Journal of Transport Geography 88 (2020) 102870

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

A social equity lens on bus bridging and ride-hailing responses to unplanned subway disruptions

Rick Liu[a], Matthew Palm[b,*], Amer Shalaby[a], Steven Farber[b]

[a] Civil and Mineral Engineering, University of Toronto, Canada
[b] Human Geography, University of Toronto, Scarborough, Canada

ARTICLE INFO

Keywords:
Transport equity
Public transit
Transit resilience
Service disruption

ABSTRACT

During subway disruptions, commuters are often left stranded while they wait for bus bridging services. Some are able to change their mode of transport midway through their trip, often by requesting a ride-hailing service like Uber or Lyft if they are affordable. Many agencies use in-service buses to provide bus bridging services during subway disruptions, leading to reduced levels of service for other bus riders. Bus bridging policies and the affordability of ride-hailing raise questions regarding the equitable distribution of transit capacity during subway disruptions. After analyzing 78 major subway disruptions in Toronto, we found that bus routes serving disadvantaged populations were more likely to be negatively impacted by diversions for subway disruptions, than routes operating in more affluent areas of the city. We also found that ride-hailing demand increased during subway disruptions, but not in the more disadvantaged neighbourhoods. The research points to inequalities in how transit riders are impacted by subway disruptions, and further identifies how ride-hailing actually serves to reinforce these inequalities, rather than ameliorate them.

1. Introduction and purpose

Policymakers are paying increased attention to unplanned subway disruptions, as transit agencies struggle to maintain service with limited funding. Many transit agencies respond to unplanned rail disruptions by redeploying in-service buses as replacement shuttles to fill subway service gaps, a strategy known as bus bridging (Itani et al., 2019). As one study found, bus bridging is one of the most common disruption recovery strategies among rail systems worldwide, and just under half of surveyed rail systems divert in-service buses to bus bridging (Pender et al., 2013a). Recently, ride-hailing is becoming a popular alternative to waiting for replacement buses during these unplanned disruptions. Ride-hailing use around subway stations in Toronto doubles during unplanned disruptions lasting over 30 min (Big Data Innovation Team and UTTRI, 2019, p. 34). Ride-hailing prices often surge in these situations, leading to excoriating media coverage and accusations that ride-hailing firms are taking advantage of stranded transit riders (O'Neil, 2019; Posadzki, 2015).

Unplanned disruptions may cause serious hardship to transit-dependent riders and low-income individuals who are already less likely to use ride-hailing in normal conditions (Young and Farber, 2019). Further, the choice to bridge subway services by pulling shuttles from active bus routes may create additional hardships, as disadvantaged travelers depend more heavily on bus service than on other modes of transit (Pucher and Renne, 2003; Taylor and Morris, 2015). No prior research considers the social equity implications of subway disruptions, bus bridging responses, or the role of ride-hailing in disruptions, despite some evidence that disruptions can be particularly costly to disadvantaged travelers (Bureau of Policy and Research, 2017; Gorton and Pinkovskiy, 2018). This study examines bus bridging and ride-hailing responses to subway disruptions in Toronto through a social equity lens.

Our approach combines a detailed database of 33 million ride-hailing trips with census demographic data and detailed records of subway disruptions and associated bus re-routings. Data are analysed through summary statistics and the Getis-Ord local G_i^* statistic (Getis and Ord, 1992), proposed in the literature as an optimal hot spot detector for transportation operations analysis (Songchitruksa and Zeng, 2010).

Our results offer two findings for the literature. First, the TTC's bus bridging policy disproportionately impacts bus routes with high racialized ridership.[1] This result stems from the agency's preference to pull buses from its 10-min network, which predominantly serves suburban racialized communities. Second, ride-hailing demand response to subway disruptions is significantly lower in the city's disadvantaged

* Corresponding author.
E-mail address: matthew.palm@utoronto.ca (M. Palm).

[1] In the Canadian context about which this paper is written, *racialized* is the accepted term of use (Ontario Human Rights Commission, 2020).

https://doi.org/10.1016/j.jtrangeo.2020.102870
Received 3 July 2020; Received in revised form 23 September 2020; Accepted 28 September 2020
Available online 05 October 2020
0966-6923/

neighbourhoods compared to other neighbourhoods. Our findings illustrate that ride-hailing is providing a convenient way out of subway disruptions for travelers in more advantaged neighbourhoods while other travelers remain left behind.

2. Literature

This paper intersects with transportation research on three topics: social equity, subway disruptions, and ride-hailing. This review starts with a high-level discussion of transport equity and then argues for the relevance of subway disruptions and ride-hailing demand response as un-examined topics worthy of study from equity lenses.

2.1. Social equity and public transit

Transportation equity research evaluates how the benefits and burdens of transportation infrastructure are distributed by socio-economic strata (Guo et al., 2020). These analyses inform planning decisions for infrastructure investments or examine changes to existing service. Researchers in this area generally draw upon one of two equity lenses to interpret their results: horizontal equity and vertical equity. A proposed investment or service change is horizontally equitable if the benefits of the change are distributed equally between groups. Vertical equity, instead, is characterized by benefits being distributed proportionally in relation to groups' needs. For example, a transit project that provides more benefits to an under-served neighbourhood may still be considered equitable through vertical lenses if that neighbourhood contains a higher share of carless households whose need for transit is greater.

While a growing equity literature informs long range transportation planning (Allen and Farber, 2020; Karner, 2018; Karner and Niemeier, 2013), little work examines the equity of transit operations (Palm et al., 2020). Within North America, only the United States government mandates equity assessments of transit operations. The Federal Transit Administration's interpretation of Title VI of the Civil Rights Act requires agencies to episodically compare routes labeled as serving ‘minority’ and ‘non-minority’ communities with respect to service quality, but only at a very aggregated scale (FTA, 2012). The variables compared include on-time performance, vehicle loading, fleet age, and station quality, among others. However, average differences between routes serving different demographic groups may mask the existence of very poor performing routes serving disadvantaged and transit-dependent travelers (Palm et al., 2020). The choice of data inputs can also significantly alter the results of these techniques (Karner and Golub, 2015).

FTA Title VI monitoring does not include tracking of disparate impacts from major service disruptions or agency recovery strategies such as bus bridging. Theoretically at least, an agency with a bus bridging policy that disproportionately pulls in-service buses from routes serving marginalized communities would be less likely to report equitable on-time performance in an FTA review. However, no explicit equity assessment of bus bridging strategies has been conducted in either the policy context or the academic literature, at least to our knowledge. This constitutes a significant research gap that this study aims to fill. The following section outlines the need to fill this gap, focusing first on the impacts of unplanned disruptions before discussing the impacts of agency responses and ride-hailing.

