10 years of school closures and consolidations: the impact on school accessibility

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Abstract

Reducing motorized travel and increasing active travel are top priorities for many communities. However, these priorities are confronted with pressures to reduce the fiscal burden of public services, including schools. Public school boards have been strained to do more with less, and opting to close under-capacity schools to deliver educational services more cost-effectively. However, once a school is closed, students' proximity to schools decreases, and those who previously lived close enough to walk or cycle can no longer do so. In this paper, the City of Hamilton, a mid-sized city in Ontario, Canada, which experienced a 10% decrease in elementary school locations between 2011 and 2021, serves as a case study. We quanitfiy how these closures and consolidations have reshaped accessibility for the elementary school-aged population and discuss their implications for active and motorized travel. To measure accessibility, spatial availability, a singly-constrained multimodal measure of spatial accessibility is used. This method's proportional allocation mechanism enables interpretable comparison between accessibility 'before' and 'after' the implementation of school closure/-consolidation policy considering changes in potential travel time and population. The analysis is conducted at the parcel level, considering all school seats as eligible and incorporating observed home-to-school travel patterns for motorized and non-motorized modes. We present system-wide impact estimates resulting from these closures. The findings reveal that overall spatial availability in the city declined. While the school consolidation policy may have achieved cost savings in facility operation and maintenance, the burden falls on students, families, and communities through *potentially* reduced opportunities for physical activity through an active journey to school and increased motorized travel externalities.

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

Introduction

The amount of services accessible within communities oscillate: economic and demographic shifts, rural and urban configurations and political in/action all induce change. These forces spur pressures to reorganization and consolidation of public facilities that provide services, potentially improving access for some but not for all (Christiaanse 2020; Rosik, Puławska-Obiedowska, and Goliszek 2021). Schools are a compelling case study in this respect. In many communities globally, school closure and consolidation policies have been pursued by governments to optimize per-student operational cost-efficiency (Rong et al. 2022; Dai et al. 2019). Research has highlighted that these polices have knock-on implications, including the weakening of communities' social infrastructure (Butler, Kane, and Cooligan 2019; Irwin and Seasons 2012; Autti and Hyry-Beihammer 2014) and negative household-level fiscal impacts such as a reduction of property values (Merrall, Higgins, and Páez 2024). Operationally, savings may be experienced but they are paid at different levels by students, families, communities and society.

A school offers many things to a community: but one dimension is the travel to and from school, often overlooked by decision-makers considering school closure and consolidation policies (Bierbaum, Karner, and Barajas 2021; J. Lee and Lubienski 2017). Schools and residential locations often proximately co-located, the journey-to-school is an excellent opportunity for physical activity (Desjardins et al. 2024). However, closures exchange the physical activity of students' realized active trips or "reserved" active trips (Morency, Roorda, and Demers 2009; Morency, Demers, and Lapierre 2007) (e.g., trips that could be made active) for motorized travel (Rong et al. 2022). Indeed, motorized travel to school is the largest contributor of carbon emissions from personal daily travel after the journey-to-work (Rong et al. 2022; Pantelaki, Claudia Caspani, and Maggi 2024). Despite these societal implications, many communities are closing and/or consolidating schools (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).

In this paper, we explore the case study of Hamilton, a mid-sized city in Canada that has pursued similar school closure and consolidation policies. We detail the Canadian political context that incentived these policies and quantify their transportation implications using data that constructs where students may have lived and the capacity of schools in 2011, 2016 and 2021. To quantify transportation implications, we use a novel multimodal extension of a singly-constrained accessibility measure known as spatial availability (Soukhov et al. 2023; Soukhov et al. 2024). Spatial availability is used to estimate active (i.e., walking) and motorized (i.e., car) accessibility considering the capacity of each school, and the residential location and quantity of school-aged population, and travel times from residential locations to schools for three time periods. In this way, this work contributes a empirical findings documenting how government austerity hurts public education, along with a methodology that results in interpretable accessibility values that can be compared across modes, the City, and three time periods.

To foreshadow the paper's conclusions, our findings indicate that school seats have became less spatially available in the city. This change happened unevenly, with certain communities being disproportionately affected. The school closure and consolidation policy pursued may have achieved cost savings in facility operation and maintenance. However, it has come at a cost to families, students, and communities, resulting in lost opportunities for healthier active travel and a potential increase in motorized travel. We investigate: were the closures and consolidations worth the operational savings? 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 is publicly available within the lead author's GitHub repository.

Background

Overview of proximity and equity in the school accessibility literature

The examination of access to public services is a well established area of the transportation literature: from parks (El-Murr et al. 2021) to healthcare (Pereira, Braga, et al. 2021) and associated dimensions of inequities (Tiznado-Aitken, Munoz, and Hurtubia 2021; Bittencourt and Giannotti 2023; Kelobonye et al. 2020), spatial accessibility has been explored in cases studies worldwide.

Accessibility to schools has been a public service explored across several transportation dimensions. For instance, Marques, Wolf, and Feitosa (2020) demonstrates that lower-income neighbourhoods, compounded by other intersecting dimensions of disadvantage, tend to have lower accessibility to schools compared to more advantaged neighbourhoods in Portugal. Similar conclusions are drawn in West Virginia, US by Talen (2001), England by Burgess et al. (2011), Baton Rouge, US by Williams and Wang (2014), São Paulo and Curitiba, Brazil by Moreno-Monroy, Lovelace, and Ramos (2018), Pizzol, Giannotti, and Tomasiello (2021), and Bittencourt and Giannotti (2023), and Santiago, Chile by Tiznado-Aitken, Munoz, and Hurtubia (2021). Research has also demonstrated that when school closures occurs, what schools end up closing are not a politically neutral decision. For instance, these spatial trends are explored in the context of England by Pinch (1987), areas of declining school-aged populations in Dreseden, Germany by Müller (2011), rural Finnish communities by Autti and Hyry-Beihammer (2014), and Chicago, US by J. Lee and Lubienski (2017).

The methods applied to measure school accessibility have been varied, from simple indicators to complex metrics. Beginning from more simple, Marques, Wolf, and Feitosa (2020) present indicators of school seats per student along with the shortest distance from origin to schools within a school catchment, methods also used in Talen (2001) and Burgess et al. (2011). Authors make refinements to these methods; Müller (2011) considers travel time by public transit from origins to schools and Pizzol, Giannotti, and Tomasiello (2021) considers travel times by different modes and multiple schools from a single origin along with other indicators related to school quality. By contrast, Williams and Wang (2014), J. Lee and Lubienski (2017), Moreno-Monroy, Lovelace, and Ramos (2018), Tiznado-Aitken, Munoz, and Hurtubia (2021), and Bittencourt and Giannotti (2023) use more complex approaches such as the two-step floating catchment area (2SFCA). The 2SFCA is popular in measure in evaluating access to healthcare services (Antonio Páez, Higgins, and Vivona 2019) and yields a supply-to-demand ratio that accounts for the population demanding a service and the quantity that is supplied within a certain distance range (Shen 1998; Luo and Wang 2003). The consideration of the supply of service is pertinent in the case of schools and is acknowledged to as a limitation to using simpler accessibility measures (Pizzol, Giannotti, and Tomasiello 2021).

In addition to competition for school-seats, theoretically, the advantage students using faster modes (e.g., motorized modes) offer in terms of a wider range in school-seat choice is also important. Though some of the reviewed works using 2SFCA approaches consider multiple modes, explicit attention to the modal *advantage* has not been discussed. To this end, in this work we use spatial availability, a singly-constrained measure of spatial accessibility (Soukhov et al. 2023; Soukhov et al. 2024). Spatial availability allows for the representation of how many 'school-seats' are spatially available to motorized- and active-trip taking elementary school-aged student population at a spatial-level, facilitating interpretable comparison across years. Further, spatial availability can be represented as school-seats per capita, mathematically equivalent to the supply-to-demand ratio of the 2SFCA (see appendix in Soukhov et al. (2023)).

