

School closures and consolidations: the active travel and emission implications of reduced accessibility

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Abstract

Reducing emissions and increasing active travel are top priorities for many communities. Often, though, these priorities are confronted with pressures to reduce the fiscal burden of public services, including schools. Public schools have been strained to do more with less, and governments are opting to close under-capacity schools and expand existing schools to accommodate lost capacity. The objective of this study is to quantify the travel burdens of school consolidation/closure policies. We do this through the case of Hamilton, a mid-sized city in Ontario, Canada. Between the years 2011 and 2015, 7% of the elementary schools closed in the city. We study how these closures changed the accessibility landscape for the elementary school aged population, as well as the active travel and emission implications. In terms of methods, we use spatial availability, a singly-constrained multimodal measure of spatial accessibility. Thanks to its proportional allocation mechanism, spatial availability allows for an interpretable comparison between ‘before’ and ‘after’ the implementation of school closure/consolidation policy.

Analysis is conducted at the parcel-level with all school seats being eligible and travel behaviour based on observed home-to-school patterns for motorized and non-motorized modes. We report estimates of system-wide impacts that result from the closures, such as potential growth in GHG emission and reduction of walking minutes. Findings demonstrate that overall, spatial availability decreased in the city. Though the school consolidation policy may have resulted in cost-savings in operation and maintenance of facilities, students, families, and communities pay the price in reduced opportunities for physical activity and greater motorized mobility-related pollution.

Keywords: accessibility; spatial availability; carbon emissions; journey-to-school; walkability; active transportation; school consolidation policy; service provision thresholds

Introduction

Communities are by nature in flux: economic and demographic shifts, rural and urban configurations, and political pressures all combine to produce change. These forces spur the re-organization and consolidation of public facilities in communities around the world where changes to service provision may improve the quality of service for some but not for all (Christiaanse 2020; Rosik, Puławska-Obiedowska, and Goliszek 2021). While change is natural, oftentimes top-down consolidation decisions are driven by operational cost-savings that do not take into consideration the full extent of losses in benefits.

From this perspective, school closure policies have been pursued by governments to optimize per-student operational cost-efficiency (Rong et al. 2022; Dai et al. 2019) but other implications, such as the impact of closures on property values (Merrall, Higgins, and Páez 2024), their effects on the social infrastructure of communities (Butler, Kane, and Cooligan 2019; Irwin and Seasons 2012), and particularly their travel implications have often been overlooked by decision makers (Bierbaum, Karner, and Barajas 2021; J. Lee and Lubienski 2017). This seems a mistake: journey-to-school trips are tremendously important, and travel for this purpose is currently the largest contributor of carbon emissions from personal travel after the journey-to-work (Rong et al. 2022; Pantelaki, Claudia Caspani, and Maggi 2024), where it could be instead an excellent opportunity for physical activity (Desjardins et al. 2024). Alas, in many communities globally, schools are closing (Sageman 2022). For instance, 65% of comprehensive schools (e.g. grades 1 through 9) in rural Finland since 1990 closed (Autti and Hyry-Beihammer 2014), 10% of elementary schools (kindergarten through grade 8) in Chicago, USA in 2013 (J. Lee and Lubienski 2017), and 7% of primary and lower secondary schools (kindergarten through grade 9) were closed in Denmark between 2010-2011 (Beuchert et al. 2018). School closures often increase the distance to school for many students and thus tend to induce motorized trips (Rong et al. 2022).

We focus on the transportation implications of school closure and consolidation policies. While some research has considered the “steps in reserve”, that is, the potential for active travel hidden behind motorized trips (Morency, Roorda, and Demers 2009; Morency, Demers, and Lapierre 2007), school closures potentially make actual steps vanish, sent to the reserve for the foreseeable future. In exchange for less physical activity, communities get more motorized travel, with the concomitant costs and burdens, including emissions. Quantification of losses in potential active travel and associated growth in carbon emissions is scarce in the literature, and the focus of this paper. In addition to its empirical contributions, this work makes use of a novel multimodal and singly-constrained accessibility measure, called spatial availability (Soukhov et al. 2023; Soukhov et al. 2024), which we use to estimate the changes in accessibility and travel after a recent wave of school closures/consolidations in Hamilton, Ontario.

The results of the research indicate that, overall, school seats became less spatially available in the city. This change happened unevenly, with some communities being disproportionately affected. Though the school consolidation policy pursued by the province and implemented by the local school board may have resulted in cost-savings in operation and maintenance of facilities, families, students, and communities now pay the price in terms of lost opportunities for healthier active travel, as well as increased emissions from motorized travel.

Background

Hamilton is a mid-size city (~570,000 pop) with rural, suburban and urban characteristics in the province of Ontario, Canada (Government of Canada 2022). In 2013, the Hamilton-Wentworth District School Board (HWDSB), the largest public English school board in the city, released its Long Term Facilities Master Plan (HWDSB 2013). To ensure “equitable, affordable and sustainable learning facilities”, the Master Plan indicated that 80% of its elementary schools (attended by students aged 5 to 13) would be subjected to accommodation evaluations, including an “Accommodation Review”, the outcome of which historically has been school closures/consolidations (HWDSB 2013; Craggs 2013; Seasons 2014b). These decisions, underhandedly supported by the province, were in part motivated by a search for operational savings based on projected reductions in student population and underutilized school capacity (Craggs 2012). Hamilton was particularly affected, as the HWDSB underwent an unprecedented number of Accommodation Reviews relative to other school boards (Seasons 2014a).

Though the Accommodation Review guidelines outline a community-focused process to assess the value that a school provides to students, the community, and the local economy (Seasons 2014b; Ministry of Education 2006), in practice residents felt that a wholesome breakdown of costs to repair/maintain schools was not made consistently available (Kleinhuis 2013). Further, others pointed to flawed incentive structures motivating the HWDSB: “By closing three schools the HWDSB would have a strong case with the Ministry of Education to receive full funding for a new school” (Kleinhuis 2013). Along with insufficient funding to maintain schools in a state of good repair

(Auditor General of Ontario 2015), the operational savings as a case for school closures is a long-standing critique of the school “funding formula” established by the conservative provincial government in 1998 (Mackenzie 2018; Irwin and Seasons 2012). Within a backdrop of budget cuts, the funding formula pits the financing of school maintenance and student needs against the financial compensation of staff and the powers of local school boards, which depend on the province for the allocation of resources (Mackenzie 2018).

In the wave of school accommodation reviews between 2013 and 2016, 12 elementary schools closed in Hamilton. These closures represented a 7% and 4% decline in elementary school locations and capacity between 2011 (before the school closures) and 2016, despite the elementary-aged student population in the city slightly increasing between 2011 and 2016(from 58,265 students to 58,865 students).

While accommodation reviews were undertaken to reduce operational costs, how might have the closure of schools impacted local communities? In this paper, we hypothesize that the school consolidation policy reduced accessibility to schools for many students. By extension, this loss in access and the consequent displacement of active trips to school increased transportation-related emissions. To test these hypotheses, the paper examines the following: how does the (1) spatial availability, (2) loss in walk minutes and (3) associated carbon emissions change for home-to-school trips after a city closes and consolidates schools? Further, this work examines (4) what communities, based on low-income prevalence, experienced the greatest losses as a result of this policy.

