Modifiable Areal Unit Problem and Modifiable Temporal Unit Problem effects on accessibility to supermarkets in Montreal, Canada

A thesis submitted to McGill in partial fulfillment of the requirements of a degree of a

Master of Sciences in Geography

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June 2023

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Abstract

Accessibility is the ease of reaching a location within a given time or distance by a specific mode of transport, such as walking, cycling, public transport, or cars. Every accessibility measure uses a specific spatial scale, such as traffic analysis zones (TAZ), census tracts (CTs), dissemination areas (DAs), or dissemination blocks (DB); various zoning schemes, such as hexagons or squares. Also a specific temporal resolution or granularity is chosen, such as measuring every minute, every five minutes, every 10 minutes, etc; a specific temporal segmentation, such as using peak-hour or off-peak hours; or a temporal boundary, which is how long the process is (e.g. a time threshold of 15 minutes or 30 minutes). However, many studies choose a temporal and spatial resolution or temporal segmentation arbitrarily or because it is the only one available. Most of the time, it is different from reality. The bias or error of using non-ideal spatial and temporal components is known as the Modifiable Areal Unit Problem and the Modifiable Temporal Unit Problem, respectively.

Despite the importance of these two problems, previous studies have only focused on understanding one problem or the other, and no studies consider both effects simultaneously. Understanding both effects has yet to be studied or structured in general literature and transport studies and has been named the Modifiable Spatio-Temporal Unit Problem (MTSUP). This research measured the misestimation levels of these problems on the accessibility of supermarkets in the city of Montreal, Canada. I compared accessibility at various spatial and temporal resolutions and temporal segmentations to the finest temporal and spatial unit of analysis at the ideal temporal segmentation: building lots every minute from 10:00 am to 11:00 am. The results indicated that the coarser the temporal and spatial resolution and a temporal segmentation that do not represent the hour in which most of the trips to supermarkets are made, the higher the misestimation (overestimation and underestimation). Likewise, differences were found between various socioeconomic groups. Studying this problem is essential in urban planning because if a specific temporal and spatial resolution has higher levels of accessibility, than the accessibility at the building lot level (overestimates accessibility), it indicates that the building lot does not need transportation and land use intervention.

Résumé

L'accessibilité est la facilité d'atteindre un lieu dans un délai ou une distance donnés par un mode de transport spécifique, comme la marche, le vélo, les transports en commun ou la voiture. Chaque mesure d'accessibilité utilise une échelle spatiale spécifique, comme les zones d'analyse du trafic (ZAT), les secteurs de recensement (CT), les aires de diffusion (AD) ou les îlots de diffusion (DB); divers schémas de zonage, tels que des hexagones ou des carrés. Une résolution ou une granularité temporelle spécifique est également choisie, telle que la mesure toutes les minutes, toutes les cinq minutes, toutes les 10 minutes, etc. une segmentation temporelle spécifique, telle que l'utilisation d'heures pleines ou d'heures creuses ; ou une limite temporelle, qui correspond à la durée du processus (par exemple, un seuil de temps de 15 minutes ou 30 minutes). Cependant, de nombreuses études choisissent une résolution temporelle et spatiale ou une segmentation temporelle arbitrairement ou parce qu'elle est la seule disponible. La plupart du temps, c'est différent de la réalité. Le biais ou l'erreur

d'utilisation de composants spatiaux et temporels non idéaux est connu sous le nom de problème d'unité surfacique modifiable et de problème d'unité temporelle modifiable, respectivement.

