Breaking into emergency shuttle service: Aspects and impacts of retracting buses from existing scheduled bus services

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ABSTRACT

High-quality transit service is a vital aspect of any modern city. When unexpected interruptions to the transit service occur, they reduce the quality of service provided to the public. One of the main strategies that is employed to deal with rail service interruptions is “bus bridging,” whereby buses from scheduled services are deployed to offer shuttle services. Very few efforts are found in the literature that investigate this policy effectiveness. Therefore, this study aims at exploring the different aspects and impacts of retracting buses from scheduled services in response to subway and streetcar service interruptions in Toronto. It explores the size of the deployment, as well as the system response and recovery times using detailed subway and streetcar shuttle service reports collected in 2015. The paper shows remarkable fluctuations not only in the utilized number of shuttle service buses over time, but also on the service response and recovery times.

Key words: subway, streetcars, system interruption, public transit, shuttle service, bus bridging

1. INTRODUCTION

Public transit is considered an essential service for any city, due to its indispensable role in supporting the daily activities of city residents. When unexpected interruptions to the public transit service occur, they reduce the quality of service provided to the public and diminish the system's ability to retain existing customers and attract new ones. As discussed in the literature, transit users are usually concerned not only about their average travel and waiting times, but also about the uncertainty and variability in transit service, which affects their decision-making and time-planning processes (Bates et al. 2001, Nam et al. 2005, Noland and Polak 2002). Thus, transit agencies and authorities implement several disruption management strategies (or emergency response plans) to mitigate and reduce the impact of unexpected disruptions and incidents on users' costs. Several studies have been conducted around these issues, focusing mainly on proposing conceptual frameworks, testing different approaches for disruption management or categorizing incidents according to some criteria (Codina and Marin 2010, Kepaptsoglou and Karlaftis 2009, Schmöcker et al. 2005, Wang et al. 2014). To name just a few examples, Pender et al. (2015) tested a new method to explore the economic viability of providing dedicated bus service reserved for bus bridging purposes for rail system disruption. Bus bridging refers to the strategy of providing temporary bus shuttle services that restore connectivity between disrupted subway or railway stations (Kepaptsoglou and Karlaftis 2009). Darmanin et al. (2010) developed a mathematical model to minimize commuter discomfort when a service disruption occurs in the Metro system in Melbourne. Another recent study by van der Hurk et al. (2016) proposed a mathematical model to estimate shuttle line frequencies under budget constraints for the Massachusetts Bay Transportation Authority, Boston, Massachusetts.

Notwithstanding the previous efforts concerning the provision of a dedicated bus fleet reserved for bus bridging purposes, according to a recent international survey of 71 transit agencies regarding disruption recovery strategies, about 45% of the responding transit agencies reported retracting buses from existing scheduled bus service to deal with rail transit service disruptions. This has been done with no reserved buses for bus-bridging purposes. Toronto Transit Commission (TTC), the public transit provider in the City of Toronto, Canada, is one of these transit agencies (Pender et al. 2013). Interestingly, the TTC noted in this survey that by doing that *"you may in fact be simply shifting the problem or causing additional ones."* In view of that, and due to the fact that there has been little effort in the literature to document and explore the aspects and impacts of retracting buses from scheduled bus services, this research aims at filling this gap. In fact, this disruption recovery strategy presents a challenge to transit agencies, since sourcing of buses can be problematic at some locations and at some time periods. In addition, the effects of retracting buses from existing scheduled must be considered and integrated by transit planners during various operational stages to add the appropriate amount of recovery time, if possible, or to redirect bus system users to other routes that suffer no reduction in their frequencies.

Other researchers focused on exploring other important operational, managerial and user behavioural aspects of rail service disruptions. For example, recent efforts developed and executed a transit user behaviour survey and modelled user's travel behaviour in response to subway service interruptions in Toronto (Lin 2017, Lin et al. 2017). A second study focused on understanding the impact of subway service interruptions on the service performance of both bus and streetcar routes that are within a short walking distance from affected subway stations (Diab and Shalaby 2017). Another recent study explored the managerial framework used by different transit agencies to deal with unplanned rail service disruptions (Pender et al. 2013). However, these and similar studies have not tackled the various operational aspects of retracting buses from scheduled services to offer emergency shuttle services nor analyzed this strategy using actual operational data collected from a real-world system. Therefore, the main aim of the presented study is to explore the different aspects and impacts of retracting buses from scheduled services in response to subway and streetcar service interruptions in the City of Toronto. The paper explores the size and impacts of emergency shuttle service deployment, as well as the system response and recovery times using detailed subway and streetcar shuttle service reports collected in 2015 by the TTC.

2. DATA AND RESEARCH METHOD

This study focuses on the City of Toronto, which is the largest city in Canada and the fourth largest in North America, with a total of 2.8 million inhabitants in 2015. The city's population is expected to increase considerably by 32% to reach 3.7 million in 2041 (Ontario Ministry of Finance 2015), adding more pressure on the current public transport system. The TTC operates a multimodal transit system consisting of four subway lines, 11 streetcars lines, and 141 bus routes (TTC 2013), serving more than 2.7 million passengers on a daily basis (American Public Transportation Association (APTA) 2013). The TTC subway network extends to a total length of 68 km serving 69 stations, while the streetcar route network extends to a total of 104 km serving 685 stops. Around 1.3 million passengers-trips per day used the subway system in 2013, while about 300,000 passenger-trips per day were made using the streetcar system (TTC 2012). The TTC bus system is comprised of seven different divisions, where each bus route is operated and monitored by a specific division based on its geographic location. All bus routes are coloured in Figure 1 according to the division they are managed by.

The data used for this study includes the shuttle bus service reports acquired from the TTC's Route Management Department for year 2015. A shuttle bus service log (or report) is generated when an incident in either the streetcar or subway systems occurs and the TTC deploys emergency shuttle service. Each incident is documented in one report which includes detailed information on both the incident and deployed shuttle bus service, specifically the incident type, date, time started, time cleared and location, as well as the number of shuttle buses requested and assigned from different divisions. The report also includes detailed information on each assigned shuttle bus including the vehicle number, original route number, assigned run number, time off route to serve in the shuttle service, arrival time to the shuttle route and returning time to its original route. These reports are filled manually (i.e., handwritten) in many cases by both the Route Management Department (the Control Centre) and bus division(s), and they are normally stored by the Control Centre for one calendar year before disposal. In total, more than 6000 pages, belonging to a total of 1094 shuttle service reports, were scanned, digitized and used in this study. This unique dataset represents a rich resource to better understand the aspects and impacts of retracting buses from scheduled service at the system level. The following analysis is based on the available data from all shuttle service reports; however, missing information can be found occasionally. To ensure accurate results, only data entries with complete information for a specific analysis were used. For instance, a record with no information on the time a given bus was retracted from its original route was used only in the geographical and incident analyses but not used in the response time analysis (discussed later).

[FIGURE 1: TO BE ADDED HERE]

This research employs various measures to explore the challenges associated with service resumption and recovery following subway and streetcar disruptions. It explores the magnitude of the problem by investigating the number of incidents, average delay per incident as well as the number of requested and assigned buses per incident. It also investigates the affected scheduled bus service by examining the number of buses retracted from each regular bus route. The system response time to service interruptions and system recovery time to return to normal operations are also explored. Finally, the paper explores the most frequent types of subway and streetcar incidents that impacted the scheduled bus service in 2015. To better understand the system response time, this study breaks it into three major components as illustrated in Figure 2. The first component is the *Initial Response Time*, which is the time it takes the TTC's Route Management Department (Control Centre) from the incidents' start time to react to incidents. This portion of time includes the incident reporting time to the Control Centre and the time it takes the Control Centre to call bus divisions placing a request for shuttle service. Indeed, transit agency internal communication efficiency and effectiveness is a crucial issue in responding successfully to service interruptions, which was highlighted by several transit agencies (Pender et al. 2013). The second component is the *Bus Pull out Time,* which is the time it takes the TTC's bus divisions to unload and take buses off the scheduled service. If the Control Centre made more than one call, each bus pull out time is calculated according to the associated call. The third component is *Bus Deadhead time,* which is the travel time of buses from their original routes to the location of shuttle service.