Spatial availability, a singly-constrained measure of spatial accessibility (Soukhov et al. 2023; Soukhov et al. 2024), is used to quantify accessibility before- and after- school closures, and the associated impacts for the city of Hamilton and the elementary school-aged student population as a result of a policy with narrowly defined benefits. The methods used in this paper can be applied by decision-makers to evaluate the spatial and transport-related impacts of public service provision policy. Furthermore, to increase the diffusion of this analysis, all work is transparent and reproducible, following best practices in the spatial sciences (Brunsdon and Comber 2021; Antonio Páez 2021). Accordingly, all associated code and data will be publicly available within the lead author’s [GitHub repository](#)

Data

Our focus is to evaluate the impact of school consolidations between 2011 and 2016 on multimodal school spatial availability and travel-related GHG emission in Hamilton. To facilitate comparison, two scenarios are generated. Each scenario reflects the conditions in 2011 and 2016 respectively, assuming the school configurations in each year, as well as average student population and low-income prevalence of households, residential parcel locations, and estimated modal travel times. The difference between the two scenarios is quantified in terms of accessibility, emissions and equity implications and discussed in context with the school consolidation policy. Data was retrieved at different levels of spatial granularity from the following sources.

Schools

First, schools and associated school catchments were retrieved from the City’s school boards. In Hamilton, the majority of student-aged population attends a school in one of the two English public school boards (FAO 2023). One board is referred to as *public* (i.e., Hamilton Wentworth District School Board (HWDSB)) in our work and the other is referred to as *public-catholic* (Hamilton Wentworth Catholic District School Board (HWCDSB)). These catchments indicate what residential property is assigned to what school, by default. Families can decide to attend schools out of catchment; in fact, 21%-23% of motorized school trips are out of catchment according to the regional travel survey, the Transportation Tomorrow Survey (TTS) in 2011 and 2016 (Data Management Group 2018). The elementary school locations and catchments were provided by the HWDSB and HWCDSB for the 2010-2011 and 2015-2016 academic years, and are shown in Figure 1.

Formally, elementary schools are defined as schools that provide instruction to any combination of grades between kindergarten to grade 8 (i.e. typically children aged 5 to 14). As such, elementary includes middle schools that only instruct grades 6 to 8 (*MidElem*), primary schools that only instruct kindergarten to grade 5 or 6 (*JrElem*), and all grade elementary schools (*Elem*) which instruct all grades from kindergarten to grade 8. The number of ‘seats’ available in the school beyond or below which it will be over/under- capacity is calculated by the provincial Ministry of Education; this value is referred to as the on-the-ground capacity (*OTGC*), and is assigned to each school. The current/historic OTGCs are not publicly available (Ontario 2017). However, for schools that underwent the full Accommodation Review process, OTGCs for a given year could be obtained from publicly available School Information Profiles. A regression model was used to estimate the OTGCs for schools that lacked OTGC information. The independent variables in the model were 1) the school’s building footprint (F) in units of (m^2); 2) the school’s shortest Euclidean distance from the centroid of Hamilton’s central business district area ($DistCBD$) defined in units of (m); and 3) coefficients associated with a binary variable indicating the type of school grade instruction (*MidElem*, *JrElem*, *Elem*). The building footprint from an archived spatial data set (Spatial 2015) and the 2016 footprints were retrieved from OSM (OpenStreetMap 2021). Because the age of construction for different schools is not available, we used each school’s distance from the centroid of the Downtown Business Improvement Area (Hamilton 2014) as a proxy for school age as the oldest buildings are generally located closer to the city centre (Merrall 2021). Of note, the models were also used to estimate OTGC of secondary schools (*Sec*) though not included in the scope of this work; these public institutions provide instruction for grades 9 to 12 (i.e., children aged 14 to 17).

Equations (1) and (2) describe the estimated OTGC for public schools and catholic schools respectively. School status and OTGC summed by catchment is also visualised in Figure 1. As seen in Table 2 in the Appendix, the coefficient of determination for these models is $R^2 = 0.999$ and $R^2 = 0.998$ for the Public $OTGC_{Public}$ and Catholic $OTGC_{Catholic}$ Boards respectively, and the residual standard deviation is $\sigma = 0.212$ and $\sigma = 0.331$.

$$OTGC_{Public} = F^{0.346} - e^{0.00003*DistCBD} + e^{3.123*JrElem} + e^{3.752*Elem} + e^{3.068*MidElem} \quad (1)$$

$$OTGC_{Catholic} = F^{0.471} - e^{0.00003*DistCBD} + e^{2.333*Elem} \quad (2)$$

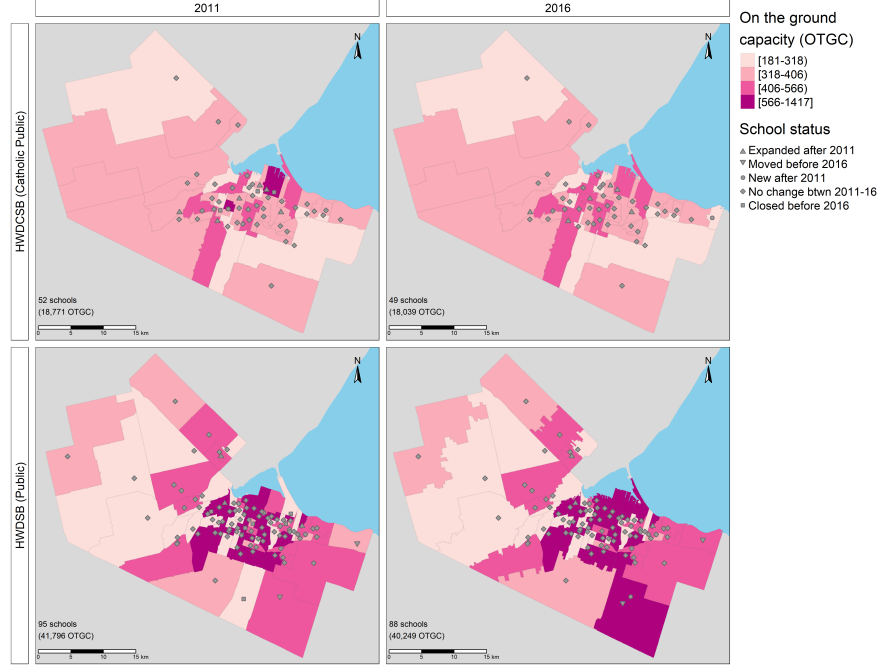


Figure 1: The school catchments, estimated On The Ground Capacity (OTGC) of schools summed per catchment, and school status for both public and public catholic school boards for year 2011 and 2016. OTGC scale is presented by quartiles.

Students, residential locations and low-income prevalence

In addition to OTGC for schools, statistics about the student population and proportion of low-income after tax (LIM-AT) households were retrieved from the 2011 and 2016 Canadian Census (Canada 2011, 2016) using the {cancensus} R package (Bergmann, Shkolnik, and Jacobs 2021). The census releases population data by age group category, so the population aged between 5-9 years and 10-14 years were retained. LIM-AT refers to the proportion of private households that are below the median after-tax income (Government of Canada 2017). The LIM-AT prevalence for households with children under 18 (there is no LIM-AT prevalence tabulated for

households with exclusively elementary aged children) was retrained. Population and LIM-AT variables were taken at the Dissemination Area (DA) level, which is the finest geographic unit publicly available. DAs are designed by Statistics Canada with the aim of population uniformity hence DAs greatly vary in area but represent between approximately 400 and 700 (1st and 3rd quartile) in total population. The population aged 5 to 14 and the proportion of LIM-AT are visualised in the first and last rows in Figure 2.

The third source of data consists of centroids of residential parcels in 2011 and 2016 that are used to represent residential locations (Teranet 2009). There are 134,340 and 139,467 residential locations in 2011 and 2016 respectively, representing 203,806 and 211,596 dwellings (according to the Canadian Census (Canada 2011, 2016)). As the number of children per parcel are publicly unavailable, the average number of 5 to 14 year olds for each DA is divided by the number of residential households in that DA. Then the potential number of children at each dwelling is calculated by multiplying this DA rate by the number of dwellings in each parcel. Due to the proprietary nature of the parcel data, the middle row in Figure 2 visualises an aggregation of the information: the average rate of 5-14 year olds per residential household at the DA level.