2.2. Unplanned subway disruptions

Major rail and subway disruptions warrant equity assessment due to their regularity and the potential severity of their impact on transit travelers. For metros and subways, a major disruption is generally defined as an incident requiring the closure of a track for an extended period of time (Schmöcker et al., 2005). Major disruptions are caused by a wide array of events, including extreme weather, accidents, malfunctions, broken tracks and fires. Agency policies can mitigate the likelihood of these occurrences. For example, in Toronto, the probably of an incident taking place on weather-exposed line segments increases as the amount of snowfall on the ground reaches 15 cm. But after 15 cm it declines, as the agency switches to storm trains when grounded snowfall exceeds 15 cm (Diab and Shalaby, 2019). Weather-exposed tracks are more likely to experience major disruptions in general, a concern for cities like Toronto with large segments of exposed tracks. Agencies must also contend with safety-related service disruptions, such as fires, suicides, and unauthorized use of the track level. These types of problems can cause longer service delays than other incidents when agencies take a ‘safety first’ approach to such situations, as the TTC does in Toronto (Louie et al., 2017).

Regardless of cause, the delays introduced by disruptions alter the levels of accessibility that public transit provides urban residents in significant and non-random ways (Wessel and Farber, 2019). This makes the spatio-temporal patterns of subway disruptions and their impacts on the entire transit system relevant for those seeking accurate assessment of the benefits delivered by transit service. Operators across the world define and report major disruptions in different ways. The New York MTA defines a disruption as major if at least 50 trains are delayed. The agency's subway system has experienced roughly 62 major incidents per month over the last five years, with a high of 105 in January 2018, and a low of 29 in January 2020 (MTA, 2020). Toronto's TTC also releases delay data for each incident. A public analysis of that data suggests that TTC vehicles are delayed by between 37 and 80 h per month (Davis and Weatherburn, 2017).

The frequency and magnitude of disruptions makes agency responses similarly significant and impactful. Frequent major subway disruptions mean lost bus service for bus riders when agencies bridge disruptions by pulling in-service vehicles off their routes. Roughly 45% of agencies surveyed globally pull in-service vehicles for bus bridging of rail or subway systems (Pender et al., 2013a). The impact of this decision can vary depending on how agencies structure their bus bridging protocols. Our case study agency, the TTC, aims to pull shuttles evenly from each of its major dispatch divisions. The agency does this to minimize the loss of bus service in any one part of the city. This decision introduces inefficiencies as it often means buses are diverted to subway disruptions located on the opposite end of the city, increasing the number of deadhead miles during which the shuttle is not actively serving stranded subway riders or regular bus service users (Diab et al., 2018). Agencies may also temper the number of shuttles it diverts to an incident based on the capacity of local surface transit around that incident. For example, the TTC tends to deploy fewer shuttles during disruptions in the core of the city where parallel streetcar service is available. This decision preserves bus service elsewhere in the city, but researchers have implicated this choice with sharper drops in streetcar speeds when subway incidents occur nearby (Diab and Shalaby, 2018).

Researchers have responded to the quandary of sacrificing bus service for bus bridging by developing optimization tools that can help agencies minimize total time lost by subway and bus riders jointly (Kepaptsoglou and Karlaftis, 2009). Recent work in this area focuses on optimizing bridging routes (Deng et al., 2018), as well as optimizing the selection of buses to pull from across a network (Aboudina et al., 2020; Itani et al., 2020) Minimizing the impacts of bus bridging means pulling buses from routes nearest to disrupted segments of subway lines and minimizing dispatch times (Itani et al., 2019, 2020). Better estimates of incident duration at the start of incidents can also reduce the likelihood of agencies re-deploying in-service buses that end up not being needed (Louie et al., 2017). The availability of alternative transit lines can also greatly reduce travelers' delays (Itani et al., 2019). These modelling techniques, however, focus on aggregate time savings across all travelers, and do not explore in detail how the burden of delays are distributed across different groups of impacted travelers. Furthermore, many existing optimization tools do not account for how some delayed passengers may turn to taxis and ride-hailing while waiting for replacement shuttles to arrive.

2.3. Ride-hailing, transit and social equity

The added presence of ride-hailing during subway disruptions further complicates the equity implications of disruptions. Most travelers impacted by subway disruptions will wait or switch to another transit mode (Adelé et al., 2019; Pnevmatikou et al., 2015; Zhu et al., 2017). However, the minority who do switch modes during a disruption are more likely to be of higher incomes (Lin et al., 2018; Pnevmatikou et al., 2015; Zhu et al., 2017). This is in-line with findings that ride-hailing is used disproportionately by higher income travelers in general (Conway et al., 2018; Young and Farber, 2019). The extent of ride-hailing use during subway disruptions may vary depending on the severity and location of a disruption. More recent analysis of ride-hailing trips suggests that use of these services nearly doubles during major subway disruptions that last longer than 30 min (Big Data Innovation Team and UTTRI, 2019). The impact of this new service on the overall loss of traveler time, and the distribution of that loss by socio-economic strata, is also not well understood. This paper fills this gap through an equity analysis of subway disruptions in Canada's largest city.

3. Methods

This study seeks to bridge two gaps in the transportation equity literature. First, what are the equity impacts of bus bridging policy that pulls in-service buses? And second, who benefits from the availability of ride-hailing during unplanned subway disruptions? This methodological discussion begins with an overview of how the authors identified a dataset of subway disruptions, and then outlines our approaches to answering the two questions motivating this paper. These three subsections are followed with a brief discussion of study limitations and a case study section that maps summary statistics from the data sources.

3.1. Defining subway incidents

The Toronto Transit Commission (TTC) lists every subway delay through an open data portal. We limit our study to those lasting 30 min or longer, as this is the threshold over which the TTC will deploy bus bridging. The nature, location, and severity of incidents may vary by season, so we included a full year's worth of major incidents, from October 2017 to September 2018, resulting in a final sample of 78 major subway incidents with bus bridging response, about 1.5 major incidents per week.

3.2. Equity analysis of bus bridging response

For each of the 78 incidents, the TTC provided a list of buses pulled from in-service routes across the city. Conducting an equity assessment of these decisions required classifying bus routes with respect to the populations they serve. In this instance, we borrowed a Canadian adaptation of the U.S. FTA's operational equity guidance (Palm et al., 2020). This approach classifies bus routes as equity or non-equity based on the demographics of neighbourhoods they serve. In the Toronto context, this meant that routes passing through non-white-majority neighbourhoods for at least a third of their service lengths were classified as equity routes, while all other routes were classified as non-equity routes. Neighbourhood demographic data came from the 2016 Census, and were defined at the Dissemination Area scale. The Canadian Census' Dissemination Area contain between 300 and 700 residents on average (Statistics Canada, 2018).