Hamilton's school closures and consolidation

Hamilton is a mid-size city (~570,000 pop) with rural, suburban and urban characteristics in the province of Ontario, Canada (Government of Canada 2022a). The city's public English education is covered by the Hamilton-Wentworth District School Board (HWDSB). In 2013, the HWDSB 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 approximately 5 to 14) would be subject to evaluations, including a "Pupil Accommodation Review" (HWDSB 2013). This Master Plan and the slated Pupil Accommodation Reviews prompted public outcry, as the outcome of Pupil Accommodation Reviews are typically schools closures and consolidations (Craggs 2013; Seasons 2014b).

Like all school boards in Ontario, HWDSB relies on funding from the province which is distributed through a formula based on pupil enrolment (Mackenzie 2018; Irwin and Seasons 2012). However, it has been demonstrated that this funding formula has become insufficient to maintain schools in a state of good repair (Auditor General of Ontario 2015). Further, existing "top-up" programs to assist in operation and maintenance costs (e.g., School Facilities Operation and Renewal Grant) were entirely phased out by 2018 (TDSB 2024). Within this funding backdrop, the Pupil Accommodation Review guidelines outlined a "community-focused" process to assessing the value that a school provides to students, the community, and the local economy (Seasons 2014b; Ministry of Education 2006). However in practice, critical residents felt the outcomes of the Pupil Accommodation Reviews were predetermined (Thompson, Collins, and Dean 2024): older schools were slated to be closed, and a wholesome breakdown of costs to repair and maintain schools were not made available (Kleinhuis 2013). Other critics pointed to unbalanced incentives 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). The Ministry's framework promotes the closing and consolidation of schools rather than cost-effective solutions for keeping older schools open (Kleinhuis 2013).

The HWDSB and the Hamilton-Wentworth Catholic District School Board (HWCDSB), which together provide public English education to the majority of school-aged children in Hamilton (FAO 2023), were particularly impacted. While Accommodation Reviews were a province-wide trend during this period, Hamilton's school boards underwent an unprecedented number of reviews compared to other boards in other Ontario municipalities. (Seasons 2014a). In the wave of Pupil Accommodation Reviews between 2013 and 2016, 12 of the 147 elementary schools closed in Hamilton. Likely in part due to the public unpopularity of school closures, in 2017, the provincial government introduced a moratorium on beginning new Pupil Accommodation Reviews. In the following years, the HWDSB addressed its backlog and closed 12 more schools between 2017 to 2021 (HWDSB 2023). Though elementary school locations declined by 10% between 2011-2021, HWDSB intends to conduct future Pupil Accommodation Reviews as initially scheduled, waiting until the end of the moratorium before dates are assigned (HWDSB 2023).

A justification in these Pupil Accommodation Reviews are operational savings based on “projected” reductions in student population and “under-utilized” school capacity (Craggs 2012; TDSB 2024; OPSBA 2024). As later demonstrated in this study, these policies in fact did result in school capacity per student reducing overall. Indeed, school seats in the city declined 5%. It should be noted that though closures dominated the Pupil Accommodation Review process, some schools were “consolidated” e.g., a school or two were closed and another school was expanded or opened to accommodate students from closed schools. Taken that school locations decreased more than overall school-seats, elementary schools in Hamilton are on average larger than they once were.

In 2024, the moratorium on Pupil Accommodation Reviews is still in place and school boards are motivated by the same funding conditions. In absence of new revenue-generating levers and under the same funding formula with even lower inflation adjusted per-pupil funding, many school boards are calling for the end of the moratorium (OPSBA 2024; TDSB 2024; Draaisma 2024). In the meantime, some school boards are reducing specialized and community-wide programming (TDSB 2024). Under the status-quo, the end of the moratorium will result in further school closures. These pertinent decisions, made under an austere funding formula and flawed school board incentives does not create an environment where solutions for a sustainable public education system can thrive.

Though schools have a plethora of benefits not captured by their maintenance and operational costs (Butler, Kane, and Cooligan 2019; Irwin and Seasons 2012; Autti and Hyry-Beihammer 2014), this paper’s scope is limited to their travel implications. For students who live in proximity to schools, their closure or consolidation directly eliminate the realized or potential active trips that are, or could have been, made. Closing a school permanently reduces the potential for active trips and further entrenches reliance on motorized travel. Additionally, from the perspective of modal equity, school-aged populations with access to motorized transport gain a speed-time advantage, providing them with greater flexibility and choice in accessing school-seats.

The spatial and population-level distribution of these impacts are of question for this paper. Specifically, the paper’s aim is to demonstrate how these policies impacted the motorized and non-motorized (active) school-seat accessibility landscape. We hypothesize that the school closure and consolidation policies reduced accessibility to school-seats for many students. By extension, this loss in access and the displacement of active trips likely resulted in decreased potential active travel minutes and increased motorized travel minutes, with these impacts distributed inequitably across space and populations. To test these hypotheses, the paper examines the following:

- How has spatial availability changed for home-to-school trips following school closures and consolidations?
- What is the extent of the loss in walking minutes for these trips?
- How has motorized travel increased as a result?

- Which communities, particularly households with a high prevalence of low-income and hence more likely experiencing transport poverty, experienced the greatest losses due to this policy?

Data

Our focus is to evaluate the impact of school consolidations between 2011, 2016 and 2021 on multimodal school-seat spatial availability in Hamilton. To facilitate comparison, the following conditions are constructed for each year: 1) school configurations, 2) average student population, low-income prevalence of households, and residential parcel locations, and 3) estimated multimodal travel behaviour. The following sub-sections describe these three types of data.

Schools

First, elementary schools locations, how the changed throughout the study period and their capacities are required for each studied year.

Concerning school locations, the City's school boards provided the authors with locations and associated school catchments for the 2010-2011 and 2015-2016 academic years. Data for 2021 locations was retrieved from the City's open data portal (Hamilton 2024). In Hamilton, the majority of student-aged population attend school in one of the two English public school boards (FAO 2023). One school board is referred as Hamilton Wentworth District School Board (HWDSB) and the other as Hamilton Wentworth Catholic District School Board (HWCDSB). School catchments for the public and public-catholic catchments indicate what residential property is assigned to what school by default. However, families can decide to attend schools out of catchment; in fact, 21%-23% of motorized school trips for populations aged 5 through 14 are out of catchment according to the regional travel survey (the Transportation Tomorrow Survey (TTS)) in 2011 and 2016, the most recent TTS available at the time of writing (Data Management Group 2018).

In addition to the school's location in 2011, 2016 and 2021, all schools were also tagged with a school status regarding their existence and/or change in location or school-seat capacity. A summary of the status of schools through 2011 to 2021 is illustrated in Figure 1. Figure 1 also displays a count of the number of schools with the status between years, the number of schools overall present in each year, and the symbolic representation of a school status that is used in Figures throughout the paper. Overall, a school can have one of seven school statuses in any given year. Either: 1) the school did not change throughout 2011 to 2021, 2) the school expanded (i.e., increased school-seat capacity) or was 3) relocated and expanded (N.B., schools expanded only between 2011 through 2016 as they were typically done *before* school closures and no new Pupil Accommodation Review was commenced after 2017), 4) the school closed sometime after 2011 and before 2016 or 5) after 2016 and before 2021, and 6) the school opened sometime after 2011 and before 2016 or 7) after 2016 and before 2021.

