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Transportation Research Procedia 82 (2025) 2030–2045

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2023 Montreal 17-21 July 2023

Identifying the Influence of Dangerous Intersections in Measuring Accessibility for Children's Independent Mobility, A Case Study in Montreal, Canada

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Abstract

Background: In transportation planning, children are marginalized and often neglected, as the focus is primarily on adult needs and abilities. The daily travel destinations of children are also different from those of adults. Walking speeds and abilities limit the distances that children can travel. Additionally, fear of traffic danger can also prevent children from traveling independently. Intersections are junctions that allow children to change direction but are also locations where conflict between road users can be frequent, which can limit children's travel. As such, their impact on children's independent travel is important.
Objective: The objective of this study is to understand to what extent children's independent travel accessibility could be limited by the level of traffic danger at intersections.
Methodology: Using open data, the methodology for this study has two key steps. First, "dangerous" intersections for children (aged 8 to 12) were identified in a specific area of the city of Montreal based on three major traffic danger components available in open datasets: speed limit, road class and design, and traffic control. Weights were given to each of these components based on experts' prioritization. The second step involved the calculation of children's accessibility on foot (measured as the number of destinations within a specific distance) with and without dangerous intersections considered as barriers.
Results: Among all intersections in the selected neighborhoods, 1673 dangerous intersections were identified. Accessibility without considering traffic danger ranges between 1 to 45 destinations. When considering traffic danger, accessibility drops to between 0 and 19. This reflects a 20% decrease in children's walking service areas.
Conclusion: Our results demonstrate that children's accessibility is different when traffic danger is taken into account, which could be a major deterrent to choosing to walk to destinations, either by the children themselves or with their parents.

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Peer-review under responsibility of the scientific committee of the 16th World Conference on Transport Research
10.1016/j.trpro.2024.12.170

Keywords: Children's independent mobility, Traffic danger; Intersection; Accessibility

1. Introduction

The right to travel safely is a fundamental right for children as they travel to school, play with friends, or engage in other activities (Amiour et al., 2022). Children have been encouraged to become more physically active by using active modes of transportation (walking, cycling) to school in recent years (Pabayo et al., 2012; Rothman et al., 2021). Transport, especially active modes, facilitates children's access to a variety of destinations, including sports, leisure, and education (Giles-Corti et al., 2013; Pollard & Lee, 2003; Waygood, 2020). However, children's independent mobility (CIM), defined as having a trip without an adult supervision, is neglected within the transport planning decision-making process, which focuses mainly on (working) adults' capacities and needs.

Children's travel needs differ from those of adults, which can result in negative outcomes for them. For example, children are shorter than adults and therefore less visible by drivers, especially where on-street parking is permitted (Ewing & Dumbaugh, 2009; Waygood, 2020). Children also have different daily destinations compared to adults: they mainly go to schools, to parks, to their friend's place and their travel is often more locally-based. Fear of traffic danger can also limit children's independent mobility since some streets are so dangerous that children should not cross them or are not permitted to cross (by their parents) (Mitra, 2013; Waygood et al., 2017; Waygood et al., 2019). In addition to this fear, real risk of crashes involving pedestrian children exists, especially at intersections with high traffic volumes (Morency et al., 2015), what may also discourage them from traveling independently. It has been shown that traffic danger is one of the most significant barriers to children's independent travel (Mitra, 2013). As such, the objective of this study is to understand how the level of traffic danger at intersections can limit children's active and independent accessibility to destinations within a city.

2. Literature Review

When considering children's accessibility, there are two key components: child-relevant destinations within a reasonable walking distance and traffic danger. Traffic danger can limit children's travel as parents and children may judge intersections too dangerous to use. As such, this section will begin with traffic danger and then discuss accessibility.

2.1. Sources of traffic danger at intersections

Traffic danger is one critical direct negative effect of transportation on human health (Widener et al., 2016) and it is a major source of injury and death for children (Rothman et al., 2019). Since children are small and have fully developed, they are more vulnerable to motor vehicle collisions and more likely to suffer severe injuries or death (Rothman et al., 2021). According to a prior study, around 66% of children's crashes and injuries happened at intersections (Miranda-Moreno et al., 2011). Therefore, a crucial consideration is whether the infrastructure is safe enough. Analyzing the level of safety for each intersection could shed light on the comfort, quality and safety of children's walking. There has been considerable research regarding the relationship between the built environment, including intersections, with collision risks among children (Aliyas, 2022; Amiour et al., 2022; Cloutier et al., 2007; Rothman et al., 2021). Several aspects of road design and infrastructure have been studied in the past, including, among others, speed limit, road class, walking infrastructure, road and intersection characteristics, and traffic control. We will briefly discuss each below:

- Speed limit

High vehicle speeds pose a significant risk to pedestrian safety because they increase the likelihood of children being injured or killed (Rothman et al., 2019). Among school-aged children, high speed limits increase their risk of injury, and have also been found to increase the likelihood of injury and death among middle and high school children (Abdel-Aty et al., 2007). Speed also influences the distance travelled before a vehicle stops.

