New evidence on walking distances to transit stops: Identifying redundancies and gaps using variable service areas

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ABSTRACT

The percentage of the population being served by a transit system in a metropolitan region is a key system performance measure but depends heavily on the definition of service area. Observing existing service areas can help identify transit system gaps and redundancies. In the public transit industry, buffers at 400 meters (0.25 miles) around bus stops and 800 meters (0.5 miles) around rail stations are commonly used to identify the area from which most transit users will access the system by foot. This study uses detailed origin-destination survey information to generate service areas that define walking catchment areas around transit services in Montreal, Canada. The 85th percentile walking distance to bus transit service is around 524 meters from home-based trip origins, 1,259 meters for commuter rail. Yet these values are found to vary based on our analysis using two statistical models. Walking distances vary based on route and trip qualities (such as type of transit service, transfers and wait time), as well as personal, household, and neighbourhood characteristics. Accordingly, service areas around transit stations should vary based on the service offered and attributes of the people and places served. The generated service areas derived from the generalized statistical model are then used to identify gaps and redundancies at the system and route level using Montreal region as an example. This study can be of benefit to transport engineers and planners trying to maximize transit service coverage in a region while avoiding oversupply of service.

Keywords: Walking distance, Transit stops, Service area, Pedestrian access, Accessibility to transit, Redundancy in transit service, and Gaps in transit service

INTRODUCTION

The percentage of the population served by a transit system in a metropolitan region is a key system performance measure (Fielding, Glauthier, & Lave, 1978). This performance measure depends on the definition of service areas. A service area around a transit station or stop is broadly defined as the area from which potential riders are drawn. Delineating the service area around public transit stations is a complex and important issue, and is used to determine optimal stop spacing, identify redundancy and gaps at the route and system levels, and understand and predict demand for transit. Stop spacing here is referred to the distance between two consecutive stops along the same route. Redundancy occurs when the same parcel is being served by multiple stops along the same route due to short stop spacing or is being served by multiple routes leading to the same destination. Gaps occur in areas that are not served by any stops or routes. Many transit planners and engineers depend on simplified methods when determining service areas around transit stations especially in regard to walking. A 400-meter buffer (0.25 miles) is defined around bus stops (O'Neill, Ramsey, & Chou, 1992; Zhao, Chow, Li, Ubaka, & Gan, 2003) and an 800-meter buffer (0.5 miles) is used for rail stations (Kuby, Barranda, & Upchurch., 2004; Schlossberg, Agrawal, Irvin, & Bekkouche, 2007) as the areas from which most users accessing the system by foot originate. On the other hand, some researchers feel that this definition is not comprehensive enough and accordingly they use a more inclusive service area based on a 482 meter (0.3 mile) buffer around the bus station (Kimpel, Dueker, & El-Geneidy, 2007). These simplified service areas assume that all transit stations or stops are alike for a given mode, which is not entirely true. This method of defining service areas imposes an error when trying to understand the demand for transit and/or when identifying gaps and redundancies in the existing transit service. Redundancy in the transit service provided can lead to poor and unreliable service. Redundancy is an output of poor stop spacing where the bus is required to stop at every block in the network or it is an output of poor system design when several competing routes are present. The definition of service areas should be related to the type of service being offered, its frequency (Fielding et al., 1978) and its reliability. In this research paper, we offer a new method for understanding and defining service areas around transit stations for users accessing transit by foot using Montreal, Canada as a case study. This is done through analyzing a detailed origin-destination survey conducted in 2003 (Agence métropolitaine de transport, 2003) and combining it with service, demographic and built environment characteristics to generate service areas around existing transit stops. This is done with the goals of identifying areas with high levels of redundancy in transit service and identifying gaps where new or improved services are needed.

The paper starts with a review of bus and rail transit service area literature followed by a description of the study region. The next section pertains to the methodology used to prepare and analyze the data for developing service areas. These sections are followed by a discussion of those results and a conclusion.

LITERATURE REVIEW

The most common standard measure of walking distance to transit stops and stations has been 400 meters (0.25 miles) (Gutiérrez & García-Palomares, 2008; Hsiao, Lu, Sterling, & Weatherford, 1997; Kimpel et al., 2007; Murray & Wu, 2003; Neilson & Fowler, 1972; O'Neill et al., 1992; Zhao et al., 2003) since 1972. However, a substantial body of research attempts to refine the analysis of access to transit facilities. According to Murray and Wu (2003), access to transit service is an important factor in transit service planning. The more people residing and/or employed around transit stations, the greater the probability that the service will be used. This definition of the service area involves the use of distance decay to estimate walking distances to transit facilities (Hsiao et al., 1997; Kimpel et al., 2007; Lam & Morrall, 1982; O'Sullivan & Morrall, 1996; Zhao et al., 2003). Authors using distance decay express distances in terms of proportions of riders who will walk no more than a certain threshold. Zhao and her collaborators (2003) noted that in southeast Florida, the number of riders walking over half a mile (800 m) was negligible. In Toronto, Canada, Alshalalfah and Shalaby (2007) showed that among transit users, 60% live within 300 metres from their stop and 80% within 500 metres. In Calgary, Canada, Lam and Morrall (1982) observed a median walking distance to bus stops of 292 metres, while the average was 327 metres and the 75th percentile, 450 metres. Also in Calgary, O'Sullivan and Morrall (1996) distinguished between walking to light-rail transit stations in the suburbs and in the central business district. They found an average distance of 649 metres and a 75th percentile equal to 840 metres in the former, while the average distance was 326 metres and the 75th percentile was 419 metres in the latter. Studying walking distances to rail transit stations in Portland, WA, and San Francisco, CA, Schlossberg and his collaborators found a median distance of 0.47 miles (756 m) (Schlossberg et al., 2007).While Daniels and Mulley (2013) found the mean walking distance to bus service 461 meters with 75th percentile at 566. In the same study they found mean walking to rail around 805 meters and the 75th percentile at 1018. It is clear that variation exists in the distance users are walking to transit and bus services between studies. Also it is clear that these distances are beyond the 400 meters for buses and 800 for rail. These differences reflect variations between sections in the regions where data were collected as well as variations between regions. Accordingly, service areas around transit stations should vary according to the service being offered and the location in the region.