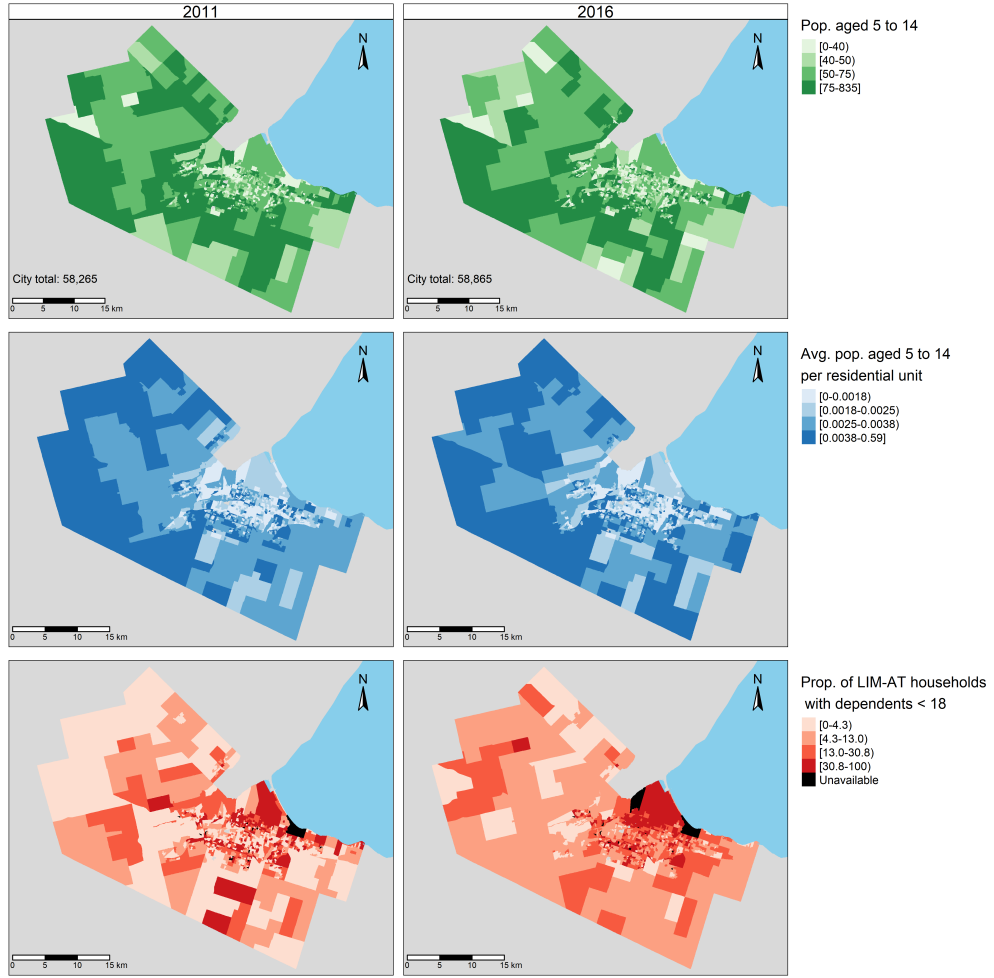


Figure 2: The magnitude (top row) and rate per residential unit (middle row) of elementary aged student population per DA in 2011 and 2016. Bottom row: the proportion of low-income households (prevalence of low-income after-tax, LIM-AT, measured by the 2011 and 2016 Canadian Census) with dependents under 18 years old shown. All scales are represented in quartiles.

Estimated travel times and emissions

It is assumed that children can go to any elementary school, but there is a preference for facilities that are more proximate. Based on this assumption, the fourth source of data is information regarding the mode-used and origin-destination locations of home-to-school trips from the 2011 and 2016 TTS (Data Management Group 2018). The TTS is a travel survey conducted in the Greater Golden Horseshoe Area in Ontario

every five years. With a target 5% sampling rate, the survey is expanded to be representative at the traffic analysis zone (TAZ) level of geography. TAZ are spatial units created for the purpose of the TTS and pulled from the R data package {TTS2016R} (Soukhov and Páez 2023); a few DAs typically nest within each TAZ. The trip-level travel data extracted for this paper represent 13,715 and 12,878 motorized trips (mode used includes private car passenger, school bus, taxi, and transit) and 2,736 and 1,430 non-motorized trips (mode used includes walk and cycling) for 5 to 13 year olds from home-to-school in 2011 and 2016 respectively. The travel times for motorized and non-motorized travel are estimated using {r5r} (Pereira et al. 2021), which interfaces with the java-based R5 routing engine developed separately by Conveyal (Conveyal [2015] 2022). As travel times are not associated with the TTS, motorized and non-motorized travel times are estimated for all TAZ centroids to all TAZ centroids. We estimate motorized travel to be by car and non-motorized travel to be by walk as those are the most used modes in their respective categories. The travel times and the intensity of modal home-to-school flows are visualised in Figure 3 along with the boundaries of the TAZ and DAs. In Figure 3, not all TAZs capture an elementary school trip by both modes. For this reason, the proportion of motorized modal share is aggregated at the community level. Hamilton (Ancaster: 85%-95%, Dundas: 89%-100%, Flam-borough: 91%-97%, Glanbrook: 92%-95%, Hamilton Central: 80%-87%, and Stoney Creek: 82%-88%).

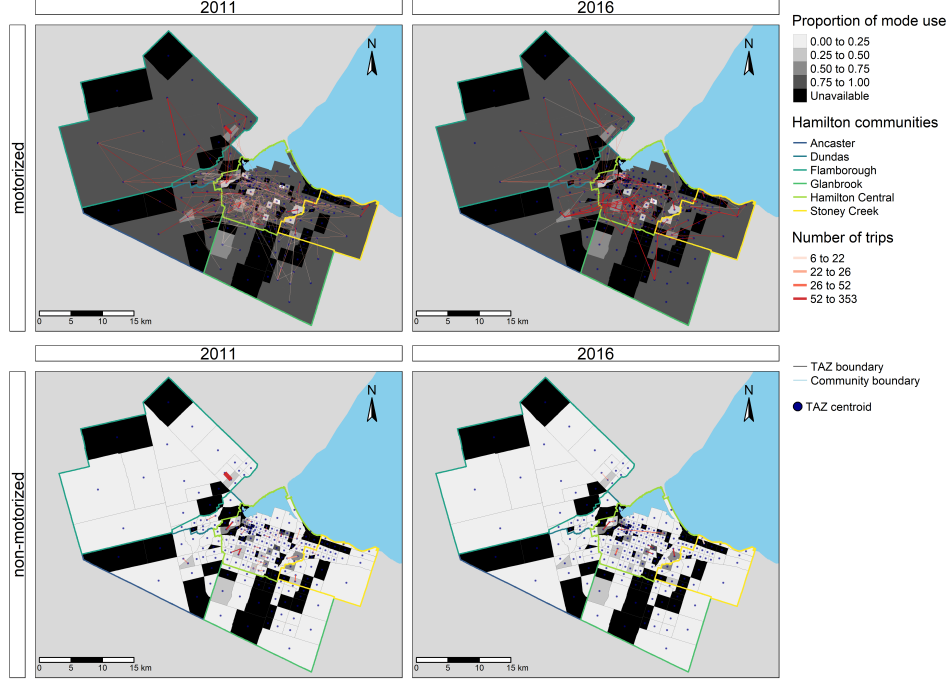


Figure 3: The origin-destination flows from home-based motorized and non-motorized school trips for students between 5-13 years old as retrieved from TTS 2011 and 2016. Flows are mapped atop the proportion of TAZ non/motorized modal share from the TTS 2011 and 2016, DA boundaries, and Hamilton community boundaries.