In this study, we also classify buses into three categories to better recognise the challenge of providing shuttle bus service. These categories include buses requested by the Control Centre, buses assigned by divisions, and buses that actually arrived to the shuttle service location and provided the required emergency service. The main reason for having these different types of buses is that not all requested buses by the Control Centre are normally provided by the bus divisions. Also, some incidents could be cleared before the assigned buses arrive at the shuttle service location. Thus, a *Division response rate* measure is developed to account for the number of buses assigned by divisions divided by the total number of buses requested by the Control Centre. Bus recovery time is the time it takes the buses to return to their scheduled service which includes the *Bus Service Time* on the shuttle service and *Bus Returning Time* to original routes. A conceptual workflow cycle for a shuttle bus service implementation is shown in Figure 2.

[FIGURE 2: TO BE ADDED HERE]

3. TTC'S PROTOCOLS AND CURRENT PRACTICE

The TTC employs specific protocols to initiate the emergency shuttle bus service. These protocols mainly exist to deal with subway service interruptions. The decisions on shuttle service deployment and number of assigned shuttle buses are based on the location of service interruption along the subway system (central, east end, west end), subway line (main subway lines, Scarborough Line, and Sheppard Line), day of week (weekday, weekends), time period (AM, Midday, PM, etc.), number of subway affected stations (1-4 stations, 5-9 stations, 10+ stations) and the expected duration of subway interruption (1 to 30 minutes, 30+ minutes). Table 1 presents one example from these protocols. It shows the percentage and number of required buses to deal with subway system service interruptions along the main subway lines (i.e., (Yonge-University-Spadina Line and Bloor-Danforth Line). The protocol categorizes the incidents by the expected duration of delay and number of affected (or closed) subway stations, and it provides the required percentage of shuttle buses for each category according to the time period of the day. For example, up to 10% of the buses serving on scheduled bus routes could be retracted for deployment as shuttle buses, when a subway interruption is expected to last more than 30 minutes and affects more than 10 subway stations. This percentage of buses is retracted equally from all bus divisions, with no spatial consideration of the location of incident. As different divisions have different numbers of buses in regular service, the number of buses to be retracted from different divisions may vary so as to minimize the impact on divisions with small fleets. Generally, similar protocols can be found requiring all divisions to source buses for service interruptions along the main subway lines, except for a few exceptions, irrespective of the incident location. This may lead to low efficiency in some cases where shuttle buses have to travel a long distance if provided by a division which is not adjacent to the incident location.

Bus divisions are advised to retract buses from high frequency routes first. Trippers, which stand for the extra buses scheduled for peak hour service, are always the first candidates. However, other factors may affect the decision making such as bus driver's schedule and route ridership. Out of courtesy, supervisors normally call the driver of the following bus to advise them of pulling the bus ahead out of service to expect more than normal riders. In some unusual cases, shuttle buses can be taken directly from garages, if spare drivers are available to operate these buses. The TTC's Transit Control center calls bus division once the incident started to place a request, however, in exceptional cases, it can call back the bus divisions up to three times in total to request more buses or to follow up. The TTC has no strict geographical boundaries for "central", "east end" and "west end" locations and it is left to the Transit Control's supervisors to determine which shuttle guidelines to follow. Therefore, for the purpose of our study we divide the subway system into four different sections based on location to better understand the spatial impacts of the shuttle service (Figure 1). In contrast to the subway system shuttle service protocols, the TTC has no well-defined protocols for the streetcar shuttle service, and the decisions for deploying such a service are made usually on an ad-hoc basis.

[TABLE 1: TO BE ADDED HERE]

4. OVERVIEW OF SUBWAY AND STREETCAR INCIDENTS

Number of Incidents and System Delay

In 2015, the TTC dispatched shuttle bus services in response to 924 and 144 incidents in the streetcar and subway networks, respectively. Averaging at about 2.5/0.4 incidents per day in the streetcar/subway system, these incidents caused a total daily delay of 216.7 and 34.4 minutes in the streetcar and subway systems, respectively (see Figure 3-A). Here, delay refers to the incident duration, which was calculated based on the incident clearance time minus the start time, as indicated by shuttle service reports. Nevertheless, a simple division suggests that the average delay per incident is 86.7 minute for streetcars and 86.0 minutes for subway, which are very close. These lengthy delays are expected, since the analyzed data come from the shuttle service reports which mainly deal with 'Major' incidents that triggered shuttle service deployment.

As expected, the TTC experienced more incidents per day on weekdays than weekends for the streetcar and subway systems (Figure 3-B). These incidents are not equally distributed over the different day periods for the subway system (Figure 3-C). More incidents occurred during the mid-day and evening periods, for both the subway and streetcars systems. Nevertheless, more delaying incidents occurred during the evening period for the streetcar system than the subway system. The south (or Central) section which lies within the downtown area had the lowest number of daily incidents (0.02 incidents per day) while the west section had the highest number of incidents (0.14 incidents per day). This indicates more major incidents occurring at the west section that required TTC to deploy the shuttle service. Also, this reflects the TTC's efforts in clearing incidents more swiftly along the south section. It should be noted that some subway incidents were reported at the entire route or a portion of route, instead of at a stop level. Therefore, these incidents were removed from the spatial analysis because it was not possible to link them to a specific location along the subway lines. Figure 3-E illustrates a clear trend of more incidents and lengthier delays occurring during the winter season for both the streetcar and subway systems.

[FIGURE 3: TO BE ADDED HERE]

The Number of Requested and Assigned Buses

About 6500 buses were requested by the Control Centre to provide shuttle services in 2015, with an average of 23.1 and 3.5 buses per subway and streetcar incident, respectively (Figure 4-A). This is intuitive due to the more frequent subway services and higher capacity of subway trains (one subway train can carry up to1100 passengers while one streetcar may only carry between 100-200 passengers). About 71% of the requested buses are assigned by bus divisions with a total of 17.1 and 2.3 buses per subway and streetcar incident, respectively. The breakdown of the number of requested and assigned buses by day of week and time of day (Figures 4-B and 4-C) depict similar patterns to those shown in the corresponding figures of the previous section. Nevertheless, the number of requested and assigned buses differ slightly according to the time of the day. A slightly higher division response rate during peak hours can be observed (Figure 3-C), with a low response rate during the evening time. This perhaps reflects the higher availability of trippers during the peak periods which could diverted for shuttle service.

Regarding the geographic location of the subway incidents (Figure 4-D), the results for west and north sections agree with previous section too, showing that more buses are requested and assigned due to incidents. The south section requires few buses compared to other sections. This is related to the TTC's used protocols of deploying less number of buses at this central section due the availability of parallel regular streetcar service.

[FIGURE 4: TO BE ADDED HERE]

Figure 4-E gives the year's profile of the number of buses requested and assigned per month, which agree with number of incidents in Figure 3-E. The response rate, however, does not have a clear trend, and February shows an overall low response rate, despite having the greatest number of incidents and requested buses. Therefore, a new figure was generated to explore the daily trends during this month (Figure 4-F). As seen in the figure, an inconsistent response rate can be observed over the days of the month. This may highlight the need for more consistent policies for bus assignment.

To summarize, several temporal, monthly and spatial trends in the number of incidents and their total delays can be observed across the subway and streetcar systems. The TTC's protocols have been used to source the requested number of buses but monthly variations have been observed, suggesting a thorough review of applying the used protocols may be in order. There may be a need for more flexible protocols that enhance the system capacity of sourcing buses during the winter season while relaxing these protocols during the other less demanding seasons, such as summer.