- Road class and design

Several studies have shown that children are more often injured on main roads, including arterials and collectors (Hwang et al., 2017; Rothman et al., 2017; Rothman et al., 2015), compared to local roads, which were associated with a reduced likelihood of collisions (Hwang et al., 2017; Yu, 2015). According to a case-control study in Oakland, USA, children aged 5-15 injured in motor vehicle collisions are affected by the type of street they cross on their way to school (Tester et al., 2004). Additionally, collector roads were associated with more motor vehicle collisions involving children pedestrians than local roads (Rothman et al., 2014). Local roads further decreased the likelihood of collisions (Hwang et al., 2017). Typically, road class relates to different street designs as they are intended to move different volumes of vehicles at different speeds. Previous studies have found that the design of a street is associated with youth injury rates (Mecredy et al., 2012). Finally, children are 2.5 times more likely to be injured on two-way streets than on one-way streets (Wazana et al., 2000).

- Traffic control

The density and presence of traffic lights (versus their absence) were associated with child collisions (Rothman et al., 2014). This may be due to several factors, including the fact that traffic lights are located at busy intersections to separate road users in time and space. However, traffic lights also facilitate high-speed crossing and many vehicles will try to “beat the red”, meaning that they accelerate through when the light is turning, creating greater danger for those waiting to cross. Similarly, child pedestrian crashes were associated with a lack of stop signs in other studies (Bennet et al., 2015; Blazquez et al., 2013). Stop signs in contrast require vehicles to come to a stop (even if they do not come completely to a stop), meaning that speeds are reduced to nearly 0 for all vehicles when they start to enter the intersection.

2.2. Accessibility and relevant indicators related to children's independent mobility

In the context of land use and transport planning, accessibility refers to the ease with which individuals can access multiple opportunities or valued destinations within a territory (Levinson et al., 2020). In measuring accessibility, location-based metrics measure the ease of reaching destinations from a point of origin. Such measures consider the ease of moving from one place to another (the transport component) and the spatial distribution of opportunities (the land use component) (Geurs & Van Wee, 2004). A common location-based metric is based on cumulative opportunities. This measure counts the number opportunities (i.e., destinations) that can be reached within specific thresholds (time, cost, or distance) (Boisjoly & El-Geneidy, 2017). Another location-based metric is the gravity-based measure that discounts opportunities according to their travel distance or time. This means that opportunities located farther away are given less weight than those located closer (Boisjoly & El-Geneidy, 2017). While gravity-based are more theoretically sound, they present challenges in terms of operationalization and interpretation. As a result, cumulative-opportunity measures have been shown to be much more applicable in practice (Boisjoly & El-Geneidy, 2017).

In the context of children's independent mobility (CIM), the land use and transport components considered in the accessibility measures require careful consideration. Common accessibility indicators consider all transport segments that are available to pedestrians. However, as detailed above, not all intersections can be considered viable for children. Knowing that traffic danger is a key determinant of CIM, the transport component should consider if the transportation infrastructure is safe enough for children to use (Rothman et al., 2020). Further, it is important to identify if child-relevant destinations are available, and if they are within appropriate distances or travel time (Bell, 2009; Boisjoly & El-Geneidy, 2017). In addition to the issue of traffic danger explained above, appropriate destinations and reasonable travel distances must be determined.

- Children's destinations

Identifying children's destinations is another key component of children's accessibility. Travel destinations for children differ from those for adults due to their different needs and desires (Desjardins et al., 2022). Previous research has identified numerous important destinations for children beyond just schools and parks. Destinations can fall into different activity categories such as education, food, retail, health, public transport, recreation, social, and cultural (Babb et al., 2017; Fyhri et al., 2011; Oliver et al., 2007). A recent systematic review identified the following destination types important to children: park, recreational facilities, sporting field, public open spaces, library and community centers, friends and relative houses, and restaurants (Desjardins et al., 2022). Similarly, the most common destinations among different studies are schools, retail shops, sport facilities, other recreational destinations, parks, and public transport (Badland et al., 2015; Fyhri et al., 2011).

- Reasonable distance for children to travel

In discussing the relationship between CIM and accessibility, the ability to move from one place to another needs to consider the distance children can travel (walk) without adult supervision (Hillman et al., 1990). Some research has found that children between the ages of 10- and 12-years old walk on average between 610 and 630 meters (Marten et al., 2004; Timperio et al., 2006). However, other research has proposed that a reasonable distance would relate to the 80 % threshold for all walking trips by children at different ages (Morency et al., 2011; Waygood & Susilo, 2015). Those studies propose distances closer to 1 km for children aged 10. These thresholds may be influenced by social and environmental barriers (such as a highway, busy segments or intersections, and personal safety), thus affecting their ability to reach destinations independently (Oliver et al., 2007; Villanueva et al., 2013). It is with that in mind that we aim to identify dangerous intersections and examine their potential influence on CIM.

