1 **Planning a High-frequency Transfer-based Bus Network: How Do We Get**
2 **There?**
3
4 **Emily Grisé**
5 School of Urban and Regional Planning, University of Alberta
6 E-mail: egrise@ualberta.ca
7
8 **Anson F. Stewart**
9 Conveyal
10 Email: astewart@conveyal.com
11
12 **Ahmed El-Geneidy**
13 School of Urban Planning, McGill University
14 E-mail: ahmed.elgeneidy@mcgill.ca
15
16
17
18
19
20
21
22 Word count: 7206 + 1 Table = 7,456 words
23
24 *Submitted [July 30, 2019]*
25
26
27
31

32

33

34

35

1 ABSTRACT

2 As cities have grown more dispersed and auto-oriented, demand for travel has become increasingly
3 difficult to meet via public transit. Delivering high-quality bus service in this challenging
4 environment has recently brought attention to bus network design. Commonly, bus networks
5 are designed with a door-to-door approach, which often entails a circuitous route design leading to
6 slow and infrequent service, especially in the suburbs. Alternatively, high-frequency transfer-
7 based networks have been promoted as the optimal network design for ridership, experience and
8 operational efficiency. For cities wishing to adopt such a network design, there is presently no
9 comprehensive, easy to follow methodology for transitioning to this network model. This study
10 presents a methodology to guide transport professionals through the process of redesigning an
11 existing door-to-door network to a transfer-based high-frequency service, using Longueuil,
12 Quebec, as a case study. A variety of data sources that capture regional travel behaviour and
13 network performance are overlaid using a GIS-based grid-cell model, to identify priority bus
14 corridors, which is followed by a network redesign that is constrained by the existing number of
15 buses. Changes in accessibility to jobs are used to evaluate the benefits of the proposed network.
16 This methodology provides transit professionals with a flexible and reproducible guide for
17 designing a transfer-based network, while ensuring that such a network overhaul maximizes the
18 number of opportunities that residents can access by transit and does not add an additional burden
19 to an agency's operating budget or users in terms of total travel time for current trip patterns.
20
21 **Keywords:** Public transport, Bus network planning, Direct-service bus network
22

23

24

1 **INTRODUCTION**

2 Public transit ridership has been on the decline in major North American regions (*1*). In response,
3 many cities have undertaken major bus network redesigns. The redesigns generally happens to: (i)
4 reflect a city structure changes that have occurred over time and altered travel demand, (ii)
5 integrate bus networks with new transit infrastructure (mostly new rail), (iii) respond to budget
6 cuts or decline in revenue, and (iv) deliver service that is aligned with user expectations. For transit
7 systems to be aligned with existing and potential users expectations, a minimal level of service
8 must be provided (*2*). While there is a common assertion that rail is inherently more attractive than
9 bus, Ben-Akiva and Morikawa (*3*) refuted this theory and found that high performance bus service
10 with similar frequency and service attributes as rail (i.e. exclusive right-of-way) have similar
11 ridership attraction. Service attributes associated with the common door-to-door bus network
12 structure, or direct-service network, typically embody neither of these service attributes. A door-
13 to-door bus network is designed to connect origin-destination pairs directly, with little need for
14 transferring. Due to the existing sprawl in North American cities, providing door-to-door service
15 requires circuitous routing, thereby extending travel times, and extensive coverage which acts as
16 a tradeoff for service frequency. Currently many cities are wishing to adopt a high-frequency
17 transfer-based network, which have been demonstrated to improve operational efficiency and
18 effectiveness (more users) in some North American cities (*4; 5*). In this paper, we present a
19 practice-ready and easy to adopt methodology to guide transport professionals through the process
20 of transitioning an existing door-to-door suburban network to a high-frequency transfer-based
21 network, using Longueuil, Quebec as a case study, while keeping the service coverage and number
22 of buses used in the system at the same levels.
23

24 **BACKGROUND**

25 Transit network structure can be broadly categorized as either direct-service and transfer-based
26 (*6*). Direct-service models, commonly referred to as a door-to-door model, connect suburban and
27 inner-city areas with a central location, typically the downtown core. Typically trips taken on a
28 direct-service model are designed so users can complete their trip using a single line. Routes in a
29 direct-service network are predominantly designed in isolation of each other. Commuter trips are
30 best served under this network model, providing efficient peak hour service to the CBD and
31 sometimes other employment centres (*5*). Little or no transferring is required, which is a common
32 motivation for adopting this network structure due to the common perception that transfers are
33 disliked by passengers (*5*). A central issue with this service model, is that some users do want to
34 reach destinations other than the CBD, but using direct-service transit systems make this only
35 possible with indirect travel through the CBD (*4*). Furthermore, people need and want to travel at
36 times in addition to the peak.
37   Transfer-based networks are designed to allow riders to access multiple destinations when
38 transfers are utilized. Common direct-service networks take on either a hybrid structure, which
39 consists of a central grid network with radial routes serving suburban areas (see Daganzo (*7*)), or
40 a grid structure. Transfer-based networks are increasingly adopted with knowledge that
41 destinations are increasingly dispersed in metropolitan areas (*5*), and in some settings this network

1 model has been found to better satisfy dispersed mobility patterns (*2; 6; 8; 9*). Transit networks
2 with many transfer opportunities offer passengers a significantly greater selection of travel paths
3 compared to direct-service networks comprised of a large number of integrated lines that involve
4 little or no transfers (*6*). Transferring, however, can interrupt travel and cause significant travel
5 time delays when timed poorly. With careful planning, such as good station design, convenient
6 and safe walking paths, and frequent service across all routes, the inconvenience associated with
7 transferring is minimized and benefits associated with transferring can be realized.
8   It would appear that for planners to induce new ridership they should develop transit route
9 structures oriented to larger and increasing segments of the spectrum of travel within a region,
10 which will likely exceed patronage lost due to added transfers (*4; 9*). For reasons such as this, we
11 are now seeing cities globally transitioning from direct-service to transfer-based networks. A well-
12 studied example of this is the example of Barcelona, Spain, which in 2012 transitioned from a
13 direct-service network to a transfer-based network, based on the proposed network design by
14 Estrada et al. (*10*). The network design followed these three properties: full area coverage with
15 each transfers and non-circuitous routings, easy to understand (i.e. grid), and high frequency
16 (average headway of 6.2 minutes) (*11*). Preliminary analyses of this network transformation found
17 that demand is already rising, and this growth is supported by transfers, suggesting that users are
18 not averse to transferring when using a well-connected, high-frequency network. Complimenting
19 these findings, Allen, Muñoz and Rosell (*12*), analyzed user satisfaction levels over a three year
20 period following the implementation of the transfer-based network, to better understand how users'
21 perceive the network reform. The authors observed higher satisfaction levels among the new lines
22 relative to the existing service, due to increased frequency and improved reliability, but also for
23 the added access to opportunities provided by the new network. Furthermore, it was observed that
24 transferring does not penalize user satisfaction, suggesting that the improved mobility offered by
25 transfer-based networks can more effectively produce satisfied customers, despite the additional
26 transfers occurred when travelling.
27

28 **STUDY AREA**

29 Réseau de transport de Longueuil (RTL) provides public transit services to the five suburban cities
30 that comprise the Agglomération de Longueuil: Boucherville, Brossard, Saint-Bruno-de-
31 Montarville, Longueuil, and Saint-Lambert. The service area is 309.6 km^2 and serves a population
32 of 427,050 residents and on average experiences 100,000 trips per weekday (*13*). Presently, 23%
33 of residents in Longueuil commute to work by public transit (*14*).
34   Longueuil is located on the south shore of Montreal, and a large portion of residents
35 commute daily to work in Montreal. The RTL network can be classified as a door-to-door bus
36 network (or direct-service network), consisting of radial routes that follow circuitous routing for
37 collection/distribution in the low-density suburban residential areas and bring passengers to
38 Montreal either via Terminus de Longueuil, which is a subway station operated by the Société de
39 transport de Montréal (STM) or directly to Terminus Centre-Ville in downtown Montreal via the
40 Champlain Bridge, see Figure 1. Median all-day route headways, as shown in Figure 1, are varied
41 across the network and are typically large due to the extensive network coverage and length of the
42 network (790km (*15*)).