5. IMPACTED BUS ROUTES

In 2015, an average of 1.25 buses per route and incident were retracted from 82 buses routes, with a standard deviation of 0.3 buses. These routes represented a total of 65% of TTC's bus routes in regular service. The analysis of 4,568 shuttle buses used in 900 incidents is presented in this section. Figure 5-A shows that not all buses retracted from regular routes were fully deployed to the target shuttle service location, due to some incidents getting cleared before the shuttle bus arrival. Around 88 % (5.2/5.9) and 85% (5.8/6.8) of the assigned buses were actually utilized as a shuttle service for the streetcar and subway system, respectively. Some buses are deployed from remote routes which may explain the less than perfect utilization rate. In addition, the higher percentage of utilization for the streetcar system reflects its shorter response time (discussed in the following section).

As shown in Figure 5-B, a percentage of buses were dispatched from garages as opposed to scheduled route services. However, this percentage varies by the time period of day, with the smallest parentage of buses dispatched from garages during the morning peak hour (14%) and the evening period (15%), while the largest during the midday period (22%) and the afternoon peak (23%). This is expected and highlights the problem of sourcing buses during some periods of the day due to the availability of spare drivers, which has been discussed in the literature (Pender et al. 2013). In order to get a better idea about the impacts of retracting buses from regular bus routes, the following discussion focuses on the top 20 bus routes from which shuttle buses were sourced most frequently. From these 20 routes, around 2,000 shuttle buses were extracted in 2015 (Figure 5-C), ranging from 53 to 209 buses per route. The figure also shows the daily ridership per route in thousands, which is a reflection of the route offered capacity and headway. The routes daily ridership ranges from 6,400 to 45,700 riders per day. The figure shows that the number of assigned buses per route is not always proportionate to its ridership level. On average, about 1.5 buses were retracted from each bus route during incident days (Figure 5-D), despite differences in ridership levels. This practice may have considerable impacts on the users of low frequency bus routes. The increase in users' waiting and travel times along the routes would likely have negative impacts on users' perceptions and loyalty (Diab et al. 2017). In order to better understand the impacts of retracting buses from scheduled route service on the performance and users of those routes, a separate study is recommended.

[FIGURE 5: TO BE ADDED HERE]

6. RESPONSE TIME

The response time is analyzed by mode, weekday vs. weekend, time period, month and location for a total of 3,097 shuttle buses that covered 688 incidents. As seen in Figure 6-A, the total response time to subway incidents is longer than the response time to streetcar incidents for all three time components, with an average total time of 41.3 and 28.9 minutes per bus for the subway and streetcar systems, respectively. These values are considerably shorter than the average response time reported for rail transit bus-bridging of 90 minutes for a case study in Australia (Pender et al. 2015). The difference between the subway and streetcar shuttle bus response time can be attributed to the fewer shuttle buses required per streetcar incident, the sources of which could be decided upon quickly (shorter initial response and pull out times) and deployed from nearby bus routes (shorter deadhead times) relative to subway incidents which are more complex and large-scale. The response time per bus on weekends is longer than weekdays (Figure 6-B). This may be due to the limited staff resources and reduced bus fleet in service on weekends which could limit shuttle bus options and delay the overall decision making process.

Figure 6-C indicates that the shuttle bus service is delivered more rapidly during peak hours, with an average response time of 29 minutes per bus, compared to an average of 38 minutes per bus during off-peak periods. This may be due to the availability of trippers in most routes during peak periods, offering rich and wide access to shuttle bus options. The shorter deadhead times in peak periods, shown in the figure, supports this proposition. As expected, longer response time can be observed during the winter months and into April (Figure 6-D) mainly due to increases in pull out and deadhead times, reflecting the negative impacts of weather conditions on bus service operations (Diab and El-Geneidy 2013). In contrast, the initial response time does not vary much by season.

Figure 6-E breaks down spatially the response time according to the incident location along the subway system and bus division. This figure was constructed using a total of 79 subway incidents that caused the closure of 5 or more subway stations and required all bus divisions to provide a similar percentage of buses (see Table 1). As seen in the figure, some buses from some bus divisions can take an enormous amount of time to provide such a shuttle service. For instance, for incidents in the west section of the subway, the average response time of buses deployed from routes belonging to the Malvern division (which a northern-eastern bus division) was 58 minutes while the average delay for the subway system was around 87 minutes. There is a large probability that an incident in the west section could be cleared before shuttle buses arrive from the Malvern division. Longer response times inevitably increase the total waiting time for users that are stuck and frustrated while waiting for shuttle service, and they also increase the overall “clearance” time of incidents. As indicated previously, the southern section is a special case, representing the downtown core of the city of Toronto. For this section, the assignment of shuttle buses from all the Northern divisions (e.g., Malvern, Arrow, Wilson,

Queensway) in response to subway incidents takes a considerable amount of time. This reflects a challenge of deploying buses from these locations in response to central subway service interruptions.

[FIGURE 6: TO BE ADDED HERE]

7. RECOVERY TIME FOR REGULAR BUS ROUTES

Recovery time, a key element of the overall shuttle service process, should be examined carefully by transit agencies, since clearing incidents swiftly will mean quicker return of shuttle buses to their original routes. Recovery time includes two components, namely service time on the shuttle service and returning time to the scheduled service after the incident is cleared. A total of 1,930 shuttle bus runs for 567 incidents were analyzed based on that. Interestingly, Figure 7-A and B show that the returning time was relatively longer than the response time discussed in the previous section, with an average of 44.4 and 32.4 minutes per bus for the subway and streetcar systems, respectively. This might be because many shuttle buses did not return immediately after the incidents were cleared, since they probably had to transport passengers on board to the shuttle route terminal point before they could go back to their original routes. However, a study that investigates the average speed, ridership and driver's behaviour using the actual bus operational (AVL) data is recommended to identify the causes of this increase in returning time. Indeed, understanding the reasons behind that would help in implementing actions to reduce the returning time. Similar patterns can be observed regarding the average recovery time per bus by weekdays vs. weekends, by time period, and by month, relative to the system response time, with longer returning times being observed. The higher efficiency observed for peak hours is also shown in the incident recovery time, highlighting the need to further improve recovery times for incidents on non-peak periods. In addition to the above cases, and for long delay incidents, with an average of 6 hours (about 70 incidents), a total of 256 buses went back directly to their routes before the clearance of the incident with a total average recovery time of 188 minutes.

[FIGURE 7: TO BE ADDED HERE]

8. INCIDENT ANALYSIS

This section explores the most frequent incidents that occurred in Toronto's streetcar and subway networks in 2015, which is important to highlight how transit agencies react differently to different type of incidents. The analysis reports on the average incident delay, number of buses requested and assigned, and response time by incident type. Table 2-A indicates that over 30% of major streetcar incidents were caused by surface traffic accidents. However, these incidents were cleared rapidly, resulting in shorter delays (53.6 min per incident) and requiring fewer shuttle buses (1.8 buses per incident) than the average values for all major streetcar incidents (87 minutes and 2.3 buses, respectively). On the other hand, the overhead wire problem, resulting in a 2.5-hour delay (152 minutes) on average, led to the largest number of shuttle buses utilized. However, cold weather (including snow conditions) was to blame for the highest rate of delay for streetcars, with an average delay of more than 7 hours per incident. To give an example, on January 7th 2015, a large segment of streetcar Route 506 was down from 11:06 AM to 7:43 PM due to cold weather and snow on the ground. In response to that, the TTC requested 20 shuttle buses, 17 of which arrived and served on the temporary shuttle route. Such long service delays could undoubtedly have substantial impacts on the perception of passengers, both streetcar users travelling on the shuttle service and riders of bus routes from which shuttle buses were deployed. This is particularly important in the winter season, where passengers are more sensitive to any increase in their outdoor times including their waiting and walking times (Lam and Morrall 1982). The response time for all incident types ranged between 16.8 to 36.8 minutes, except for cold weather incidents that suffered from a much longer response time of 61.3 minutes. Regarding the subway system incidents, Table 2-B shows that power problems, which are often related to cold weather and system level failures, led to the longest delay in the subway system as well as the longest response time. Fire, smoke and burning odour was the most frequent subway incident type, but each incident was cleared swiftly for most of the cases.