The fifth source of data consists of estimated travel time matrices from all residential parcel locations to all elementary schools for both motorized and non-motorized travel. The travel times are also estimated using the `{r5r}` package (Pereira et al. 2021), with car mode and walking representing motorized and non-motorized travel respectively. For both motorized and non-motorized modes, the inputs assume a maximum travel time threshold of 60 minutes and the free-flow OpenStreetMap road network of Hamilton (retrieved using Geofabrik (Geofabrik 2022) and manually edited to only include the network within Hamilton). Further, only walking trips shorter than 27 min minutes were retained. This travel time is approximately equivalent to 1.6 km which is the point within-catchment students qualify for transport provided by the school board (HWDSB 2019). Estimated trip-weighted motorized travel times are on average 16.5 minutes in 2011 and 16.8 minutes in 2016 (summary statistics for both years are approximately; min: 0.5, Q1: 11.0, Q2: 16.0, Q3: 21.0, max: 60.0). Estimated trip-weighted non-motorized travel times are on average 18.0 minutes in 2011 and 18.1 minutes in 2016 (summary statistics for both years are approximately; min: 0.5, Q1: 13.0, Q2: 19.0, Q3: 24.0, max: 27.0).

These travel time matrices along with the origin-destination flows were used to create modal trip length distribution (TLD) functions. Analysis of the TLD is a useful technique to calibrate impedance functions as they are a representation of the propensity of travel by trip length (Horbachov and Svichynskyi 2018; Batista, Leclercq, and Geroliminis 2019). The empirical TLD is used to fit a density distribution using maximum likelihood and moment matching techniques and the Nelder-Mead and Brent methods for direct optimization available within the `{fitdistrplus}` package (Delignette-Muller and Dutang 2015). Based on goodness-of-fit criteria and diagnostics, the gamma and exponential distributions were selected for the motorized and non-motorized modal distributions respectively. The gamma distribution is defined by the shape (α) parameter of 1.939 (2011) and 2.046 (2016) and the rate (β) of 0.233 (2011) and 0.236 (2016). The exponential distribution is defined by the rate (β) parameter of 0.092 (2011) and 0.1 (2016). The TLDs for the motorized and non-motorized trips are shown in Figure 4. For reference, the gamma distribution and the exponential distribution function are displayed in Equations (3) and (4) where x is c_{ij} :

$$f(x) = \beta e^{-\beta x} \quad (3)$$

$$f(x, \alpha, \beta) = \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^\alpha \Gamma(\alpha)} \quad \text{for } 0 \leq x \leq \infty \quad (4)$$

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx$$

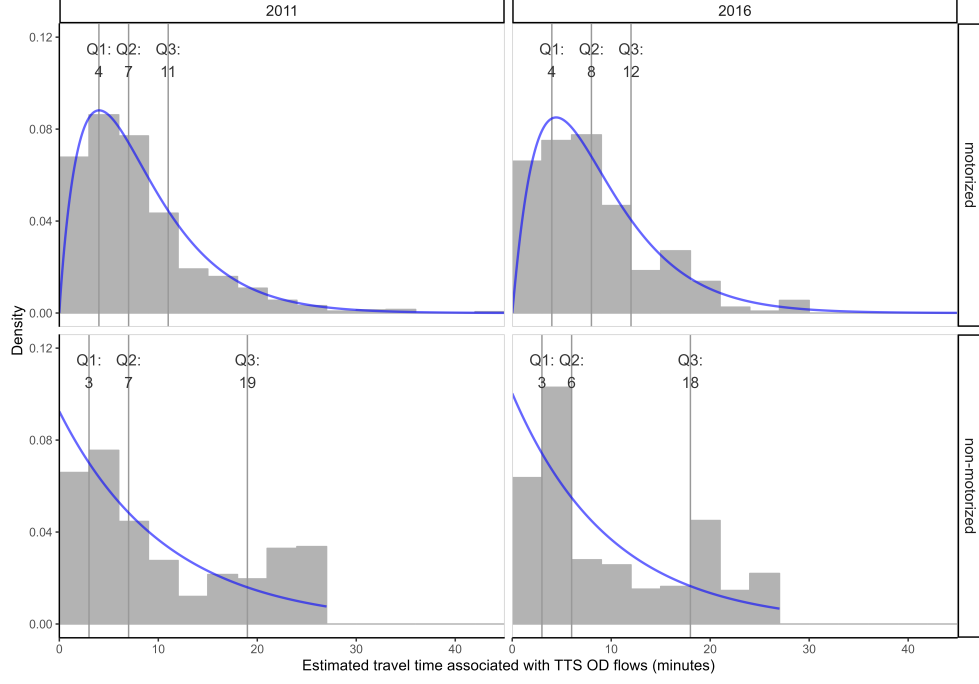


Figure 4: Empirical (grey bars) and theoretical (blue curves) motorized and non-motorized impedance functions. Motorized theoretical impedance function is based on the gamma distribution function and non-motorized on the exponential distribution function

The sixth and final data source relates to motorized GHG estimations. It assumed that all non-motorized trips produce no emissions and those that are motorized take the average emission factor of 0.1 kg CO_2e per minute travel. This emission factor is assumed based on an average speed of 40 km/h, the 2,380 g CO_2e produced when 1 L of gasoline (well-to-wheel) is combusted, and an internal combustion engine passenger vehicle fuel efficiency of 7 g/100km as discussed in Soukhov and Mohamed (2022).

Methods: Multimodal spatial availability

Accessibility is defined as the “potential for spatial interaction”. It is classically presented as the gravity-based measure popularized by Hansen (1959). It takes the following general multimodal formulation (Equation (5)):

$$S_i^m = \sum_{j=1}^J O_j \cdot f^m(c_{ij}^m) \quad (5)$$

where:

- m is a set of modes.
- c_{ij}^m is a measure of the cost of moving between i and j for each m .
- $f^m(\cdot)$ is an impedance function of c_{ij}^m for each m ; it can take the form of any monotonically decreasing function chosen based on positive or normative criteria (A. Páez, Scott, and Morency 2012).
- i is a set of origin locations ($i = 1, \dots, N$).
- j is a set of destination locations ($j = 1, \dots, J$).
- O_j is the number of opportunities at location j .
- S is Hansen-type accessibility as weighted sum of opportunities.

As indicators of urban structure, Hansen-type measures are informative, but the meaning of 10,000 accessible school-seats is harder to pin down: how many opportunities must any single student have access to? Furthermore, in scenario comparisons, the interpretation of the percentage change in accessible school seats is unclear. The interpretability of Hansen-type accessibility has been discussed in numerous studies, including recently by Hu and Downs (2019), Kelobonye et al. (2020), and in greater depth by Merlin and Hu (2017) along with Soukhov et al. (2023) and Soukhov et al. (2024). The interpretation of accessibility is suggested to depend on how many people demand the opportunity, especially for exclusive opportunity-types like schools-seats (i.e., one school-seat is for one student).