1   In the Montreal Metropolitan region, the Réseau express métropolitain (REM) light-rail
2   project is presently under construction. The REM will have implications for existing network
3   design across the Montreal region. In the case of Longueuil, the REM will connect Longueuil to
4   the Island of Montreal through Terminus Panama (Figure 1), and this service is projected to be
5   operational in 2020. Presently, a large number of routes travel directly to Montreal via the
6   Champlain Bridge, and this service will be replaced by the REM. To ensure a seamless transition
7   of passengers to the REM, we are proposing an express bus service to connect passengers at
8   Terminus Panama to downtown Montreal, which will be cancelled when the REM is constructed.
9   A challenge presented by this case study is the irregularity of Longueuil's street network.
10 There is little pattern or order to streets in Longueuil. The most intuitive method of designing a
11 transfer-based network is to follow a grid pattern, so that the network is easy to understand (*11*).
12 With that being said, it is still very plausible to develop a transfer-based network in a city with an
13 irregular street network, and in fact a grid-like network of north-south and east-west interconnected
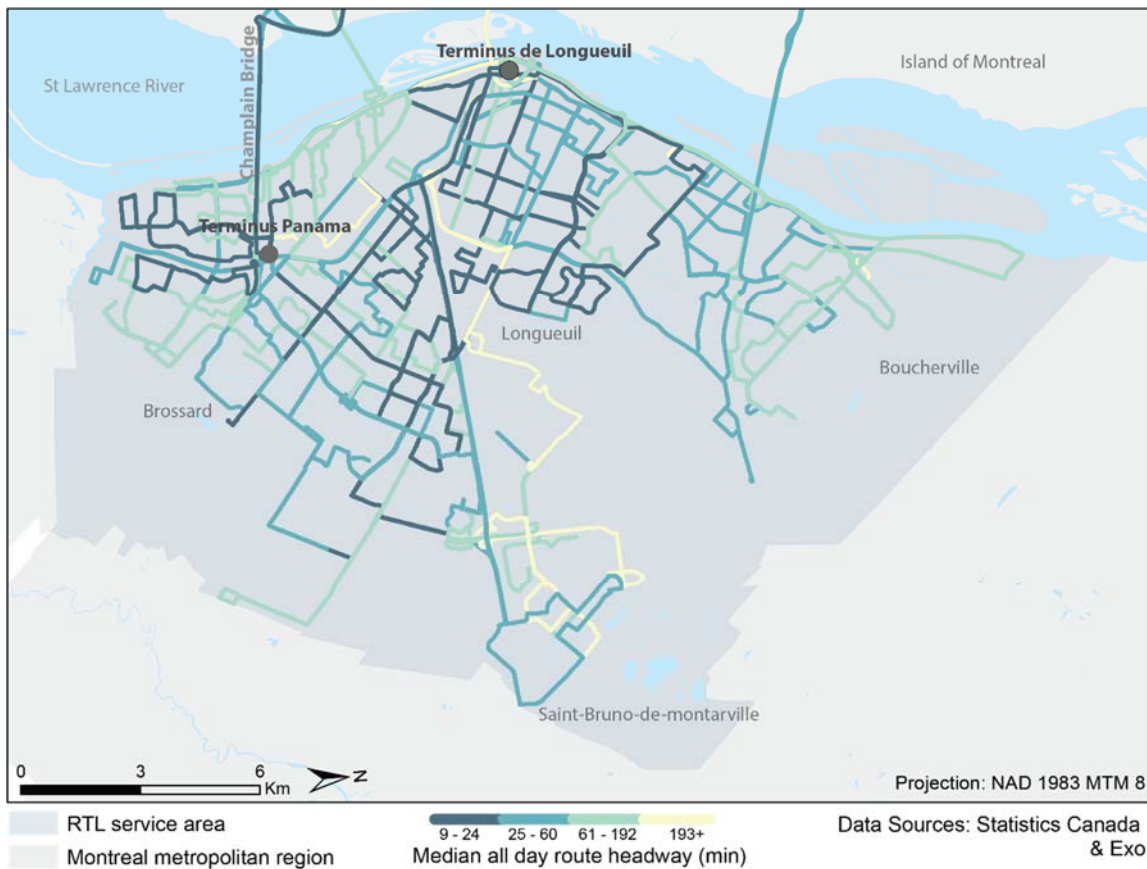14 routes can still be developed.
15

16
17 **Figure 1 Existing door-to-door bus network, showing existing median all day route headways**
18 **(minutes)**

1

METHODOLOGY, APPLICATION AND RESULTS

3   The objective of this study is to develop a comprehensive methodology for transport engineers and
4   planners to follow when transitioning an existing door-to-door bus network to a high-frequency
5   transfer-based network. We outline below in detail the main steps deriving our proposed
6   methodology for devising a new network and outline how this proposed network can be evaluated
7   against the existing service. The approach taken is to devise a new network from scratch, rather
8   than modifying the existing network, with the goal of identifying new patterns for service
9   according to travel demand and land use characteristics, while being conscious to retain strong
10   features in the exiting network.
11   First, we develop a prioritization index using a Geographic Information System (GIS) grid-
12   cell model to identify priority corridors for bus routes according to existing land use characteristics,
13   regional travel demand, and existing network performance. Second, we propose high and medium-
14   priority bus routes, which is guided by the prioritization index. Third, we evaluate the coverage of
15   the proposed network and measure changes in accessibility to jobs. According to these network
16   evaluations, modifications to the proposed network were made. This process is completed
17   iteratively, until we arrive at a new network that meets our two conditions: (i) offers sufficient
18   network coverage to residents, and (ii) increase accessibility to jobs within 60 minutes by a
19   minimum of 10 percent for all residents within the RTL service area. We complete our analysis by
20   measuring whether the proposed service levels assumed in the accessibility analysis can be
21   supported by the existing fleet. The existing fleet serves as a constraint in our analysis, whereby
22   we are ensuring that the proposed network does not require the purchase of additional buses to
23   deliver.

Prioritization index for new bus corridors

25   To identify priority bus corridors, we consider a range of indicators that capture demand for travel
26   in the Longueuil region and existing network performance and utilization. Specifically, seven
27   indicators are considered in this analysis, which are described in detail below, and are each
28   standardized and combined to a grid in GIS. This GIS-based grid cell prioritization model has been
29   demonstrated in other applications, such as bicycle facility planning in Quebec City and Montreal,
30   Canada (*16; 17*). The seven indicators comprising this priority index were selected to capture
31   existing and potential public transit demand and to help visualize optimal corridors.

Land use characteristics

33   The first two indicators are employment and population density. Using data obtained from the
34   Statistics Canada 2016 Census, employment and population density were calculated at the census
35   tract level. These indicators ensure that proposed bus corridors are operating with high frequency
36   in areas with high proportions of residents and jobs.

Regional travel demand

38   We then evaluated travel behavior in the region, using origin-destination (OD) survey data
39   collected by the L'Autorité régionale de transport métropolitain (ARTM) in 2013 (*18*). This data
40   was used to generate desire lines, which represent demand for travel on each street segment. The

1 OD survey collected by the ARTM surveys approximately 5% of the Montreal Metropolitan region
2 population and asks sampled participants over the phone to recall all trips made by themselves and
3 other members of their household during the previous day. An expansion factor was applied to
4 realistically capture the actual number of trips occurring in the region. Two indicators were
5 generated, first an indicator representing all home-based trips for the purpose of work or school,
6 and second all home-based trips by public transit.