Malgré l'importance de ces deux problèmes, les études précédentes ne se sont concentrées que sur la compréhension d'un problème ou de l'autre, et aucune étude ne considère les deux effets simultanément. La compréhension des deux effets n'a pas encore été étudiée ou structurée dans la littérature générale et les études de transport et a été nommée problème d'unité spatio-temporelle modifiable (MTSUP). Cette recherche a mesuré les niveaux de mésestimation de ces problèmes sur l'accessibilité des supermarchés dans la ville de Montréal, Canada. J'ai comparé l'accessibilité à différentes résolutions spatiales et temporelles et segmentations temporelles à l'unité d'analyse temporelle et spatiale la plus fine à la segmentation temporelle idéale : construire des terrains toutes les minutes de 10h00 à 11h00. Les résultats indiquent que plus la résolution temporelle et spatiale est grossière et une segmentation temporelle qui ne représente pas l'heure à laquelle la plupart des déplacements vers les supermarchés sont effectués, plus la mauvaise estimation (surestimation et sous-estimation) est élevée. De même, des différences ont été trouvées entre divers groupes socio-économiques. L'étude de ce problème est essentielle en urbanisme car si une résolution temporelle et spatiale spécifique a des niveaux d'accessibilité plus élevés que l'accessibilité au niveau du terrain à bâtir (surestime l'accessibilité), cela indique que le terrain à bâtir n'a pas besoin d'intervention de transport et d'aménagement du territoire.

Acknowledgements

I would like to express my sincere appreciation to Prof. Kevin Manaugh for accepting me into the McGill Transportation Lab and for his invaluable kindness, guidance, expertise, and mentorship support during the last two years. I am especially grateful for our meaningful and productive discussions, which greatly enriched my understanding of all the topics related to transportation planning.

I would also like to thank Prof. Grant McKenzie for providing insightful comments and suggestions as a committee member, which have greatly contributed to the refinement of my thesis. I am grateful to Prof. Ahmed El-Geneidy, the external committee member, for providing valuable insights and perspectives that have enriched the depth of my research. Dr. Tim Elrick, thank you for providing me with access to the Geography R Studio Server. His assistance in resolving technical issues has been valuable.

I want to express my heartfelt gratitude to my family for their unwavering support and encouragement throughout this journey. Despite being 5000 kilometers away, my mom Coco and my dad Arturo, my brother Leo and my sister Valeria have been a constant source of support, and I am incredibly grateful for their belief in me.

To my friends in the Department of Geography, thank you for making my school experience awesome. Your camaraderie has made the journey more enjoyable and memorable. Special thanks go to my partner Ellen, who has been with me every step of the way during the entire writing process. Your unwavering support, understanding, patience and love have been invaluable.

Contribution of Authors

Prof. Kevin Manaugh supervised the thesis and provided valuable intellectual contributions and assisted in editing the thesis by offering insightful comments throughout the process. Prof. Grant McKenzie offered valuable comments and suggestions on the thesis. Prof. Ahmed El-Geneidy shared valuable insights related to the research. José Arturo Jasso Chávez took the lead in writing the code, creating maps and figures, performing all statistical analyses, and served as the primary author of every chapter of the thesis.

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1. Introduction

While studying different processes and phenomena, geographers, sociologists, urban planners, and other researchers face biases that directly affect the results of urban and transportation studies. Many of these biases are related to the selection and the use of specific temporal and spatial resolutions.

In the literature, the misestimation levels of using coarser spatial scales or various zoning schemes are known as the Modifiable Areal Unit Problem (MAUP) (Gehlke and Biehlge,1934). In contrast, the misestimation levels of coarse temporal resolutions, segmentations, or boundaries are known as the Modifiable Temporary Unit Problem (MTUP). The MAUP refers to the variations in results when studying a phenomenon at different resolutions: spatial scale and zonings. For example, results and interpretation differ depending on whether data at a Canadian postal code level is aggregated into larger scales, such as dissemination areas (DA) or census tracts (CT); or whether geographies will have different delimitations or limits. For example, whether geographic boundaries have the shape of a hexagon instead of a square. The MTUP is the analogy of the MAUP, which refers to the variations in results due to the election of temporal configurations and has three main components: aggregation, segmentation, and boundary. For example, the temporal aggregation depends mostly on how coarse the temporal resolution is, for example, when information is available or calculated every minute of a specific period versus every hour during the same period. Temporal segmentation refers to the misestimation levels of choosing several segments of the time. For example, the differences between choosing or studying a phenomenon from 1:00 pm to 2:00 pm instead of 8:00 am to 9:00 am. The boundary refers to the duration of the effect. Regarding accessibility, this is the time threshold and the boundary study of the differences between the thresholds.