The first element to consider when analyzing walking distance to transit stops is that pedestrians first and foremost seek to minimize both the distance and time of the walking portion of their trip (O'Sullivan & Morrall, 1996; Schlossberg et al., 2007). After that, individual characteristics, station and area characteristics, transit route features, and temperature can have an effect on walking distances. According to Loutzenheiser (1997), individual characteristics are the most important factors influencing walking trips. Household incomes (Hsiao et al., 1997; Kuby et al., 2004; Loutzenheiser, 1997) and blue collar neighbourhoods (Loutzenheiser, 1997) negatively affect propensity to walk while population and dwelling density (Hsiao et al., 1997; Loutzenheiser, 1997; Zhao et al., 2003) and education (Loutzenheiser, 1997) have positive effects, although not necessarily on distances of those who do walk. Vehicle availability relates negatively to walking likelihood (Hsiao, Lu et al. 1997) but positively to walking disance, presumably because car-owning households locate with less emphasis on transit access (Alshalalfah and Shalaby 2007). Pedestrian access to a transit service, which is the opportunity for using a system (Murray, Davis, Stimson, & Ferreira, 1998), is strongly associated with bus ridership (Hsiao et al., 1997), meaning that if a reliable transit system exists within a walking distance from a population the probability of this system to be used by the residents increases. Area characteristics favouring pedestrian access include the absence of barriers (O'Neill et al., 1992; Zhao et al., 2003), a grid street pattern providing for more pedestrian linkages (Hsiao et al., 1997; Loutzenheiser, 1997; Zhao et al., 2003), higher densities, land use mix (Fitzpatrick, Perkinson, & Hall, 1997; Hsiao et al., 1997; Loutzenheiser, 1997; Zhao et al., 2003), a small number of parking spaces at the station (Loutzenheiser, 1997), safety (Fitzpatrick et al., 1997; O'Sullivan & Morrall, 1996; Schlossberg et al., 2007), and an attractive and reliable transit service (Schlossberg et al., 2007). In terms of transit stops, the number of transit lines at a stop or station (Kuby et al., 2004; Zhao et al., 2003) increases the willingness to walk, while waiting time (Lam & Morrall, 1982; O'Sullivan & Morrall, 1996) and the number of transfers during a trip (Alshalalfah & Shalaby, 2007) decrease access walking distances. Finally, the effect of temperature is unclear because temperatures away from 18°C seems to discourage walking in the United States (Kuby et al., 2004), while winter walking distances are slightly longer than summer ones in Calgary (Lam & Morrall, 1982), a difference that the authors do not explain using temperature.

Walking distances, measured or ascribed, influence buffers or service areas around transit facilities. Service areas are used to help understand the existing demand and determine the proportion of the population using the service at the station or stop. There is a consensus in the transit literature that Euclidean buffers (circular buffers around a point) overestimate the service area of a stop and that network buffers are preferable (Gutiérrez & García-Palomares, 2008; Hsiao et al., 1997; Kimpel et al., 2007; O'Neill et al., 1992; Zhao et al., 2003). This overestimation leads to several errors especially when estimating the demand for transit around stations or stops (Gutiérrez & García-Palomares, 2008). Although they tend not to account for off-street shortcuts, network buffers, which incorporate street layout, are better approximations of actual service area shapes and sizes. Importantly, the size of service areas directly affects bus stop spacing strategies, which impact running time and reliability of service (El-Geneidy, Strathman, Kimpel, & Crout, 2006) - factors mentioned above as important attributes for service attractiveness. Most studies looking at bus stop spacing use 400-meter (0.25-mile) service areas around bus stops when revising stop spacing (Furth & Rahbee, 2000) or when removing redundancy imposed by poor spacing (Murray & Wu, 2003).

The transit industry widely applies the 400-meter (0.25-mile) and 800-meter (0.5-mile) rules of thumb when estimating service areas around bus and rail stations. The application of these conventions can lead to several measurement errors that need to be highlighted and addressed. Previous research has concentrated on the errors generated based on using Euclidean distance, yet to our knowledge there has not been any research looking at the effect of using these generalizations at a regional level. Accordingly, more research is needed in order to understand and properly define service areas around transit stations and stops to address redundancy in the system and generate better stop spacing strategies, which directly relate to the quality of service being offered.

CASE STUDY

Montreal, Quebec is the second most populous metropolitan region in Canada with 3.7 million residents. The Agence metropolitaine de transport (AMT) is an agency of the Quebec Ministry of Transport that is responsible for regional transit in Montreal. In this study, the region served by the AMT will be used as the study region. The AMT operates 5 commuter rail lines, 16 intermodal terminals, 60 park-and-ride facilities, 2 express bus routes, and 85 kilometers of bus, taxi, and/or high-occupancy vehicle lanes. In addition, the AMT plans future transit and collaborates with the 14 local transit agencies in the Montreal region, the largest ones being the Société de transport de Montréal (STM), the Réseau de transport de Longueuil (RTL), and the Société de transport de Laval (STL). **Figure 1** maps the Montreal metropolitan region and existing major transit corridors.