We conducted our analysis by comparing two values. The first is the proportion of buses pulled from equity routes. The second is the proportion of in-service vehicles that were operating on equity routes during the incident. In this approach, a disparate impact occurs when the percentage of bus bridging shuttles diverted from equity routes is greater than the proportion of in-service vehicles operating on equity routes at the time of the disruption. The condition of disparate impact is described in Eq. (1) below,

$$\frac{\sum_i (x_{ij}y_i)}{\sum_i x_{ij}} > \frac{\sum_i (z_{ij}y_i)}{\sum_i z_{ij}} \quad (1)$$

where x_{ij} refers to the number of vehicles pulled from route i for incident j, y_i equals one for an equity route and zero otherwise, and z_{ij} refers to the number of vehicles in-service on route i during incident j. We aggregated these results by subway line to explore if disparate impacts in bus bridging outcomes varied across the city. Differences in proportions were tested with the chi-squared test.

Finally, vehicles pulled from routes further away from incidents may be impacted more by the time during which the shuttles are deadheading to the disruption from their original route and back. To capture this deadheading impact, we also compared the capacity reduction between equity and non-equity routes impacted by bus bridging. Capacity loss is measured temporally: the time from the moment when the bus left its scheduled route to the moment when it returned to regular service is called the bus's out-of-service time. To estimate capacity loss, we divided each bus's out-of-service time by its route cycle time. One route cycle equates to a vehicle going the full length of its route in both directions. The resulting metric captures the full duration of bus service time lost to bus bridging as a function of how much service the bus could have provided on its own route during that time. The condition of disparate impact in capacity loss is described in Eq. (2) below,

$$\frac{\sum_i (a_{ij}y_i)}{\sum_i a_{ij}} > \frac{\sum_i (b_{ij}y_i)}{\sum_i b_{ij}} \quad (2)$$

where a_{ij} refers to the number of route cycles lost to route i during incident j, and b_{ij} refers to the number of route cycles scheduled on route i on the day of incident j.

3.3. Equity analysis of ride-hailing response

Our data on ride-hailing comes from the City of Toronto, which mandated that Private Transportation Companies (PTCs) share trip level data with the city as a condition of operating within city limits (Big Data Innovation Team and UTTRI, 2019). The data constitutes a census of all ride-hailing trips that took place during the study period. Variables include trip origins and destinations at the level of the nearest intersection, as well as trip pick up times by the hour.

We hypothesize that during subway disruptions, ride-hailing pick ups will increase in neighbourhoods near the disruptions relative to normal demand at that hour. We further hypothesize that such increases will be smaller or less frequent in disadvantaged neighbourhoods. We use the City of Toronto's Neighbourhood Improvement Areas (NIAs) to define disadvantaged neighbourhoods. These are 31 of the city's 140 neighbourhoods that are identified as having high levels of social and economic marginalisation that the city aims to rectify (City of Toronto, 2020).

To test our hypotheses, we first define a ride-hailing demand baseline against which we measure the number of increases in ride-hailing pick ups during disruptions. We define the baseline as the average demand for ride-hailing during the hour of the incident, but for the other days of that month. For example, for a disruption at 4:05 pm on Tuesday in November, we consider the average demand between 4:00 pm and 5:00 pm on the other Tuesdays in November.

This baseline is used to calculate the ride-hailing response as

$$\frac{a_{ijt} - b_{ijt}}{b_{ijt}} \quad (3)$$

where a_{ijt} is the count of ride-hailing pick ups in neighbourhood i, in the hour of the incident, and b_{ijt} is the above defined baseline level of demand.

We then calculate the Getis-Ord G_i^* statistic for each neighbourhood's ride-hailing demand response during each incident to assess the clustering of changes in demand. The G_i^* detects spatial hot spots by calculating the sum of a variable for a given spatial unit and its immediate neighbours, and divides this over the total value of that variable across the study area. Larger and smaller local sums indicate hotspots and coldspots, respectively, and these can be tested against a spatially random null hypothesis using a normalized test statistic [See Getis and Ord, 1992 and 1995 for derivations]. We thus calculate the G_i^* for each of Toronto's 140 neighbourhoods for each of the 78 major incidents, producing 10,920 tests. We then compare the significance of these tests between NIA and non-NIA neighbourhoods to identify the evenness of ride-hailing demand response between advantaged and disadvantaged communities.

Like many local spatial statistics (Anselin, 1995), G_i^* comes with one drawback: an increased false discovery rate due to spatially overlapping neighbourhoods. To control for this false discovery rate, the FDR approach described by Castro and Singer was used, as the alternative Bonferroni correction was too conservative in determining the number of neighbourhoods with significant local hotspots (Caldas de Castro and Singer, 2006). The FDR approach corrects for false discovery by determining a more stringent p-value to reject the null hypothesis, and the procedure was performed for every neighbourhood during each subway disruption.

4. Results

We begin our results by providing the demographic context of bus and subway ridership in Toronto. This study is motivated, in part, by an assumption that bus bridging with in-service buses is likely to burden disadvantaged riders because they are over-represented on buses relative to subways. The literature supporting this assertion comes almost exclusively from the United States (Pucher and Renne, 2003; Taylor and Morris, 2015), so we first confirm that this assumption holds true in Toronto.

Table 1 shows the relevant demographics of bus and subway riders in Toronto, drawing on the 2016 Transportation Tomorrow Survey, the region's household travel survey (DMG, 2014). Each rider was assigned a probability of being racialized based on their home neighbourhood's demographics, in line with the approach used to classify equity bus routes (Palm et al., 2020). Bus riders are more likely to be racialized, in line with the American experience, yet the total number of racialized travelers on the subway is larger. This suggests that the equity impacts of diverting active buses to bus bridging may be dependent on the extent to which equity routes are losing capacity relative to non-equity routes. Regarding disadvantaged neighbourhoods (NIAs), the results are clearer: on both a percentage and numerical basis, residents of NIAs are overrepresented on buses relative to subways.

This demographic picture provides context to our main empirical findings, which begin in the next subsection with a high-level mapping of disruptions, impacted routes and their equity status. Subsequently, we present the results of our disparate impact analysis by subway line segment, before moving on to our spatial tests of ride-hailing responses.

Table 1
Subway and bus demographics by race and NIA residence.

		NIA Residents	All Others
Subway	Percent	15%	85%
	Count	*218,000*	*1,200,000*
Bus	Percent	28%	72%
	Count	*359,000*	*908,968*

		Racialized	White
Subway	Percent	49%	51%
	Count	*720,000*	*737,233*
Bus	Percent	57%	43%
	Count	*710,000*	*541,000*

4.1. Mapping subway disruptions, equity routes and ride-hailing responses

We organize results by subway segments defined at the station level, as our data associates each disruption with specific stations. This segmentation of the subway and associated subway stops is mapped in Fig. 1. Fig. 1 also documents which bus routes met the definition of being equity routes (in red), and non-equity routes (in grey). Finally, the blue shaded areas in Fig. 2 represent the Neighbourhood Improvement Areas (NIAs), or areas of disadvantage used in our ride-hailing analysis.