In this paper, we benefit from new developments in accessibility research, particularly the multimodal spatial availability measure (Soukhov et al. 2023; Soukhov et al. 2024). Spatial availability is a singly-constrained accessibility measure that accounts for competition by students using different modes for exclusive opportunities, such as school seats. The measure’s single constraint ensures that the marginals at the destination are met and thus the number of estimated school seats (opportunities) are preserved and allocated proportionally to the mode-using student population. This proportional allocation of opportunities yields an interpretable and meaningful measure of opportunity access, particularly when comparing across modes, at the spatial resolution of a residential parcel, and multiple time periods. See Soukhov et al. (2024) for further discussion, multimodal spatial availability V_i^m is defined as given by Equation (6).

$$V_i^m = \sum_{j=1}^J O_j F_{ij}^{tm} \quad (6)$$

where:

- F_{ij}^{tm} is a balancing factor that depends on the population and cost of movement in the system as part of the gravity modelling framework and is captured in Equation (7) for mode m .
- O_j is the number of opportunities at j .
- V_i^m is the number of spatially available opportunities from the perspective of i for mode m .

F_{ij}^{tm} can be understood as the joint probability of allocating opportunities, where F_i^{pm} is the population-based balancing factor that grants a larger share of opportunities to larger m population spatial units and F_{ij}^{cm} is the impedance-based balancing factor that grants a larger share of the opportunities to less m -travel costly centers. Together F_{ij}^{tm} ensures proportional allocation such that opportunities O (like school-seats) are preserved for the whole region (i.e., $O = \sum_j O_j = \sum_i V_i = \sum_m \sum_i V_i^m$) and is reflected in Equation (7):

$$F_{ij}^{tm} = \frac{F_i^{pm} \cdot F_{ij}^{cm}}{\sum_i F_i^{pm} \cdot F_{ij}^{cm}} \quad (7)$$

where:

- The factor for allocation by population for each m at each i is $F_i^{pm} = \frac{P_i^m}{\sum_m \sum_i P_i^m}$
- The factor for allocation by travel cost for each m at each i and j is $F_{ij}^{cm} = \frac{f^m(c_{ij}^m)}{\sum_m \sum_i f^m(c_{ij}^m)}$

It should be noted that, when summed over all spatial units in the region, the population-based allocation factors F_i^{pm} always equal 1 ($\sum_m \sum_i F_i^{pm} = 1$), likewise for impedance-based allocation factors F_{ij}^{cm} ($\sum_m \sum_i F_{ij}^{cm} = 1$).

Hansen-type accessibility is not designed to preserve the number of opportunities in the region, it simply counts the intensity of opportunities that those in a zone can potentially interact with (weighted by the friction of distance). Also, as discussed in Soukhov et al. (2023), popular competitive accessibility measures such as the 2SFCA (Joseph and Bantock 1982; Weibull 1976; Shen 1998; Luo and Wang 2003) are internally inconsistent, and the only way it preserves the number of opportunities is if the effect of the impedance function is ignored when expanding the values of opportunities per capita to obtain the total number of opportunities. On the other hand, the proportional allocation procedure associated with calculating multimodal spatial availability V_i^m consistently returns a number of opportunities available to populations by mode that matches the total number of opportunities in the region when summed. By doing this consistently, it is possible to define a measure of multimodal spatial availability per capita as presented in Equation (8) for use as a benchmark to compare against the regional opportunities per capita ($\frac{\sum_i O_j}{\sum_i P_i}$).

$$v_i^m = \frac{V_i^m}{P_i^m} \quad (8)$$

This paper uses the multimodal spatial availability V_i^m and spatial availability per student v_i^m measures to quantify accessibility changes for the following reasons.

First, all residential parcels are associated to their respective census DA, TTS TAZ, and community boundary based on spatial location (aggregated by DA and shown as a per capita rate in the second row of Figure 2). Each parcel is assigned a number

of ‘potential’ motorized and non-motorized student aged population (from DA) and modal share (from TTS) to calculate a motorized and non-motorized population balancing factor F_i^{pm} . For each parcel, the following is retained: the 2011 and 2016 census average elementary-aged student population per parcel (Figure 2 second row) and the average motorized and non-motorized share as informed by the TTS aggregated by community (Figure 3).

Second, the school capacity O_j is estimated and associated with each school (Figure 1). All residential locations are assumed to be able to access all schools by non-motorized and/or motorized mode. All origins (residential locations) can reach all schools by motorized mode, but few residential locations can reach schools within a 27 minute non-motorized trip.

Third, the motorized and non-motorized impedance-balancing factors F_{ij}^{cm} are calculated using a mode-specific impedance function (Figure 4) based on the respective estimated travel times for each origin (parcel) to school combination (OD flows retained from the TTS). Using network estimated travel time sensitive to observed parcel origin to school destination flows conceptually addresses the aggregation error that could result from using less granular zonal units to represent origin/destinations (Kane and Kim 2020; Kwan 1998; Hewko, Smoyer-Tomic, and Hodgson 2002). Finally, outputs from all three stages are joined together. F_i^{pm} joined with F_{ij}^{cm} yields the total balancing factor F_{ij}^{tm} which serves to proportionally allocate the school capacity O_j to each parcel. The value is multimodal spatial availability V_i^m which can be interpreted as the number of school-seats that are available to the mode-using population at that parcel. V_i^m is then summed and represented at the DA and community level along with the calculated v_i^m for interpretation.

Results

The motorized and non-motorized spatial availabilities of school seats V_i^m for both 2011 and 2016 are presented in the top half of Figure 5. The sum of V_i^m values in a year for both motorized and non-motorized population equals the city-wide OTGC (across both public and catholic school boards) in that year. This is a result of V_i^m ’s proportional allocation mechanism, singly-constraining opportunities through the proportion allocation balancing factors. In this way, V_i^m results can be interpreted as a proportion of the total OTGC in that year as the sum of V_i^m for both modes in a year is equal to the total OTGC in that year. In Figure 5, i is a DA, so V_i^m is the sum of the school seat availability per parcel in each DA. Each parcel is assigned a potential student population based on the average rate of school-aged population per residential parcel in that DA and the travel impedance weighted travel time to all schools. The top four plots of Figure 5 demonstrate different magnitudes in part due to significantly lower non-motorized modal share (refer to Figure 3), however it is apparent that both mode using populations have higher spatial availability when they are more proximate to schools. Hence, all DAs have higher values within Hamilton Central and those more proximate to schools in less-urban communities. Trends appear similar for both 2011 and 2016: this aligns with intuition, proximate populations using motorized

modes benefit from the ability to reach more distant destinations than non-motorized modes.

When V_i^m is divided by the number of students by mode in that DA, v_i^m is derived (bottom four plots in Figure 5). The v_i^m plots demonstrate different spatial distribution trends than V_i^m plots. If our aim is to provide sufficient availability to schools for both motorized and non-motorized populations (e.g., greater than 1.0 v_i^m school-seat availability per student), this rate is only achieved in the core of the city for motorized modes (greens and yellows). Notably, this rate is only available to non-motorized populations in DAs that are in less-densely populated rural areas that are school proximate and very few pockets of Hamilton Central. The majority of schools closed were within Hamilton Central, so non-motorized populations in DAs within Hamilton Central were the most negatively impacted by losses in availability while certain motorized populations captured these losses as availability gains.