[TABLE 2: TO BE ADDED HERE]

9. CONCLUSIONS AND RECOMMENDATIONS

Transit agencies are constantly faced with the challenges of managing disrupted transit service, which often requires utilizing additional resources and diverting existing ones from one location to another in an effort to minimize user discomfort and delays. The primary aim of this study was to explore in more detail one of the common disruption management strategies, namely bus bridging, which transit agencies employ in response to major service interruptions in their urban rail systems. This strategy involves retracting buses from existing scheduled services to offer an emergency shuttle service to compensate for rail service interruptions. This strategy has been used widely by transit agencies, with no thorough analysis of its diverse aspects and impacts. Thus, a major contribution of this research is its examination of the different aspects and impacts of employing this strategy using the large-case multimodal transit system of Toronto as a case study, which provides a unique opportunity to understand the effects of not only subway service interruptions but also streetcar interruptions. In order to do that, the paper explored the magnitude and impacts of emergency shuttle service deployment, as well as the system response and recovery times using detailed subway and streetcar shuttle service reports collected in 2015 by the TTC. Such a dataset, which is usually hard to access, provided very detailed information regarding the bus service retracting problem at the system level.

The paper shows considerable fluctuations in the number of incidents, number of requested and assigned buses as well as the system's response and recovery times. These fluctuations are not only within mode, but also across the two modes analyzed in this paper (i.e., subway and streetcar), highlighting the challenge of managing disruption along the two systems. Furthermore, this research highlights the need of more flexible protocols that recognize the variations in system response and recovery times throughout the year, especially during the winter season. In fact, additional categories, or different protocols, are needed to be added to previous managerial emergency response frameworks proposed in the literature (Pender et al. 2013) as well as to the one used by the TTC. These frameworks, which are based only on disruption characteristics of duration, cause, time of day, and location, need to account for seasonal changes in service response and recovery time as observed in the case of Toronto. In addition, a study that develops new protocols for an integrated approach to retracting buses from regular routes in combination with reserved spare buses (and drivers) according to the city context is recommended. This would be important for some cities that experience special seasonal weather conditions. For example, new protocols that facilitate faster response and recovery times during the winter months should be developed, since passengers during this time of year are more sensitive to any increase in their outdoor times including their waiting and walking times (Lam and Morrall 1982).

One of the contributions of this study is providing a detailed framework based on actual case study to understand different aspects of the shuttle bus service workflow. For example, this study broke down the system response time into three major components: Initial Response Time, Bus Pull out Time and Bus Deadhead time, while breaking the bus system recovery time into Bus Service Time on the shuttle service and Bus Returning Time to original routes. It also classified buses into three categories to better examine the challenge of providing shuttle bus service, including buses requested by the control centre, buses assigned by divisions, and buses that actually arrived to the shuttle service location and provided the required emergency service. Also it developed Division Response Rate measure to account for the number of assigned vs. requested buses by divisions. This framework could be adapted for other transit agencies to compare the relative performance across agencies, monitor trends over time for individual agencies, and understand the impacts of new response management strategies.

Another policy implication of this study is the need to employ a specific protocol to initiate the emergency shuttle bus service by sourcing buses from scheduled service. An effective communication plan is required in order to alert promptly the passengers of the affected bus routes about the removal of scheduled trips. This is an important issue since, since passengers tend to overestimate their waiting time compared to the actual wait time when it is imposed by others (e.g., transit system) whereas they accurately estimate their waiting time when they themselves choose to wait (Hess et al. 2004). Thus, by informing passengers, through social media for example or by using transit apps alerts and bus stop variable message signs, about the removal of some trips and the reasons behind that would help reduce the negative impact of service cancellation on users' perception. Nevertheless, a more detailed study about the impact of information provision and the type of used media on bus user travel behaviour and satisfaction is recommended.

While the challenge of sourcing the adequate number of buses from the existing scheduled service is well-understood, another policy implication of this paper is to reconsider the number of buses taken from certain divisions (or locations). For example, instead of having a fixed percentage of buses that should be sourced from a division, new criteria that weight the percentage of buses according to the division's average response and recovery times can be explored. In other words, fewer buses should be retracted from far locations, since these buses would take more response and recovery times, leading to longer cancelled times for their users than users of nearby routes. Thus, providing more flexibility in the percentage of required buses from each division according to its location and incident location will mean a higher overall system efficiency.

Finally, this study provides a broad evaluation of the current bus bridging practices, highlighting some operational and managerial challenges related to pulling buses from regular bus service. For example, in addition to the previous points discussed above, the number of requested buses by route management does not normally match the number of assigned buses by the various bus divisions. In addition, some of retracted buses arrive to the subway disruption location after the clearance of the incidents, thereby failing to serve as a shuttle service. Furthermore, the number of retracted (or assigned) buses per route is not always proportional to its ridership level and frequency, which highlights a considerable impact on the users of low frequency bus routes. This study also shows considerable challenges in terms of longer recovery and response times during weekends and off-peak periods, which can be attributed to the reduced bus fleet in service during these periods, with less available trippers for retraction. This limits the shuttle bus options for the transit agency and prolongs the system response and recovery time as well as the overall decision making process.

The previous observed challenges call for a better and more sophisticated tool for the optimal design of the bus bridging strategy. In fact, the presented study provides useful and necessary insights which serve to inform ongoing work by the authors on developing such a tool. The study also serves as a baseline against which to compare the new optimal bus bridging analytics. This optimal strategy could be formulated to minimize the system total user costs in terms of bus and subway users' total waiting and travel times. The solution of this optimization problem can be based on several inputs including: subway incidents location, start time and expected duration; subway through and local user volumes; and total number of required buses from a route and their response and recovery times (i.e., Pull out Time, Deadhead time and Returning time). The optimal strategy must respect some service quality constraints such as making sure that gaps in the bus service due to pulled buses are still within the headway policy of the transit agency, and all requested buses arrive and serve in the shuttle service, which would help in providing more efficient and comprehensive bus bridging solutions.

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REFERENCES

American Public Transportation Association (APTA). 2013. APTA transit ridership report, Second Quarter, 2013. American Public Transportation Association (APTA), Washington, D.C.

Bates, J., Polak, J., Jones, P., and Cook, A. 2001. The valuation of reliability for personal travel. Transportation Research Part E: Logistics and Transportation Review **37**(2–3): 191-229.

Codina, E., and Marin, A. 2010. A design model for the bus bridging problem, Lyons, France.

Darmanin, T., Lim, C., and Gan, H. 2010. Public railway disruption recovery planning: A New recovery strategy for Metro Train Melbourne, Melaka, 7-10 December 2010

Diab, E., and El-Geneidy, A. 2013. Variation in bus transit service: Understanding the impacts of various improvement strategies on transit service reliability. Public Transport **4**(3): 209-231.

Diab, E., and Shalaby, A. 2017. Understanding the impacts of subway's system interruptions on streetcar and bus transit service performance, Santiago, Chile.

Diab, E., van Lierop, D., and El-Geneidy, A. 2017. Recommending transit: Disentangling users' willingness to recommend transit and their intended continued use. Travel Behaviour and Society **6**: 1-9.

Hess, D., Brown, J., and Shoup, D. 2004. Waiting for the Bus. Journal of Public Transportation **7**(4): 67–84.