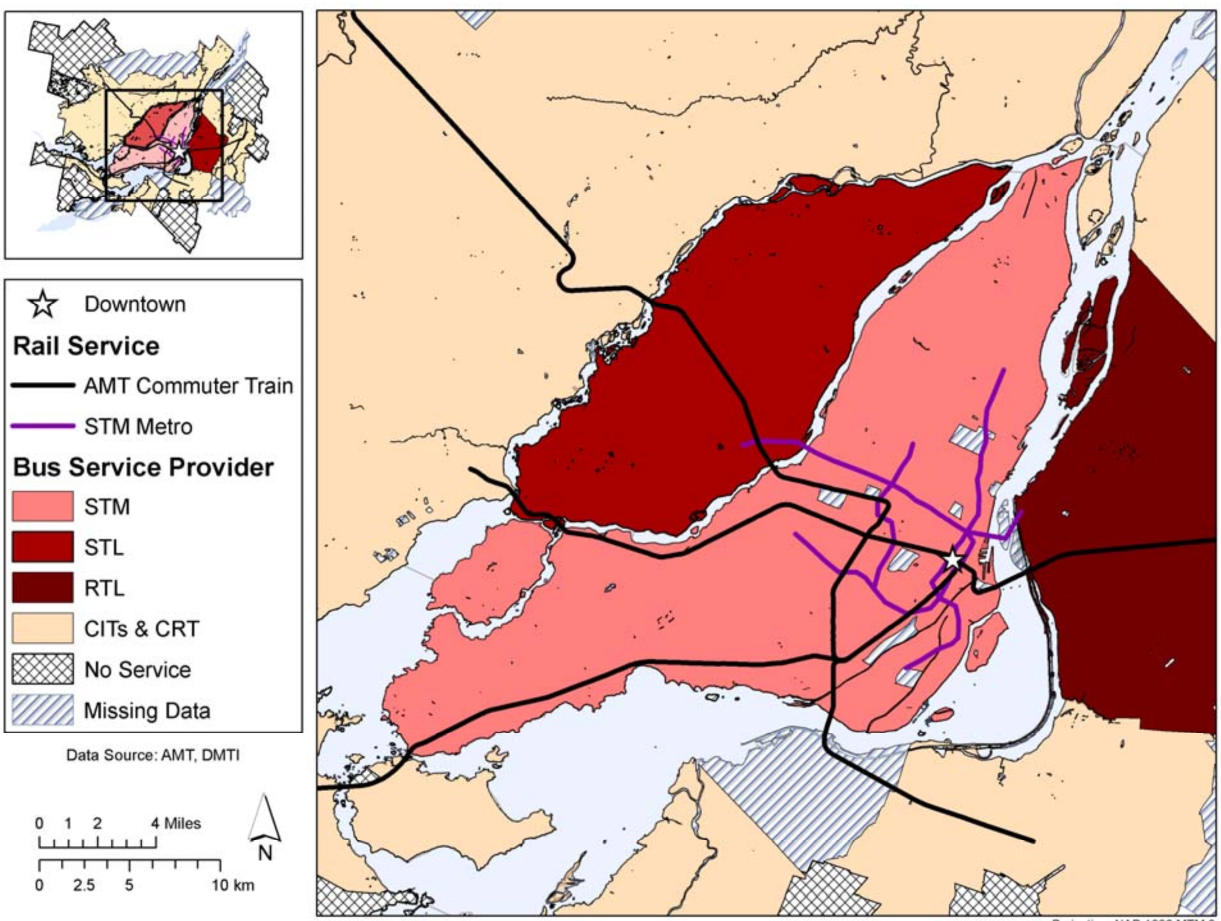

Figure 1: Transit services in the Montreal metropolitan region

According to the 2003 Montreal origin-destination (OD) survey (Agence métropolitaine de transport, 2003), 69.3% of trips are done by car, 13.7% by public transit, 10.2% by foot, 4.8% by school bus, and 1.1% by bicycle during a 24 hour period. In terms of trip purpose in the Montreal metropolitan region, 18.3% are work trips, 10.2% are school trips, 7.6% are shopping trips, 5.0% are leisure trips, and 44.6% are back-to-home trips. The proportion of those trips made by public transit is 15.4% for work trips, 21.7% for school trips, 7.6% for shopping trips, 9.2% for leisure trips, and 14.8% for back-to-home trips.

METHODOLOGY AND DATA PREPARATION

The objective of this paper is to generate variable service areas based on existing service and neighborhood characteristics to help in understanding redundancies and gaps in the existing transit system. This method of generating service area will be compared to traditional methods and conventions. The first step toward generating accurate service areas is to understand and document how far people are walking to use transit in the studied region. Service areas can be modeled around stations or stops using walking distance information from detailed travel behavior data, here from transit users in the 2003 Montreal OD survey (Agence métropolitaine de transport, 2003).

The OD survey is conducted every five years in the Montreal region. The survey records disaggregate trips that were made by each person residing in a household. Each trip origin and destination is geocoded and passes through a series of rigorous validation processes to ensure the trip is ends are geocoded correctly. Five percent of households in the Montreal region were surveyed. The OD survey includes questions asking each transit user the routes used to reach his/her desired destination and if other transportation modes were employed.

Any trip that involved the use of another mode (i.e. car, cycling, taxi, etc.) is excluded from this analysis. Trips using night bus service or dedicated high school services were also excluded, as were non-home-based trips, and only one randomly selected trip was included per person to ensure the randomness of the dataset. Since the OD survey does not record the actual transit station or stop used but only the routes, walking distances to the closest stop served by the first route used were measured using street network and 2003 stop location information. Walking distance from destination to the last transit route used was calculated using the same method.

Measuring walking distances to and from transit stations or stops is the first step in preparing the data for the first statistical model, which examines walking distances along the network to access transit using the individual as the unit of analysis. This model is generated to assess the reliability of the data in hand and compare factors affecting walking to transit in the Montreal region to previous studies. Several factors need to be controlled for in this model. For example, controlling for competing routes is an important step in the process of studying the demand for transit (Kimpel et al., 2007) and was therefore originally included in the walking distance model. A route is considered competing only if it is accessible within a certain network distance threshold measured from both the origin and the destination of the transit trip. This threshold is defined as the value representing the 75th percentile of all walking trips to transit (510.9 meters). Another, more obvious, factor influencing how far users walk is distance at which people live. Network buffers at 200m radius intervals were mapped around each stop or station and linked to Dissemination Area-level census population counts, with populations assumed only to occupy land zoned residential or commercial. The ratio between people residing in the first 400m and 800m captures most of the observed population concentration.

Variables used capture individual, household, neighborhood, trip and route characteristics. These variables are included in the individual model to understand how far people are walking to access transit services. Since we do not know the detailed direction for every stop serving a route, we summarized the information for both directions on the transit route. The shortest headway of the two directions is assigned to every walking trip. Headway is defined according to the starting time of the trip at the origin. Since some users start walking to transit before service begins in a few cases, we assigned the maximal headway on the route for these observations. Lastly, headways were converted to waiting time for improved model and theoretical fit by halving short headways (up to 15 minutes) or assigning eight minutes for longer headways. Users vary (Fan & Machemehi, 2009), but beyond about 15 minutes headway riders often consult schedules rather than showing up uninformed to wait on average half the headway time (Hall, 2001). Bus stop spacing was calculated for both directions using a linear referencing technique in GIS after snapping the stops to the nearest transit line. **Table 1** lists the variables for the individual and stop models. Others, notably competing routes, stop spacing, walking distance to destination, and several occupation status dummies, were removed if found overly related in a correlation matrix or found insignificant after stepwise variable reduction.

Table 1: Variable definitions

Variable Name	Description
Walking distance	Walking distance measured using the street network from trip origin to nearest transit station or stop along transit route used
Both models: route/trip	
Metro	Dummy variable equaling one if Metro is first transport mode in trip
Train	Dummy variable equaling one if suburban train is first transport mode in trip
CIT/CRT bus	Dummy variable equaling one if CIT/CRT bus (transit agencies in the region other than STM, STL and RTL) is first transport mode in trip
Wait time	Wait time of transit route used at starting time of trip
Both models: neighbourhood	
Number of intersections	Number of street intersections around trip origin within 510 meters
Distance to downtown	Euclidean distance from first transit stop or station used to downtown point (kilometers)
Population 800m	Population within 800 network meters of first stop or station used
Population 400m of 800m	Population within 400 network meters of first stop or station used divided by population within 800 network meters of first stop or station used
Individual model: trip	
Number of transfers	Number of transfers during trip
Trip distance	Total in-vehicle trip distance (kilometers)
Work trip	Dummy variable equaling one if work trip
AM peak trip	Dummy variable equaling one if trip is starts between 6:30 am and 9:30 am
Individual model: household	
Number of vehicles	Number of vehicles owned by household
Household size	Number of persons in household
Income above 80K	Dummy variable equaling one if annual household income exceeds $80,000
Individual model: individual	
Age	Age of individual
Male	Dummy variable equaling one if individual is male

The second step is to make a more general model that can be used in generating variable service areas for each station or stop in the Montréal region without the need of using individual characteristics. The findings from this general model will then be used in a comparative analysis, comparing variable service areas with traditional rules in term of identifying redundancies and gaps in the existing services.

DATA

A total of 16,014 home-based transit trips are included in the analysis. The median walking distance to a transit station is 294 meters while the 75th percentile is 525 meters and the 85th percentile is 678 meters. Separating walking distances by type of service can give a clearer picture regarding the level of error being imposed by current conventions. **Table 2** shows summary statistics of walking distances to transit stations (origin) as well as mean values or percentages (for dummies) of independent variables. The 85th percentile of walking distances to bus service is well above 400 meters for all transit operators; for commuter rail, the 85th percentile is over 1,250 meters and is 873 meters for the metro (subway).