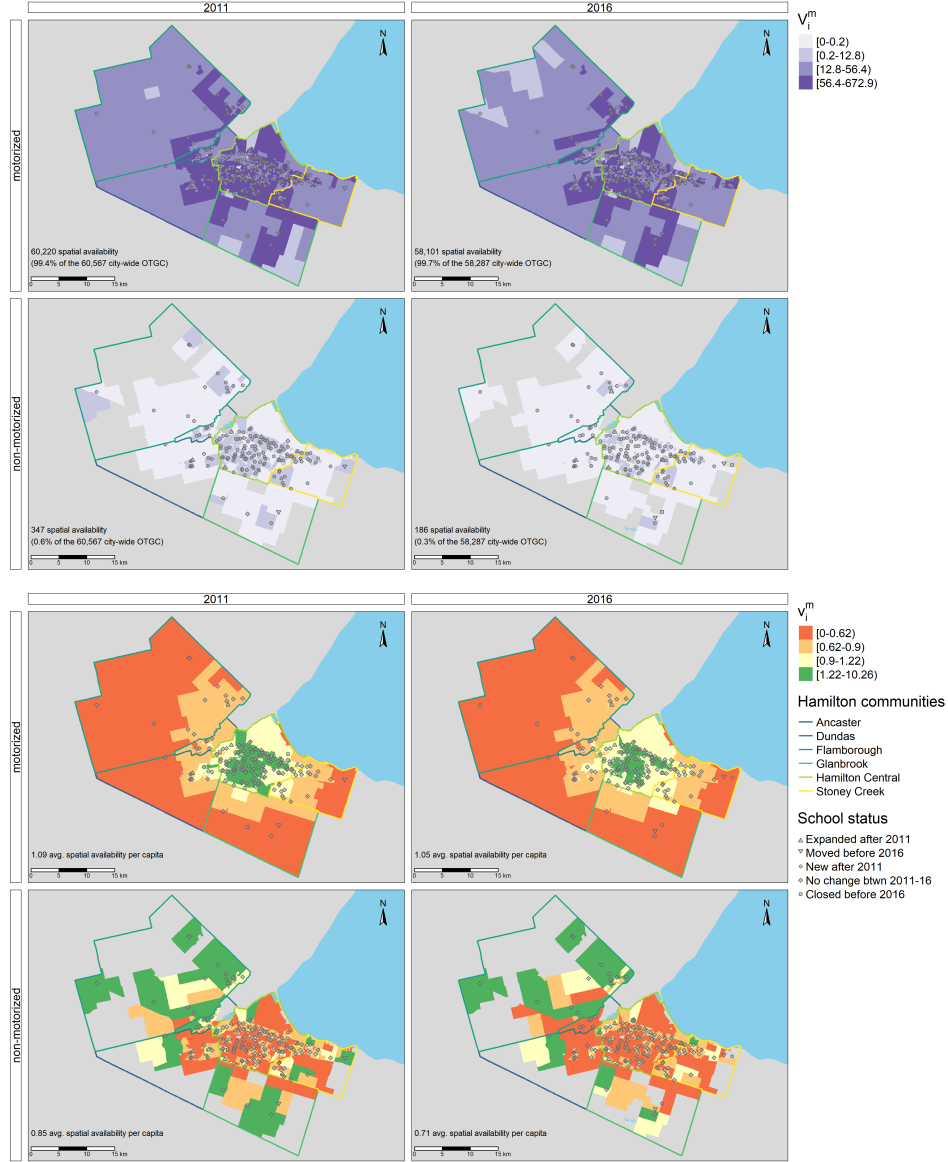


Figure 5: Multimodal spatial availability (purples) and spatial availability per mode using student (diverging reds and greens) aggregated at the DA level for 2011 and 2016. Scales are represented in quartiles.

To highlight this point, Figure 6 visualises the change in school spatial availability between 2016 and 2011 for both mode where i are 2016 DAs. Though the 2011 and 2016 DAs system are very similar (see Figure 2 and Figure 3), they are not identical:

16 DAs changed in their spatial extent (i.e., added, removed, changed boundaries). The proportional allocation mechanism of spatial availability provides flexibility in aggregating parcel-level values at whichever spatial unit is meaningful. For this case, the change in V_i^m and v_i^m represented is the subtraction between the value aggregated at 2016 DA for the 2016 and 2011 scenario.

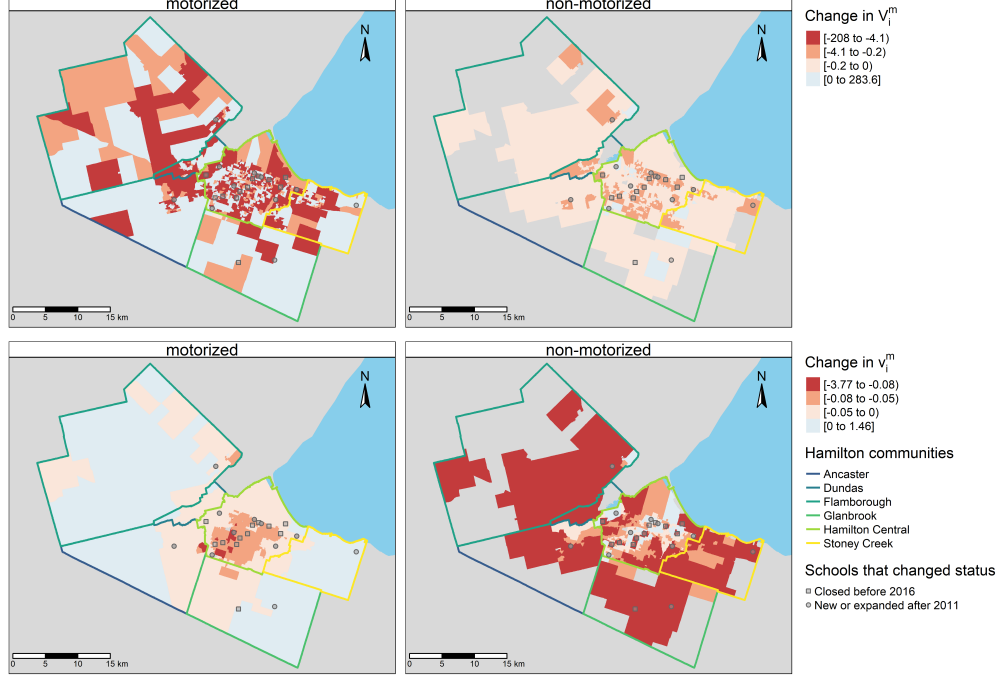


Figure 6: Change in multimodal spatial availability and spatial availability per mode-using student between 2016 and 2011. Change is the subtraction of parcel-level results between 2016 and 2011 scenarios summed for each DA in the 2016 Canadian Census DA system. Scales are represented in quartiles, with Q4 rounded to 0.

From Figure 6 (top plots), it is apparent that decreases (pinks and reds) in V_i^m appear across the city for both mode-using populations. As the majority of closed schools are within the core of the city: the more urban Hamilton Central and urban-areas of other communities see a concentration of this decreased spatial availability to school seats. Evidently, the number of OTGC in the city (equal to the sum of V_i^m) decreased between the two years, so some sort of decrease is to be expected. However, even when spatial availability is divided by the mode-using population (which also decreased between the years) v_i^m (bottom plots) continues to demonstrate decreases, especially those locally proximate to closed schools.

This decrease follows different patterns depending on the mode. $v_i^{non-motorized}$ is most impacted for parcels within a 27 minute walk travel time to schools that closed: these DAs demonstrate the most dramatic decrease. Smaller-area DAs (in Hamilton-Central) and larger-area DAs (in rural communities) proximate to closed schools present Q1 decreases (red). For $v_i^{motorized}$, the range offered by motorized mode (estimated by shortest-path car travel times) is city-wide, so since the majority of schools were centrally located, the decrease is concentrated within the downtown core of Hamilton Central. Some motorized-mode using populations in DAs do experience an increase in V_i^m and v_i^m : these DAs are often relatively proximate to schools but more immediately outside walking range. Under competitive and constrained calculations, these DAs benefit from the losses in spatial availability that are predominately experienced by the non-motorized populations within Hamilton Central.