Kepaptsoglou, K., and Karlaftis, M. 2009. The bus bridging problem in metro operations: conceptual framework, models and algorithms. Public Transport **1**(4): 275-297.

Lam, W., and Morrall, J. 1982. Bus passenger walking distances and waiting times: A summer–winter comparison. Transportation Quarterly **36**(3): 407–421.

Lin, T. 2017. Transit user mode choice behaviour in response to TTC rapid transit service disruption Department of Civil Engineering, University of Toronto, Toronto.

Lin, T., Shalaby, A., and Miller, E. 2017. Transit user behaviour in response to subway service disruption, London, Ontario, Canada.

Nam, D., Park, D., and Khamkongkhun, A. 2005. Estimation of value of travel time reliability. Journal of Advanced Transportation **39**(1): 39-61.

Noland, R., and Polak, J. 2002. Travel time variability: A review of theoretical and empirical issues. Transport Reviews **22**(1): 39-54.

Ontario Ministry of Finance. 2015. Ontario population projections update, 2015–2041. Available from http://www.fin.gov.on.ca/en/economy/demographics/projections/ [accessed 24 July 2016 2016].

Pender, B., Currie, G., Delbosc, A., and Shiwakoti, N. 2013. Disruption recovery in passenger railways: International survey. Transportation Research Record: Journal of the Transportation Research Board(2353): 22-32.

Pender, B., Currie, G., Shiwakoti, N., and Delbosc, A. 2015. Economic viability of bus bridging reserves for fast response to unplanned passenger rail disruption. Transportation Research Record: Journal of the Transportation Research Board(2537): 13-22.

Schmöcker, J., Cooper, S., and Adeney, W. 2005. Metro service delay recovery: Comparison of strategies and constraints across systems. Transportation Research Record: Journal of the Transportation Research Board **1930**: 30-37.

TTC. 2012. Surface ridership 2012. Available from https://www.ttc.ca/About_the_TTC/Transit_Planning/Surface_Ridership_2012.jsp [accessed 24 July 2016].

TTC. 2013. TTC Operating Statistics 2013. Available from https://www.ttc.ca/About_the_TTC/Operating_Statistics/2013.jsp [accessed May 2nd 2016].

van der Hurk, E., Koutsopoulos, H., Wilson, N., Kroon, L., and Maróti, G. 2016. Shuttle planning for link closures in urban public transport networks. Transportation Science **0**(0): null.

Wang, Y., Guo, J., Currie, G., Dong, W., and Pender, B. 2014. Bus bridging disruption in rail services with frustrated and impatient passengers. IEEE Transactions on Intelligent Transportation Systems **15**(5): 2014-2023.

Table 1: Number of required buses to be retracted for the shuttle service

Expected incident time		+30 MINS			1 - 30 MINS		
Closed subway stations		**1-4**	**5-9**	**10+**	**1-4**	**5-9**	**10+**
Percentage (%)		3.33%	6.66%	10%	1.67%	3.33%	5.00%
Time period	Number of buses for regular service	Number of required buses for the shuttle service					
6:00 – 9:00	1325	44	88	133	22	44	66
9:00 – 15:00	881	29	59	88	15	29	44
15:00 – 19:00	1426	47	95	143	24	47	71
19:00 – 22:00	819	27	55	82	14	27	41
22:00 – 1:00	506	17	34	51	8	17	25

**Source: TTC's Route Management Department*

Table 2: Five most frequent reasons for streetcar and subway incidents

Reason	Incidents	Buses Requested	Buses Assigned	Average Response Time (min)	Average Clear Time (min)
A. Streetcar incidents					
Auto/Pedestrian Accident	372	1.9	1.8	21.7	53.6
Disabled Streetcar	145	1.9	1.7	18.0	52.9
Cold Weather	83	2.6	2.3	61.3	453.6
Overhead Wire Down	30	3	2.4	31.6	152.8
Working Fire/Fire on Streetcars	15	2.2	2	36.8	85.2
Medical Emergency	11	1.9	1.7	16.8	21.8
B. Subway incidents					
Fire, Smoke or Burning Odour	32	6.3	6.2	31.5	60.8
Power Problem	14	12.5	9.9	52.5	307.2
Suicides on the Subway Tracks	12	9.6	9.4	40.1	111.8
Unauthorized at Track Level	10	6.3	5.6	23.3	51.8
Medical Emergency	10	6.7	7.5	44.6	111
Cold Weather	7	5	4.7	20.8	41.6