Table 2: Summary statistics of walking access distances from home to transit stations or stops in the Montreal region

	All modes	Metro	Train	STM bus	RTL bus	STL bus	CIT bus
Walking distance							
Mean	**374.80**	**564.80**	**817.98**	**275.96**	**314.50**	**347.01**	**488.73**
Median	294.21	527.14	785.03	213.80	243.16	277.36	401.80
Maximum	1497.60	1496.83	1491.28	1490.49	1486.32	1440.36	1497.60
75th percentile	524.58	730.73	1102.84	371.10	427.20	471.51	653.97
85th percentile	678.34	873.35	1259.41	484.09	556.36	601.05	897.04
SD	308.64	297.37	360.10	245.50	282.00	285.27	370.37
75th percentile + 1.5 SD	987.53	1176.79	1642.99	739.35	850.20	899.41	1209.54
Independent variable both models (mean or %)							
Wait time	5.38	2.52	8.00	5.72	7.21	7.67	7.76
Number of intersections	145.27	145.51	147.04	146.72	142.50	137.94	138.95
Distance to downtown	9.19	4.79	17.62	8.93	9.41	16.27	23.81
Population 800m (000s)	8.80	12.25	3.82	9.33	4.16	4.10	2.53
Population 400m of 800m	28.50%	25.57%	26.16%	29.73%	29.00%	28.81%	28.92%
Independent variable individual model (mean or %)							
Number of transfers	0.83	0.62	0.60	0.85	1.09	0.95	1.09
Trip distance	9.14	7.07	19.13	7.89	11.32	12.47	22.69
Work trip	43.94%	49.50%	70.79%	38.64%	51.66%	41.71%	47.21%
AM peak trip	60.66%	54.96%	83.16%	58.63%	69.29%	67.42%	75.28%
Number of vehicles	0.85	0.59	1.46	0.76	1.21	1.31	1.6
Household size	2.91	2.47	3.18	2.95	3.13	3.44	3.5
Income above 80K	12.83%	11.93%	37.32%	10.01%	19.41%	13.08%	22.12%
Male	43.60%	48.48%	51.72%	41.64%	42.69%	43.07%	37.92%
Age	33.45	33.83	36.2	33.89	32.61	29.7	29.99
n	**1614**	**3723**	**493**	**8745**	**1628**	**887**	**538**

It is important to note that the demand around transit stations or stops is not equally distributed and a distance decay affected is observed. Previous research used distance decay curves as a means of understanding service areas (Hsiao et al., 1997; Levinson & Brown-West, 1984; Upchurch, Kuby, Zoldak, & Barranda, 2004; Zhao et al., 2003). **Figure 2** shows distance decay curves representing cumulative percentages of walking distances beyond specified thresholds to each transit service type. Fourth order polynomial fit lines aid visual interpretation.

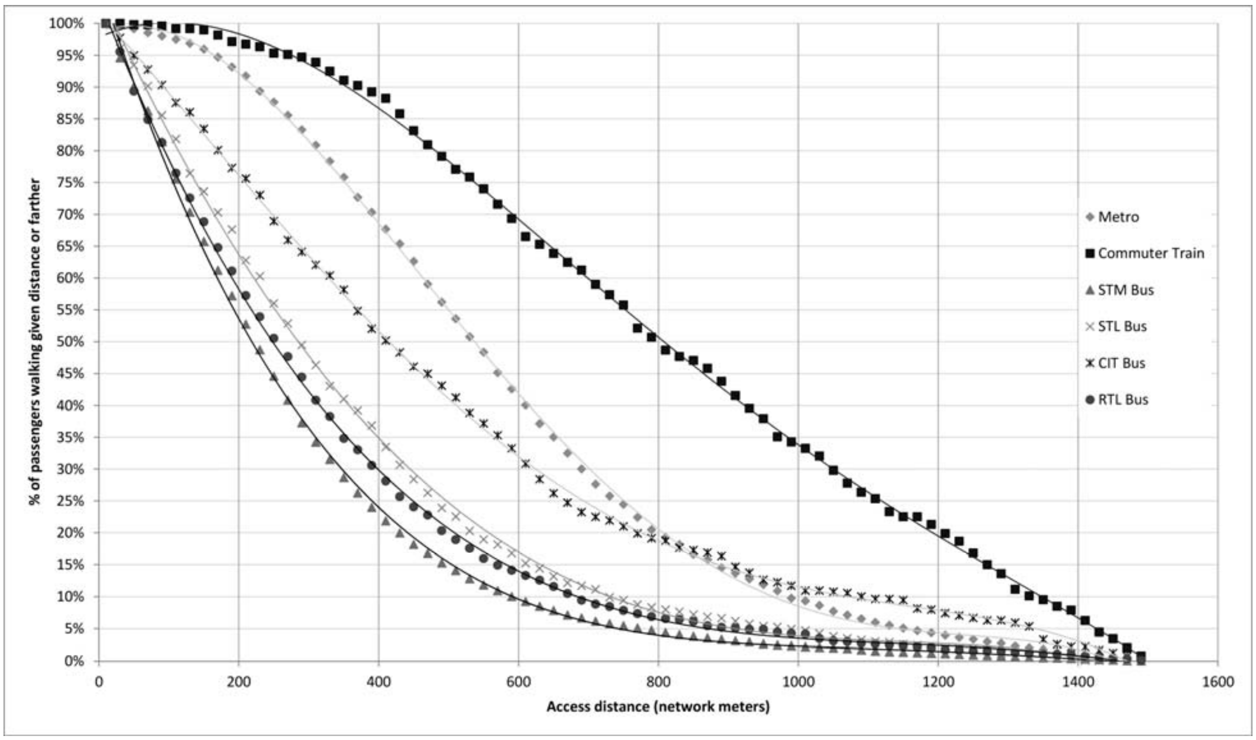

Figure 2: Distance decay to metro, train and bus services

The curves all terminate near 1500 meters but their shapes differ considerably, most of the bus types approximately exponential and the rail (and CIT bus) more linear. Non-cumulative frequencies were also plotted for the two most popular services (not pictured): an exponential curve fit STM bus service well (R^2=0.95) but was not much better than a linear curve for the Metro (R^2=0.43 and 0.34 respectively). Rail services have relatively few origins near stations, stations being less ubiquitous than bus stops and land, especially near the Metro, being generally more expensive due to the premium offered by transit accessibility. They also have wider drawing power, offering high speed and convenience. These impedance curves reflect the rather limited speeds attainable by pedestrian travel. However, an interesting result is that a surprising number of trips are made at distances up to and even exceeding 1 km (0.6 mile). This result is consistent across trip purposes, suggesting that individuals might be willing to walk considerably farther than the 400-meter (quarter mile) and 800-meter thresholds considered standard in transit planning. It is important to note that distances walked to buses are generally shorter compared to suburban trains and Metro due to the differences in types of service, comfort, frequency of service, and stop spacing. Stop spacing for suburban trains and Metro is generally bigger than bus stop spacing.

ANALYSIS

A linear regression model for individual walking distances is tested using individual, household, trip, route and neighborhood characteristics. This model had an adjusted R^2 value of 0.275, a reasonable fit, with high explanatory power compared to recent trials (Daniels & Mulley, 2013). But a likelihood ratio test suggested that route and stop/station nesting ought to be accounted for making the use of linear model not appropriate for such analysis. Accordingly a multi-level regression modeling technique is used. The resulting multi-level regression output is reported in **Table 3**.