Based on research on children's independent mobility, traffic danger is a key barrier to accessing destinations. However, there is no clear definition of what traffic danger is. Simply using crash history would not identify intersections that are so dangerous that pedestrians, especially children, do not use them. Crashes are merely the tip of the of the traffic danger "iceberg", meaning that many near misses exist for each crash, and various factors exist that influence the likelihood of these potential crashes. However, current accessibility measures do not take that barrier into account. The above synthesis of the literature shows that a real gap exists in understanding how traffic danger limits children's accessibility.

3. Objective

This study aims to first estimate traffic danger at intersections so that its impact on children's independent accessibility to destinations can be estimated.

4. Methodology

This study has several methodological components: 1) a survey to judge the influence of different available factors on traffic danger; 2) developing a scale of traffic danger; 3) applying those results to determine which intersections should be considered barriers; 4) determining accessibility to child-relevant destinations. In order for this approach to be applied in other cities, we use only open-access data. We start with a description of the study area and the available data.

4.1. Data and study area

The data for this study were all from Open Data Montreal, an open access portal managed by the city of Montreal (OpenDataMontreal, 2022). Intersection point data were extracted from Open Data Montreal. Following a prior study, traffic danger data was joined with the intersections using a 15 m buffer around intersection points (Miranda-Moreno et al., 2011).

The traffic danger variables are based on data availability and follow the themes highlighted in our literature review (Table 1): speed limit (from "less than 30 km/h" to "more than 70 km/h"), road class and design (classification from "local" to "main arterial" and directions: one-way or not), and traffic control (traffic signals or stop signs).

Table.1 The traffic danger components and their measurement

Components	Indicators	Category
Speed limit	Posted speed limit	Less than 30 Km/h
		30 Km/h
		40 km/h
		50 km/h
		60 km/h
		70 km/h
		More than 70 km/h
Road class and design	Road classification	Main arterial road
		Secondary arterial road
		Collector
		Local road
		Back lane
		Pedestrian street
	Direction	The street is one-way

Traffic control	Stop signs	The presence of stop signs
	Traffic signals	The presence of traffic signal for vehicles and pedestrians
		The presence of traffic signals only for vehicles

The accessibility variables (destinations and network) are from Open Street Map and Open Data Montreal respectively. For measuring the accessibility in the census block level, these variables were extracted based on data from Statistics Canada (StatisticsCanada, 2022).

The initial study area was the road network of the city of Montreal, but due to missing data on some parts of the territory, our analysis was completed for 13 boroughs (Figure 1).

Fig.1. Selected neighborhood in the city of Montreal

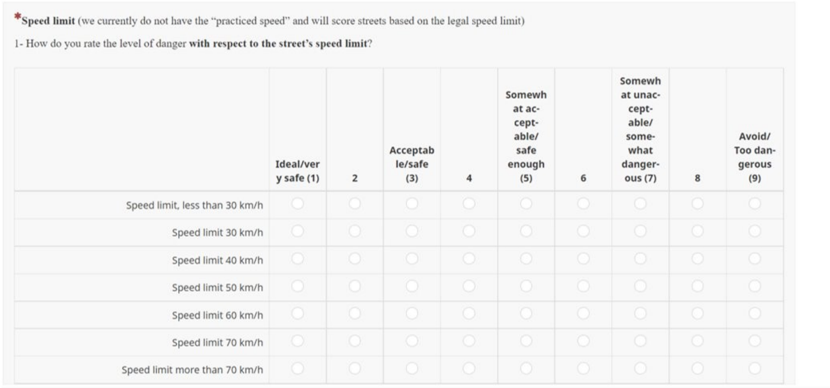
4.2. Estimating the level of traffic danger at intersections

To estimate the level of traffic danger at intersections, we characterize the danger level of each intersection based on relevant variables available in the open-data (see above). A survey was conducted with experts (see below) to determine the level of danger for each variable and their relative influence. Then, to combine these influences, the Al Shammas method of assigning weights to variables (Al Shammas et al., 2019) was used.

Data collection: Experts' survey

The survey created for this project included 9 questions within three sections. The opinions of 14 experts on children's travel and traffic safety related to the project were sought in October, 2022. The experts self-identified as being from traffic safety, children's travel, urban design, travel behavior, children's rights, and psychology.

In the first section, each category of each indicator of traffic danger were rated individually using a 9-point Likert scale from "ideal / very safe" (score of 1) to "avoid / too dangerous" (score of 9). Figure 2 shows an example for the categories of the posted speed limit indicator.

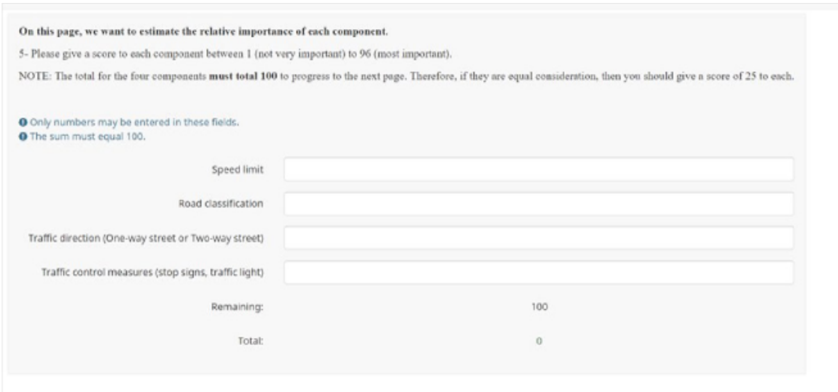

*Speed limit (we currently do not have the "practiced speed" and will score streets based on the legal speed limit)

1- How do you rate the level of danger **with respect to the street's speed limit**?