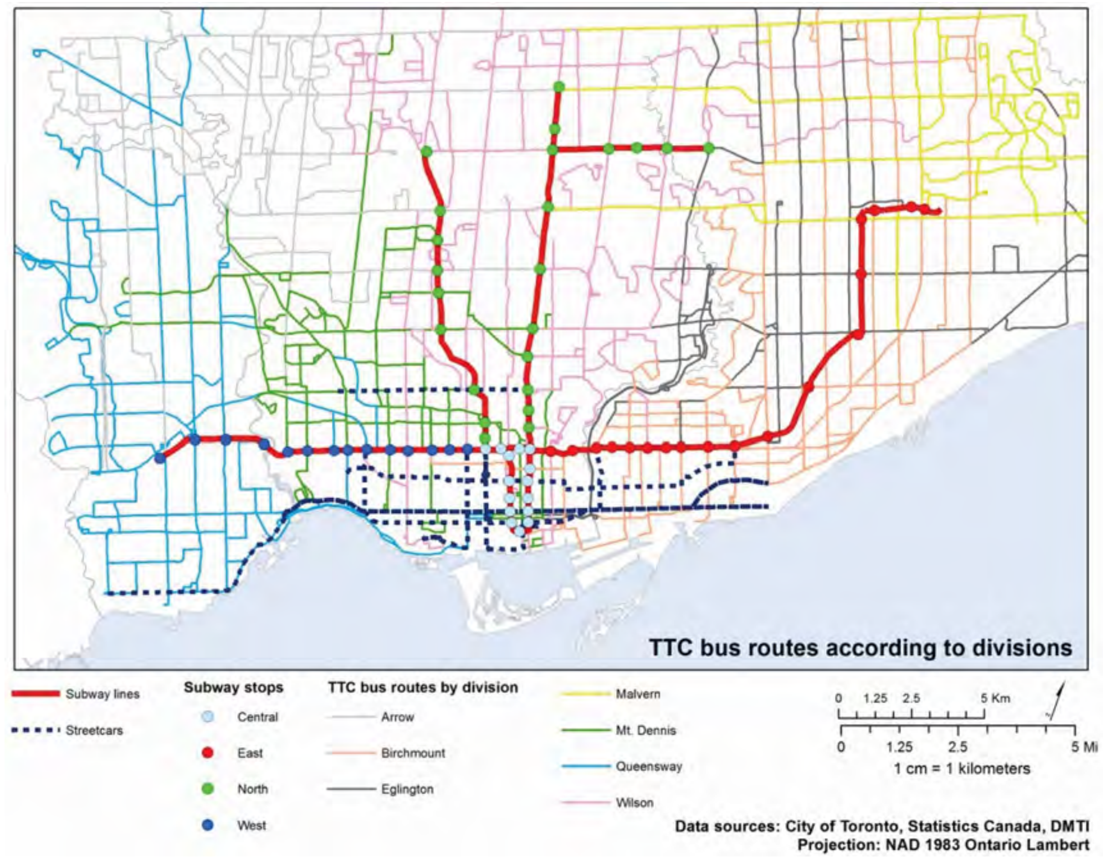

Figure 1: TTC system map of streetcar, subway and bus lines

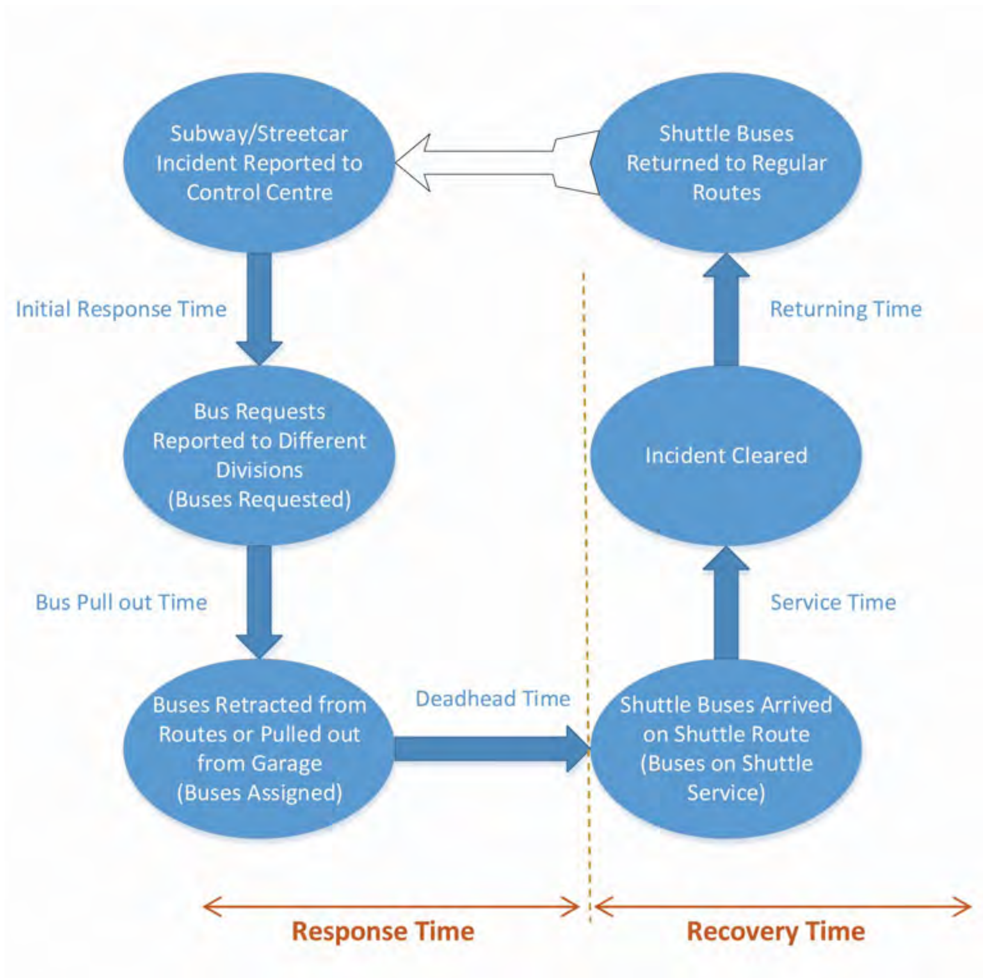

Figure 2: Regular workflow cycle for a shuttle bus service.

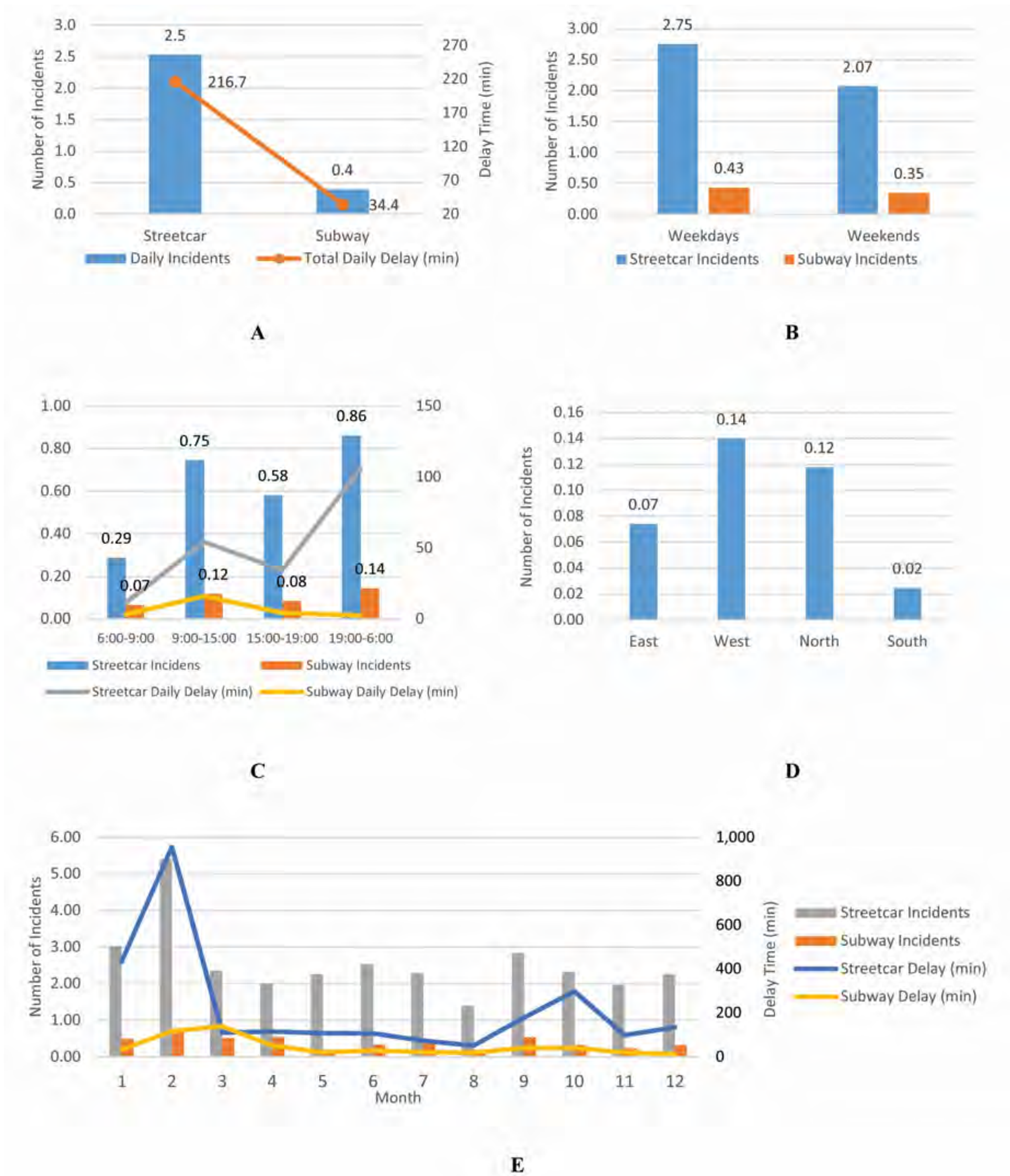

Figure 3: A- Daily incidents and total daily delay by mode, B- Daily subway incidents by weekday vs weekend, C- Daily incidents and average delay by time period, D- Daily subway incidents by location, and E- Daily incidents and total daily delay by month.