Table 3: Individual multilevel walking distance model

Variable	Coefficient	Z	P>z	95% Confidence Interval	
Metro	209.13	14.46	0.00	180.79	237.48
Train	281.98	12.51	0.00	237.80	326.17
CIT/CRT bus	57.78	3.58	0.00	26.17	89.39
Wait time	-2.38	-1.65	0.10	-5.21	0.45
Number of intersections	0.07	1.99	0.05	0.00	0.13
Distance to downtown	5.02	6.67	0.00	3.54	6.49
Population 800m (000s)	-2.06	-2.07	0.04	-4.02	-0.11
Population 400m of 800m	-642.77	-15.21	0.00	-725.61	-559.94
Number of transfers	-34.35	-11.36	0.00	-40.28	-28.42
Trip distance	2.98	6.69	0.00	2.11	3.85
Work trip	13.44	3.05	0.00	4.80	22.07
AM peak trip	-9.34	-2.08	0.04	-18.16	-0.53
Number of vehicles	22.97	7.90	0.00	17.27	28.67
Household size	6.91	3.97	0.00	3.50	10.32
Income above 80K	33.78	5.24	0.00	21.14	46.41
Male	11.65	2.92	0.00	3.83	19.46
Age	-0.48	-3.53	0.00	-0.75	-0.21
Constant	411.77	17.30	0.00	365.11	458.44
Random-effects Parameters	**Estimate**	**Standard error**		**95% Confidence interval**	
Stop_route: Identity					
sd (Constant)	133.60	3.70		126.54	141.05
sd (Residual)	234.87	1.49		231.95	237.81
Dependent variable: Walking distance to transit at origin (meters)					

As one would expect, walking distances to transit are largely influenced by population concentration around stops and stations. If populations are high very near stops but low at somewhat greater distances, most users are likely to walk short distances, but several other neighborhood variables are also significant. Street connectivity, as indicated by number of intersections, appears to facilitate slightly longer actual walking distances – not just longer

Euclidean distances. This may or may not be related to untested neighborhood characteristics such as visual interest or apparent safety, but is interesting in any case. Conversely, people are shown to walk on average about five meters farther with each kilometer from downtown and about two meters shorter per 1000 people nearby, possibly reflecting denser service offerings possible in more central and populous areas. Attempts to more directly model such service characteristics, namely distance to stops adjacent the nearest on first route used and count of potential competing routes, proved less effective and surprisingly insignificant. Determining generalizable rules governing what constitutes a potential competing route for a particular user is difficult and might be refined in subsequent work. Shorter distance between stops on a route seemingly should be found to reduce average walking distances, but stops in Montreal are often quite close together (e.g. **Figure 4**) and in many cases much of the walk might consist of getting to the street with the route.

It is clear from the model that the type of transit service being offered, and to some extent the service quality, affect average walking distances to use public transit. Accounting for all else, underground Metro riders walk 209 meters farther than most bus users and commuter rail riders walk on average 282 meters farther. Both these services offer exceptional in-vehicle speed, although commuter rail fares are higher than those for most other Montreal region transit. Differences between bus sorts seen in summary statistics (**Table 2**) are largely attributable to neighborhood and other factor types, but CIT/CRT buses on the region's periphery still have average access walks 58 meters longer than the rest. The areas they serve are largely automobile-dominated, with wide spaces between routes in which people live. One direct service quality measure that was found significant, if here only at the 90% confidence level, is wait time: for each additional minute of wait time, users walk on average a little over 2 meters less, suggesting wider appeal of more frequent buses. It is suspected that this is a conservative portrayal of the importance of frequency: high-frequency bus routes require high ridership to be viable so they necessarily locate very near large rider pools, likely reducing average walking distances. Too, a very good relevant route might attract transit-using populations to live nearby. Still, slightly longer average walking distances are seen to relate to shorter wait times.

Individual trip characteristics also show significance. Each transfer used in a trip reduces average walking distance by 34 meters. This can reflect a disutility of transfers that people will walk a little farther to avoid, as well as the reduced walking distance necessary when one is less selective about which route, or combination, to take to reach the destination. Walking distances also increase by three meters for each in-vehicle kilometer of the trip. Explanations relating to suburban origins or captivity should be better captured by neighborhood variables above or individual/household variables below. Another possibility is that access walking distance is a less important part of longer trips and long-distance riders make added effort to reach the least time-consuming overall of the routes available. Riders walk about 13 meters farther for work trips than other types of trip purposes, again possibly reflecting overall time budgets. Conversely, they walk about nine meters less during the AM peak, when work trips are most frequent, than at other times of day, probably due to additional services available at such hours such as frequent buses on otherwise infrequent routes. Unexpectedly, walking distance between destination and nearest stop on last route used was not found to be significant, although it showed a marginal effect on earlier models that included trips not originating from home.

Household and individual-level characteristics found significant include number of vehicles, household size, income category, gender and age. As expected, walking distances are longer for those from households with more vehicles. These households, as a whole, might be less dependent on transit and thus comparatively unwilling to pay a premium for better-accessible housing. However, they might still include individuals who do not drive or choose not to drive for certain trips. Household size and high-income status have similar effects, potentially related to additional housing space needs or preferences and accessibility premiums (or absolute availability of large properties near major routes). It is also important to note that this isn't a transit demand model where we could expect that some of these variables (number of cars, etc.) would be negative. Males walk about 12 meters longer than females and walking distances decrease by about ½ meter for each year increase in age.

The random part of the multilevel regression model shows the standard deviations of the intercept and residuals (error term). In general, the idea of the random coefficient demonstrates that the overall error variance consists of two parts: the first results from the random variation of the intercept (standard deviation of the constant), and the second results from the variance of the error (standard deviation of the residual). The Intraclass correlation coefficient (rho) is a statistic that measures the degree of dependence among observation nested within transit stops. In other words, the interclass correlation coefficient explains the proportion of variability of walking distances to transit stops that occurs between transit stops rather than within transit stops. The model suggests that 24.5% of the variability of walking distances to transit stops is due to differences between transit stops characteristics. Lastly, the mean walking intercept of the sample was 411.7 meters; it was estimated that 95% of the random coefficient of the walking distance varied between 149.9 meters and 673.6 meters, suggesting significant variability of walking distances to transit stops between different transit stops.

The first model follows transit research theory. Accordingly, a generalized model is generated. This model can be then used to generate variable service areas for each station or stop in the entire Montreal region and compare to the traditional methods of generating service areas. As above, a linear regression model was generated, with an adjusted R^2 value of 0.255, but following likelihood ratio test results, a multilevel generalized model was chosen, presented in **Table 4**.

