 25 mm	0.10	0.63	-0.21	0.41	0.28	1.25	-0.16	0.71
Rain with above than 25 mm	**-0.43**	**-3.21****	**-0.69**	**-0.16**	**-0.63**	**-3.39****	**-1.00**	**-0.26**

Interactions								
Out* Rain less than 12 mm	0.12	0.91	-0.15	0.39	-0.14	-0.74	-0.52	0.24
Out * Rain less than 25 mm	-0.13	-0.63	-0.53	0.28	-0.16	-0.56	-0.73	0.41
Out * Rain above than 25 mm	0.04	0.26	-0.29	0.37	**0.41**	**1.76***	**-0.05**	**0.87**
N	140				140			
Adjusted R Square	0.7				0.53			
F statistics/significance	(11, 128) 30.7 / 0.00				(11, 128) 15.3/ 0.00			

Bold indicates statistical significance

*** Significant at 99% ** Significant at 95% * Significant at 90%

Table 3-B presents the results of the amount of snow models. As seen in Table 4, similar trends can be observed in terms of direction and significance, with a few minor differences. This model indicates that *Indoor track distance* variable has a positive significant coefficient. However, the key policy variable, *Outdoor Track Distance*, indicates a higher degree of association with the frequency of service interruption. This suggests higher frequency of service interruptions along outdoor tracks than indoor tracks. Other variables follow the same signs and magnitudes as the previous model, including rocket train, and layover station.

The amount of snow shows no correlation with the frequency of service interruptions. However, the interaction terms show different results. Less than 7.5 cm of snow on the ground has no significant association with the frequency of service interruptions. However, if the snow increases to an amount of less than 15 cm, it has a positive significant coefficient, increasing the frequency of service interruptions. If this amount if snow increases to reach 15 cm or more on the ground, which is the threshold used by Environment Canada to alert the public about adverse weather conditions, the associated number of service interruptions becomes lower than the previous number. This can be explained by the special attention and measures that the TTC dedicates along the outdoor tracks when weather alerts are issued (TTC, 2013c). These measures include the employment of *storm trains*. These trains run back and forth to check the tracks and to prevent the build-up of snow and ice, while applying glycol to the power rail, offering better conditions for the system operations. This suggests that such a policy is successful in reducing the negative effects of large amounts of snow (more than 15cm) on the number of service interruptions. Thus, the employment of a similar measure during regular and more frequent conditions, of less than 15 cm of snow on the ground, is worth consideration in order to reduce the number of interruptions related to the amount of snow on ground along outdoor tracks. As seen in Table 3-B.2, similar patterns can be observed regarding the amount of delay, particularly the impact of outdoor tracks and the amount of snow in conjunction with the outdoor tracks.

Table 3.C. presents the results of the amount of rainfall models. As seen in the table, similar patterns to the previous models can be observed in terms of direction and significance of different variables. The model also indicates that outdoor track distance has a positive significant coefficient, while indoor tracks having a positive but no significant impact on the frequency of service interruptions. With regard to the amount of rain, compared to no rain precipitation (the base case), rain has different impacts on the frequency of service interruptions, increasing it in the case of less than 12 mm of rain, while decreasing it in case of the amount of rain reaches more than 25 mm. This reduction in the number of incidents at the stop level may be attributed to a fewer number of incidents along the indoor tracks recorded during these time periods. Nevertheless, while the outdoor tracks have no significant relationship with the frequency of service interruptions, they have a positive significant coefficient in correlation with the amount of

delay (Table 3-C.2), specifically when the amount of rainfall equals or exceeds 25 mm. More than 25 mm of rainfall is expected to increase the amount of delay. Therefore, developing mitigating strategies to reduce the effects of major rainfall storms with 25 mm or more is recommended.

6. CONCLUSIONS

The objective of this paper is to understand the relationship of outdoor track segments of the subway system and weather conditions with the frequency and duration of service interruptions. In order to achieve that, the paper uses descriptive statistics as well as several statistical models. Descriptive statistics showed that the frequency and duration of service interruptions per kilometer, season, day and track type are considerably higher at outdoor tracks, particularly during the winter season compared to the indoor tracks. To better understand these findings, while controlling for influential variables, six statistical models were estimated.

The models indicate that outdoor tracks have a statistically significant association with subway system's service interruptions. Longer outdoor track distances are linked to both higher frequencies and delays of service interruptions. Weather conditions, in terms of the amount of snow on the ground and rainfall interactions with outdoor tracks, have also a significant association with the frequency and duration of service interruptions. More specifically, if the amount of snow on the ground increases to reach less than 15 cm, this will increase the frequency and duration of service interruptions. In contrast, when the amount of snow equals or exceeds 15 cm the outdoor tracks do not experience more service interruptions, which can be attributed to the employment of storm trains in those cases. Nevertheless, these trains may have a negative impact on the service, since a few extra trains along the tracks can decrease the service frequency, speed and on-time performance, especially when the subway service is operated at very short headways. Therefore, a study that uses the actual train movement data to investigate the impacts of using storm trains on system performance is recommended. If their impacts are minimal, the employment of a similar measure in less extreme conditions could be recommend in order to decrease the number of incidents related to the amount of snow along outdoor tracks. While rainfall conditions have no impact or association with the frequency of service interruptions in relation to outdoor tracks, they are associated with the increases in the amount of service delay when rainfall reaches 25 mm or more. This indicates a need for improving the sewer system or providing a pump system that is capable of handling the added amount of water during these events.

Finally, these results help transit agencies predict the frequency and severity of service interruptions in order to enhance their ability to account for their effects on users and resources, providing them with valuable policy-relevant information that could be used to support planning of a resilient public transport system. Indeed, the provision of a resilient public transport system will contribute to better equitable and sustainable communities. This paper uses one year worth of interruption data to investigate the impacts of outdoor tracks and weather conditions at the stop level of analysis. Therefore, expanding this study to investigate the very rare events of an entire or portion of route interruptions using several years worth of data is recommended, which was not possible to do within this study. Other transit agencies, beside TTC, can expect similar impacts of outdoor tracks on their transit service interruptions. Nevertheless, by utilizing a similar methodology and type of data, they may analyze these impacts at different setups, locations and meteorological conditions (e.g., harsh summers).

ACKNOWLEDGEMENTS

This research was funded by Natural Sciences and Engineering Research Council of Canada (NSERC) and the Ontario Research Fund (ORF). The authors would like to acknowledge the members of Nexus research group, particularly Siva Srikukenthiran and Erin Morrow, for their feedback and comments that helped improve the study. The ideas and findings presented in this paper represent the authors' views in an academic exercise.

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