	Ideal/very safe (1)	2	Acceptable/safe (3)	4	Somewhat acceptable/safe enough (5)	6	Somewhat unacceptable/somewhat dangerous (7)	8	Avoid/Too dangerous (9)
Speed limit, less than 30 km/h									
Speed limit 30 km/h									
Speed limit 40 km/h									
Speed limit 50 km/h									
Speed limit 60 km/h									
Speed limit 70 km/h									
Speed limit more than 70 km/h									

Fig. 2. Example of a question (speed) to estimate the level of danger of each category individually

In the second part, respondents were asked to estimate the relative importance of each traffic danger component compared to others. Each participant had a total of 100 points that they could distribute over the components. The survey software would not accept responses where the total was different from 100. To help respondents, they could see the remaining points available for distribution and the total (Figure 3).


On this page, we want to estimate the relative importance of each component.

5- Please give a score to each component between 1 (not very important) to 96 (most important).

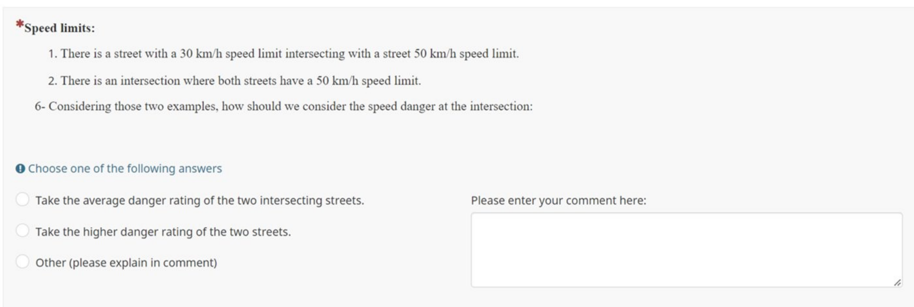
NOTE: The total for the four components **must total 100** to progress to the next page. Therefore, if they are equal consideration, then you should give a score of 25 to each.

Only numbers may be entered in these fields.
The sum must equal 100.

Speed limit
Road classification
Traffic direction (One-way street or Two-way street)
Traffic control measures (stop signs, traffic light)
Remaining: 100
Total: 0

Fig.3. Question to estimate the relative importance of each traffic danger component

In the third section, participants were asked to choose between different methods of assigning danger to an intersection based on the street segments found at the intersection. For instance, if there are two streets with speed limits of 30 km/h and 50 km/h respectively, how do we determine the overall traffic danger value for the intersection, between the average or the maximum level of danger.


***Speed limits:**

1. There is a street with a 30 km/h speed limit intersecting with a street 50 km/h speed limit.
2. There is an intersection where both streets have a 50 km/h speed limit.

6- Considering those two examples, how should we consider the speed danger at the intersection:

Choose one of the following answers

- Take the average danger rating of the two intersecting streets.
- Take the higher danger rating of the two streets.
- Other (please explain in comment)

Please enter your comment here:

Fig.4. Question the method to use considering street segments at intersections

4.3. Calculation of traffic danger at intersections

We calculated the traffic danger score for each intersection by using the weighted sum method in ArcGIS Pro. The formula is as follow, including the value (frequency) R_n of each component (which was between 1 and 9) and the weight w_n of each indicator (which was between 0 and 100) based on the average of all the experts:

*Traffic danger score = ((speed limit) w_n * (R_n speed limit categories))+ ((road classification) w_n w_n * (R_n road class) + ((traffic calming measure w_n * ((R_n presence of stop sign)+(R_n presence of traffic signal))) + ((street direction) w_n * (R_n One way or Two way))* (1)

The final value of each intersection was calculated by joining the intersection (points) to the weighted-sum raster.

4.4. Measuring accessibility

To measure children's accessibility, we used the cumulative accessibility measure, which counts the number destinations that can be accessed within a specific threshold (Geurs & Van Wee, 2004). As mentioned above, the cumulative-opportunity measure is commonly used to quantify accessibility across a region via active or motorized modes, given its ease of operationalization and interpretation (Boisjoly & El-Geneidy, 2017). This is especially called for in this study, given the lack of detailed travel behavior information, which does not allow us to calculate the distance-decay function.

The measure was calculated using the centroid of each census block and based on the maximum reasonable distance that children can travel independently. Based on previous research, a 1 km threshold was selected for this study. A previous study from Quebec City, Canada found that it would seem reasonable to consider trips over 1 km (Euclidean distance) as an independent trip, as this study showed that after 1 km, the likelihood that the trip was independent drastically dropped (Cervesato & Waygood, 2019).