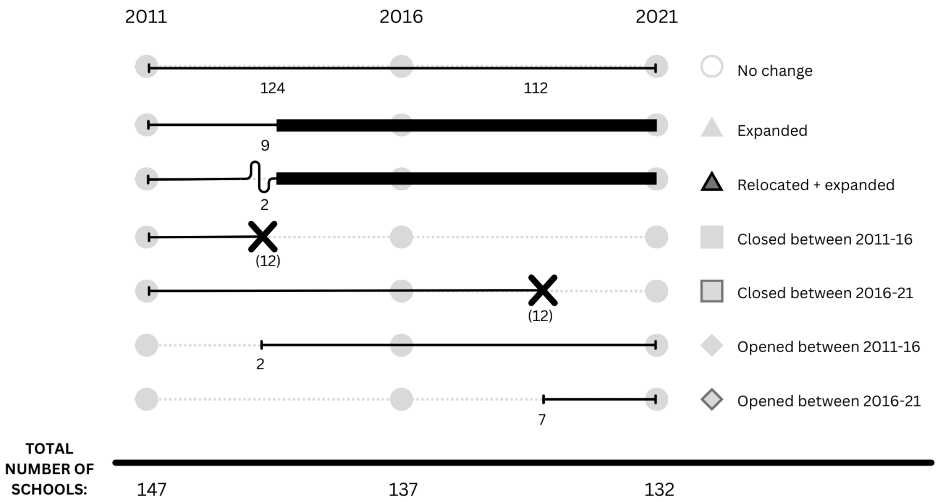

Figure 1: Overview of the number of schools in Hamilton in 2011, 2016 and 2021 along with the type of school status change..

The capacity of each school is also required for each simulated year. This capacity is reflected as the number of 'seats' available in the school. Enrolment exceeding this capacity indicates over-enrolment, while enrolment below it indicates under-enrolment. This value is calculated by the provincial Ministry of Education and referred to as the on-the-ground capacity (OTGC). The current and historic OTGCs for schools are no longer publicly available (Ontario 2017), so we estimated them using a multivariate regression model and validated the results with a set of OTGC values manually gathered. These values were retrieved for schools that had undergone a completed Pupil Accommodation Review and had publicly available School Information Profiles.

For schools lacking OTGC values, two regression models were created: one for public schools and another for public catholic schools. The independent variables in the model were 1) a dummy variable indicating the type of school grade instruction (*MidElem*, *JrElem*, *Elem*), 2) the school's building footprint (F) in units of (m^2), and 3) the school's shortest Euclidean distance from the centroid of Hamilton's central business district area (*DistCBD*) defined in metres:

- 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. *MidElem* and *JrElem* school grade instruction type is only present in the public school board.

- The building footprint F was retrieved from an archived spatial data set (Spatial 2015) and footprints from newer schools in 2016 and 2021 from OSM (OpenStreetMap 2021).
- *DistCBD* was calculated 'as the crow flies' from each school to the centroid of the Hamilton CBD (43.256684°N, 79.869039°W). Notably, this variable can also be seen as a proxy for school construction age as older buildings in Hamilton are generally located closer to the CBD, the "old" Hamilton community (Merrall 2021).

Equations (1) and (2) summarise the OTGC regression model for public schools and public catholic schools respectively. As seen in Table **??**, the coefficient of determination for these models are fantastic: $R^2 = 0.999$ and $R^2 = 0.998$ for the public $OTGC_{Public}$ and public catholic $OTGC_{PublicCatholic}$ school boards respectively, and the residual standard deviation is $\sigma = 0.212$ and $sigma = 0.331$.

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

$$OTGC_{PublicCatholic} = F^{0.471} - e^{0.00003*DistCBD} + e^{2.333*Elem} \tag{2}$$

Taken together, Figure 2 displays the city's elementary schools locations, status and their estimated or retrieved OTGCs for 2011, 2016 and 2021. For additional context on the degree of residential urbanization in Hamilton, the percentage of residential parcels considered 'urban' compared to 'suburban' or 'rural' is reflected at an aggregated spatial unit across all six plots in Figure 2. This land-use classification is available within the 2021 residential parcel file described in the following sub-section. In Figure 2, it can be seen that the majority of schools that changed status are in the HWDSB, with OTGC capacity decreasing in 2016 and 2021 compared to the previous year. Most school closures took place in the central and eastern parts of Hamilton's urban area (Hamilton Central), as well as in rural areas of western Hamilton (Flamborough). When schools did open or expand, it was primarily in the more recently urbanized southeastern area of Hamilton (Glanbrook), with a few also in Hamilton Central to offset some of the lost capacity.

Students, residential locations and low-income prevelance

Secondly, a detailed account of the average student population, low-income prevalence of households, and where they may live is required for each studied year.

Concerning the student population and poverty, information from the 2011, 2016 and 2021 Canadian Census (Canada 2011, 2016, 2021) was sourced 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

Table 1: 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.

	Dependent variable:	
	log(OTGC)	
	(Public)	(Public Catholic)
log(F)	0.346^{***}	0.471^{***}
	(0.107)	(0.153)
JrElem	3.123^{***}	
	(0.834)	
MidElem	3.068^{***}	
	(0.893)	
Elem	3.752^{***}	2.333^{*}
	(0.861)	(1.212)
Sec	4.094^{***}	2.936^{**}
	(0.978)	(1.398)
urban.dist	-0.00003^{***}	-0.00003^{**}
	(0.00001)	(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)
Note:		*p<0.1; **p<0.05; ***p<0.01

years were retained. A common poverty measure across all three census years is the low-income after-tax measure (LIM-AT), which reflects the proportion of private households that are below the median after-tax income in the region (Government of Canada 2017). The LIM-AT prevalence for households with children under 18 was retrained for this paper as there is no LIM-AT prevalence tabulated for households with exclusively elementary aged children. Population and LIM-AT variables were taken at the Dissemination Area (DA) level, 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 3. LIM-AT prevalence is notably more concentrated within the centre of Hamilton (Hamilton Central) through 2011 to 2021, overlapping the most urbanised land-use and the largest amount of schools closed (Figure 2). Also of note, LIM-AT prevalence drastically decreased in 2021 as a result of Pandemic benefits that reduced income inequality (Government of Canada 2022b).

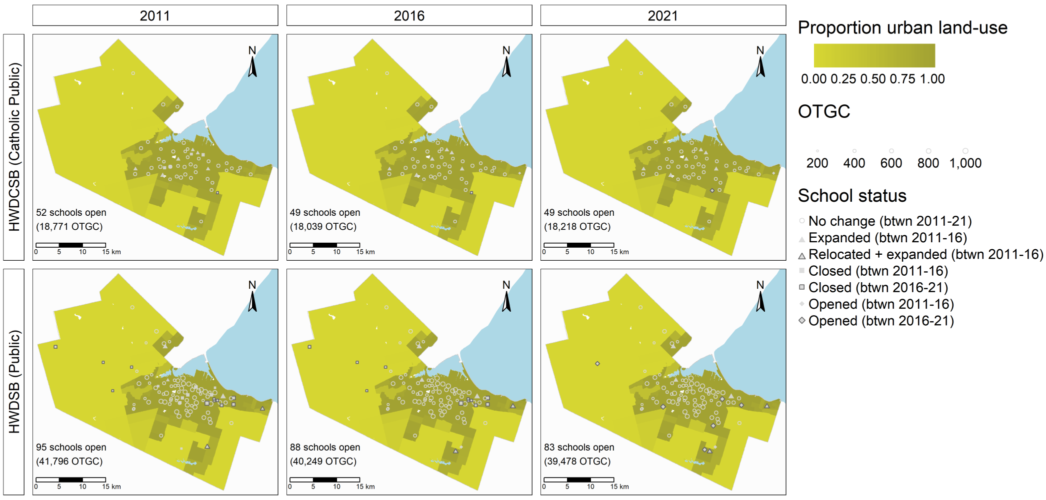

Figure 2: The on-the-ground capacity (OTGC) of schools and school status for year 2011, 2016 and 2021 for both the HWDSB and HWCDSB. Schools are presented overtop a layer visualising the degree of residential urbanisation in 2021.