Table 4: Generalized multilevel walking distance model

Variable	Coefficient	Z	P>z	95% Confidence Interval	
Metro	212.19	14.48	0.00	183.48	240.90
Train	307.91	13.58	0.00	263.48	352.33
CIT/CRT bus	76.32	4.72	0.00	44.60	108.04
Wait time	-2.97	-2.09	0.04	-5.75	-0.18
Number of intersections	0.07	2.03	0.04	0.00	0.14
Distance to downtown	6.92	9.35	0.00	5.47	8.37
Population 800m (000s)	-4.27	-4.29	0.00	-6.23	-2.32
Population 400m of 800m	-681.22	-15.81	0.00	-765.66	-596.78
Constant	455.08	20.75	0.00	412.09	498.06
Random-effects Parameters	**Estimate**	**Standard error**		**95% Confidence interval**	
Stop_route: Identity					
sd (Constant)	137.86	3.73		130.74	145.37
sd (Residual)	237.01	1.51		234.07	239.99
Dependent variable: Walking distance to transit at origin (meters)					

All personal characteristic variables are removed from this model. Attempts were made to substitute in corresponding aggregates from tract-level census data, such as median income, but none showed significant effects. Variables in the generalized model have the same signs as in the individual model, providing some validation, but most have slightly stronger coefficients, without the refinement offered by the omitted variables. The lone variable with appreciably reduced significance, the AM peak trip dummy, likely suffers primarily from the absence of the counter-balancing work trip dummy, and becomes insignificant. AM peak service will be used to generate service areas as an example in this paper, but without the previously noted 9-meter reduction, following this generalized model.

The Intra-class correlation coefficient (rho) for the generalized model suggests that approximately 25.5% of the variability of walking distances to transit stops is due to between transit stops variation. The Intra-class correlation coefficient of the generalized multilevel model is over estimated by 1% than the individual multilevel model, which is an expected outcome, as the individual multilevel model picks up more of the within bus stop walking distance variation. The estimated 95% of the random coefficient of the walking distance varied between 184.8 meters and 725.5 meters. Again if you compare the variation range (difference between upper bond and lower bond) of the random coefficients between the generalized model (540.4 meters) and individual models (523.7 meters), you will find that the generalized model range is less by 16.7 meters in total.

Using the specifications obtained from the generalized model, we generated a mean walking distance for every transit stop in the region during the morning peak period. A total of 17,248 transit stops were used. The number of stops excludes the directional effect of the service to avoid double counting. Double counting occurs when two transit stations serving the same route are present across the street from each other, yet each one of them is serving a different direction. Since the wait time, a function of headway, had a statistically significant negative effect on walking distance, we used the direction with the shortest headway for generating service areas. Accordingly, this mean walking distance can be used in generating variable service areas around each stop. Since service areas are defined as the area including most of potential riders around a transit station, the mean walking distance to a station or stop needs to be adjusted. Firstly, 0.3% of stops were calculated to have impossibly negative mean walking distances, mostly due to the high importance of population concentration and the existence of a few isolated residential areas surrounded by open space or industry, which were set to zero. Then the difference between the mean and the 75th and the 85th percentiles for every type of service, STM, RTL, STL, CIT/CRT, Metro, and Commuter rail (see **Table 2**), were added to the calculated mean distances for every stop used in the generation of variable length service areas. An additive function was chosen over a multiplicative function so as to minimize impacts of extreme values.

To understand the system-wide implications of different service area definition methods, buffers were generated along the road network using the conventional thresholds (400 meters for bus and 800 meters for rail), the mean values obtained directly from the statistical model, and modified service areas at the 75th percentile and 85th percentile. Since we are modeling walking distances around transit stations, freeways were excluded from the network beforehand. The total area covered by all buffers using the fixed conventional buffers equals 748 square kilometers. Using the mean value derived from the statistical model yields similar total coverage (729 square kilometers), but the 75th and 85th percentile buffers, which more accurately represent walking area for most users, encompass 859 and 964 square kilometers, respectively. It is important to note that overlapping service areas are measured once in this calculation and no double counting is included. It is clear that using 400- and 800-meter service areas around stations underestimates service coverage by approximately 29% when compared to the 85th percentile estimates.

Figure 3 shows the overlapping service areas that are generated from the 85th percentile estimate for the entire region. The figure can serve two purposes. The first is identifying existing gaps in the Montreal region's transit system. Identifying gaps is the first step toward identifying areas where new services or modifications to existing services are needed. The existing gaps in the service are represented as white areas in the figure below. After identifying system gaps, transportation engineers and planners can overlay the results with land use information to determine whether there is a demand for improved services within these gaps. They can also work on modifying the existing service through shortening wait times, adding road links, or moving or adding stops to expand or add new service areas. The second purpose of this map is to identify areas with excessive system redundancy. The shades from yellow to red are mainly areas with high levels of redundancy in the services being offered.

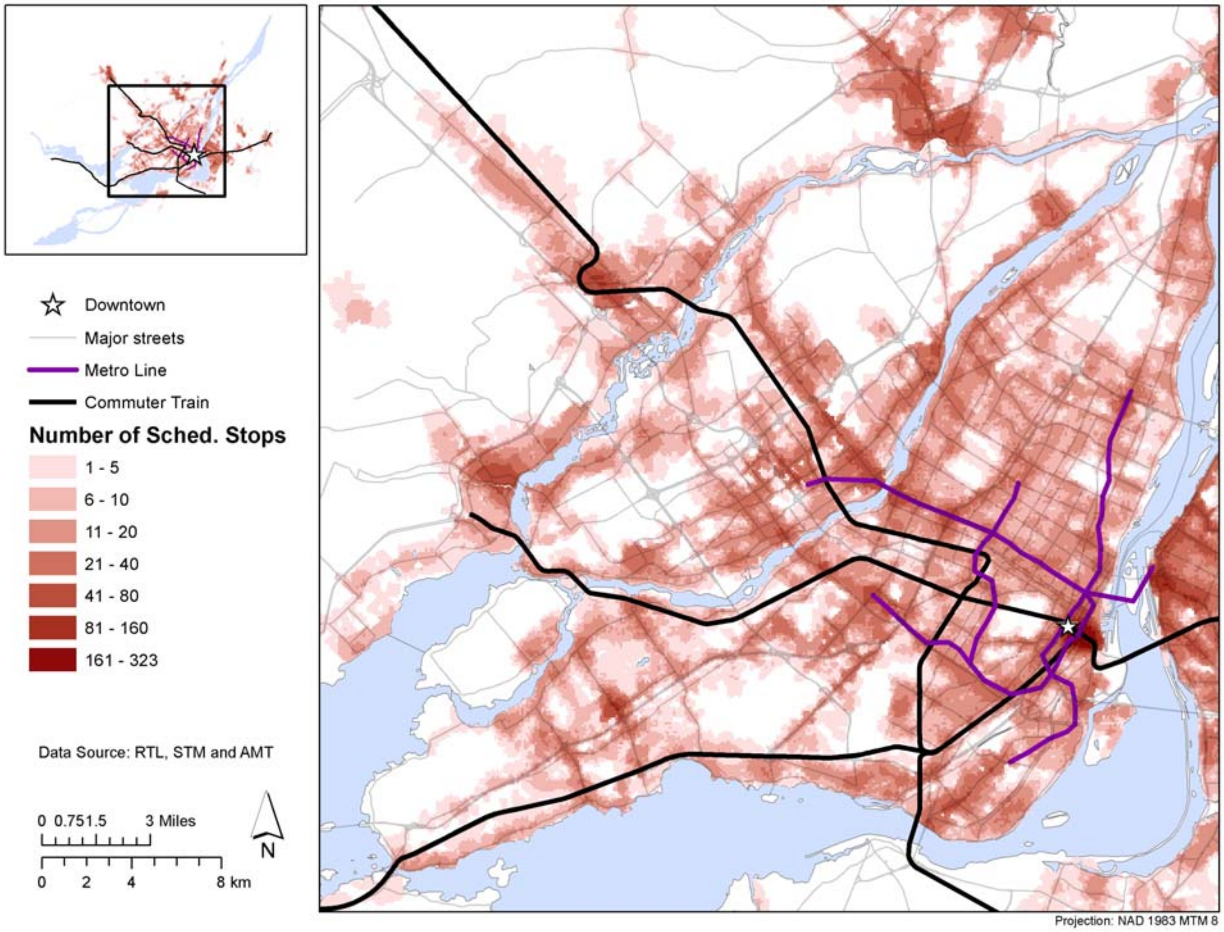

Figure 3: Overlapping service areas using 85th percentile estimate network buffers