The destinations included in the accessibility measures are based on the finding from a systematic review (Desjardins et al., 2022) and on data availability. The data for these destinations was obtained from the Open Street Map and based on the availability of the data; the destinations, which are used for this study, are the following: libraries, community centers, supermarkets, cinemas, fast food restaurants, playgrounds, and pharmacies.

To observe to what extent children's accessibility is restricted when considering dangerous intersections as a barrier, we generated two measures of accessibility: one that includes all intersections, and one that excludes all intersections that are considered dangerous. For each accessibility measure, the number of destinations that can be reached within the service area of 1 km of the centroid of each census block was calculated based on the network distance. The network used for this analysis is Open Data Montreal that was applied in ArcGIS. For this analysis, we removed highways from the network, as they are only accessible by motor vehicles. The analysis is done using ArcMap (10.8.2), ArcGIS Pro (10.8.2), and QGIS (3.24).

The network includes all streets, with the exception of highways, and all pedestrian links. First, a service area is generated to identify the area that is accessible within a 1 km network distance. In the second case, the service area is restricting by identifying the dangerous intersections as barriers. The number of accessible destinations was then calculated by intersecting the service area with the destination points, and the number of destinations within each service areas was summed up.

5. Results

5.1. Traffic danger indicator

The first part of the survey indicated that for posted speed limits, the level of danger given by participants increases sharply above 40 km/h. Arterial roads received the top dangerous score for road class. Collector roads were also identified as dangerous roads. This is likely due to the fact that collector roads transfer traffic from local streets to arterial roads and have a higher traffic volume than local streets. In contrast, pedestrian streets, back lanes, and local roads were judged to be safer. For street direction, the survey results are unclear with both one-way and two-way judged to have similar levels of danger. Finally, traffic signals were judged to be safer than stop signs, except when there is no pedestrian signal.

It is extremely important to note that the purpose of this survey was not to establish a perfect estimation of traffic danger at intersections, but to facilitate a simple estimation as a "proof on concept" to demonstrate how children's accessibility is likely significantly reduced by traffic danger. Future research will apply more advanced decision-making processes such as multi-criteria decision aiding to better estimate traffic danger.

Each component was scored in the survey from 1 to 9 on their level of danger, where 1 was ideal/very safe and 9 was avoid/too dangerous. As discussed in Calculation of traffic danger at intersections, the frequency of each value is considered as the final value for each category. The value of each category based on survey results is shown in Table 3.

Table. 2. Traffic danger score for indicators

Indicators	Category	Value	Frequency of each value
Speed limit	Less than 30 Km/h	1	12
	30 Km/h	2	8
	40 km/h	3	5
	50 km/h	7	7
	60 km/h	7	5
	70 km/h	9	9
	More than 70 km/h	9	13
Road classification	Main arterial road	9	8
	Secondary arterial road	7	5
	Collector	5	5
	Local road	3	6
	Back lane	2	6
	Pedestrian street	1	9
Direction (One-way or Two-way streets)	The street is one-way	3	5
	The street is two-way	3	4
Stop signs	The presence of stop signs	5	5
Traffic lights	The presence of traffic light	3	6
	The presence of traffic light without pedestrian light	7	6

The second section of the survey showed that the speed limit is the most important component, with an importance of 20 to 74 out of 100. It was followed by traffic control with importance values between 10 and 40. For road class and design, the value was between 7 and 40 and the value for traffic direction was between 5 and 25. Taking the average value for each, the speed limit value is 43, followed by traffic control at 22 and then road class and design at 21. Finally, for traffic direction the average was 14.

For intersections, the experts were asked whether the danger level should be the average of the road segments adjoining it, or the highest value. The results found that for 10 out of 13 respondents, the highest value was deemed the most appropriate. This is probably related to the fact that in terms of CIM, the most dangerous situation for measuring the traffic danger is more significant than the average.

The intersection danger scores range from 0 to 864 using the Weighted Overlay function. These were classified into nine classes using the natural break method. In this process, ArcGIS identifies break points based on how similar values are grouped and the differences between groups are maximized. Following discussion, class 1 and 2 were defined as ideal and very safe and classes 8 and 9 were defined as barriers for children's travel when estimating their accessibility. Figure 5 shows the nine classes of intersection danger score and Figure 6 presents their spatial distribution in the selected boroughs of Montreal.

0	40	Ideal/very safe
40	150	2
150	240	Acceptable/safe
240	305	4
305	390	Somewhat acceptable/ safe enough
390	475	6
475	556	Somewhat unacceptable/ somewhat dangerous
556	650	8
650	864	Avoid/ Too dangerous