The decrease in school seat spatial availability can be further interpreted. How does potential non-motorized travel to school decrease? How does the increase in potential motorized travel minutes impact GHG emissions? Figure 7 visualises these related intermediates for one-way home-to-school travel in a given day. The top plot of Figure 7 demonstrates the sum of the change in non-motorized minutes per 2016 DA. These travel time minutes are the difference between the aggregated 2016 and 2011 scenarios for non-motorized travel times multiplied by the proportion of walking/cycling mode-use and rate of student population associated with the parcels in each 2016 DA. It can be seen that Q1 decreases are proximate to closed schools. Smaller decreases (and even a few increases) are apparent in a range further from closed schools, especially those also in proximity to the few opened/expanded schools. Intuitively, these trends mirror what is shown within the $V^{non-motorized}$ landscape in Figure 6 (Pearson correlation coefficient of 0.796) as travel time is an input into the cost balancing factor F_{ij}^{cm} . Similarly, the bottom plot (Figure 7) visualises the change in estimated emissions from motorized travel minutes. The change in GHG emissions is also highly correlated with $V^{motorized}$ in Figure 6 (Pearson correlation coefficient of 0.838) as it is also a product of travel time.

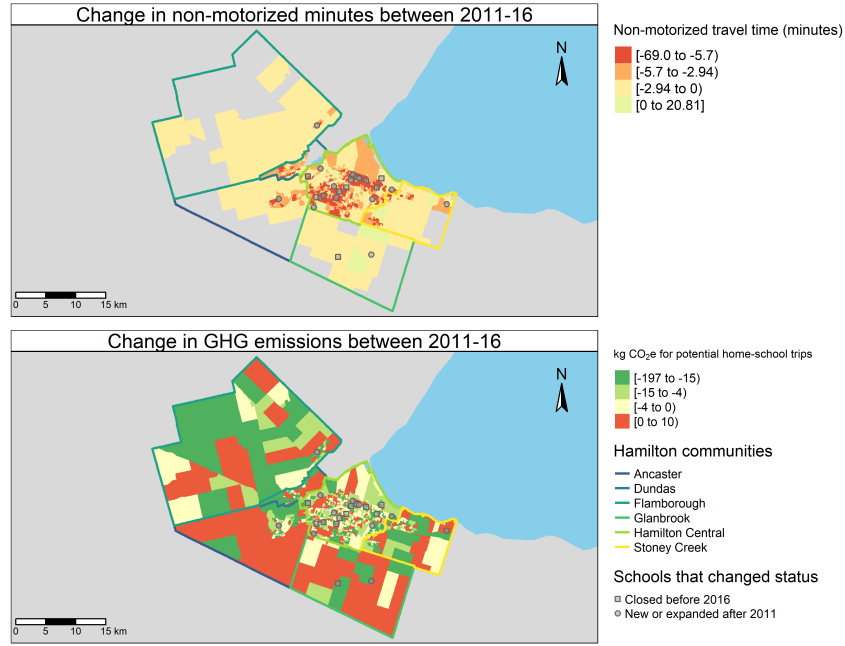


Figure 7: Change in active travel time minutes (top plot) and home-to-school GHG emissions (bottom plot) between 2011 and 2016 scenarios. Change is the subtraction of parcel-level results between 2016 and 2011 scenarios summed for each DA in the 2016 Canadian Census DA system. Scales are represented in quartiles, with Q4 rounded to 0.

Notably, the mode type of spatial availability loss is important. The change in active travel minutes and GHG emissions highlights the negative externalities of *decreased* non-motorized spatial availability. Normatively, our cities should be increasing spatial availability for non-motorized mode users given the climate crisis. The wave of school closures in Hamilton increased motorized spatial availability and, hence, potential GHG emissions. The policy drastically reduced non-motorized spatial availability, and this is seen in the decrease in potential non-motorized travel minutes as well as increased GHG emissions in rural areas that did benefit from motorized spatial availability gains. The proportion of non-motorized mode use is low in both 2011 and 2016, however, the closure of schools that are more proximate to student-population density eliminates the potential of those trips ever becoming active. And who is most impacted by the reduction of non-motorized spatial availability? A summary of spatial availability per Hamilton community and associated dimensions in 2016, along with the percentage change between 2011 and 2016, is summarized in Table 1.

Table 1: Spatial availability and associated dimensions aggregated by communities

	Hamilton C.		Dundas		Stoney Creek		Ancaster		Flamborough		Glanbrook	
	% Δ		% Δ		% Δ		% Δ		% Δ		% Δ	
LIM-AT	27.0	14%	12.5	10%	11.6	10%	8.9	24%	7.6	4%	7.5	-14%
Pop.	33437.7	-4%	2365.3	-8%	8070.3	6%	5387.5	12%	5172.4	-4%	4150.0	58%
OTGC	36878.3	-8%	2377.0	0%	9387.8	4%	3404.7	0%	4638.2	2%	1601.8	22%
Motorized												
V (mt)	39626.9	-8%	1817.7	-8%	6656.8	6%	4338.0	8%	3290.3	-2%	2371.7	58%
v (mt)	1.2	-4%	0.8	0%	0.8	0%	0.8	-4%	0.6	2%	0.6	0%
GHG	47788.1	-2%	4851.7	-8%	15183.3	8%	9470.9	14%	12839.1	-4%	8798.4	60%
GHG/pop	1.4	2%	2.1	0%	1.9	0%	1.8	2%	2.5	0%	2.1	2%
Non-motorized												
V (nmt)	152.7	-44%	0.0	-100%	23.9	-42%	4.0	-68%	3.9	-64%	1.9	-2%
v (nmt)	0.6	-8%	0.0	-100%	0.7	-18%	0.7	-18%	1.7	-6%	1.4	-16%
tt	4365.7	-38%	0.0	-100%	585.3	-28%	103.3	-62%	40.4	-62%	22.5	12%
tt/pop	18.2	0%			17.8	2%	18.3	2%	17.9	-2%	16.4	-4%

Due to spatial availability's flexible proportional allocation mechanism and this cases' calculation at the parcel level, results can also be summarized by community (Table 1). The majority of schools were closed in Hamilton Central. This community represents 60% of the 5-14 year old population in 2016. Though the population between 2011 and 2016 decreased, the rate of school-seat spatial availability decreased disproportionately more (population by -4% and spatial availability by -8%). This disproportionate decrease is greatest in Hamilton Central than any other community. This may have equity concerns as Hamilton Central has the highest LIM-AT prevalence, with 27% of households LIM-AT in 2016, 3.7 times greater than Glanbrook, a community with the lowest level of LIM-AT prevalence in the city. Between 2016 and 2011, Hamilton Central had the lowest levels of emissions per student and saw the highest per student increase in 2016. Hamilton Center had the highest non-motorized trip potential, and it was reduced in part by the school closure policies.

Conversely, communities with the lowest LIM-AT benefit the most, notably in gains to motorized spatial availability. Glanbrook, Flamborough and Ancaster have the lowest prevalence of LIM-AT of any Hamilton Community and together account for 30% of the 5-14 year old population in 2016. These communities experienced a growth in student population (or only a small decrease) and proportionally benefited from an increase in motorized spatial availability.

Across the city, those who commute by non-motorized mode see the most drastic loss in spatial availability. In all communities, spatial availability decreases at greater levels than population. Notably in Dundas (2nd highest LIM-AT), the only school in the community closed, leaving the population in the community with no other option but to use motorized modes. Glanbrook (lowest LIM-AT), which experienced a relatively sharp increase in student population along with non-motorized using population, suffered a loss in non-motorized spatial availability despite seeing the highest increase in motorized spatial availability. Overall, the gain in motorized spatial availability resulted in a further erosion of non-motorized spatial availability. This erosion is related to a loss in potential active home-to-school travel minutes (3309.3 fewer minutes than in 2011, decreasing the potential active travel time per (all mode using) student from 0.14 to 0.09 minutes), as well as an increase in potential GHG emissions city-wide (3416 kg CO_2e more emission than in 2011, increasing the kg CO_2e per child rate for home-to-school trips from 1.64 to 1.68).