7 ***Existing network performance***
8 The next three indicators we incorporated in our prioritization index were from automatic vehicle
9 location (AVL) and automatic passenger counter (APC) data to assess existing network
10 performance and demand. The three indicators include passenger activity, passenger load, and
11 speed. AVL/APC data were provided by the RTL and included approximately two weeks of trip
12 data in 2016 (December 5–18) and 2017 (September 4–17). We started by cleaning the data, to
13 ensure that all records in our dataset were from trips operated by buses equipped with APC units,
14 and we also removed incomplete trips from our sample. Our final sample consisted of weekday
15 peak hour trips (6–9 AM and 4–6 PM) void of any holidays.
16   Passenger activity was calculated as the average number of boardings and alightings (ons
17 and offs) occurring at each bus stop in the RTL network. In the case of a stop which serves multiple
18 routes, passenger activity was calculated as the average number of boardings and alightings
19 observed from all routes serving that stop (in both directions). This indicator was used to capture
20 frequently used stops in the existing network to assign high priority to these locations for the future
21 network.
22   Route passenger load was calculated using the maximum load field within the AVL/APC
23 data, which indicates the highest load observed during a trip. Passenger load is the total number of
24 onboard passengers at the time of departure from each stop and is used in this analysis to identify
25 heavily used bus corridors. Load was calculated for each route in the network by obtaining the
26 average maximum load of all trips in our sample.
27   Our final network performance indicator is stop-level speed. Speed was calculated using
28 travel time obtained from AVL/APC data, and distance travelled was obtained using GIS. A
29 network of routes was generated in GIS by using the sequence of stops as recorded by AVL/APC
30 data and stop coordinates provided by General Transit Feed Specification (GTFS). The stop
31 coordinates were plotted in GIS and a network of routes was generated in Network Analyst[1].
32 Network distance between subsequent stops along each route was then obtained, and speeds then
33 calculated using the average travel time between subsequent stops from the AVL/APC. Speed was
34 incorporated in the prioritization index to identify low performance routes in terms of segment-
35 level speed. The objective is to identify low performing routes where investments in priority bus
36 corridors are needed, such as exclusive bus lanes, signal priority for buses or off-board payment
37 methods to reduce dwell time associated with boarding passengers or adjusting stop locations (i.e.
38 near-side versus far-side).

---

[1] We first snapped stops streets, and then these stops were loaded into Network Analyst and grouped according to a route ID (route number and direction fields concatenated) and drawn according to their relative sequence along the route.

1 ***Combining and spatially aggregating indicators to a grid***
2 Next, we aggregated the seven indicators to a grid cell with a 200m resolution. For example, we
3 spatially joined the passenger load indicator to the grid cells, to determine the average passenger
4 load of routes intersecting each grid cell. Grid cells with high passenger load indicates areas where
5 existing service is highly used and should be a priority for frequent bus service in the future
6 network. In the case of the public transport commuting trips indicator, we measured the number
7 of trips passing through each grid cell. Following the spatial aggregation of each indicator to the
8 grid cell, we standardized each indicator in order to add each indicator to the prioritization index.
9   To combine all indicators into one priority index, we added each standardized indicator as
10 follows:
11   *Prioritzation index*
12   *= Population density + Job density + Passenger activity*
13   *+ Passenger load + Flows all trips*
14   *+ Flows public transport trips − Speed*

15 Average speed is inversely added to our prioritization index as the goal of this analysis is to identify
16 optimal corridors for high-frequency public transport services, whereby investments are made to
17 improve the quality of service and reduce travel times. Note, we aggregated the seven indicators
18 equally, and future applications of this method can consider applying a weighting scheme to
19 prioritize certain indicators. The final prioritization index is presented in Figure 2.
20
21
22
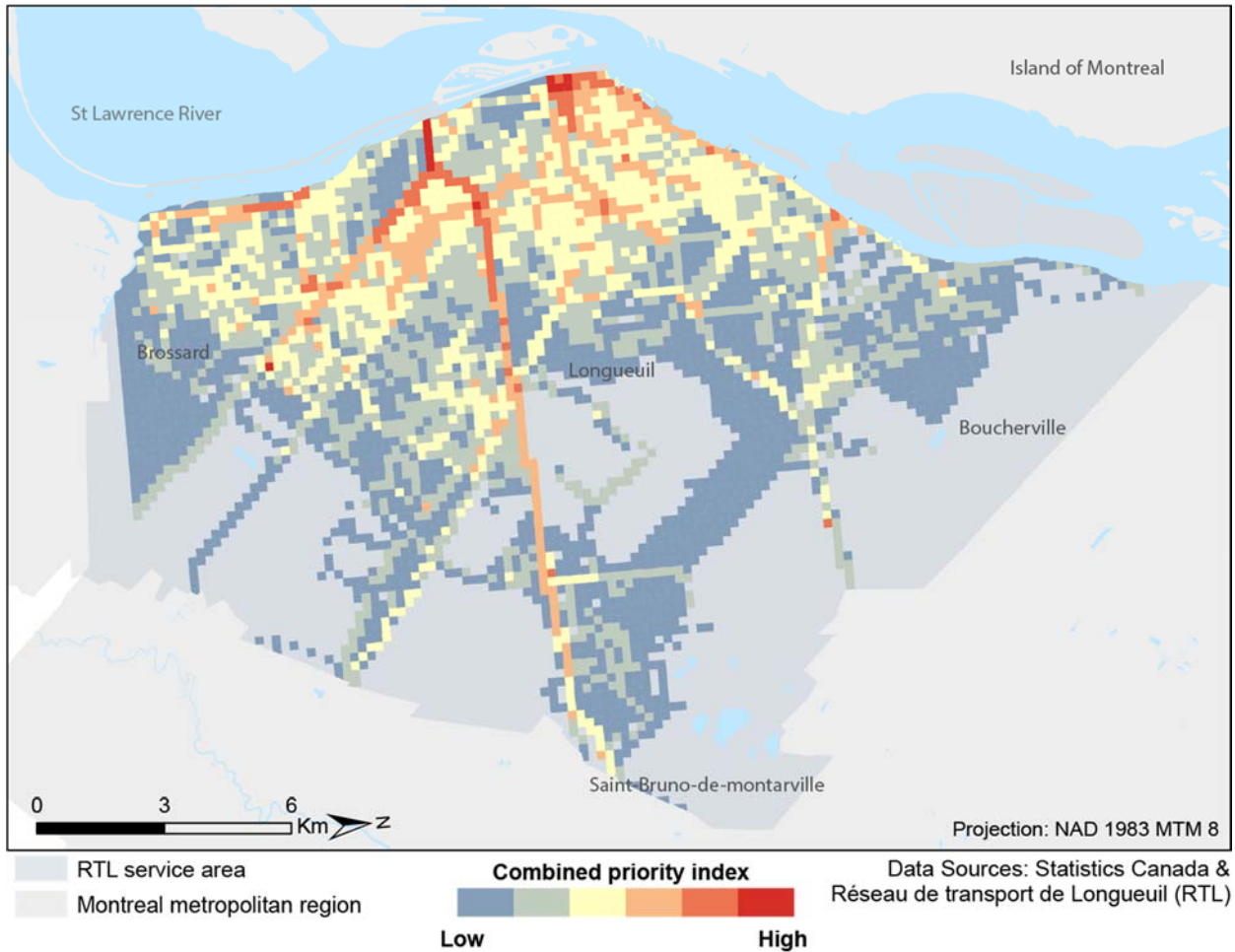
1
2 **Figure 2 Final priority index**

3

4 **Proposed high and medium-priority bus routes**

5 Through close examination of the prioritization index (Figure 2), we can easily identify several
6 priority bus corridors where we drew bus routes to follow priority grid cells (red colored). Proposed
7 routes will predominantly terminate at either Terminus Panama (future stop of the REM light rail
8 service) or Terminus de Longueuil (subway station). At Terminus Panama passengers will transfer
9 to an express downtown service to Terminus Centre-ville in downtown Montreal, which will be
10 replaced by the REM service when it is completed. An average waiting time of 90 seconds is
11 recommended for this route to minimize any inconvenience associated with transferring at this
12 terminal. When drawing routes, we aimed to propose routes that follow major arterials and will
13 flow in either a north-south or east-west direction to generate a grid. Also, when proposing routes
14 along parallel corridors, whenever possible we attempted to place routes approximately 800 meters
15 apart, so the maximum walking distance (laterally) is approximately 400 meters or 5 minutes.
16 While shorter walking access is desirable, due to the importance of frequency for passenger
17 attraction (*6*), we maximized frequency at the expense of access in some cases.