Fig.5. Overall traffic danger score by Class

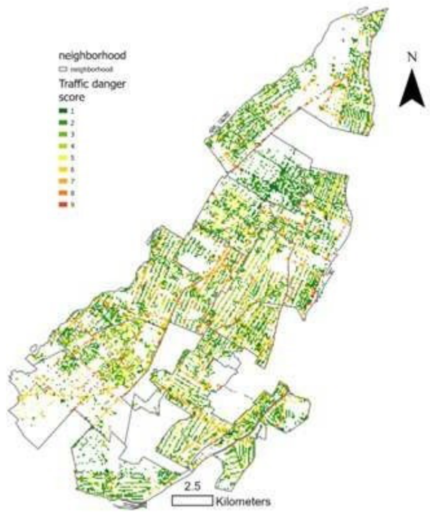


Fig. 6 spatial distribution in the selected boroughs of Montreal

5.2. Children's accessibility

- One-km walking distance service area

The average percentage change in accessible destinations by borough is shown in Figure 7. This figure highlights the boroughs where dangerous intersections likely significantly restrict children's independent movement. To help explain the change, a visualization of the available network (based on a 1-km reasonable walking distance) is shown in Figure 8 when traffic danger is not considered (left) and when intersections with a danger rating of 8 or 9 are considered barriers (right). In the first scenario (without the barrier), the road length within the service area is 29 kilometers, while in the second scenario, it is reduced to 19 kilometers, a 32% reduction. This example demonstrates how dangerous intersections can significantly reduce the accessible area available to children. Overall, the reduction in the number of kilometers of roads within these service areas varied between 4 to 45 km^2 for the 10,012 census blocks analyzed.

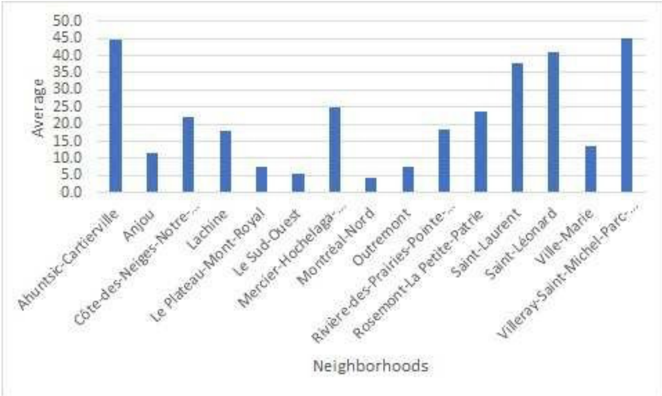
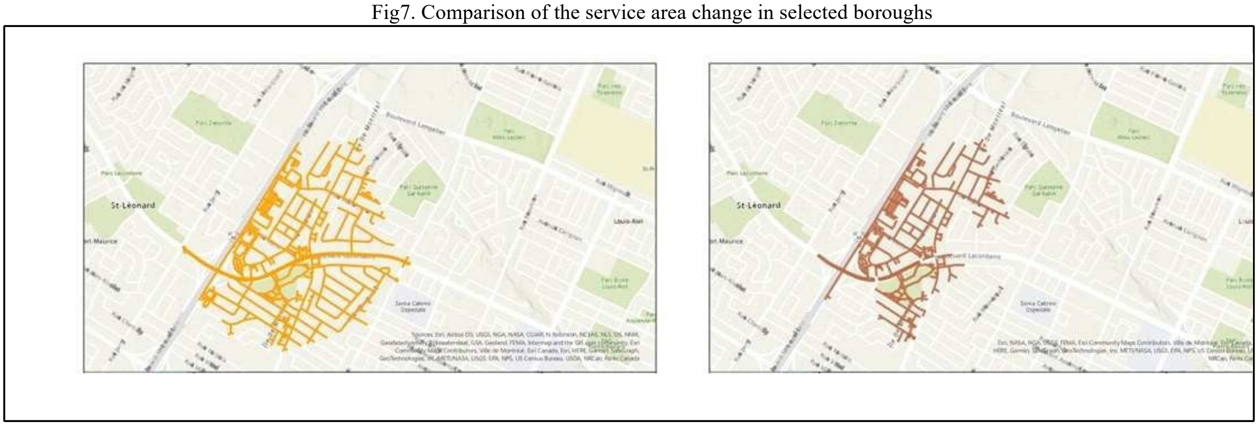


Fig7. Comparison of the service area change in selected boroughs



Without barrier with barrier

Fig.8. Comparison of one accessible service area with and without dangerous intersections as a barrier.

- Accessibility to child-relevant destinations

The number of different destinations accessible from each census block are shown in Figure .9 when no barriers are taken into account and in Figure 10 for the calculation including dangerous intersections as barriers. In the first case, the total number of destination ranges from 0 to 46 within each of the 1-km walking distance service area previously calculated. Most census blocks located in the central area (downtown) have access to more than 10 different destinations. However, 38% of census blocks only have access to one destination or less within 1,000 metres on foot. In most cases, these low-access blocks are located outside central areas, where land-use is less mixed and less dense. When adding dangerous intersections as barriers to children's accessibility (Fig. 10), results vary: the maximum number of destinations decrease from 45 to 19, and 38.9% of census blocks only have access to one destination or less.