We note that the subway lines themselves only border NIAs on Lines 3 and 2 in the east and on Line 1 West in the northwest. This pattern is further reflected in the classification of equity routes, which constitute nearly all the bus service in the city's east, north, and northwest. Notably, most of the subway network's weather-exposed track are located in these same areas, particularly the northern end of Line 1West, Line 3, and eastern end of Line 2 east (Diab and Shalaby, 2019). Many of the bus routes surrounding these areas of the subway are also a part of the city's 10-min network, or routes with 10-min daytime headways. Seventy percent of the routes on the city's 10-min network are classified as equity routes by our calculation. This means that subway disruptions in the east and north are likely to draw shuttles more heavily from equity routes on the 10-min network. These dynamics are apparent in Fig. 2, which maps subway disruptions, associated shuttle pulls and ride-hailing responses.

In Fig. 2, the thickness of bus routes is defined by the number of buses diverted from such routes to subway incidents, which are represented as points on the subway line. Greener shading of neighbourhoods represents relative increases in ride-hailing responses during disruptions, while red denotes a decrease. Ride-hailing responses to incidents are strongest along Line 1 Central, Line 2 West and Line 1 East, which also happen to be areas of the city with little or no presence of equity routes or NIAs. Shuttle pulls from equity routes are strongest in the city's east, around Line 2 East and Line 3, a region that is almost entirely racialized-majority neighbourhoods. These impacts cannot be judged as inequitable, however, without demonstrating that they are disproportionately falling on equity routes, the topic of the following subsection.

4.2. Tests of disparate impacts of bus bridging

The results of our disparate impact analysis are presented in Table 2. For each section of the subway, we find a significant difference between the proportion of vehicles pulled from equity routes and the scheduled proportion available to pull from. In five out of seven of these segments, buses are pulled disproportionately from equity routes, indicating disparate impacts of bus bridging across much of the city.

The degree of disparate impact varies across these five segments, from a 1.4 percentage point difference on Line 2 West, to a 27.1 percentage point difference on Line 3. While the overall results present an equity concern, disruptions on Line 3 appear to disproportionately affect disadvantaged populations by much larger magnitudes when measured this way. Line 3's geography explains these results: Line 3 passes through areas where all bus routes are equity routes, as previously plotted in Fig. 2.

Our tests for disparate impact in capacity reductions are presented in Table 3. Differences are significant for all subway segments except for Line 1 Central. Five of the six segments with significant results yield disparate impacts in capacity reduction.

The magnitudes of disparate impact are much smaller for capacity reductions compared to shuttles pulled, ranging from a 0.3 percentage

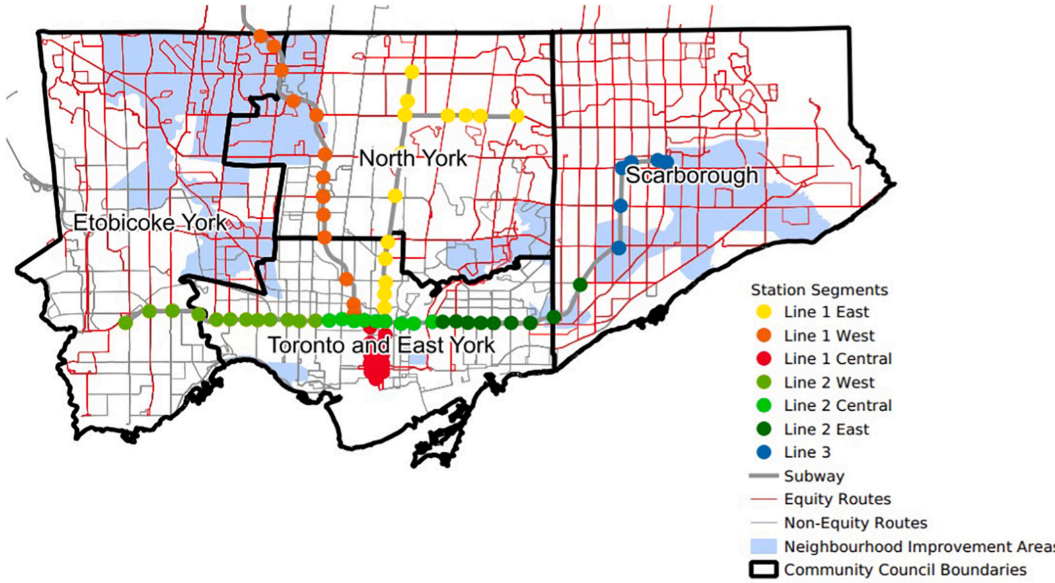

Fig. 1. Subway segments, NIAs and equity routes in toronto.

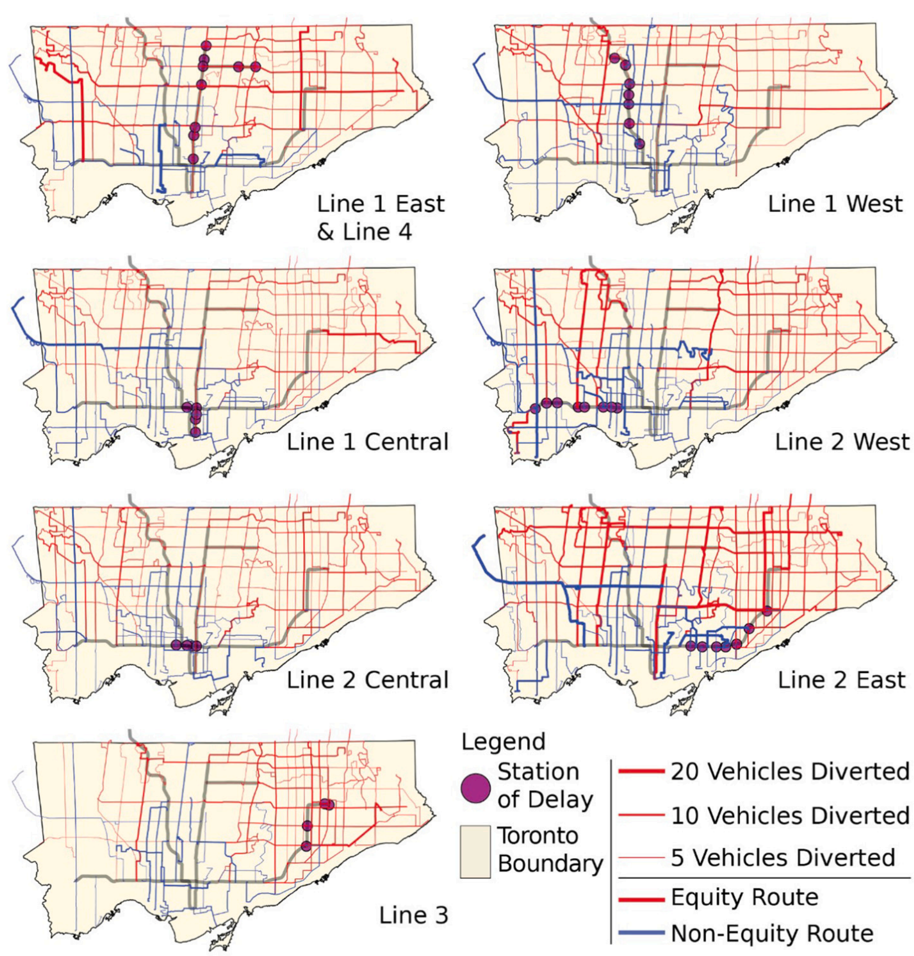

Fig. 2. Subway disruptions, bus bridging, and ride-hailing responses by subway line segment.