The map above is derived from intersecting 100 by 100 meter grid cells with the network distance service areas. Accordingly, the number of stops displayed represents the count of service areas intersecting with each grid cell. If a bus stop is serving two different transit lines then two variable service areas are derived for this stop based on the route and neighbourhood characteristics. The number of stops in the figure does not represent the number of physical stops since a stop is created for each route operating during the AM peak where multiple routes serve the same stop. Areas with high levels of redundancy need to be explored further to identify whether the redundancy is justified or not. For example in the downtown core, 323 scheduled stops are in service during the AM peak period. The downtown area has the highest number of bus, metro, and train routes in the entire region. Similarly, areas around major transit centers are expected to have high levels of redundancy. Yet, more analysis at the route level is required to understand the reasons for redundancies in other areas. The above figure only generates a general picture of the situation.

Figure 4 shows the redundancy in the service being offered by two STM bus routes (Bélanger 95 and Beaubien-18). In part A of the figure, we intersected the generated variable 85^{th} percentile service areas for each stop serving route Beaubien-18 with 30 by 30 meter grid cells, showing overlapping service areas. This method can help identify redundancies and evaluate stop spacing along a single route. Since transit service does not exist in a vacuum, studying service area requires obtaining information from competing routes as well running in parallel to a route of interest. In part B of the figure we intersected the generated variable 85^{th} percentile service areas for every stop serving both bus routes, Belanger 95 and Beaubien-18, with another set of 30 by 30 meter grid cells. The figure shows the number of service areas generated from scheduled stops intersecting with each grid cell.

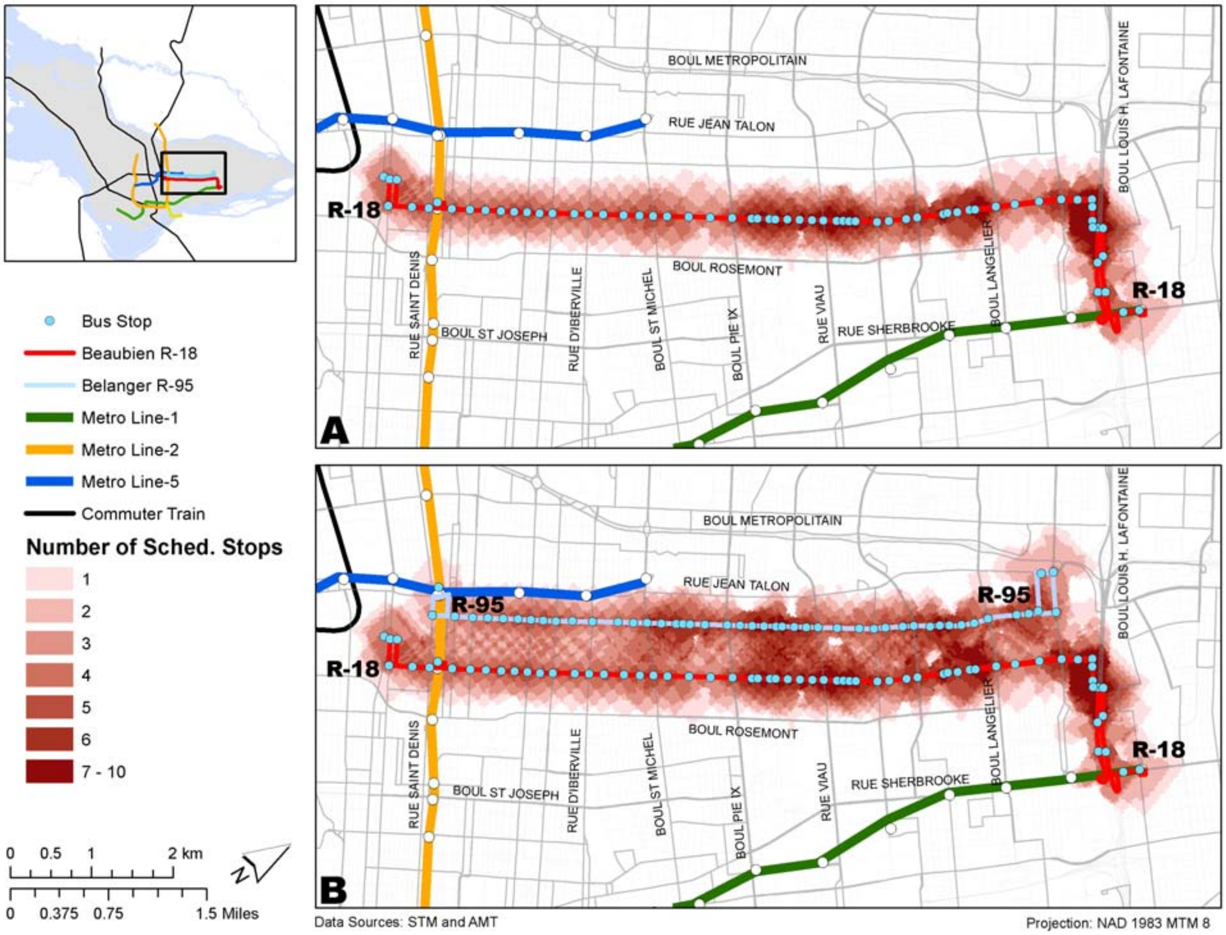

Figure 4: Bus route sample for overlapping service areas using 85th percentile estimate network buffers

Looking at part A from the figure above, it is clear that redundancies exist in the middle and the eastern sections of the route where the bus stop spacing is inconsistent. Another important observation is that the area being served by one scheduled stop is equal to 23% of the total service area around the transit line, while the area served by two stations represents 19% of the total service area around the entire transit line. Around 58% of the area served by this route is covered by at least 3 stops. Having an overlap in the service area along the same route is acceptable to a certain level. However, when the number of overlapping service areas reaches five or six and they represent a big proportion of the service area around a bus route (30% for example) then revision of stop spacing and route characteristics is a must.