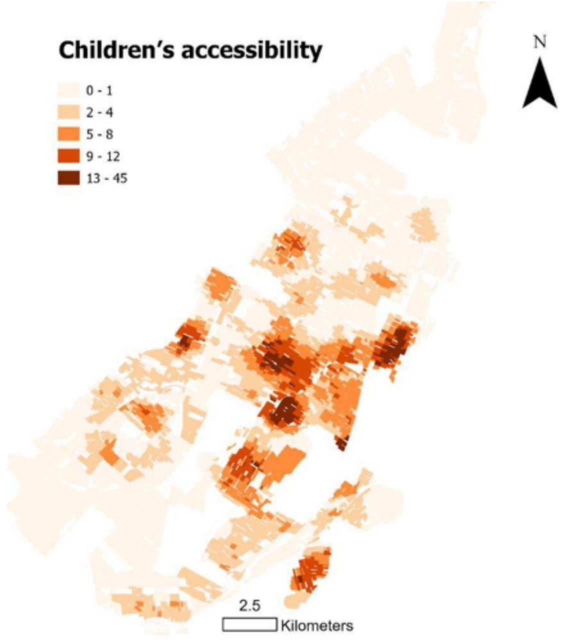


Fig.9. Accessible destination for children regardless of hazardous intersections

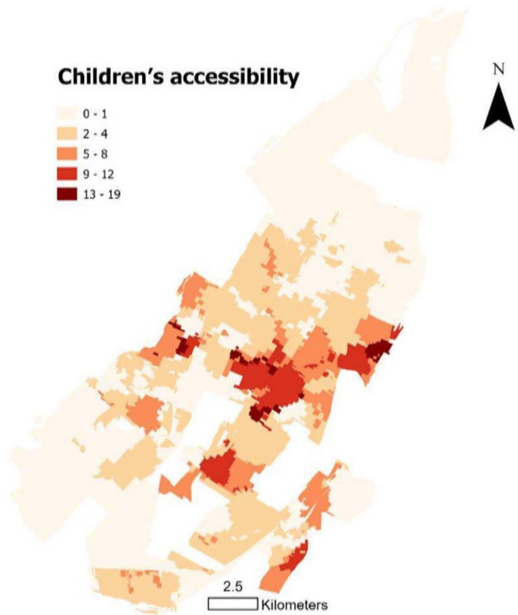


Fig.10. Accessible destinations for children with respect to intersection danger score

To understand the influence of dangerous intersections on the calculated accessibility, Fig. 11 shows the change in accessibility, which is the difference of accessibility with and without the traffic danger barrier. According to Fig.12 the difference in destinations between the two calculations is large, ranging from no reduction in the number of destination (21% of census blocks) to a reduction between 21 and 41 destinations (1.2% of census blocks). Census blocks with the highest reduction are scattered throughout the city, with peaks in more dense areas such as Ville-Marie.

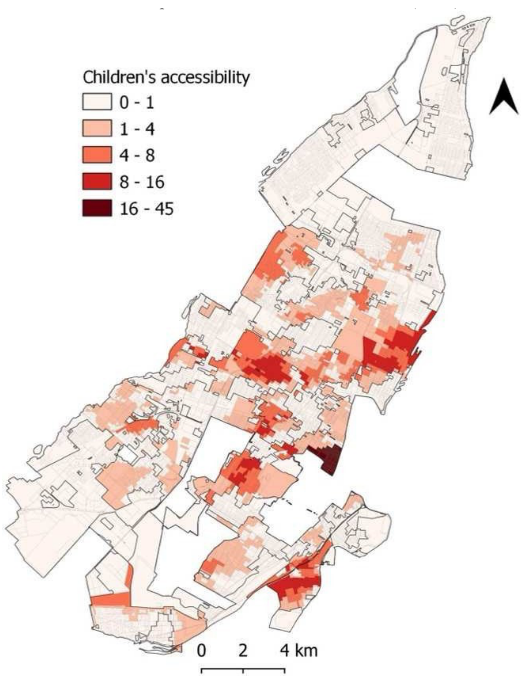


Fig. 11 The difference in the accessibility between all intersections and intersections as barrier

6. Discussion

Previous research has found that after distance, traffic danger concerns are a major reason by parents restrict their children's independent travel. This research demonstrated that when traffic danger is taken into consideration, children's estimated accessibility is considerably reduced. It geographically identified intersections and it highlighted which boroughs are most impacted by this problem. Such information can be used by policy makers to better understand how the promotion of vehicular movement can create barriers to others such as children and elderly. By spatially identifying the most dangerous intersections, practitioners can direct interventions depending on other input (such as the number of children in those boroughs or wanting to make certain boroughs safer).

This research used expert input to develop a tool to estimate traffic danger at intersections. Previous research has focused on fatalities, severe injuries, or collisions and associations with different road layouts and built environment characteristics. However, such an approach has limitations. First, such counts are merely the "tip of the iceberg" when it comes to traffic danger. For every fatality, there are many more collisions. For every collision, there are many more near-misses. Intersections that are extremely dangerous likely result in pedestrians avoiding them or children not being allowed to use them. Thus, pedestrian-motor-vehicle collisions might be missing in such an instance, yet the traffic danger is such that it is a barrier. However, further work can be done to examine whether the intersections deemed too dangerous are judged as such by parents (who give permission for children to travel) and by other experts who did not participate in the initial survey. Perhaps a different threshold is required, perhaps further refinement of the tool is required.