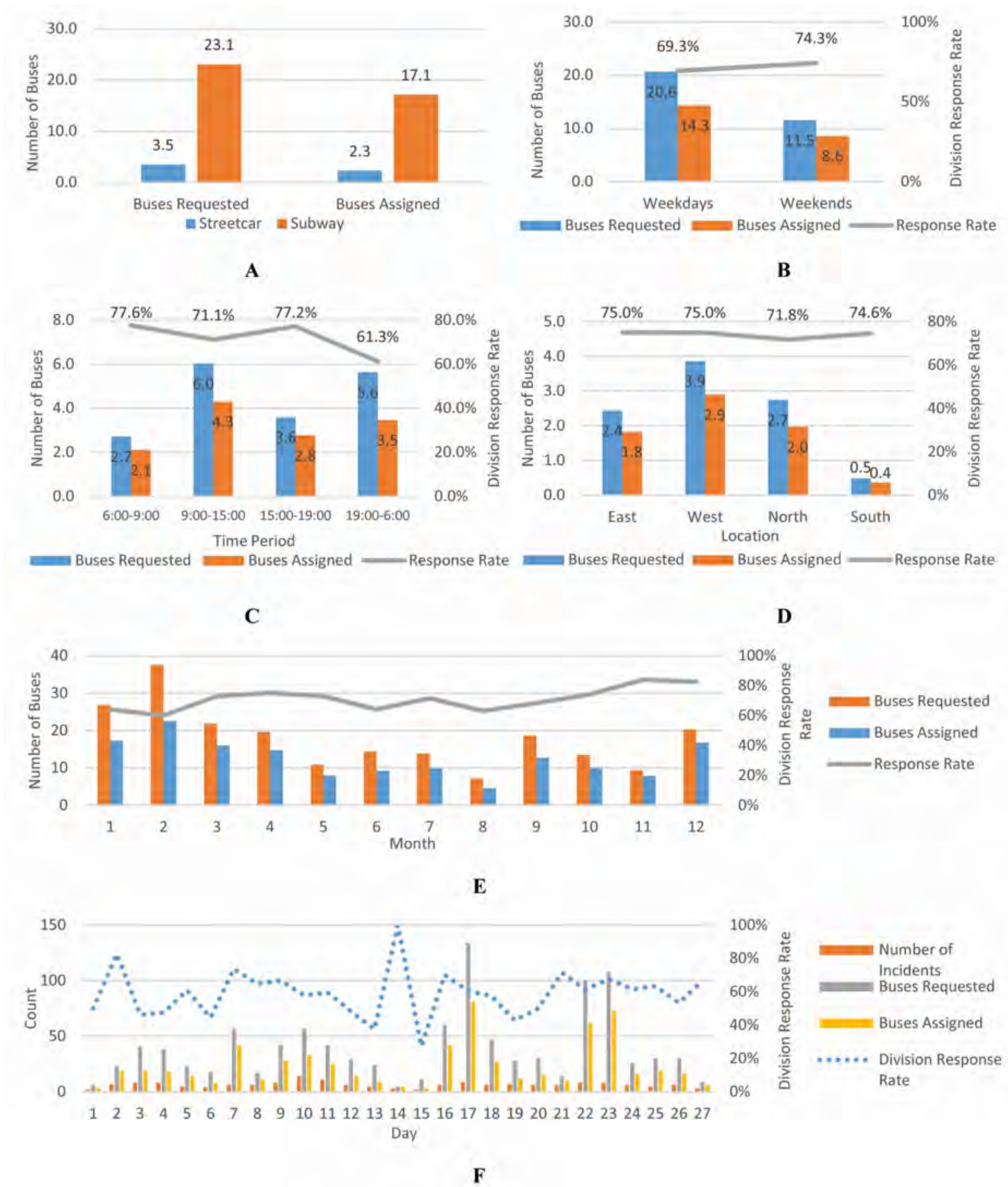

Figure 4: A- Buses requested and assigned per incident by mode, B- Daily buses requested and assigned by weekday vs. weekend, C- Daily buses requested and assigned by time period, D- Daily buses requested and assigned by location (for the subway system), E- Daily buses requested and assigned by month, and F-. Daily shuttle bus service analysis for February 2015.

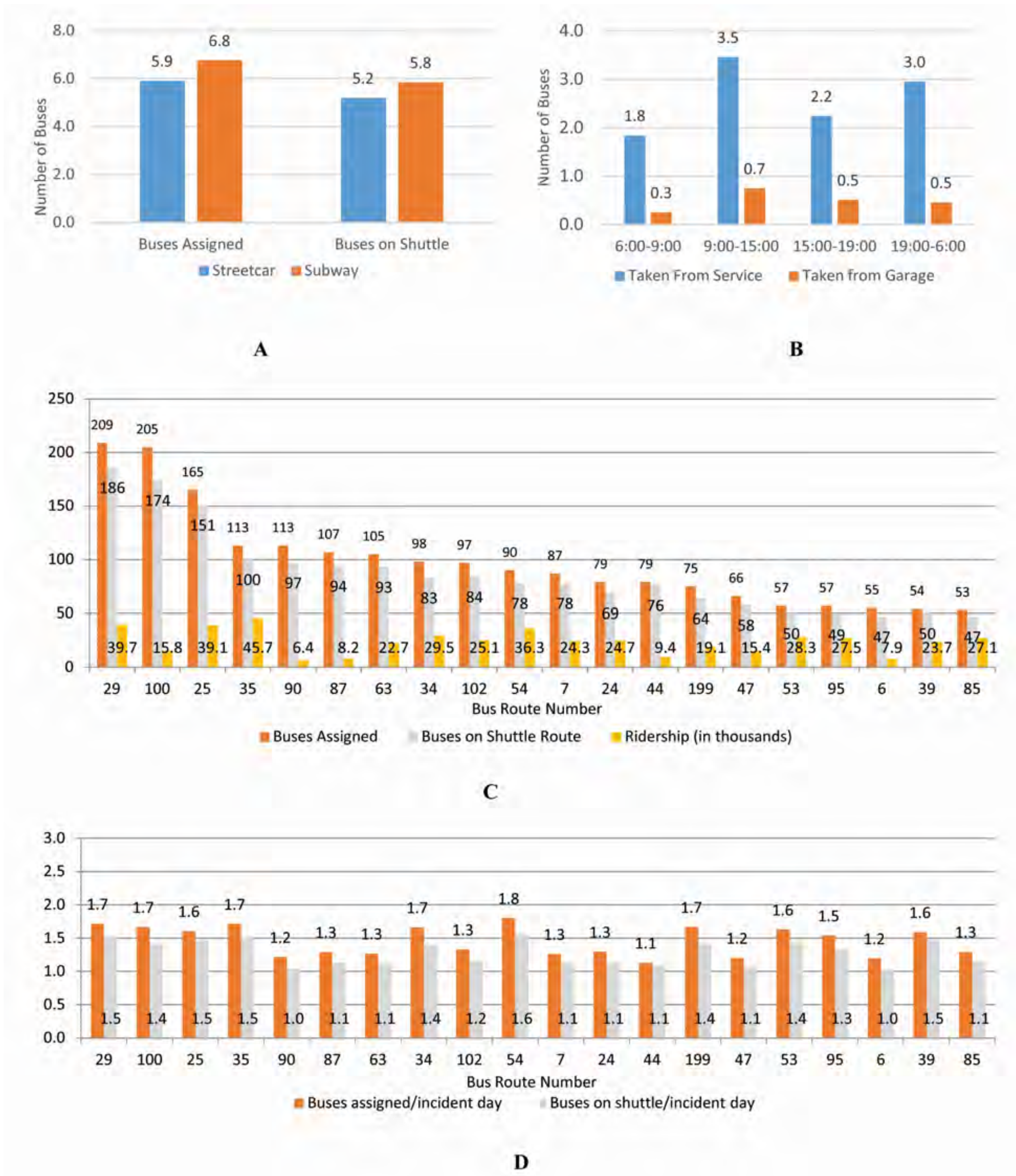

Figure 5: A- Daily assigned and in-shuttle buses by mode, B- Daily buses retracted from scheduled service and garages by time period, C- Top 20 bus routes that supplied buses for shuttle service in 2015, and D –Buses retracted from scheduled service on the incident days.