Where students live are estimated at the level of the residential parcel. Centroids for parcels in 2011, 2016 and 2021 are retrieved from Teranet (2009), representing 134,340, 139,467 and 143,890 unique locations in those years, respectively. The datasets do not provide information on the number of households or children per parcel. To estimate this value, the average number of students per parcel is calculated using the number of school-aged population in each DA is divided by the number of households in each DA. This rate is assigned to all parcels within an associated DA. Due to the proprietary nature of the parcel data, the second row in Figure 3 visualises an aggregation of the information: the average rate of 5-14 year old population per residential unit (parcel) at the DA level. Notably, though the rate of 5-14 year old population per parcel is higher in more peripheral (and rural) communities, there are many DAs within Hamilton Central that have high rates and populations that are similar to those in these more peripheral communities.

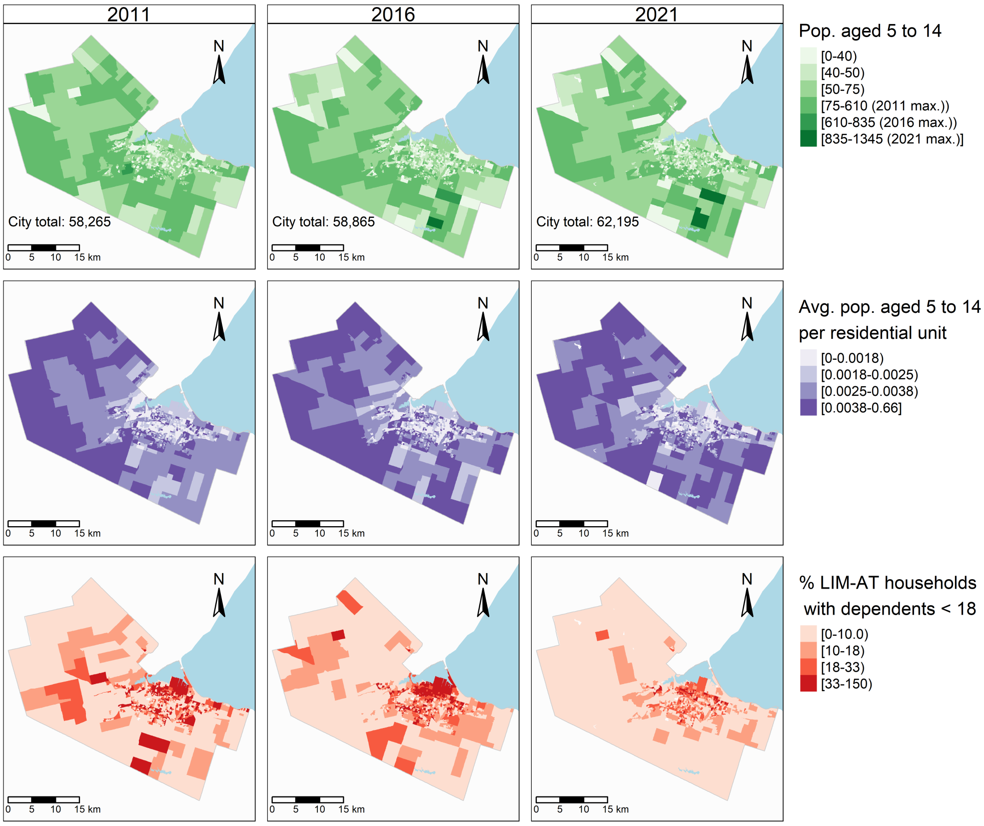

Figure 3: The magnitude (top row) and rate per residential unit (middle row) of elementary aged student population per DA in 2011, 2016 and 2021. Bottom row: the proportion of low-income households (prevelance of low-income after-tax, LIM-AT, measured by the 2011, 2016 and 2021 Canadian Census) with dependents under 18 years old shown. All scales are represented in quartiles.

Multimodal travel behaviour

To reflect multimodal travel behaviour for all studied years, two types of data are estimated and complied. First, observed home-to-school trips by mode are retained from travel surveys. Next, travel times are calculated assuming active and motorized modes at parcel-to-school level and at the level matching the travel survey. Then, travel impedance functions are calibrated using the observed travel data, and using the functions and the parcel-to-school calculated travel times as input, the travel impedance values for each residential location to each school (origin-destination pair) is estimated. These three steps are described as follows:

First, we retrieve information about the mode used and origin-destination locations of home-to-school trips from the 2011 and 2016 Transportation Tomorrow Survey

(TTS) (Data Management Group 2018); the 2021 TTS survey is unavailable at the time of writing so 2016 flows are assumed for the 2021 year. The TTS is a travel survey conducted in the Greater Golden Horseshoe Area in Ontario typically 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 7,432 and 7,085 non-motorized trips (mode used includes walk and cycling) for 5 to 14 year olds from home-to-school in 2011 and 2016 respectively. The intensity of modal home-to-school flows are visualised in Figure 4 along with the boundaries of the TAZ and DAs. Also in Figure 4, 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 - 2011: 78%and 2016:94%, Dundas - 2011: 71% and 2016: 67%, Flamborough - 2011: 90% and 2016: 91%, Glanbrook - 2011: 91% and 2016: 78%, Hamilton Central - 2011: 55% and 2016:50%, and Stoney Creek - 2011: 71% and 2016: 79%).

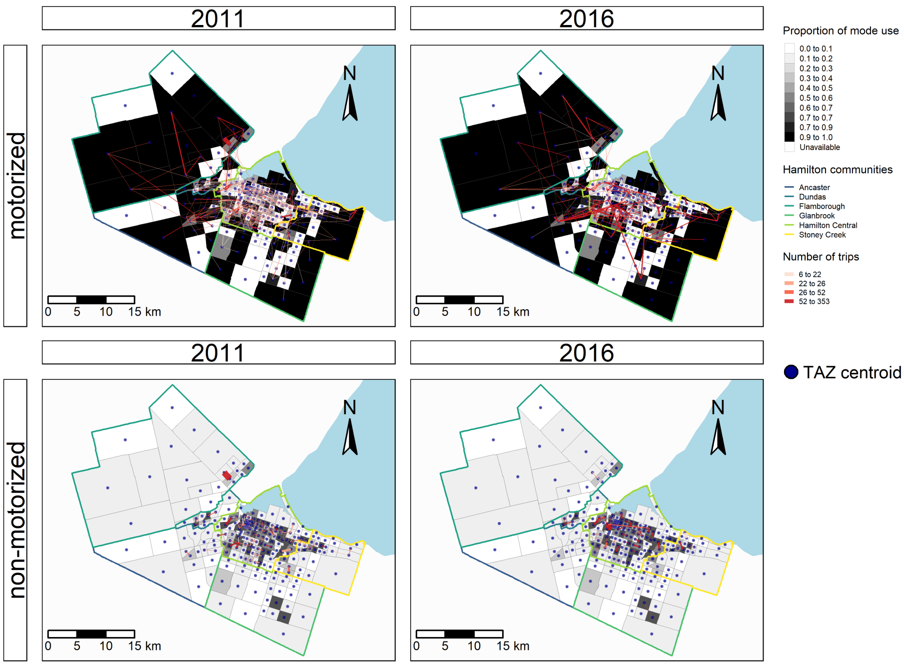

Figure 4: The origin-destination flows from home-based motorized and non-motorized school trips for students between 5-14 years old as retrieved from TTS 2011 and 2016. Flows are mapped atop the proportion of TAZ non/motorized modal share from the TTS 2011 and 2016, DA boundaries, and Hamilton community boundaries.