point difference on Lines 1 East and Line 4, to a 7.0 percentage point difference on Line 2 Central. The dramatic disparity in shuttles pulled for Line 3 (Table 1) translates to only a 1.8 percentage point disparity in capacity reduction (Table 2). This difference is largely a function of deadheading and geography: the relatively fewer number of shuttles pulled from non-equity routes to bridge Line 3 had to traverse much of the city to reach the line. In contrast, shuttles pulled disproportionately from equity routes came from neighbourhoods close to Line 3 where all bus routes are equity routes. Regardless, the capacity impact on equity routes is still greater. Geography and deadheading also explain the

Table 2
Proportion of shuttles from equity routes, and capacity reduction on affected routes.

Subway Segment	Incidents	Shuttles Pulled	Proportion of Shuttles Pulled from Equity routes	Scheduled Proportion of Shuttles on Equity routes
Line 1 East & Line 4	14	609	67.6%*	57.4%
Line 1 West	11	562	60.7%*	57.1%
Line 1 Central	5	474	71.0*	57.8%
Line 2 West	17	1025	58.7*	57.3%
Line 2 Central	6	502	47.7*	57.1%
Line 2 East	15	1056	67.7*	57.8%
Line 3	10	413	84.1*	57.0%

* indicates statistically significant chi-squared test at $p < .01$.

Table 3
Proportion of vehicles from equity routes, and capacity reduction on affected routes.

Subway Segment	Incidents	Shuttles Pulled	Equity routes Capacity Reduction	Non-Equity routes Capacity Reduction
Line 1 East & Line 4	14	609	23.8%*	23.5%
Line 1 West	11	562	19.7%*	17.6%
Line 1 Central	5	474	17.2%	16.0%
Line 2 West	17	1025	17.2%*	16.7%
Line 2 Central	6	502	20.0%*	14.0%
Line 2 East	15	1056	24.8%*	28.5%
Line 3	10	413	20.6%*	18.8%

* indicates statistically significant chi-squared test at $p < .01$.

largest disparity, on Line 2 Central. Only a couple of routes touching downtown Toronto are equity routes, meaning that shuttles pulled from equity routes to bridge disruptions downtown will be out of regular service much longer due to deadhead miles. These results present only part of the story, however, as ride-hailing has provided travelers with new ways out of disruptions. We turn to the statistical analysis of ride-hailing responses to disruptions next.

4.3. Ride-hailing analysis

We conducted G_i^* tests for each neighbourhood across each incident. A significant test result indicates that the demand response constituted a hot spot in a given neighbourhood for a given incident. We plot the density of G_i^* *p*-values in Fig. 3. Each point used to generate these density plots represents a neighbourhood's G_i^* p-value for one incident, meaning each neighbourhood is represented 78 times in each plot. To unpack spatial relationships in the significance of these p-values, densities are plotted along two axes. For a given incident and neighbourhood value, the x-axis is the Euclidean distance of the neighbourhood centroid to the associated incidents' nearest subway stop. The y-axis is the unadjusted p-value of the G_i^* statistic for the neighbourhood during that incident. Thus, the left panel presents the density contours of 10,920 neighbourhood-incident G_i^* p-values. The plots are presented as densities because raw plots would be unintelligible. By extension, the centre plots show results just for the 31 NIAs across the same 78 incidents (2418 tests), and the right shows all other neighbourhoods (8502 tests). This exercise was done to see whether the same level of significance for local hotspots exists across NIAs and non-NIAs when distance to the subway incident was controlled for. In these figures, then, a dark spot in the bottom left corner indicates that a large number of neighbourhoods near subway disruptions had significant ride-hailing demand hot spots during those disruptions. A bottom row of figures replicates the analysis, but only for disruptions on Line 2 East. We select Line 2 East as it is the only line with a significant number of disruptions taking place both inside NIAs (6), and in non-NIA neighbourhoods (9), allowing for a robust comparison.

The left-hand figures indicate that, Toronto neighbourhoods near subway disruptions become significant ride-hailing demand hot spots. The lack of dark spots in the bottom left corners of the middle column plots indicates that disruptions near NIAs do not result in localized ride-hailing demand spikes. When NIAs are removed, the pattern of significant hot spots near subway disruptions only intensifies (right hand column).

These results show that ride-hailing does not serve displaced subway customers in NIAs to the same degree as those in non-NIAs. One possibility is that there are fewer commuters in NIAs willing to hail an Uber of Lyft trip in the event of a subway disruption due to their income level, as identified elsewhere (Zhu et al., 2017). Another possibility that is more troubling for equity, is that ride-hailing availability is worse for those starting their trips in NIAs, such as longer wait times in NIAs, so customers are unwilling to switch modes to ride-hailing apps. The following subsection tests if this finding holds when more stringent hot spot tests are applied to the data.

4.4. FDR test results

The authors applied FDR tests to results for every neighbourhood during each incident to ensure our G_i* results were not an artifact of multiple testing. Then, for each incident, the authors calculated the percentage of neighbourhoods still generating a positive and significant demand response. This statistic—the percentage of neighbourhoods with FDR-corrected hot spots—was aggregated across incidents based on the distance of the incident to the nearest NIA. This allowed the authors to understand how subway incidents' proximity to NIAs influenced the scale and spread of ride-hailing demand responses. As anticipated, the FDR tests produced fewer significant hot spot results compared to G_i*, but the surviving significant hot spots still presented a clear socio-economic pattern, presented in Fig. 4.

The further a subway incident was from a disadvantaged community, the greater the ride-hailing demand response. Specifically, subway incidents within 2 km of an NIA resulted in half as many neighbourhoods having a statistically significant hotspot of ride-hailing pickups compared to subway disruptions more than 6 km away from the nearest NIA. As results in Fig. 4 were calculated city wide, the data may also be picking up residents in more advantaged areas along a disrupted subway line choosing to Uber from their communities and skip the subway entirely.