9

1   We began by recommending our high-priority routes, shown in pink in Figure 3, which
2   comprise the high-frequency routes forming the backbone of our network. These are
3   predominantly radial routes, converging at either Terminus Longueuil or Panama. Our high-
4   priority routes covered as many priority grid cells as possible, however there are various barriers
5   in the network that made this impossible, such as highways and railyards. These barriers also act
6   as a hindrance from proposing a grid bus network. For example, there are limited locations for
7   buses to travel east-west across the region, as many streets terminate on either side of the major
8   north-south highway in Longueuil.
9   Next, we proposed medium-frequency bus routes (green routes shown in Figure 3) to
10   integrate with the high-frequency buses and provide adequate coverage to the residents. When
11   drawing these routes, we covered as many remaining high and medium-priority grid cells as
12   possible, while also trying to optimize the location of parallel routes. Some of these medium-
13   priority routes do not converge downtown and help comprise the grid transit network that we are
14   aiming for, thereby allowing for more diverse travel patterns to be possible. Many of the proposed
15   routes in the new network followed existing route alignments in order to utilize existing stops in
16   the future, although in most cases we simplified routes, eliminating circuitous routing on local
17   streets, to reduce travel time.
18
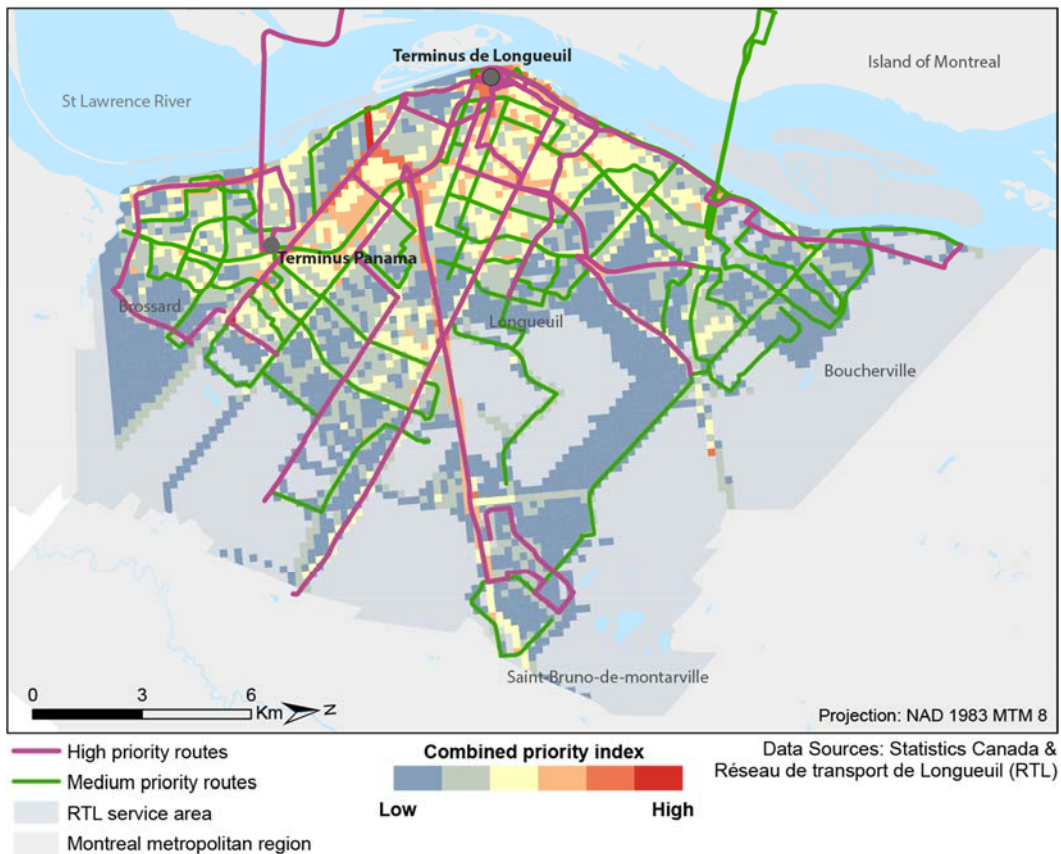
19
20   **Figure 3 Proposed high and medium-priority bus routes**

1

Coverage analysis

3   To evaluate our proposed network, we first conducted a coverage analysis to identify gaps in our
4   network that require improvements. This was done iteratively, until a satisfactory level of coverage
5   in the region was achieved, therefore meeting our first condition of a satisfactory network: 'Offers
6   sufficient network coverage to residents'. To do so, we first measured the coverage of the existing
7   network using 400m network buffers and then generated 600m buffers around stops of the
8   proposed bus network. A network buffer of 400m is the most common standard measure of
9   walking distance to bus stops (*19-23*), although more recently studies have examined this buffer
10 and found varying walking distances according to service type and frequency (*24*). We adopted a
11 600m buffer for the proposed network as this is a high frequency network, and analyses of travel
12 behaviour have found that people walk further distances to routes with shorter waiting times (*24*).
13   Next, we compared the levels of coverage offered by the existing network and proposed
14 network (Figure 4) and applied modifications to the proposed network when major gaps were
15 observed. As shown in Figure 4, we see minor losses of coverage within Longueuil. This sub-
16 optimal spatial coverage was similarly observed in the case of Barcelona, due to a lack of
17 suitability among select streets for operating high-frequency bus service (*10*). Following close
18 examination of these gaps in coverage, we determined that these were in suburban
19 neighbourhoods, with a striking lack of street connectivity and high proportion of cul-de-sacs. Due
20 to the poor walkability of these neighbourhoods, residents have to walk further distances to access
21 bus service on nearby arterials. To mitigate this, we suggest for planners to consider alternatives
22 to connect theses residents to bus service, such as improved pedestrian connectivity to arterial
23 streets or various services to help complete the first mile/ last mile (e.g. transport network company
24 (TNC) partnerships). Alternatively, some peak hour trips can offer additional coverage into
25 suburban neighbourhoods with greater walking access. Interestingly, there are also areas in the
26 city where the proposed network offers more coverage than the existing one. What is most
27 important to emphasize is the level of coverage achieved by the proposed network with the reduced
28 kilometers of service proposed (790km of existing service compared to 420km of proposed
29 service).