Next, the travel times matrices for motorized and active travel are estimated using the 'travel_time_matrix()' function part of the {r5r} package (Pereira, Saraiva, et al. 2021). Travel time matrices are estimated for all TAZ centroids to TAZ centroids (matrices of size for 2011 and 2016: 234 x 234) as they ar enot reported in the TTS. Additionally matrices are estimated for all residential parcels to schools (matrices of size 134,340 x 147 for 2011, 139,467 x 137 for 2016, and 143,890 x 132 for 2021) for additional granularity. {r5r} is a R-based interface to the R5 routing engine developed separately by Conveyal (Conveyal [2015] 2022). For simplicity, we assume motorized travel is by car and non-motorized travel is by walking, as these are the most common modes in their respective categories. For travel time calculations, we set a maximum threshold of 60 minutes and use the free-flow OpenStreetMap road network of Hamilton (Geofabrik 2022). While all car trips are retained, walking trips over 27 minutes are filtered out. This value approximately corresponds to a distance of 1.6 km at a walking speed of 3.6 km/h, which is the threshold for qualifying for motorized transport provided by the school board (HWDSB 2019).

In terms of the travel impedance function: we assume that children can go to any elementary school, however, there is a preference for facilities that are more proximate. Based on this assumption, we match the associated TAZ-to-TAZ travel times to all observed student-to-school travel flows from the TTS; these are visualised as grey bar columns in Figure 5. Using these observed values, the *theoretical* trip length distribution (TLD) functions are calibrated. TLDs can be interpreted as travel impedance functions as they represent the propensity of realized travel, by trip length (Horbachov and Svichynskyi 2018; Batista, Leclercq, and Geroliminis 2019). The TLDs are calibrated using the maximum likelihood and moment matching techniques and the Nelder-Mead and Brent methods for direct optimization available within the {fitdistrplus} R package (Delignette-Muller and Dutang 2015). The theoretical TLD for each mode and available study year is visualised in blue in Figure 5. 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). For reference, the gamma distribution and the exponential distribution function are displayed in Equations (3) and (4) where x is c_{ij}:

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

$$\begin{aligned} f(x, \alpha, \beta) &= \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \quad \text{for } 0 \leq x \leq \infty \\ \Gamma(\alpha) &= \int_0^{\infty} x^{\alpha-1} e^{-x}\, dx \end{aligned} \tag{4}$$

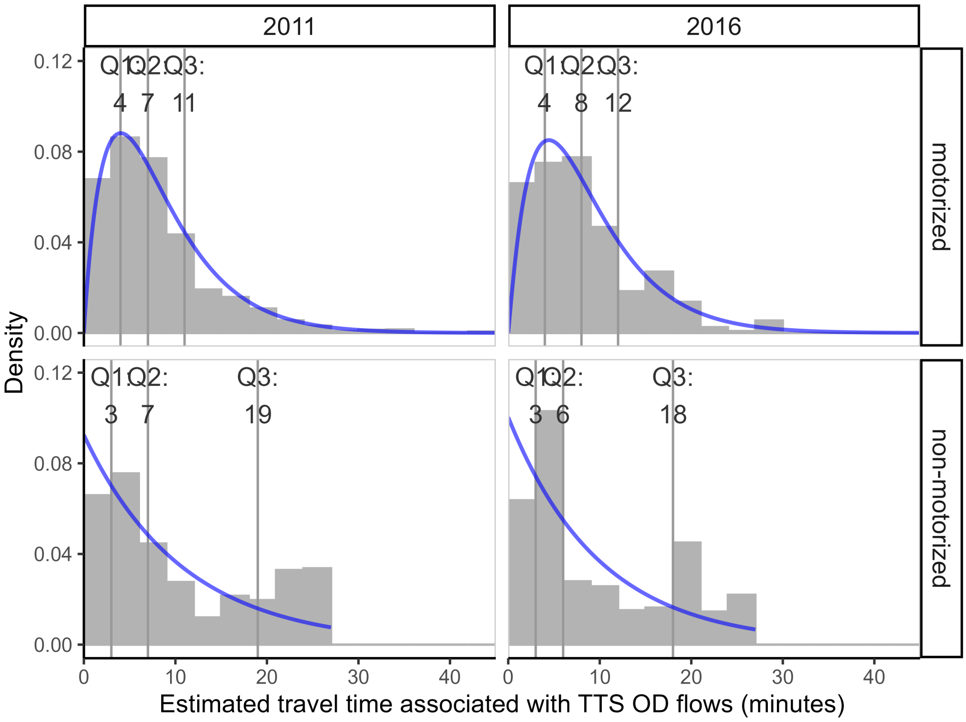

Figure 5: Observed (grey bars) and theoretical (blue curves) motorized and non-motorized impedance functions. Motorized theoretical impedance function is based on the gamma distribution function and non-motorized on the expoential distribution function

Lastly, to achieve greater granularity, the TLDs calibrated using TAZ-to-TAZ flows are used to estimate travel impedance values for each parcel-to-school flow based on calculated parcel-to-school travel times. These values represent the likelihood that students in a parcel will travel to a school, informed by observed home-to-school flows from the TTS.

Methods: Multimodal spatial availability

Accessibility is defined as the "potential for spatial interaction". It is classically presented as the gravity-based measure defined in Hansen (1959) and takes the following general multimodal formulation:

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

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 ($i = 1, \cdots, N$).
- j is a set of destination locations ($j = 1, \cdots, J$).
- 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 accessibility measures like Equation (5) are informative in reflecting the magnitude of access but meaning of the value itself is elusive. The significance of 10,000 accessible school-seats is hard to pin down: how many opportunities must any single student have access to? Furthermore, this opaque interpretation especially is complicated when comparing accessibility of school seats between years, such as different years as in this work. 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 depends on how many people demand for the opportunity, especially for exclusive opportunity-types like schools-seats (i.e., one school-seat is for one student).

In this paper, our work benefits 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):

$$V_i^m = \sum_{j=1}^{J} O_j \; F_{ij}^{tm} \tag{6}$$

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):

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

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_i^{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 two-step floating catchment area (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 ($\frac{\sum_j O_j}{\sum_i P_i}$).

$$v_i^m = \frac{V_i^m}{P_i^m} \tag{8}$$

To summarise the methodology and the data as described in Section 3, multimodal spatial availability V_i^m and spatial availability per student v_i^m is calculated for each parcel for each studied year as follows:

- First, all residential parcels are associated to their respective census DA, TTS TAZ, and community boundary based on spatial location. 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 elementary-aged student population per parcel (Figure 3 second row) and the motorized and non-motorized share as informed by the TTS aggregated by community (Figure 4) is retained.
- Second, the school capacity O_j is estimated and associated with each school (Figure 2). 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 5) based on the respective estimated travel times for each origin (parcel) to school combination. 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 probability density plots of the spatial availability values V_i and the per capita spatial availability v_i values for both modes and all three years are displayed in Figure 6 as a city-wide overview. The left column displays parcel-level values, and the right reflects parcel-level values aggregated at the 2021 DA grid. Both the parcel and DA level values reflect the spatial unit at which they were calculated or aggregated. However, the values of the V_i plots are not directly comparable since the x- and y- axes are set at different scale limits to highlight between year differences. However, overall trends in their distribution can be compared: in all four V_i plots, the 2011 data is more right-skewed than more current years, indicating that spatial availability values used to be higher (e.g., more school-seat access). School closures and consolidations had an impact despite the background dynamics of assumed student population, mode use, travel time and parcel location. The DA level V_i plots show the distribution of each DA value, which is the summation of all parcel V_i values within a DA. In 2011, DAs can be observed to also have more right-skewed spatial availability values than previous years. In contrast, the 2016 and 2021 distributions are more intense and heavily skewed toward lower values.