5. Conclusions

We conclude that the Toronto Transit Commission's bus bridging strategy could be more equitable, as we identify small but significant disparities in service capacity loss between equity and non-equity routes. However, this reflects the agency's preference to minimize the impact of bus bridging on low frequency routes, where the loss of a vehicle to bridging can have an outsized impact on bus riders' travel times. This decision is very beneficial to transit dependent-riders using low frequency routes, however these routes are less likely to be equity routes. This highlight's that the bus network, in total, is mostly

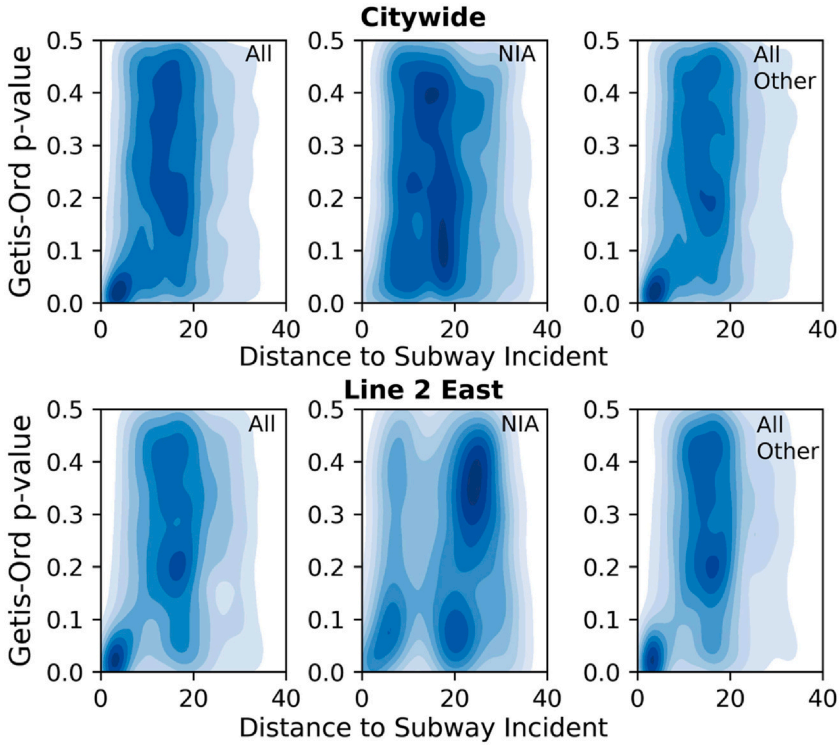

Fig. 3. G_i^*test p-values of ride-hailing hot spots during subway disruptions, by neighbourhood distance to subway incident across all incidents: All neighbourhoods, NIAs, and non-NIAs.

structured to provide frequent service to diverse communities. This makes the negative equity impacts from a bus bridging strategy that uses in-service buses somewhat inevitable. Additionally, the most inequitable outcomes are found along Line 3, where a decades old decision to build a weather exposed track has meant poorer service for both the line's users and riders of surrounding routes used for bus bridging. Fortunately, this line is slated to be replaced in the coming years by newer infrastructure that will likely have fewer disruptions. A relationship between weather exposure and equity is also apparent along the segments of Line 2 East and Line 1 West, where the segments exposed to the elements according to Diab and Shalaby (2019) mostly overlap with the segments we find passing through NIAs. In the context of Toronto's winter, infrastructure design decisions have meant that marginalized suburbs' subway service is more vulnerable to disruption from poor weather.

We also conclude that ride-hailing demand responses to subway disruptions are less frequent in neighbourhoods considered to be disadvantaged by the City of Toronto. Even along Line 2, which passes directly through several Neighbourhood Improvement Areas, increases in ride-hailing demand among NIAs near the disruptions are less likely. The further a subway incident is from any NIA, the greater the ride-hailing demand response across the city. This suggests that ride-hailing is providing a convenient way out of disruptions for travelers in better-off neighbourhoods while other travelers remain left behind. A growing literature suggests that ride-hailing disproportionately serves more socially advantaged travelers (Conway et al., 2018; Young and Farber, 2019). Our results add to this evidence by demonstrating that this inequity continues even during major subway disruptions, despite such disruptions having outsized social consequences for disadvantaged straphangers (Bureau of Policy and Research, 2017; Gorton and Pinkovskiy, 2018).

Our work also adds to the literature by demonstrating that bus riders in Toronto are more likely to be socially disadvantaged in general, paralleling transit demographic dynamics in the United States, albeit to a lesser degree (Taylor and Morris, 2015). In Toronto, racialized riders also rely on buses to reach the subway, meaning disruptions hit these

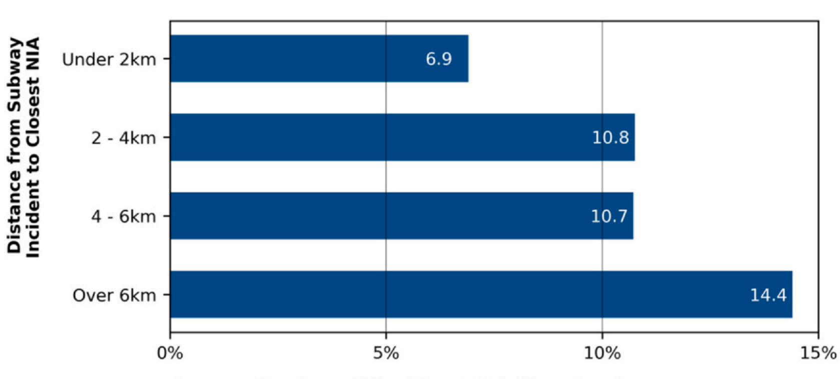

Fig. 4. Average number of neighbourhoods with statistically significant local hotspot, corrected with the FDR procedure, by distance of subway disruption to nearest NIA.

travelers twice: once from the disruption itself, and again by bridging-induced service reductions on feeder bus routes. Agencies facing equity challenges with their bus bridging strategies that result from these demographic patterns have two policy alternatives to using in-service shuttles for bridging. Adoption of these alternatives can minimize the impact of subway disruptions on bus travelers. First, agencies can consider establishing agreements with private operators to draw upon on private fleets during disruptions (Piner and Condry, 2017). Second, agencies can establish reserves of shuttles placed strategically throughout their networks to quickly replace subway service without impacting existing bus routes (Pender et al., 2013a, 2013b). These approaches are more expensive, but as our results demonstrate, reliance on in-service buses to bridge subway disruptions can come at the cost of re-distributing service loss to bus riders in marginalized communities.