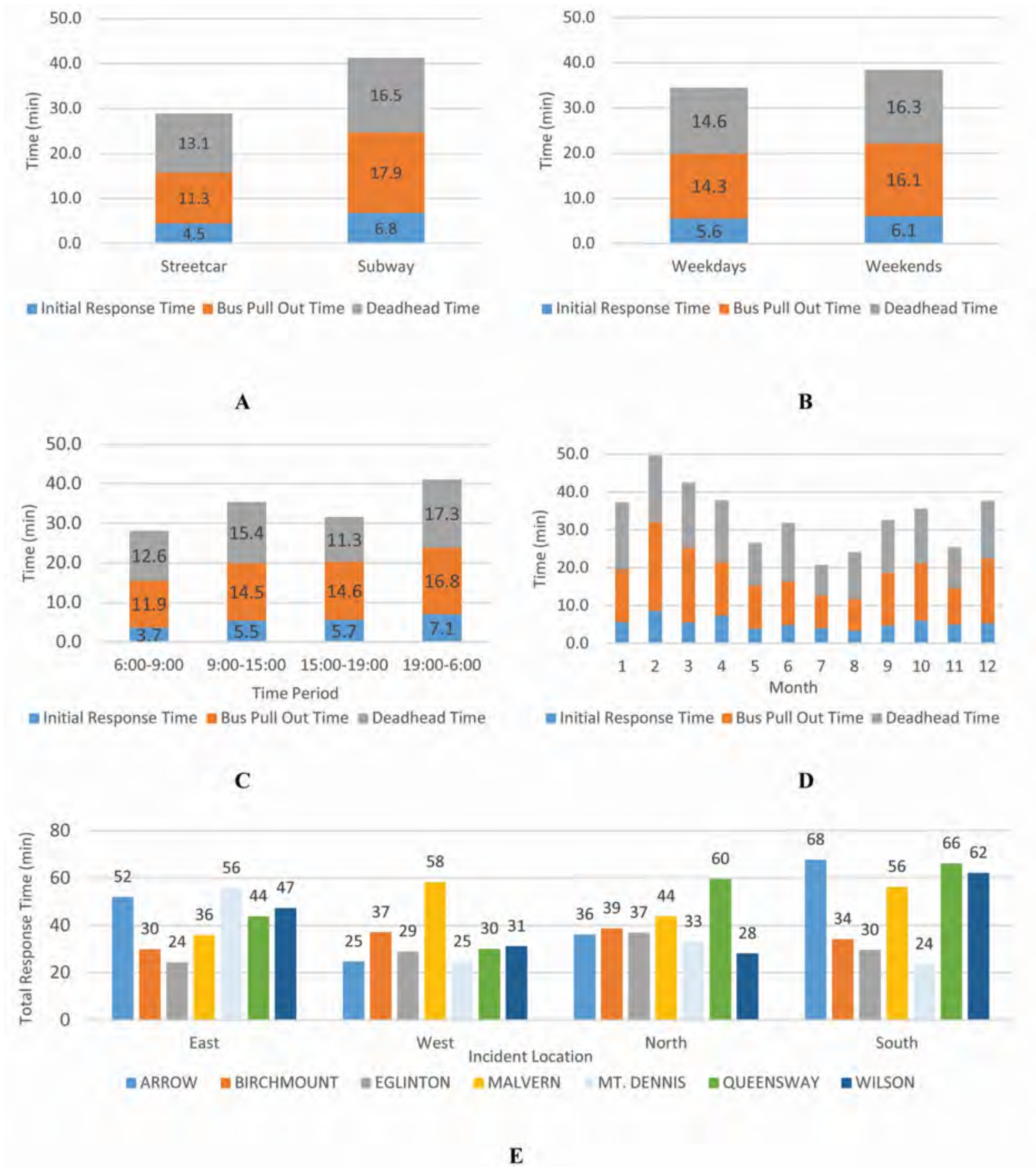

Figure 6: A- Average bus response time by mode, B- Average bus response time by weekday vs. weekend, C- Average bus response time by time period, D- Average bus response time by months, and E. Average bus response time by location in subway network

and division.

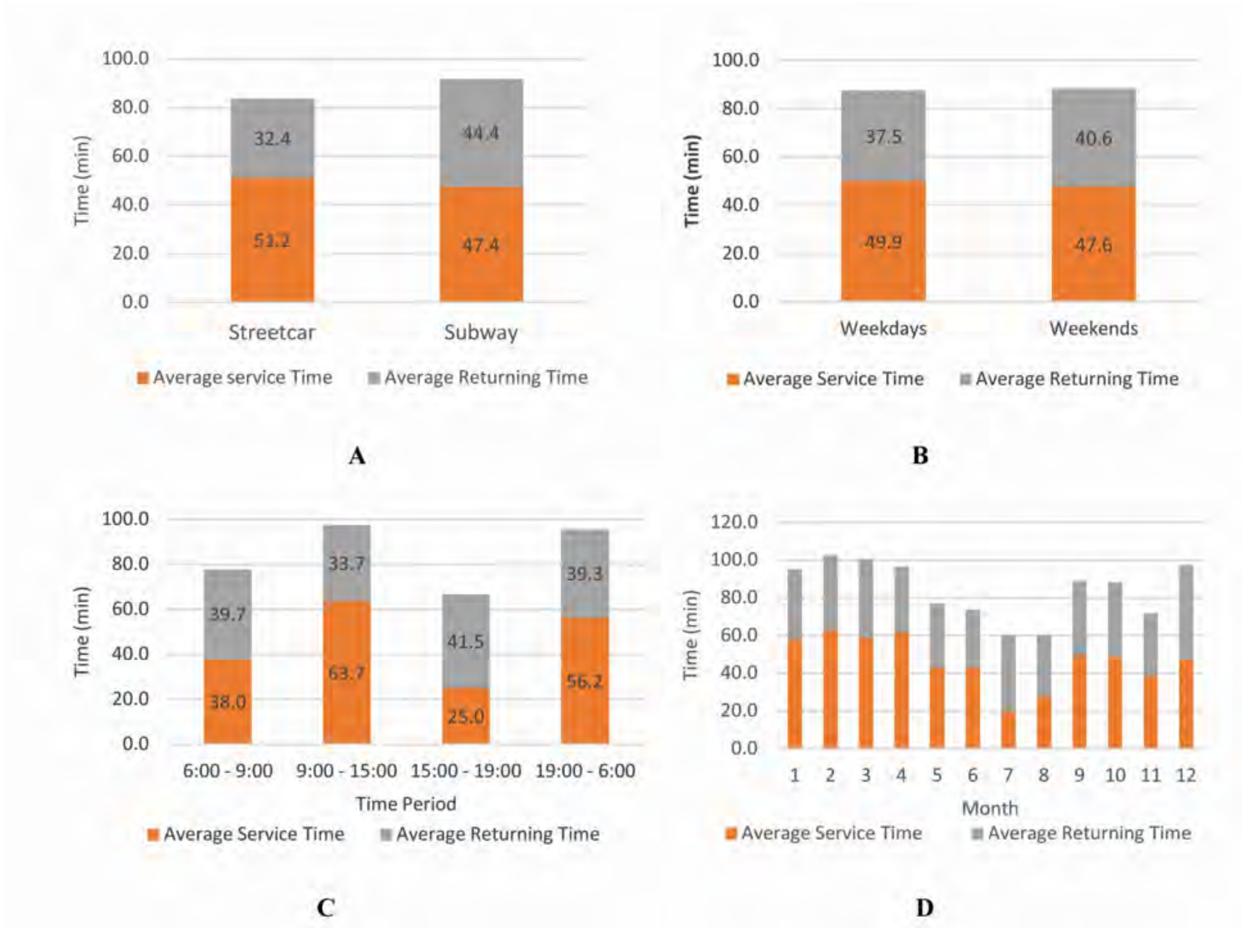

Figure 7: A- Average recovery time by mode, B- Average recovery time by weekday vs. weekend, C- Average recovery time by time period, and D- Average recovery time per bus over the months of year.