Although V_i values cannot be directly compared, zonal per capita v_i values can be as the school-age population per spatial unit (e.g., parcel or DA) is used to normalize the respective V_i value. v_i values are presented in the bottom four plots of Figure 6. It can be observed that the same 2011 right-skewed trend persists across all modes. Motorized mode-using students have access to more spatially available school seats than non-motorized mode using students (in 2011, approximately 1.3 school-seats per student as compared to 0.7 and in 2021 approximately 1.2 compared to 0.5). Due to school-seats per student at the DA level being an interpretable aggregation, values at this level will be the discussion focus of the remainder of this paper.

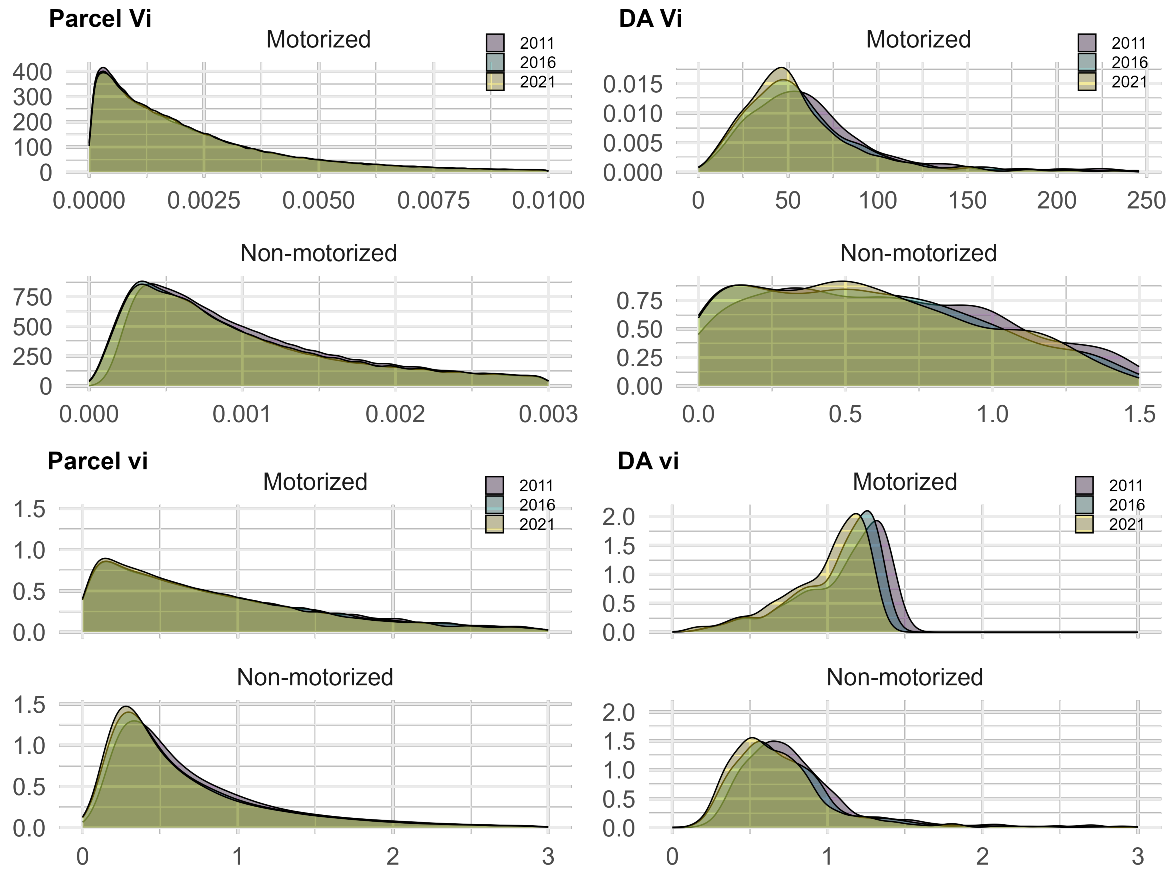

Figure 6: Spatial availability (Vi) and per capita spatial availability (vi) probability density distributions for the city of Hamilton in 2011, 2016 and 2021. Aggregated at the parcel level (left column) and DA level (right column).

Representing the right column of Figure 6 spatially, Figure 7 displays the spatial availability for each DA for a given mode-using population m (e.g., the sum of school seat availability per parcel in each DA for motorized or non-motorized students). Figure 7 visualizes the spatial distribution of motorized and non-motorized school seat availability for 2011, 2016, and 2021. As a reminder, the sum of V_i^m values for both motorized and non-motorized populations in a given year equals the city-wide OTGC (i.e., school seats across both the public english HWDSB and public english catholic HWCDSB). This is due to V_i^m's proportional allocation mechanism, singly-constraining opportunities through the proportion allocation balancing factors. In this way, V_i^m values can be interpreted as a proportion of the total OTGC for that year, as the sum of V_i^m for both modes in a year equals the total OTGC for that year.

Referring to the first two rows of V_i plots in Figure 7 (purples), it is notable that the magnitudes of V_i values for the motorized and non-motorized populations are tremendously different. Again, each V_i value reflects the number of school seats spatially available to the mode-using population at that zonal level, so due to the lower non-motorized modal share (refer to Figure 4), non-motorized values will be lower. However, both mode-using populations have higher spatial availability values (darker purples) in DAs that are more proximate to schools. Hence, all DAs have higher values within Hamilton Central and those more proximate to schools in less-urban communities. This trend persists across 2011, 2016 and 2016, aligning with intuition: populations with shorter travel times to with relatively greater schools are calculated to have high school seat spatial availability. Motorized populations have shorter travel times at DAs further in distance from schools, while non-motorized populations are only competitive at proximate distances.

The bottom two rows of v_i plots in Figure 7 (yellows to greens) demonstrate the spatial availability per mode-using student population e.g., V_i^m divided by the number of students aged 5-14 using a motorized mode or non-motorized mode. It is notable that for motorized populations, their spatial availability per student is above 1 (green) within the center of the city. Conversely, 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 in 2011 and 2016. In 2021, even fewer DAs within Hamilton Central have non-motorized spatial availability rates above 1.