The MAUP has been more broadly studied, while the MTUP has been generally overlooked in transportation-related analysis. Some studies have approached understanding one of the two problems separately but need help understanding both problems simultaneously. To my knowledge, only Gangopadhyay et al., (2004) and Marin et al. (2015) focus on the interaction of both. These studies, which focus on physical geography, compare different combinations of spatial and temporal resolutions, finding that both spatial and temporal aggregation directly impact the estimates. The misestimation of using non-ideal spatial scales or zoning schemes and temporal resolutions, boundaries and segmentations is known as the Modifiable Spatio-Temporal Unit Problem and is yet to be fully understood and structured in literature.

Understanding the effects of these two problems in transport planning and land use studies and choosing an adequate spatial and temporal resolution is essential to avoid bias affecting decision-making when planning transport and land use in cities. That becomes more relevant because it affects population groups differently, causing resource allocation to be uneven.

Specific studies of urban accessibility that have gained attention from decision-makers have aimed to understand spatial accessibility to places that sell nutritious and accessible food, mainly supermarkets or grocery stores. Food deserts are areas with limited access to supermarkets or nutritional food markets. The importance of studying accessibility to supermarkets lies in the fact that people who live in these places and lack economic resources risk not having a balanced diet, leading to high degrees of chronic diseases (Bazzano et al., 2002; Higdon et al., 2007).

Most classic studies on accessibility to supermarkets only count or measure the density of supermarkets in a specific area or buffer size or that can be reached within a determined threshold from an aggregated area. Most ignore the effect of choosing a specific spatial scale (or resolution) and most do not consider the possible effects of studying this accessibility at different hours of the day and using several temporal resolutions; there are no studies in the accessibility literature that focus on understanding both problems simultaneously. This is why it is essential to study both the MAUP and MTUP in accessibility studies. Also, results would show us the sensitivity of choosing a particular spatial and temporal resolution and a better understanding of the interaction or how much they can affect when both components are chosen arbitrarily or when they are the only available option.

Due to the arbitrariness in the choice of a specific temporal and spatial resolution, I argue that to diminish errors, bias, or misestimation levels in accessibility studies, building lots should be chosen as the spatial scale of analysis, and each minute from 10:00 am to 11:00 am, as the smallest temporal resolution and ideal temporal segmentation (most of the shopping trips in Montreal are made at this hour). To understand the effects of MAUP, MTUP and their interaction (MTSUP), I will compare the results of the finest unit of analysis (building level at every minute from 10:00 am to 11:00 am) using the case study accessibility to supermarkets in Greater Montreal and quantify the number of buildings which are misestimated using coarser temporal and spatial resolutions and non-ideal temporal segmentations.

This thesis is structured as follows. A literature review of accessibility, specifically accessibility to food stores, MTUP and MAUP, is presented in the following chapter. It will be followed by a methods section to address the Montreal context, how the travel time matrices were calculated, and how accessibility was measured using cumulative opportunities and statistical methods. Then, in the results section, I quantify the misrepresentation of buildings due to the effects of choosing a specific temporal and spatial resolution. The discussion section discusses the findings, advantages, and disadvantages of choosing a specific temporal or spatial resolution. Finally, I conclude with the importance of quantifying the effects and the implications of choosing specific resolutions while planning and future work.