Meanwhile, part B of the figure shows the level of redundancy in the service offered by two competing routes. Around 29% of the service area around both lines is being served by at least five scheduled stops from one or both of the studied routes during the AM peak period. Accordingly, the level of service coverage being offered along parallel east-west corridors at this particular location is very high. It is important to note that such methods need to be developed carefully to ensure the routes under investigation are competing and not complementing routes. The transit agency has some room to implement bus stop consolidation along several sections of these two routes. It is expected that the additional access time for passengers will be offset if not surpassed by the savings in running and waiting time. Savings in waiting and running time can also translate to savings in operating costs and other beneficial effects. Less frequent stops can mean less frequent accelerations, reducing fuel consumption and emissions, and less frequent pauses and lateral movements might help alleviate traffic congestion.

CONCLUSION

This research paper uses detailed origin-destination survey information to generate variable service areas for the Montreal region. It is clear from the summary statistics that service areas generated using rules of thumb greatly underestimate the effective service areas around transit stations. The 85th percentile walking distance to bus transit service is around 524 meters from home-based trip origins, 1259 meters for commuter rail. This finding raises the importance of careful revision of the 400- and 800-meter service area rules used in the transit industry. It also offers insights regarding the opportunities for increasing transit stop spacing in North America.

The research also highlighted differences between various bus transit operators. It is clear from this research that transit users tend to walk longer distances to use suburban service. The statistical models show that walking distances to transit stations vary based on neighbourhood, household, personal, trip and route characteristics. Notable for transit providers, people walk longer distances to routes with shorter wait time, and transit types (metro, commuter rail, and buses) vary considerably, even after accounting for neighbourhood characteristics and other variables. Accordingly, service areas around transit stations should vary based on the type and quality of service being offered. The generated service areas derived from the statistical model are used to identify gaps and redundancies in the existing transit network. These gaps and redundancies need to be analyzed carefully and in detail at the route level. Finally, the detailed analysis examining overlapping service areas along two specific routes shows the usefulness of this variable service area in identifying areas where potential stop spacing revisions can be effective without causing much harm to existing riders. It is important to note that revised stop spacing based on such methodology needs to be developed for competing routes and not complementing ones. This research suggests that stop spacing should be investigated as a variable value depending in part on the frequency and type service being offered and not just as a service standard-given number. It also opens venues for research in the area of transit-oriented development and how to identifying the exact service area around transit stations.

This study concentrated on service areas around transit stations and stops based on measured network walking distances. More research is recommended for deriving service areas around transit stations when other modes of transportation are involved. The generated service areas can be used in operation research studies involving bus stop consolidation. Combining the findings from this research with passenger movement at transit stations can help in generating better estimates of transit demand. Population concentration around transit stations and stops is a major factor influencing walking distances. Relatively disaggregated parcel-level population data would improve representation of this element and likely improve the model. In this research paper, we used scheduled rather than actual headways. Actual headways can be generated from archived automatic vehicle location (AVL) data. In addition, using on-time performance measures obtained for the AVL data can be an indication of the reliability of service, another measure of the service attractiveness that could be used to derive service areas more accurately and increase the fit of the model. Also the generated service areas could be linked back to automatic passenger counter (APC) data, if they were present, to enable a better understanding of the transit demand and the best representation of a service area. Finally, having information related to passenger activities at each transit stop/station could improve the modeling process, through testing several variable service areas beside the 85^{th} percentile estimate used in here.

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REFERENCES

Agence métropolitaine de transport. (2003). Enquête origine-destination 2003. Montréal, QC.

Alshalalfah, B., & Shalaby, A. (2007). Case study: Relationship of walk access distance to transit with service, travel, and personal characteristics. *Journal of Urban Planning and Development, 133*(2), 114-118.

Daniels, R., & Mulley, C. (2013). Explaining walking distance to public transport: The dominance of public transport supply. *The Journal of Transport and Land Use, 6*(2), 5-20.

El-Geneidy, A., Strathman, J., Kimpel, T., & Crout, D. (2006). The effects of bus stop consolidation on passenger activity and transit operations. *Transportation Research Record*(1971), 32-41.

Fan, W., & Machemehi, R. (2009). Do transit users just wait for buses or wit with strategies? *Transportation Research Record*(2111), 169-176.

Fielding, G., Glauthier, R., & Lave, C. (1978). Performance indicators for transit management. *Transportation, 7*, 365-379.

Fitzpatrick, K., Perkinson, D., & Hall, K. (1997). Findings from a survey on bus stop design. *Journal of Public Transportation, 1*(3), 17-27.

Furth, P., & Rahbee, A. (2000). Optimal bus stop spacing through dynamic programming and geographic modeling. *Transportation Research Record, 1731*, 15-22.

Gutiérrez, J., & García-Palomares, J. C. (2008). Distance-measure impacts on the calculation of transport service areas using GIS. *Environment and Planning B: Planning and Design, 35*, 480-503.

Hall, R. (2001). Passenger wait time and information acquisition using automatic vehicle location for verification. *Transportation Planning and Technology, 24*, 249-269.

Hsiao, S., Lu, J., Sterling, J., & Weatherford, M. (1997). Use of geographic information system for analysis of transit pedestrian access. *Transportation Research Record, 1604*, 50-59.

Kimpel, T., Dueker, K., & El-Geneidy, A. (2007). Using GIS to measure the effect of overlapping service areas on passenger boardings at bus stops. *Urban and Regional Information Systems Association Journal, 19*(1), 5-11.

Kuby, M., Barranda, A., & Upchurch., C. (2004). Factors influencing light rail station boardings in the United States. *Transportation Research Part A, 38*, 223-247.

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

Levinson, H., & Brown-West, O. (1984). Estimating bus ridership. *Transportation Research Record, 994*, 8-12.

Loutzenheiser, D. (1997). Pedestrian access to transit: Modeling of walk trips and theor design and urban form determination around bay area rapid transit stations. *Transportation Research Record, 1604*, 40-49.

Murray, A., Davis, R., Stimson, R., & Ferreira, L. (1998). Public transportation access. *Transportation Research Part D, 3*(5), 319-328.

Murray, A., & Wu, X. (2003). Accessibility tradeoffs in public transit planning. [Article]. *Journal of Geographical Systems, 5*(1), 93-107.

Neilson, G., & Fowler, W. (1972). Relation between transit ridership and walking distances in a low-density Florida retirement area. *Highway Research Record*(403), 26-34.

O'Neill, W., Ramsey, D., & Chou, J. (1992). Analysis of transit service areas using geographic information systems. *Transportation Research Record, 1364*, 131-139.

O'Sullivan, S., & Morrall, J. (1996). Walking distance to and from light-rail transit stations. *Transportation Research Record, 1538*, 19-26.

Schlossberg, M., Agrawal, A., Irvin, K., & Bekkouche, V. (2007). How far, by which route, and why? A spatial analysis of pedestrian preference *MTI Report 06-06*. San José, CA: Mineta Transportation Institute & College of Business, San José State University.

Upchurch, C., Kuby, M., Zoldak, M., & Barranda, A. (2004). Using GIS to generate mutually exclusive service areas linking travel on and off a network. *Journal of Transport Geography, 12*, 23-33.

Zhao, F., Chow, L., Li, M., Ubaka, I., & Gan, A. (2003). Forecasting transit walk accessibility: Regression model alternative to buffer. *Transportation Research Record*, *1835*, 34-41.