The experts who participated identified speed as the most important factor for traffic danger. This is in agreement with a previous review on objective and perceived traffic danger (Amiour et al., 2022). Speed can impact danger in a number of ways such as the likelihood of death or severe injury (non-linear increase after roughly 30 km/h), stopping distance, and even where a driver focuses their attention becomes more narrow at higher speeds (Huguenin-Richard, 2010). Several previous studies have found that a car's ability to stop and avoid a collision is drastically reduced when it travels at higher speeds: 13 meters is typically required to stop at 50 km/h, whereas only 8.5 meters are required at 40 km/h (Cloutier et al., 2021). When the speed is doubled, the stopping distance increases roughly 3-fold. In addition, a child pedestrian is three times more likely to be injured if posted speeds exceed 45 km/h (Wazana et al., 2000), recalling the importance to take this variable into account when considering traffic danger and children's independent mobility.

As for the road design direction variable, previous studies found a larger percentage of one-way roads near the schools was associated with a higher number of child pedestrian-motor vehicle collisions (Rothman et al., 2017), so further discussion related to such findings might be necessary. Similarly, our result on traffic control needs further discussion to understand if the level of trust that people have that drivers will come to a stop and remain at a stop with traffic lights might be higher. This could be debated as vehicles are legally required to stop at a stop sign but can go through traffic lights at speed (i.e, on a green). Drivers may do rolling stops at stop signs, but at least the speeds would be much lower than if a driver has a green or is trying to "beat the red" (where drivers often accelerate and may drive through on the red).

Having a greater number of destinations can increase children's independence (Riazi & Faulkner, 2018). Our research not only highlighted how traffic danger can reduce the area within which they can travel, but also how that relates to the number of destinations they can reach. This allows policy makers and practitioners to know which neighborhoods might require not only interventions to address traffic danger, but also which areas have few potential destinations for children. As children's independent mobility is linked to various health and well-being benefits for children(Waygood et al., 2017), these tools can help cities improve children's lives.

7. Limitations and future study direction

Using the open data source results in some limitations in the developed methodology. First there are limitations in the available data such as traffic volume, the street width and the number of lanes, which are other relevant factors contributing to traffic danger. As well, not all boroughs have the same available data, thus forcing decisions as to whether exclude some boroughs or limit the inputs to the model.

A threshold of 1,000 meters was chosen for walking distance to illustrate the method's feasibility. Based on the developed methodology, other thresholds and modes of travel could be investigated in future studies. These thresholds could be varied based on different children's ages or different cultural considerations.

This research used expert opinion from participants related to the project. Although these participants represent various fields of study (engineering, geography, psychology, urbanism), participants who are not directly connected to the project might have different perspectives. The participants also represented individuals from multiple continents, but were primarily academics. Future research should seek the input of practitioners as well. As well, parents are important stakeholders and it will be important to know what they feel are the appropriate thresholds to use as barriers. Finally, the voices and input of children need to be sought as their perspectives are not necessarily the same as adults' for various reasons including differences in heights and experience with traffic.

As well, the technique to determine the influence of the different factors could likely be improved upon. There are interaction effects between factors such as speed and traffic volume. Techniques exist such as multi-criteria decision aiding (Donais et al., 2019) that could be applied to better understand the influence of the different factors and how they relate to each other.

8. Conclusion

This paper examined to what extent children's independent accessibility could be limited by considering the level of traffic danger at intersections. A survey was conducted to score and weight different components included in a traffic danger score. Children's accessibility to relevant destinations was estimated both with and without dangerous intersections as barriers. Service areas were considerably reduced when the barrier effect of dangerous intersections was applied. This resulted in a much-reduced estimation of accessibility for children.

This study has several key contributions: 1) it made a first step at estimating intersection danger for children's active and independent travel; 2) it calculated the range (or service area) for children both with and without the barrier effect; 3) it calculated children's accessibility to child-relevant destinations; 4) it demonstrated how and where children's accessibility is significantly impacted by traffic danger.

Future research should aim to improve the available data to get a more accurate estimation of danger, apply appropriate multi-criteria decision aiding techniques to improve the quality of the estimation, include a wider range of stakeholders, and finally consider different thresholds for the distances traveled by children.

Acknowledgements

This work was primarily funded by the Canadian Social Sciences and Humanities Research Council (SSHRC; 435-2020-1292). The Department of Civil, Geological, and Mining Engineering at Polytechnique Montréal and CIRODD (development and reference center in the operationalization of sustainable development) provided additional funding to support the researchers. The authors would also like to thank all voluntary experts who participated in the survey.

Authors contributions

The authors confirm contribution to the paper as follows: paper concept: Abdollahi, Tavakoli, Waygood, Cloutier, Boisjoly; survey conception and design: Abdollahi, Tavakoli, Waygood; data manipulation: Abdollahi, Tavakoli; analysis: Abdollahi, Tavakoli, Waygood, Cloutier, Boisjoly; interpretation of results: Abdollahi, Tavakoli, Waygood, Cloutier, Boisjoly; draft manuscript preparation: Abdollahi, Tavakoli, Waygood, Cloutier, Boisjoly. All authors reviewed the results and approved the final version of the manuscript.

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