30

31
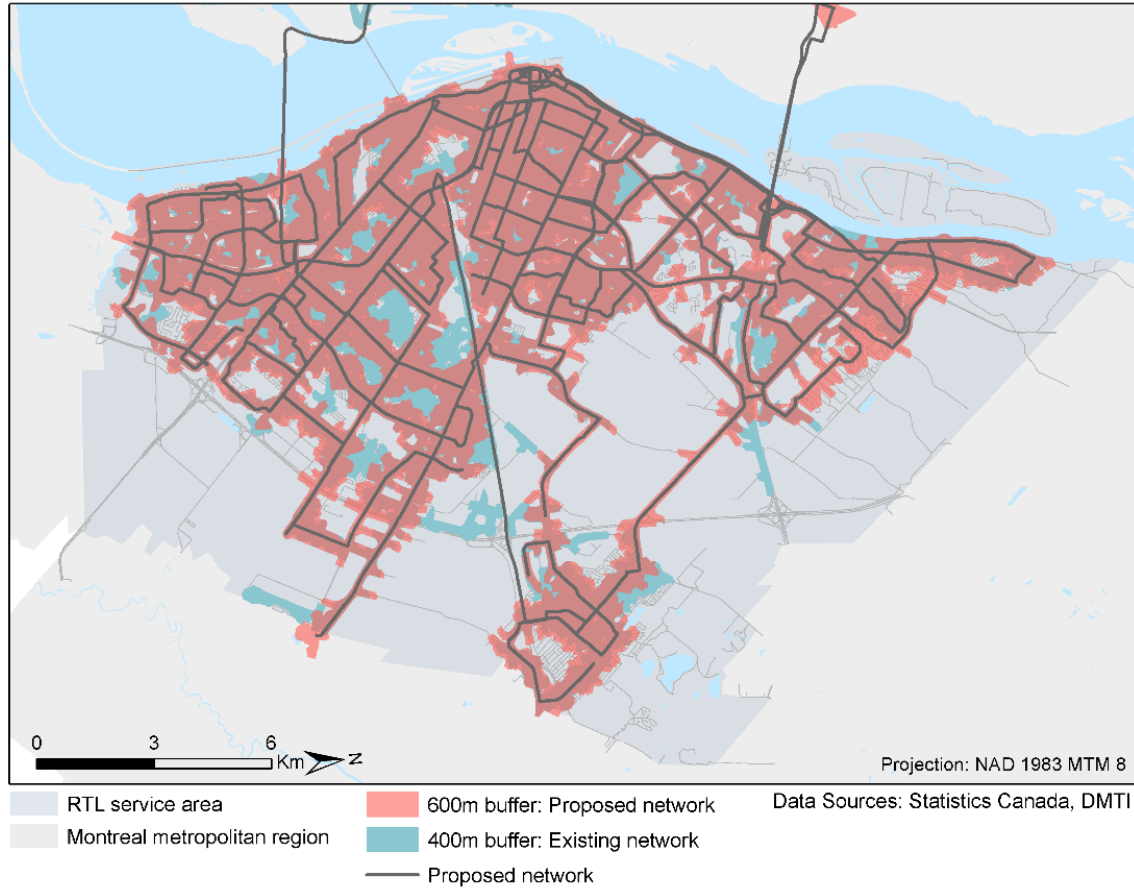
Figure 4 Comparing service coverage between the two networks

Accessibility analysis

The ultimate goal of this bus redesign is to provide users and potential users with improved access to desired opportunities locally and within the Montreal Metropolitan region. Accessibility is defined as a measure of potential opportunities (*25*). The potential for reaching potential opportunities is determined by both the transport system (reflecting the travel time for reaching a destination) and the land-use system (*26*). While reducing travel times is an important factor influencing passenger satisfaction levels (*27-29*), accessibility was selected as the focus of our network evaluation as it is essential that transport systems provides individuals with access to spatially and temporally dispersed opportunities (*30; 31*).

In this analysis, we measured accessibility to jobs, which is a commonly used proxy for density of activity in a region. A cumulative opportunity measure of accessibility of the existing and proposed network was calculated using open-source cloud-based software.[2] Jobs data was obtained from Statistics Canada 2016 Census Flow tables for the Montreal Metropolitan region, which represent the number commuters travelling between census tract (CT) pairs by mode of transport. Number of jobs is represented as the total number of commuters arriving per CT. The

---

[2] Source code available at https://github.com/conveyal/analysis-backend

1   software measures accessibility at the grid cell level, with a resolution of 216m by 216m or
2   approximately 0.05 km^2, so number of jobs per CT was disaggregated by areal proportion into the
3   grid cells intersecting each CT.
4   Travel time by public transit between all grid cells was determined using a 60-minute
5   threshold, which was selected based on the existing travel behavior of residents. According to OD
6   survey data, the median travel time of residents commuting by public transit is 55.9 minutes and
7   the 75th percentile travel time is 65.5 minutes. The resulting accessibility measures are presented
8   in Figure 5. Travel time information for the existing network was obtained using GTFS data
9   obtained from a generic Tuesday in May 2016. For the proposed network, GTFS data was drawn
10 manually using the software's web-based interface[3] using a route speed of 31km/h, which is the
11 median route speed of all scheduled daily trips in the GTFS feed of the existing network.
12 Exceptions were made for routes that operate predominantly on highways with bus priority. The
13 express route between downtown and Terminus Panama was assigned a speed of 35km/h, and the
14 remaining two express routes were assigned a speed of 45 km/h; both speeds closely resemble
15 those of existing service on these corridors. When drawing routes, default stops were generated
16 automatically at 500-meter increments, with subsequent manual adjustment to create convenient
17 transfer points between routes and represent limited-stop express service. After calculating
18 accessibility for each grid cell origin given the proposed and baseline networks, the two networks
19 could be compared graphically, highlighting remaining accessibility gaps to be addressed in
20 additional iterations of network design. Several network iterations were carried out, where minor
21 modifications to the proposed lines were made or new routes were added, until we reached a
22 network satisfying our second condition: increase accessibility to jobs within 60 minutes by a
23 minimum of 10 percent for all residents within the RTL service area.
24   Looking first at accessibility to jobs of the existing network, there are two hotspots of high
25 accessibility, which are the two major transport terminals in Longueuil, Terminus Longueuil
26 (subway station) and Terminus Panama (major bus terminal). In the remainder of the region,
27 moderate and low levels of accessibility are seen. Looking at accessibility levels of the proposed
28 network, we see that the proportion of grid cells with moderate and high levels of accessibility is
29 strikingly higher, meaning that a much larger number of residents are residing in an area with good
30 levels of accessibility to jobs relative to the existing network. We also see that levels of higher
31 accessibility for the most part follow the proposed network, and therefore all residents living
32 around the new network will experience good levels of accessibility.
33   Looking closely at percentage change in accessibility (Figure 6) we see many areas shown
34 in orange and red where significant gains in accessibility are experienced. There are also areas that
35 experience declines in accessibility, which can largely be attributed to increased walking access to
36 bus service in areas identified by Figure 4. Also, moderate reductions in accessibility in Brossard
37 can potentially be attributed to the transfer required at Terminus Panama to the downtown-express
38 bus service, whereas presently passengers can take a bus directly to the Island of Montreal. Note,
39 travel time data used to generate the accessibility measures was according to schedules, rather than
40 actual travel times. Presently there is significant bus traffic from the large number of routes that
41 terminate at Terminus Centre-ville in Montreal, resulting in additional travel time budgeted within

---

[3] Note, GTFS data of surrounding municipalities was used in this analysis, and existing RTL schedules were replaced with schedules of proposed network