Revenue-neutral policy changes can also help the TTC, and agencies like it, to minimize the impacts of bus bridging policies on marginalized riders. First, the agency could limit the capacity reduction imposed on any single bus route during a disruption. Such limits could vary by route and time of day based on known ridership and rider characteristics. Second, automatic-vehicle locator (AVL) and automatic passenger counter (APC) data could be fed into real time optimization tools such as those by Itani et al. (2020) to provide TTC dispatchers with instantaneous identification of which buses could be pulled from equity routes to minimize the number of bus riders impacted.

Our ride-hailing results also point to new directions for low-cost policy experimentation in bridging subway disruptions. The TTC could explore partnerships with ride-hailing to better coordinate ride-hailing with bus-bridging efforts in order to minimize rider delay system-wide. This could include mandating that ride-hailing trips to and from impacted stations are shared only, or that the city provide a small incentive for shared ride hailing trips from stations to reduce the number of required shuttles. However, there is potential for a surge in ride-hailing around stations to slow replacement shuttles down. The city could address this by directing ride-hailing relief to points just outside of replacement shuttle loading zones to optimize time savings across the network.

Our results also qualify previous work on the benefits of using buses nearest to a subway disruption for bus bridging (Itani et al., 2019). Bus bridging responses to disruptions taking place in disadvantaged regions of a city may draw heavily from routes serving disadvantaged bus riders if proximity is the sole criterion for selecting buses to pull. Agencies need to weigh the relative importance of minimizing aggregate traveler time loss against ensuring that disadvantaged riders do not bear disproportionate burdens from optimization strategies. Future research in bus bridging optimization should explicitly consider equity and distributional effects. Such work can help policymakers identify which disruptions force such trade-offs and how best to balance them.

Finally, this analysis contains limitations that can inform future work. First, the measurement of equitable impacts to bus riders is calculated at a route level, introducing aggregation biases identified by Palm et al. and others (2020). These biases mean that the benefits of TTC's current practice for transit-dependent riders on non-equity routes are not captured in our methodology. Nonetheless, when agencies look to pull buses for bridging, they consider impacts to service through the scale of routes, making our empirical approach practical from policy standpoint. Second, we rely on neighbourhood designations of disadvantage as a proxy for ridership demographics in our ride hailing analysis even though straphangers may not share the demographic characteristics of the neighbourhood in which they were stranded. That our results aligned with theory and existing evidence shows that this was nonetheless a useful proxy for demonstrating inequities in ride-hailing use during subway disruptions. Third, we were unable to weight the impact of each bus pulled by the relative number of riders on-board, as we did not have access to bus ridership data for the days in which each major incident occurred. The solution to all of these limitations lies in expanding existing, state-of-the-art delay minimisation tools such as Itani et al.'s (2019) to include an equity component that can identify marginalized users at the scale of the individual. Such an application would also allow policymakers to jointly evaluate the time savings and equity impacts of various solutions to bus bridging advanced in this paper and elsewhere in the literature.

Acknowledgements

This work was supported by an XSeed Grant from the University of Toronto and an Early Researcher Award from the Ontario Ministry of Research, Innovation and Science.

References

Aboudina, A., Itani, A., Diab, E., Srikukenthiran, S., Shalaby, A., 2020. Evaluation of Bus Bridging Scenarios for Railway Service Disruption Management: A Users' Delay Modelling Tool. Public Transport, Planning and Operations (In Press).

Adelé, S., Tréfond-Alexandre, S., Dionisio, C., Hoyau, P.-A., 2019. Exploring the behavior of suburban train users in the event of disruptions. Transport. Res. F: Traffic Psychol. Behav. 65, 344–362. https://doi.org/10.1016/j.trf.2019.08.009.

Allen, J., Farber, S., 2020. Planning transport for social inclusion: an accessibility-activity participation approach. Transp. Res. Part D: Transp. Environ. 78, 102212. https://doi.org/10.1016/j.trd.2019.102212.

Anselin, L., 1995. Local indicators of spatial association-LISA. Geogr. Anal. 27 (2), 93–115. https://doi.org/10.1111/j.1538-4632.1995.tb00338.x.

Big Data Innovation Team, & UTTRI, 2019. The Transportation Impacts of Vehicle-for-Hire in the City of Tor*onto* (Research & Analysis, p. 64). City of Toronto Transportation Services. https://www.toronto.ca/wp-content/uploads/2019/06/96c7-Report_v1.0_2019-06-21.pdf.

Bureau of Policy and Research, 2017. The Human Cost of Subway Delays: A Survey of New York City Riders (p. 22). New York City Comptroller. https://comptroller.nyc.gov/wp-content/uploads/documents/The-Human-Cost-of-Subway-Delays.pdf.

Caldas de Castro, M., Singer, B.H., 2006. Controlling the false discovery rate: a new application to account for multiple and dependent tests in local statistics of spatial association. Geogr. Anal. 38 (2), 180–208. https://doi.org/10.1111/j.0016-7363.2006.00682.x.

City of Toronto, 2020. Neighbourhood improvement area profiles. In: City of Toronto, . https://www.toronto.ca/city-government/data-research-maps/neighbourhoods-communities/nia-profiles/.

Conway, M.W., Salon, D., King, D.A., 2018. Trends in taxi use and the advent of Ridehailing, 1995–2017: evidence from the US National Household Travel Survey. Urban Sci. 2 (79), 1–23. https://doi.org/10.3390/urbansci2030079.

Davis, W., Weatherburn, T., 2017, June 7. Three Years of TTC Delays. MapTO. http://www.mapto.ca/maps/ttcdelays.

Deng, Y., Ru, X., Dou, Z., Liang, G., 2018. Design of bus bridging routes in response to disruption of urban rail transit. Sustainability 10 (12), 4427. https://doi.org/10.3390/su10124427.

Diab, E., Shalaby, A., 2018. Subway Service down again? Assessing the effects of Subway Service interruptions on local surface transit performance. Transportation Research Record: Journal of the Transportation Research Board 2672 (8), 443–454. https://doi.org/10.1177/0361198118791665.

Diab, E., Shalaby, A., 2019. Metro transit system resilience: understanding the impacts of outdoor tracks and weather conditions on metro system interruptions. Int. J. Sustain. Transp. 1–14. https://doi.org/10.1080/15568318.2019.1600174.

Diab, E., Feng, G., Shalaby, A., 2018. Breaking into emergency shuttle service: aspects and impacts of retracting buses from existing scheduled bus services. Can. J. Civ. Eng. 45 (8), 647–658. https://doi.org/10.1139/cjce-2017-0294.

DMG, 2014. TTS Introduction. Data Management Group. http://dmg.utoronto.ca/transportation-tomorrow-survey/tts-introduction.

FTA, 2012. Title VI Requirements and Guidelines for Federal Transit Administration Recipients (Circular FTA C 4702.1B). U.S. Department of Transportation. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA_Title_VI_FINAL.pdf.