1.1 Research questions

In summary, there is a need for a better understanding of the effects of different spatial and temporal resolutions, using as a case study accessibility to supermarkets and how they affect various socioeconomic groups to have better comprehensive and equity-oriented planning in Montreal. More specifically, the following research questions structure this thesis:

- What are the differences in estimating accessibility when using coarser spatial resolutions in relation to building lots?

- What are the differences in estimating accessibility when using coarser temporal resolutions at peak hours instead of calculating every minute from 10:00 am to 11:00 am?
- What population groups are most affected by these differences in accessibility?

These three questions are the basis for understanding temporal and spatial resolution impacts on equitable accessibility to supermarkets. However, additional research questions arise to understand these problems:

- What are the differences in estimating accessibility when several spatial resolutions and temporal resolutions and segmentation interact in relation to accessibility measures at a building lot level every minute from 10:00 am to 11:00 am?

The last question will help us better understand the nature of both problems presented and allow us to know how both problems interact simultaneously. The importance lies in knowing if the interaction is strong enough to talk about and elaborate on a Modifiable Spatio-Temporal Unit Problem, which indicates that it is crucial to analyze both problems simultaneously. This problem has not been formally studied to date. Also, I will discuss the implications of the findings related to these research questions regarding their importance in land use and transport planning and methodological considerations.

1.3 Hypothesis

I hypothesize that choosing an aggregated spatial scale and coarse temporal resolutions at a peak hour misestimates accessibility to supermarkets in Montreal. I specifically hypothesize that the coarser the spatial and temporal resolution, the higher the misestimation of building lots. Likewise, regarding the direction of the misestimation, census tracts and dissemination areas, and calculating coarse temporal resolutions will overestimate the accessibility results. Measuring accessibility at peak hours will overestimate accessibility. The levels of misestimation will increase when studying both temporal and spatial problems simultaneously. Finally, the population most affected by the choice of a specific resolution are the low-income groups, making it an equity issue.

2. Literature Review

2.1 Accessibility

The tradition of studying accessibility dates from the mid-20th century from the need of governments and academia to understand the ease with which the population can access various amenities and different areas of cities (Morris et al., 1979)

Hansen (1959) wrote one of the most classic and still valid definitions of accessibility. Hansen defined accessibility as the measure of the spatial distribution of activity sites to a point, which is adjusted according to the ability and desire of people to overcome the spatial separation between the two points. Since that year, this definition has been widely accepted, used, and interpreted differently. An example of this is the definition by Morris et al. (1979). They defined it as the ease with which activities can be reached from a given location through a particular mode of transport. Knowing this is helpful because it helps evaluate transportation systems and land use in cities to allocate resources efficiently.

In more recent years, Geurs and Van Wee (2004) established that the concept of accessibility has four components identified as having a meaningful impact when calculating accessibility: land use component, transportation component, temporal component, and individual component.

The four are explained below:

1. Land use: consists of the demand (where people live) and the opportunities of this demand (jobs, schools, shops, etc.);
2. Transportation: consists of the ability of the individual to cover the distance between an origin and a destination using a specific transport mode and includes the cost, time and effort. The transportation supply includes lanes, transport stations etc.;
3. Temporal: reflects temporal constraints, i.e. the opportunities at different times of the day, days of the week., etc.
4. Individual: reflects the needs based on the needs (socio-economic characteristics), abilities (depending on people's physical condition), and opportunities (depending on people's income and educational level).

With the context given above, accessibility could be understood as a relationship between the trips' origin and the services' location, being separated mainly by a distance or a specific time threshold (which varies depending on the mode of transport). Accessibility studies have focused mainly on measuring access to jobs (Deboosere & El-Geneidy, 2018; Grisé et al., 2019; Owen & Levinson, 2015), health centers (Bissonnette et al., 2012; Mao & Nekorchuk, 2013; Galindo, 2015; Lee et al., 2020), schools (Pacione, 1989), food stores (Battersby & Peyton, 2014; Dai & Wang, 2011; Farber et al., 2014), parks and green space (Dony et al., 2015; Nicholls, 2001; Zhou & Kim, 2013).