1 schedules to improve the operator's on-time performance. By significantly limiting the number of
2 buses that are entering Terminus Centreville, travel times may be reduced to reflect the increased
3 travel time reliability of this service.
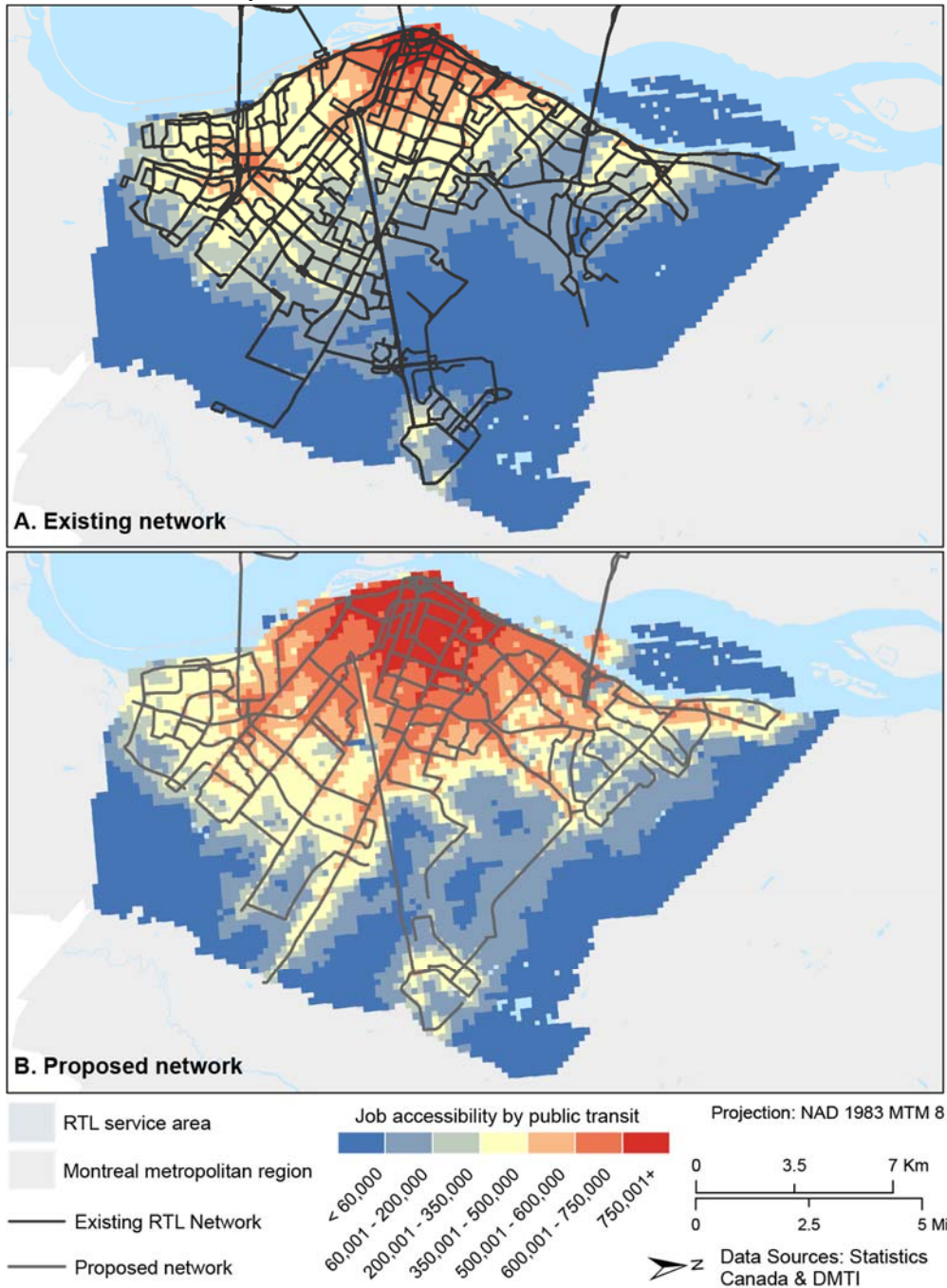
4
5 **Figure 5 60-minute accessibility to jobs (A) existing RTL bus network and (B) proposed bus**
6 **network**

7   At a more disaggregate level, we see that median accessibility to jobs within one hour
8 increases from 358,271 to 475,064. This increase in job accessibility (approximately 33 percent)
9 far exceeds our condition for an increase in accessibility of at least 10 percent. If the RTL were to

1   instate a policy target that 75% of the service area's residents should be able to access at least 10%
2   of the Montreal Metropolitan region's 1.75 million jobs, the redesign scenario would meet it:
3   Approximately 78% of the population has access to at least 175 thousand jobs in the redesign
4   scenario, versus only 68% in the baseline.
5
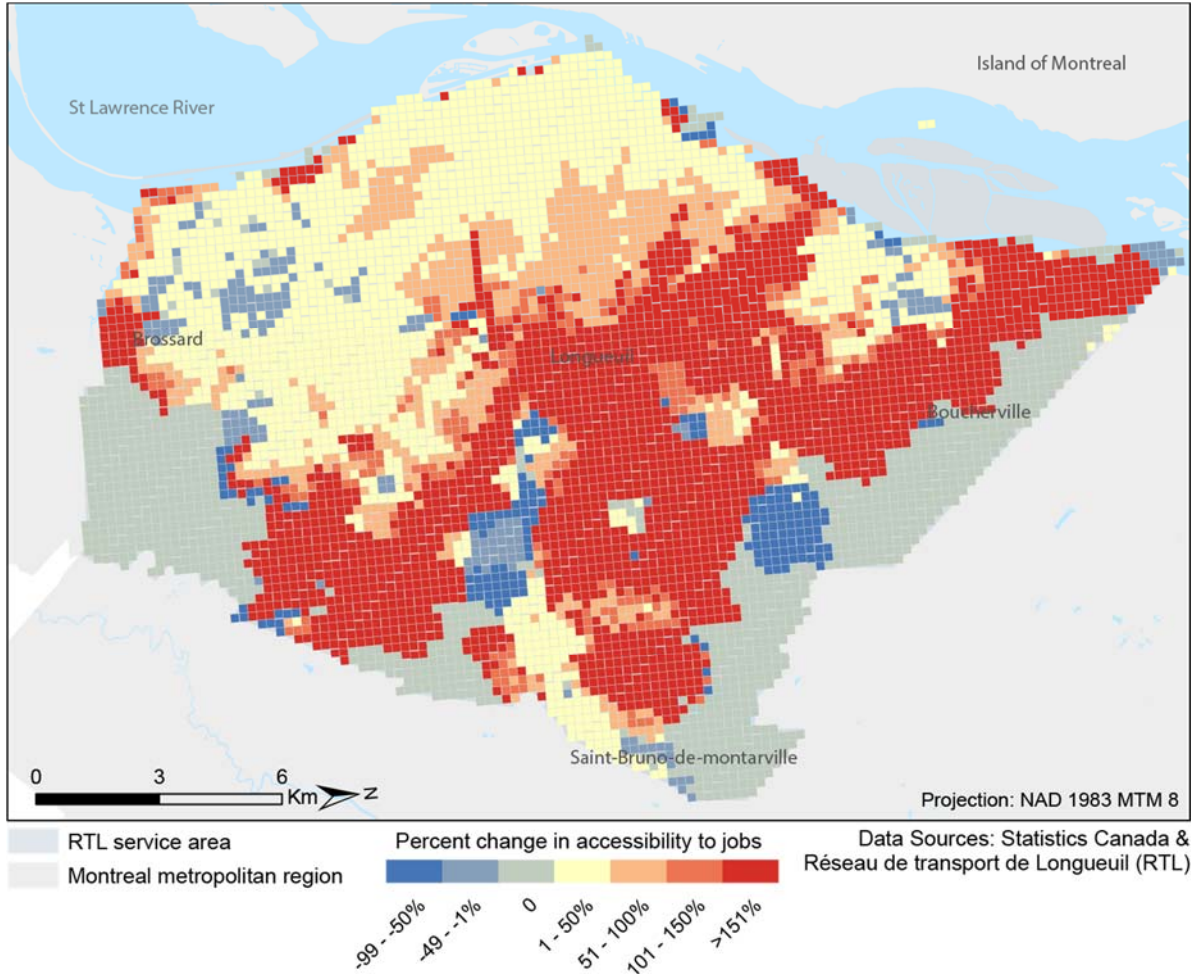
6
7   **Figure 6 Percent change in accessibility to jobs**

8

9   **Bus fleet analysis**

10   Following the proposal of a new bus network, we conducted a series of calculations to determine
11   the number of buses required to operate the proposed network at peak service hours. This step was
12   completed to ensure that the proposed network can be delivered using either the existing number
13   of buses within the RTL fleet or with fewer buses to save operating costs. Presently, the RTL owns
14   484 buses, and we assumed that at any time a minimum of 10% of this fleet will be reserved for
15   maintenance in the garage, leaving a maximum of 435 buses available to serve the network at peak.
16   We first calculated the cycle time for each route, which is the time for one vehicle to
17   complete both directions of a route (out and return). Cycle time is expressed by the relationship:
18        $Cycle\ Time\ (minutes) = Travel\ Time\ (minutes) + Layover\ (minutes)$

1
$$Cycle\ Time\ (minutes) = \frac{2 * Length\ (km) * 60(\frac{min}{hr})}{Speed\ (km/h)} + LayoverTime$$

2 In our calculations, we applied 40 minutes of layover (terminal) time, assuming 10 minutes break
3 at one end and 30 at the other end. Finally, the number of vehicles required for each route is
4 calculated as follows:

5
$$Number\ of\ Vehicles^{4} = \frac{Cycle\ time\ (minutes)}{Headway(minutes)}$$

6 Using these formulas, we calculated the total number of buses required to operate the
7 proposed network. Table 1 presents a scenario analysis, where we show total buses needed
8 according to two levels of frequency, first a conservative scenario and a high-frequency scenario.
9 We then show how operating speed changes the number of buses needed to serve each route. We
10 begin with a speed of 31km/h as used in our accessibility analysis, and then present more
11 conservative operating speeds: 28, 25 and 22 km/h. Note, a constant speed of 35km/h for our
12 express downtown route and 45km/h for the two remaining express routes was used.
13
14 **TABLE 1 Bus fleet calculation**

Conservative frequency		Operating speed			
	Headway	31 km/h	28 km/h	25 km/h	22 km/h
Express downtown	3 min	27	27	27	27
High priority routes	7 min	176	186	199	216
Medium priority routes	10 min	127	133	142	150
	Total buses needed:	**330**	**346**	**368**	**393**
High frequency		**Operating speed**			
	Headway	31 km/h	28 km/h	25 km/h	22 km/h
Express downtown	2 min	40	40	40	40
High priority routes	6 min	198	211	224	246
Medium priority routes	9 min	148	155	164	176
	Total buses needed:	**386**	**406**	**428**	**462**

15
16 We see that 330 buses are needed to serve the conservative frequency scenario with an
17 operating speed of 31km/h, and as many as 393 buses are needed for network speeds averaging
18 22km/h. Therefore, the conservative frequency scenario can be implemented with significant
19 operational savings. Alternatively, the RTL can implement the high-frequency scenario, requiring
20 386 buses if average operating speeds are 31km/h, or 406 buses for network speeds 28km/h or 428
21 for speeds approximately 25km/h. However, there would be an insufficient number of buses to
22 serve the network if speeds are as low as 22km/h. This sensitivity analysis demonstrates that the

---

[4] Calculated number of vehicles was rounded up

1   proposed network is feasible from an operational standpoint or this network can save the agency
2   operational costs which can be reinvested towards service quality improvements.
3

4   **Case study of individual travel time and accessibility changes**

5   As a final analysis of our proposed network, we randomly selected 30 individuals from the 2013
6   OD survey (previously used to evaluate travel demand), and measured changes in travel time and
7   accessibility to jobs. Trips from selected OD pairs all originated within the RTL service area and
8   each trip destination was located within the Montreal Metropolitan region. Our sample consists of
9   trips by either transit or driving for the purpose of commuting to work or school. We observed that
10 if the proposed network is implemented, these individuals on average would experience a 13.9
11 minutes reduction in their travel time, or a 36% travel time savings. In future analyses, these travel
12 time changes could be extended to the full sample of the OD survey. These travel time reductions
13 are quite significant and would likely have a positive effect on user satisfaction levels, as well as
14 potentially attracting drivers to switch to public transit. Moreover, these individuals would see an
15 83% increase in their accessibility to jobs relative to the existing network. This increase in
16 accessibility can be attributed to both reduced travel time and the improved connections to varied
17 destinations within the city due to the grid-like network.

18 **CONCLUSION**

19 For cities wishing to boost transit ridership and reduce single occupancy driving, it is essential to
20 deliver quality transit service that is an attractive alternative to driving. Transport professionals
21 have the knowledge that passengers desire frequent, reliable and fast transit service --
22 characteristics not commonly associated with a traditional door-to-door bus network. With this in
23 mind, this study presents a methodology that can guide the process of transitioning a door-to-door
24 bus network to a high-frequency transfer-based network. An overview of our methodology is
25 shown in **Error! Reference source not found.**. Using Longueuil, Quebec as a case study, we
26 developed a method in GIS that consolidates multiple datasets that describe the travel demand in
27 the region, land use characteristics, and existing network performance, and generates a
28 prioritization index that is used to visually guide the proposal of high and medium-frequency bus
29 routes.
30   In future applications of this methodology, inputs into the prioritization index can be
31 changed according to data availability and a weighting scheme can be applied to place increased
32 importance on certain data. For example, we used existing population and jobs density, other
33 approaches can apply 10- year projections of population and jobs to account for future demand.
34 Furthermore, while we accounted for passenger loads and passenger demand in the prioritization
35 index, our study should be followed by the generation of a demand model to estimate average
36 hourly demand and to calculate the expected loads based on the new frequency. Based on the
37 existing network demand (average all-day maximum route load is 11 passengers) we are not
38 expecting imminent capacity issues in the new service.
39   While the street network in Longueuil lacks a clear pattern, we attempted to create a grid
40 network to facilitate easy and intuitive transfers to spatially dispersed destinations in the city. The
41 high-frequency routes that comprises the backbone of the network are predominantly radial routes,

1   connecting to either Terminus Panama or Terminus Longueuil. Several medium priority routes do
2   not travel to either terminal but instead help form the grid pattern, thereby connecting radial routes
3   and enabling transfers.
4   Following the initial proposal of high and medium-priority routes, we evaluated the
5   coverage of the routes and accessibility to jobs and modified the network accordingly. Several
6   networks were proposed during our study, each improving on the network coverage or accessibility
7   levels observed from previous network iterations. While minor losses in network coverage were
8   observed, in some parts of the city we achieved similar levels of coverage throughout the network
9   despite reducing the length of the network by approximately 47%. Maximizing accessibility to
10 jobs throughout the region was the ultimate target when evaluating the proposed network, rather
11 than a mobility indicator such as travel time, since accessibility has been described as more
12 accurately emphasizing the needs of individuals (*31*). Whilst, we did not plan for travel time, but
13 accessibility, we noticed an average of 13.9 minutes of travel time savings, in other words travel
14 time savings will come as a byproduct when planning for accessibility. At the regional level,
15 median accessibility to jobs within one hour increases from 358,271 in the baseline scenario to
16 475,064 in the revised network. It is important to note that the proposed network although it covers
17 more areas, and provides higher accessibility levels, it also uses lower number of buses than the
18 RTL currently use in their fleet offering significant operational savings.
19   This study is intended to be easily replicated in other contexts by planners and engineers
20 wishing to undertake a bus network redesign compared to previous research that relied on
21 mathematical optimizations (*10*). This research illustrates the operational advantages of
22 implementing a high-frequency transfer-based network, namely the reduced number of buses
23 required to serve this network design relative to a door-to-door network. It is anticipated that
24 implementation of this network structure will have positive impacts on ridership and satisfaction
25 levels, as observed by Badia, Argote-Cabanero and Daganzo (*11*) and Allen, Muñoz and Rosell
26 (*12*) in the case of Barcelona's network reform. The expected opening of a new light rail project
27 in the region offered a unique opportunity to rethink the entire RTL bus network. While such an
28 opportunity does not happen every year for all agencies around the world, with the prevalence of
29 new rail projects around the world or competing forms of transportation, this methodology can be
30 of value to many practitioners who are similarly undergoing major network reforms. Alternatively,
31 as cities grow and evolve, so do transit systems, often resulting in network inefficiencies or
32 redundancies. We recommend transit agencies to conduct a network reform exercise such as this
33 to determine whether the existing service is optimal for the region or whether new routes should
34 be proposed to more effectively serve the region. A minimum average increase in accessibility of
35 10 percent is recommended as a measure to determine whether an agency should go forward with
36 a network reform, thereby ensuring that such a network reform is a worthy investment. Achieving
37 substantial improvements in accessibility are expected to result in ridership gains (see previous
38 work that has associated higher accessibility at transit stops with higher ridership (*32*)), as well as
39 increases in transit mode share, as supported by several studies (*33-35*).
40

1 **ACKNOWLEDGEMENTS**

8

9 **AUTHOR CONTRIBUTIONS**

10 The authors confirm contribution to the paper as follows: study conception and design: Grisé &
11 El-Geneidy; data collection: Grisé & El-Geneidy; analysis and interpretation of results: Grisé,
12 Stewart, & El-Geneidy; draft manuscript preparation Grisé Stwart, & El-Geneidy. All authors
13 reviewed the results and approved the final version of the manuscript.
14
15
16