Getis, A., Ord, J.K., 1992. The analysis of spatial association by use of distance statistics. Geogr. Anal. 24 (3), 189–206. https://doi.org/10.1111/j.1538-4632.1992.tb00261.x.

Gorton, N., Pinkovskiy, M., 2018, June 27. Why New York City Subway Delays Don't Affect All Riders Equally [Blog]. Federal Reserve Bank of New York Liberty Street Economics. https://libertystreeteconomics.newyorkfed.org/2018/06/why-new-york-city-subway-delays-dont-affect-all-riders-equally.html.

Guo, Y., Chen, Z., Stuart, A., Li, X., Zhang, Y., 2020. A systematic overview of transportation equity in terms of accessibility, traffic emissions, and safety outcomes: from conventional to emerging technologies. Transportation Research Interdisciplinary Perspectives 100091. https://doi.org/10.1016/j.trip.2020.100091.

Itani, A., Aboudina, A., Diab, E., Srikukenthiran, S., Shalaby, A., 2019. Managing unplanned rail disruptions: policy implications and guidelines towards an effective bus bridging strategy. Transportation Research Record: Journal of the Transportation Research Board 2673 (4), 473–489. https://doi.org/10.1177/0361198119838838.

Itani, A., Srikukenthiran, S., Shalaby, A., 2020. Capacity-Constrained Bus Bridging Optimization Framework. Journal of the Transportation Research Board, Transportation Research Record (In Press).

Karner, A., 2018. Assessing public transit service equity using route-level accessibility measures and public data. J. Transp. Geogr. 67, 24–32. https://doi.org/10.1016/j.jtrangeo.2018.01.005.

Karner, A., Golub, A., 2015. Comparison of two common approaches to public transit service equity evaluation. Transportation Research Record: Journal of the Transportation Research Board 2531 (1), 170–179. https://doi.org/10.3141/2531-20.

Karner, A., Niemeier, D., 2013. Civil rights guidance and equity analysis methods for regional transportation plans: a critical review of literature and practice. J. Transp. Geogr. 33, 126–134. https://doi.org/10.1016/j.jtrangeo.2013.09.017.

Kepaptsoglou, K., Karlaftis, M.G., 2009. The bus bridging problem in metro operations: conceptual framework, models and algorithms. Public Transport 1 (4), 275–297. https://doi.org/10.1007/s12469-010-0017-6.

Lin, T., Srikukenthiran, S., Miller, E., Shalaby, A., 2018. Subway user behaviour when affected by incidents in Toronto (SUBWAIT) survey—a joint revealed preference and stated preference survey with a trip planner tool. Can. J. Civ. Eng. 45 (8), 623–633. https://doi.org/10.1139/cjce-2017-0442.

Louie, J., Shalaby, A., Habib, K.N., 2017. Modelling the impact of causal and non-causal factors on disruption duration for Toronto's subway system: an exploratory investigation using hazard modelling. Accid. Anal. Prev. 98, 232–240. https://doi.org/10.1016/j.aap.2016.10.008.

MTA, 2020, April. Subway Performance Dashboard [Dashboard]. *MTA*.. http://dashboard.mta.info/.

O'Neil, L., 2019, December 2. Uber and Lyft Post Ridiculous Prices as Fire Shuts Down TTC Subway Line. BlogTO. https://www.blogto.com/tech/2019/12/uber-lyft-surge-pricing-ttc-chaos-toronto/.

Ontario Human Rights Commission, 2020. Racial Discrimination, Race And Racism (Fact Sheet). http://www.ohrc.on.ca/en/racial-discrimination-race-and-racism-fact-sheet.

Palm, M., Shalaby, A., Farber, S., 2020. Social equity and bus on-time performance in Canada's Largest City. Transportation Research Record: Journal of the Transportation Research Board. https://doi.org/10.1177/0361198120944923. 036119812094492.

Pender, B., Currie, G., Delbosc, A., Shiwakoti, N., 2013a. Disruption recovery in passenger railways: international survey. Transportation Research Record: Journal of the Transportation Research Board 2353 (1), 22–32. https://doi.org/10.3141/2353-03.

Pender, B., Currie, G., Delbosc, A., Shiwakoti, N., 2013b. Impact of Bus Depot Location on the Provision of Rail Replacement Services (Bus Bridging). Australasian Transport Research Forum 2013 Proceedings, pp. 15. https://pdfs.semanticscholar.org/cd86/37b8ad6f004e78486e9d4e6964f9020670ac.pdf.

Piner, D., Condry, B., 2017. International best practices in managing unplanned disruption to suburban rail services. Transportation Research Procedia 25, 4403–4410. https://doi.org/10.1016/j.trpro.2017.05.331.

Pnevmatikou, A.M., Karlaftis, M.G., Kepaptsoglou, K., 2015. Metro service disruptions: how do people choose to travel? Transportation 42 (6), 933–949. https://doi.org/10.1007/s11116-015-9656-4.

Posadzki, A., 2015. Toronto Subway Shutdown Puts Uber's Surge Pricing Model in Spotlight. Huffington Post. https://www.huffingtonpost.ca/2015/06/08/toronto-subway-shutdown-p_n_7536910.html.

Pucher, J., Renne, J.L., 2003. Socioeconomics of urban travel: evidence from the 2001 NHTS. Transp. Q. 57 (3), 48–77.

Schmöcker, J.-D., Cooper, S., Adeney, W., 2005. Metro service delay recovery. Transp. Res. Rec. 1930, 30–37.

Songchitruksa, P., Zeng, X., 2010. Getis–Ord spatial statistics to identify hot spots by using incident management data. Transportation Research Record: Journal of the Transportation Research Board 2165 (1), 42–51. https://doi.org/10.3141/2165-05.

Statistics Canada, 2018, September 17. Dissemination Area (DA). https://www150.statcan.gc.ca/n1/pub/92-195-x/2011001/geo/da-ad/da-ad-eng.htm.

Taylor, B.D., Morris, E.A., 2015. Public transportation objectives and rider demographics: are transit's priorities poor public policy? Transportation 42 (2), 347–367. https://doi.org/10.1007/s11116-014-9547-0.

Wessel, N., Farber, S., 2019. On the accuracy of schedule-based GTFS for measuring accessibility. Journal of Transport and Land Use 10, 32.

Young, M., Farber, S., 2019. The who, why, and when of Uber and other ride-hailing trips: an examination of a large sample household travel survey. Transp. Res. A Policy Pract. 119, 383–392. https://doi.org/10.1016/j.tra.2018.11.018.

Zhu, S., Masud, H., Xiong, C., Yang, Z., Pan, Y., Zhang, L., 2017. Travel behavior reactions to transit service disruptions: study of metro SafeTrack projects in Washington, D.C. Transportation Research Record: Journal of the Transportation Research Board 2649 (1), 79–88. https://doi.org/10.3141/2649-09.