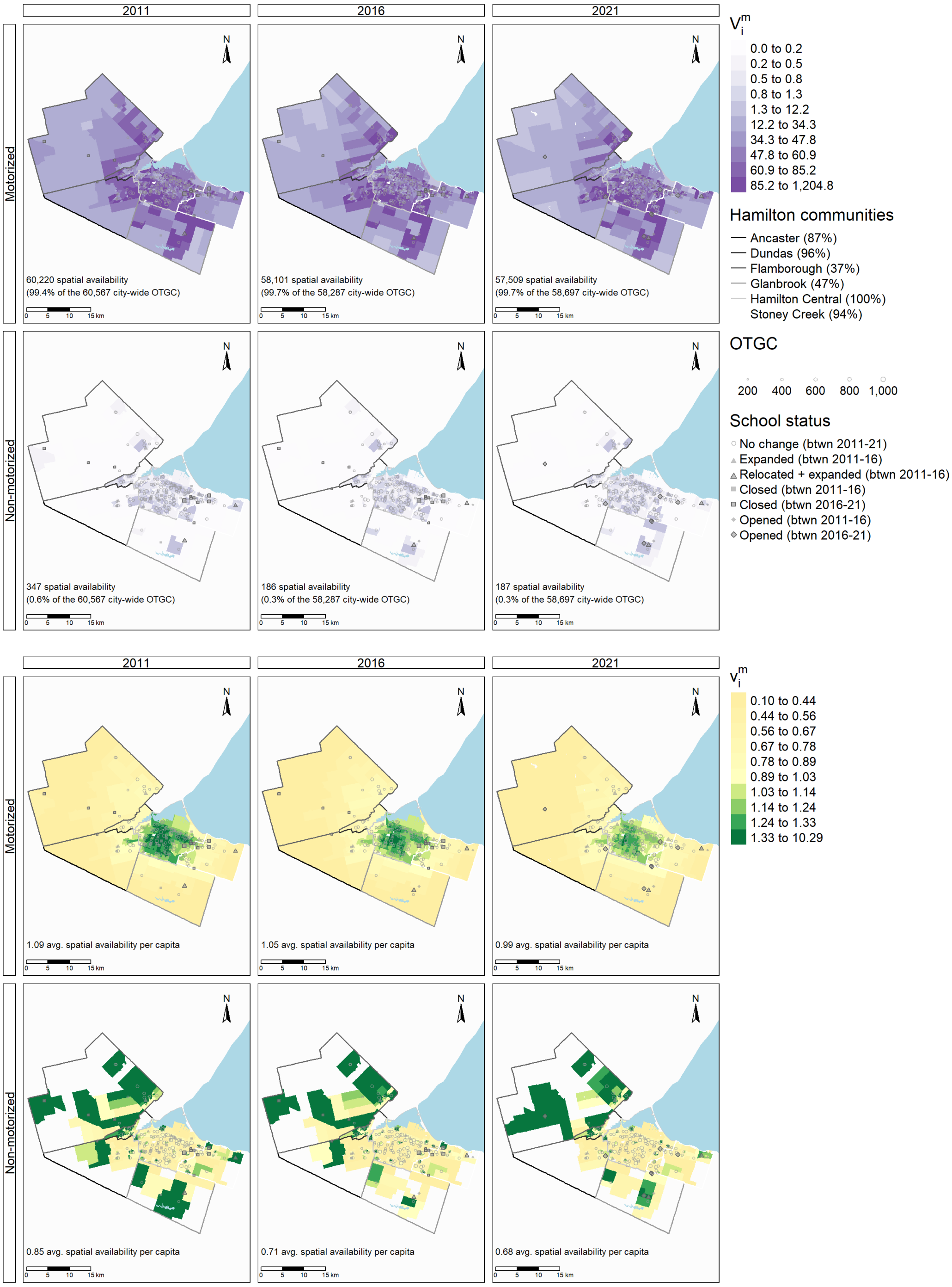

Figure 7: Multimodal spatial availability (purples) and spatial availability per mode-using student (diverging reds and greens) aggregated at the DA level for 2011, 2016 and 2021. Scales are represented in deciles

To further explore these changes, the difference in V_i (first two rows) and difference in v_i (second two rows) between 2011-2016, 2016-2021 and overall between 2011-2021 are displayed in Figure 8 along with schools that changed during that time period. 2011-2016 and 2016-2021 add together to equal 2011-2021 changes quite clearly, e.g. in the third row, the 2011-16 plots a small decrease within the core of the city, and 2016-2021 demonstrates a more significant decrease in the core and western peripheral communities. Together, 2011-2021 plot reflects the changes in these two plots.

A few interesting spatial trends can be observed in Figure 8. First, DAs in proximity to schools that closed (square points) see losses in V_i (reds) for both motorized and especially non-motorized populations. For non-motorized populations, all closed school resulted in a decrease in V_i. The majority of school closures took place in the central and eastern parts of Hamilton's urban area (Hamilton Central), as well as in rural areas of western Hamilton (Flamborough). Hence, losses characterise those neighbourhoods. Secondly, gains in V_i (blues) are seen where schools are opened (diamond points) or expanded (triangle points), especially for motorized populations. These gains are most notably in the more recently urbanized southeastern area of Hamilton (Glanbrook), along with a few pockets of DAs in proximity to new or expanded schools in Hamilton Central. Thirdly, the concentration of students in proximity to schools and the extent of their OTGC matters from the perspecitve of modal advantage. In areas with fewer proximate school options and lower OTGC relative to the amount of students, a change in a school results in a big impact on spatial availability values. For instance, in the community of Ancaster, one school expanded in the rural area in this community between 2011-2016. The motorized student population, especially in rural DAs, saw gains in spatial availability while non-motorized populations saw losses. Students in proximity to the schools in Ancaster have high non-motorized spatial availability, but when the school was expanded (and due to an under-served population) motorized populations saw an increase in spatial availability at the direct expense of non-motorized populations' spatial availability.

Exploring changes in V_i provides a holistic view of spatial availability for a given DA. However, if the focus is on the ratio of spatial availability per student, the bottom two rows in Figure 8 offer more insight. For instance, a community may have had an initially average rate of school seats per student but is expecting an increase in student population so it expands a school. However, due to an increase in population, the spatial availability per student overall still decreases between these two time periods. This case appears to occur in Ancaster between 2011 to 2016: while motorized V_i increased, motorized v_i slightly decreased, and non-motorized v_i decreased relatively more than non-motorized V_i. As shown in Figure 3, the student population and the number of students per residential unit increased more rapidly than the expanded school could accommodate, leading to a decrease in v_i values in DAs proximate to expanded schools.

Similarly, in the southeastern community of Glanbrook, student populations grew from 2011 to 2021, and new schools opened. However, v_i rates decreased because OTGC did not keep pace with student population growth. As another example, in

Hamilton Central and the eastern community of Stoney Creek, changes in V_i are unpatterned, while v_i demonstrate more uniform decreases, with the pattern varying by modal-range for motorized versus non-motorized populations. In these communities, the student population remained relatively stable, though OTGC decreased overall. v_i is illuminating to consider when comparing changes in spatial availability rates.