Conclusion

In this paper, we estimate the change in multimodal spatial availability as a result of school consolidations/closures between the years of 2011 and 2016 in an empirical case study of Hamilton, a mid-size city (~570,000 pop) in Ontario, Canada (Government of Canada 2022). The spatial availability and spatial availability per student are calculated at the parcel level and aggregated at the Canadian Census DA spatial unit and at the six Hamilton communities for comparison. Schools closed and the number of school seats decreased so spatial availability declined overall: we discuss where, for whom, and with what potential impacts.

Overall, the closure of 7% of elementary schools in Hamilton between 2011 and 2016 resulted in -4% decline in school-seat availability city-wide (2,280 fewer school-seats), but specifically a -46% decline in non-motorized spatial availability. Though non-motorized modal share was low in both 2011 and 2016, the *potential* for active transport trips was significantly eroded as schools within a 27 minute walk catchment were closed in the more densely populated and central areas of the city. Further, the communities with the highest LIM-AT prevalence were the most impacted: communities like Hamilton Central and Dundas saw the most drastic loss in non-motorized spatial availability while communities with lower LIM-AT prevalence saw gains in motorized spatial availability (as a handful of rural schools opened). The motivation of operational savings associated with public service consolidation for the school boards did not account for the mobility-related burdens *certain* families are now saddled with.

In addition to spatial availability impacts, associated mobility measures are assessed. City-wide, home-to-school non-motorized minutes (for a one-way trip) reduced by 3,309 and GHG emissions associated with motorized home-to-school travel increased by 3,416 kg CO_2e . The decision to consolidate schools, increase the length of motorized travel and decrease the potential for non-motorized impacts will have daily impacts on students and their families (Mandic et al. 2022; Pabayo et al. 2012), the broader

community (Pietrabissa 2023; Merrall, Higgins, and Páez 2024; Bittencourt and Giannotti 2023) and the environment (Pantelaki, Claudia Caspani, and Maggi 2024; Rong et al. 2022).

Like many other localities (J. Lee and Lubinski 2017; Autti and Hyry-Beihammer 2014; Beuchert et al. 2018), Hamilton is not immune to top-down operational efficiency assessments that determine if community infrastructure is underutilized and closed. From the perspective of the provincial government of Ontario, the school closures which occurred in Hamilton resulted in operational savings-per-student. We demonstrate how these decisions resulted in both families and students paying a price through spatial availability, lost potential walk minutes, and increased GHG emissions.

By quantifying the spatial availability, environmental, and active-travel implications of school closure/consolidation policies in Hamilton, our paper offers a methodology for spatial policy analysis scenario. The presented methodology can be used by researchers and decision-makers to plan and evaluate equitable and sustainable urban planning policies from a spatial perspective. At the core of the method is spatial availability (Soukhov et al. 2023; Soukhov et al. 2024), a singly-constrained accessibility measure that can be calculated at the finest spatial resolution (in our paper, parcel-level) and aggregated at whichever spatial unit is most meaningful for interpretation. We urge policy-makers to view the ‘spatial availability’ of public resources from a per-capita perspective, plan capacity and location of service provision with the cost of travel (and associated implications such as GHG emissions, active transportation mode, safety of active travel modes, etc.) that sufficiently serves the target population. In this work, we suggest and assume a benchmark of 1.0 school-seats per student which accounts for sufficiency. Spatial availability can be used to obtain this benchmark since the total number of opportunities (i.e., school capacity) is preserved in the region of analysis unlike unconstrained forms of accessibility measurement e.g., Hansen-type measure (Hansen 1959). As such, the assigned spatial availability can be divided by population at each zone to yield an interpretable per capita measurement.

Ultimately, this case study furnishes evidence that consolidation of schools was particularly ill-timed: with the advent of the COVID-19 pandemic, the education system lacked the resiliency to accommodate reduced classroom capacities and left parents who once lived within active transportation distance to schools relying on motorized transportation for their children. These top-down austerity measures left the Hamilton local school system more vulnerable to the impacts of COVID-19 by undervaluing the societal role of schools in neighbourhoods. By identifying the impact of school consolidation policies in Ontario we anticipate that researchers and decision-makers will have better information to center the wellbeing of all residents, including students, and the planet in urban planning policies.

As with all studies, our work is associated with limitations on how results should be interpreted. The calculated spatial availability assumes any residential parcel can have a student (at the DA rate of students per residential unit) so all parcels are assigned a DA rate weighted by how many residential units are contained within the parcel. Each parcel can also visit any school, though travel times based on observed

origin-destination behaviour (from the TTS) are more likely through the use of the empirical travel impedance functions. In this way, the spatial availability demonstrates what *potential interaction* a student could have based on historic and average travel behaviour and shortest network-path travel times if residing in point in space. This representation is average, and by design obfuscates considerations that could make non-average and shortest-path travel unrealistic such as safety and built-environment concerns (C. Lee et al. 2021; Yumita et al. 2021) nor considers significant non-transportation factors (Palm and Farber 2020). Further, this study does not consider transit, school-bus, or cycling modes which have implications on how the GHG emissions estimation can be interpreted. Transit and school bus modes often taken more circuitous routes (Yumita et al. 2021) but pool students thereby reducing emissions. Cycling reduces travel time over the same walking distance at no extra emitted GHG. Lastly, this study also ascribes a static emission factor to represent motorized travel minutes based on an average diesel passenger car. In reality, GHG emissions emitted per minute of driving varies extensively depending on operating conditions and vehicle characteristics (Soukhov and Mohamed 2022). In these ways, the assumptions made are to illustrate *potential* and *average* changes that resulted in a backdrop of school consolidation/closures to illustrate accessibility-related impacts for the city of Hamilton.

Declarations

Ethical approval Not applicable

Participate consent Not applicable

Competing interests The authors declare there are no personal or financial conflicts of interest.

Authors' contributions A.S., A.P., C.D.H., and M.M. all contributed to the study conception and design. Material preparation, data collection and formal analysis were performed by A.S., A.P., and C.D.H. All visuals and the first draft of the manuscript was written by A.S. A.S., A.P., C.D.H., and M.M. commented on earlier versions of the manuscript. A.S., A.P., C.D.H., and M.M. reviewed the final manuscript.

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Appendix

Table 2: Estimated on-the-ground capacity (OTGC) (units of school seats available per school) regression results for public and public-catholic school boards in Hamilton, Canada for years 2011 and 2016.

	<i>Dependent variable:</i> log(OTGC)	
	(Public)	(Catholic)
log(F)	0.346*** (0.107)	0.471*** (0.153)
JrElem	3.123*** (0.834)	
MidElem	3.068*** (0.893)	
Elem	3.752*** (0.861)	2.333* (1.212)
Sec	4.094*** (0.978)	2.936** (1.398)
urban.dist	-0.00003*** (0.00001)	-0.00003** (0.00001)
Observations	42	42
R ²	0.999	0.998
Adjusted R ²	0.999	0.997
Residual Std. Error	0.212 (df = 36)	0.331 (df = 38)
F Statistic	6,189.428*** (df = 6; 36)	3,794.875*** (df = 4; 38)
<i>Note:</i>		*p<0.1; **p<0.05; ***p<0.01