1 REFERENCES

2 [1] Boisjoly, G., E. Grisé, M. Maguire, M. Veillette, R. Deboosere, E. Berrebi, and A. El-Geneidy.
3 Invest in the ride: A 14 year longitudinal analysis of the determinants of public transport ridership
4 in 25 North American cities. *Transport Research Part A: Policy and Practice,* Vol. 116, 2018, pp.
5 434-445.
6 [2] Badia, H., M. Estrada, and F. Robusté. Bus network structure and mobility pattern: A
7 monocentric analytical approach on a grid street layout. *Transportation Research Part B:*
8 *Methodological,* Vol. 93, 2016, pp. 37-56.
9 [3] Ben-Akiva, M., and T. Morikawa. Comparing ridership attraction of rail and bus. *Transport*
10 *Policy,* Vol. 9, No. 2, 2002, pp. 107-116.
11 [4] Thompson, G., and T. Matoff. Keeping up with Joneses: Radical vs. multidestinational transit
12 in decentralizing regions. *American Planning Association. Journal of the American Planning*
13 *Association,* Vol. 69, No. 3, 2003, p. 296.
14 [5] Brown, J., and G. Thompson. Examining the influence of multidestination service orientation
15 on transit service productivity: a multivariate analysis. *Transportation,* Vol. 35, No. 2, 2008, pp.
16 237-252.
17 [6] Vuchic, V. *Urban transit: Operations, planning, and economics*. John Wiley & Sons,
18 Hoboken, N.J., 2005.
19 [7] Daganzo, C. Structure of competitive transit networks. *Transportation Research Part B:*
20 *Methodological,* Vol. 44, No. 4, 2010, pp. 434-446.
21 [8] ---. The break-bulk role of terminals in many-to-many logistic networks. *Operations Research,*
22 Vol. 35, No. 4, 1987, pp. 543-555.
23 [9] Thompson, G. Planning considerations for alternative transit route structures. *Journal of the*
24 *American Planning Association,* Vol. 43, No. 2, 1977, pp. 158-168.
25 [10] Estrada, M., M. Roca-Riu, H. Badia, F. Robusté, and C. Daganzo. Design and implementation
26 of efficient transit networks: procedure, case study and validity test. *Transportation Research Part*
27 *A: Policy and Practice,* Vol. 17, 2011, pp. 113-135.
28 [11] Badia, H., J. Argote-Cabanero, and C. Daganzo. How network structure can boost and shape
29 the demand for bus transit. *Transportation Research Part A: Policy and Practice,* Vol. 103, 2017,
30 pp. 83-94.
31 [12] Allen, J., J. Muñoz, and J. Rosell. Effect of a major network reform on bus transit satisfaction.
32 *Transportation Research Part A: Policy*
33 *Practice,* Vol. 124, 2019, pp. 310-333.
34 [13] RTL. *Annual Report*. http://www.rtl-longueuil.qc.ca/en-CA/press-room/documents-and-
35 practical-information/annual-reports/.
36 [14] Statistics Canada. *2016 Census Profile of Census Subdivisions*.
37 http://datacentre.chass.utoronto.ca/cgi-bin/census/2016/displayCensus.cgi?year=2016&geo=csd.
38 [15] RTL. *About*. http://m.rtl-longueuil.qc.ca/en-CA/rtl/about. Accessed July 1, 2019.
39 [16] Grisé, E., and A. El-Geneidy. If we build it, who will benefit? A multi-criteria approach for
40 the prioritization of new bicycle lanes in Quebec City, Canada. *The Journal of Transport and Land*
41 *Use,* Vol. 11, No. 1, 2018, pp. 217-235.
42 [17] Larsen, J., Z. Patterson, and A. El-Geneidy. Build it. But where? The use of geographic
43 information systems in identifying locations for new cycling infrastructure. *International Journal*
44 *of Sustainable Transportation,* Vol. 7, No. 4, 2013, pp. 299-317.
45 [18] Agence Métropolitaine de Transport. Enquête origine-destination 2013.In, Montreal, Quebec,
46 2013.

1   [19] Gutiérrez, J., and J. García-Palomares. Distance-measure impacts on the calculation of
2   transport service areas using GIS. *Environment and Planning B: Planning and Design,* Vol. 35,
3   2008, pp. 480-503.
4   [20] Hsiao, S., J. Lu, J. Sterling, and M. Weatherford. Use of geographic information system for
5   analysis of transit pedestrian access. *Transportation Research Record: Journal of the
6   Transportation Research Board,* Vol. 1604, 1997, pp. 50-59.
7   [21] Kimpel, T., K. Dueker, and A. El-Geneidy. Using GIS to measure the effect of overlapping
8   service areas on passenger boardings at bus stops. *Urban and Regional Information Systems
9   Association Journal,* Vol. 19, No. 1, 2007, pp. 5-11.
10   [22] O'Neill, W., R. Ramsey, and J. Chou. Analysis of transit service areas using Geographic
11   Information Systems. *Transportation Research Record: Journal of the Transportation Research
12   Board,* Vol. 1364, 1992.
13   [23] Zhao, F., L. Chow, M. Li, I. Ubaka, and A. Gan. Forecasting transit walk accessibility:
14   Regression model alternative to buffer method. *Transportation Research Record: Journal of the
15   Transportation Research Board,* Vol. 1835, 2003, pp. 34-41.
16   [24] El-Geneidy, A., M. Grimsrud, R. Wasfi, P. Tétreault, and J. Surprenant-Legault. New
17   evidence on walking distances to transit stops: identifying redundancies and gaps using variable
18   service areas. *Transportation,* Vol. 41, No. 1, 2014, pp. 193-210.
19   [25] Hansen, W. How accessibility shapes land use. *Journal of the American Institute of Planners,*
20   Vol. 25, No. 2, 1959, pp. 73-76.
21   [26] Handy, S., and D. Niemeier. Measuring accessibility: An exploration of issues and
22   alternatives. *Environment and planning A,* Vol. 29, No. 7, 1997, pp. 1175-1194.
23   [27] Mouwen, A. Drivers of customer satisfaction with public transport services. *Transportation
24   Research Part A: Policy and Practice,* Vol. 78, 2015, pp. 1-20.
25   [28] Susilo, Y., and O. Cats. Exploring key determinants of travel satisfaction for multi-modal
26   trips by different traveler groups. *Transportation Research Part A: Policy and Practice,* Vol. 67,
27   2014, pp. 366-380.
28   [29] Dell'Olio, L., A. Ibeas, and P. Cecin. The quality of service desired by public transport users.
29   *Transport Policy,* Vol. 18, No. 1, 2011, pp. 217-227.
30   [30] Straatemeier, T. How to plan for regional accessibility? *Transport Policy,* Vol. 15, No. 2,
31   2008, pp. 127-137.
32   [31] Banister, D. The sustainable mobility paradigm. *Transport Policy,* Vol. 15, No. 2, 2008, pp.
33   73-80.
34   [32] Dill, J., M. Schlossberg, L. Ma, and C. Meyer. Predicting transit ridership at the stop level:
35   The role of service and urban form.In *92nd annual meeting of the Transportation Research Board,
36   Washington, DC*, 2013.
37   [33] Cui, B., and A. El-Geneidy. Accessibility, equity, and mode share: a comparative analysis
38   across 11 Canadian metropolitan areas. *Transport Findings*, 2019.
39   [34] Owen, A., and D. Levinson. Modeling the commute mode share of transit using continuous
40   accessibility to jobs. *Transportation Research Part A: Policy and Practice,* Vol. 74, 2015, pp. 110-
41   122.
42   [35] Boisjoly, G., and A. El-Geneidy. Daily fluctuations in transit and job availability: A
43   comparative assessment of time-sensitive accessibility measures. *Journal of transport geography,*
44   Vol. 52, 2016, pp. 73-81.
45
46