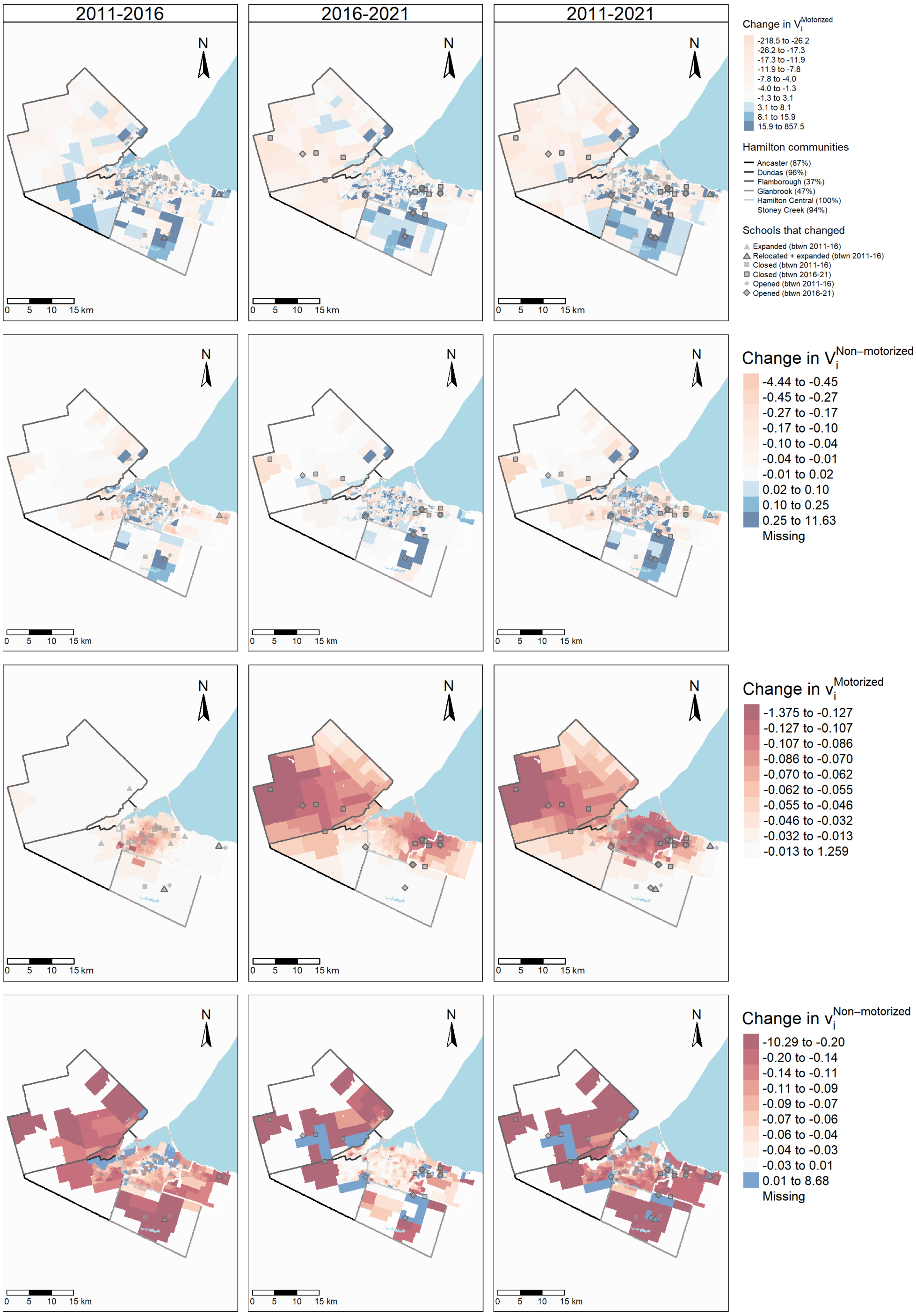

Figure 8: Change in multimodal spatial availability and spatial availability per mode-using student from 2011 to 2016, 2016 to 2021, and together from 2011 to 2021. Change is the subtraction of parcel-level results in that given year and summed for each DA in the 2021 Canadian Census DA grid. Scales are represented in deciles.

Changes in multimodal spatial availability is important: A summary of spatial availability per Hamilton community and associated dimensions in 2021, along with the percentage change between 2011 and 2021, is presented in Table 2.

Table 2: Spatial availability and associated dimensions aggregated b in 2011 and how much they changed by 2021

	Hamilton C.	% Δ	Dundas	% Δ	Stoney Creek	% Δ	Glanbrook	%
LIM-AT	23.8516970	13.2%	11.2879110	10.6%	10.8019420	9.1%	8.3083330	-2.5
Kid pop.	35310.59600	-3.2%	2590.000000	-14.7%	7514.75100	20.0%	2639.65300	108.
OTGC	39889.08200	-9.8%	2377.03800	0.0%	9010.19600	-7.6%	1313.52200	127.
						Motorized		
V (mt)	42527.75000	-11.6%	1952.259000	-22.5%	6328.010000	9.9%	1531.308000	114.
v (mt)	1.2393060	-8.9%	0.7590198	-9.0%	0.8369173	-7.1%	0.5823797	3.1
						Non-motorized		
V (nmt)	631.881725	-11.0%	28.7632500	-7.1%	65.1592800	-39.5%	2.3855420	1274
v (nmt)	0.7054674	-13.0%	1.5790158	-16.6%	0.8967578	-25.3%	1.6565846	-24.

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 2). The majority of schools were closed in Hamilton Central as seen in the largest reduction in OTGC by percentage and magnitude. Hamilton Central represents 55% of the 5-14 year old population in 2021. Though the population decreased a modest amount from 2011 to 2021, the rate of school-seat spatial availability decreased disproportionately more (population by -3.2% and spatial availability by -11.6% for both modes). Schools and additional OTGC was not sufficiently expanded to provide the same levels of spatial availability as in 2011. This disproportionate decrease in spatial availability to students is greater in Hamilton Central by magnitude than any other community.

From the perspective of equity, Hamilton Central has the highest LIM-AT prevalence, with 27% of households LIM-AT in 2016, more than 3 times greater than Ancaster, Flamborough and Glanbrook, communities with the lowest level of LIM-AT prevalence. Is the disproportionate decrease in spatial availability within Hamilton Central fair? In some ways it is: communities with the lowest LIM-AT prevalence appear to benefit from gains in motorized spatial availability. Glanbrook, Flamborough and Ancaster together account for 27% of the 5-14 year old population in 2021. However, they access 19% of the spatial availability of school seats. Hamilton Central currently captures 66% of the spatial availability for it's 55.0% of the population. With student aged population growing in other communities, OTGC should be expanded - potentially to levels that Hamilton had in 2011 or beyond (1.2 school-seats per motorized mode using student and 0.7 school-seats per active mode using student). However, should those gains come at a loss to other communities, especially those with a significantly higher proportion of households who are lower-income, a strong determinant of transport poverty?

Furthermore, while there are gains in motorized spatial availability in certain communities by some metrics, there are losses in non-motorized spatial availability per student from 2011 to 2021 in all communities. And the losses are drastic. Communities with high community averag spatial availability per students with values above 1 school-seat per student saw losses, as well as communities below this value.

Discussion and conclusion

In this paper, we compared how multimodal spatial availability changed after a wave of school closures and consolidations in Hamilton. To do so, we constructed the student-aged population, OTGC of schools and their locations, and their travel behaviour to generate spatial availability landscapes for the three study years. We aggregated the resulting values at the DA and community level and descriptively compared differences. We demonstrated that city-wide there are decreases in V_i for both mode-using populations: the majority of students in the city have access to fewer school-seats than they would have in 2011. Furthermore, as the majority of closed schools are within the core of the city: the more urban Hamilton Central and urban-areas of other communities saw the largest amount of this decrease. And at a local-scale, students in residences proximate to schools that closed also saw dramatic reduce in non-motorized spatial availability values.

Evidently, the number of OTGC in the city decreased between 2011 and 2021, so some sort of decrease was to be expected. However, should that decrease be felt hardest within neighbourhoods with the highest LIM-AT? By students who have the potential to travel actively to school? Normatively, our cities should be increasing spatial availability for non-motorized mode users given the benefits of active travel and the climate crisis. Hamilton's policies from 2011 through 2021 drastically reduced non-motorized spatial availability, and gains in motorized spatial availability especially in more rural areas. The proportion of non-motorized mode use is low in both 2011 and 2021, however, the closure of schools that are more proximate to student-population density eliminates the potential of those trips ever becoming active.

Overall, the closure of 10% of elementary schools in Hamilton between 2011 and 2021 resulted in 5% decline in school-seat availability city-wide (5% fewer school-seats), but specifically a 90% 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. The decision to consolidate schools, likely has increased the length of motorized travel, though this would need to be further investigated. A decrease in non-motorized trips 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 Lubienski 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 multimodal spatial availability.

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 that impact fulsome school accessibility like quality (Bittencourt and Giannotti 2023). 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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Availability of data and materials The manuscript text, code, analysis and data supporting this work is available in the lead author's GitHub repository : https://github.com/soukhova/School-closures-accessibility-impacts

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