In the context of food accessibility studies, the literature distinguishes between the different places that sell food. The 2002 North America Industry Classification System (NAICS) groups these places into different categories or groups, such as supermarkets (e.g. in the Canadian context IGA, Metro, Provigo), grocery stores, and specialized food stores (e.g., meat markets, fish and seafood, dairy markets, fruit and vegetable markets, etc.) Other categories include convenience foods or convenience stores (or *depanneurs* in Quebec e.g. Couch-tard, Ultramar), dollar stores (e.g., Dollarama), and pharmacies (e.g. Pharmaprix, Jean Coutu) (Sharkey & Horel, 2008).

Several studies distinguish between those types of food stores depending on whether they sell healthy or unhealthy food (Bao et al., 2020). This is important because the lack of accessibility to healthy food can compromise the supply of nutritious food, allowing for maintaining good health and preventing chronic health conditions such as obesity, cancer, or cardiovascular diseases (Bazzano et al., 2002; Higdon et al., 2007). Accessibility to supermarkets is usually chosen as a proxy for healthy food, arguing that they offer various products necessary to cover the basic basket at reasonable prices (Block & Kouba, 2006). This research focuses on places that sell food, specifically supermarkets.

In this context, different methods exist to calculate accessibility to food stores. One of the most classical methods is to count the number or density of supermarkets in a specific area, such as buffers of various diameters, census tracts, or dissemination areas (Morland et al., 2002; Mohammadian et al., 2017); within a specific threshold following a euclidean distance (Pearce et al., 2006; Bertrand, 2008; Winkler et al., 2006); using the road network (Apparicio et al., 2017). Another part of the literature measures the distance or time to the nearest or determined number of supermarkets (Apparicio et al., 2017) or uses the two-step floating catchment method (Chen, 2019; Jin & Lu, 2022). More advanced accessibility methods using public transport with data in the General Feed Transit Specification (GTFS) format allow for analyzing the variability of accessibility throughout the day (Farber et al., 2014; Widener et al., 2015).

2.2 Modifiable Areal Unit Problem

The MAUP has a long tradition in geography and other disciplines (Hui & Cho, 2018; Pereira, 2018; Wong, n.d.). This problem was first described by Gehlke and Biehlge (1934). They stated that statistical correlation measures change when different census tracts are zoned and grouped and refer to the problem that the analysis results vary depending on the spatial resolution (Fotheringham & Wong, 1991).

It was not until 1983 that it became more widely defined and detailed in the literature. Openshaw states that even disaggregate/point data is not a viable solution for many types of analysis, and it introduces other sorts of error, such as inaccuracy and distortion. Openshaw stated: "the areal units (zonal objects) used in many geographical studies are arbitrary, modifiable, and subject to the whims and fancies of whoever is doing, or did, the aggregating." (Openshaw, 1984, p.3). Also, he implies that 'the MAUP will disappear once geographers know what the real objects they wish to study are'' (Kwan & Weber, 2008).

This idea is vital because most studies measure the bias using aggregated areas (coarser resolutions) instead of using the finest unit of analysis, which will depend on the process under study. As argued later, this research considers residential buildings as the finest unit of analysis in accessibility studies.

MAUP has two components: scale and zoning (Kwan & Weber, 2008), which will be addressed in the following subsections.

2.2.1 Scale effect

The scale effect refers to the disparity in numerical results depending on the size of the aggregated area and the number of spatial units (Lowell, 2008). In the context of Canada, different scales of research can be identified, which can range from municipalities, census agglomerations (CA), census tracts (CT), dissemination areas (DA), postal codes, dissemination blocks, and building lots. Figure 1.1 shows an example of the structure of CTs, DAs, and building lots in Montreal, which are three different spatial scales used in this research. The sizes of all the scales vary significantly. The census tracts are the coarsest scale, while the building lots are the finest scale.

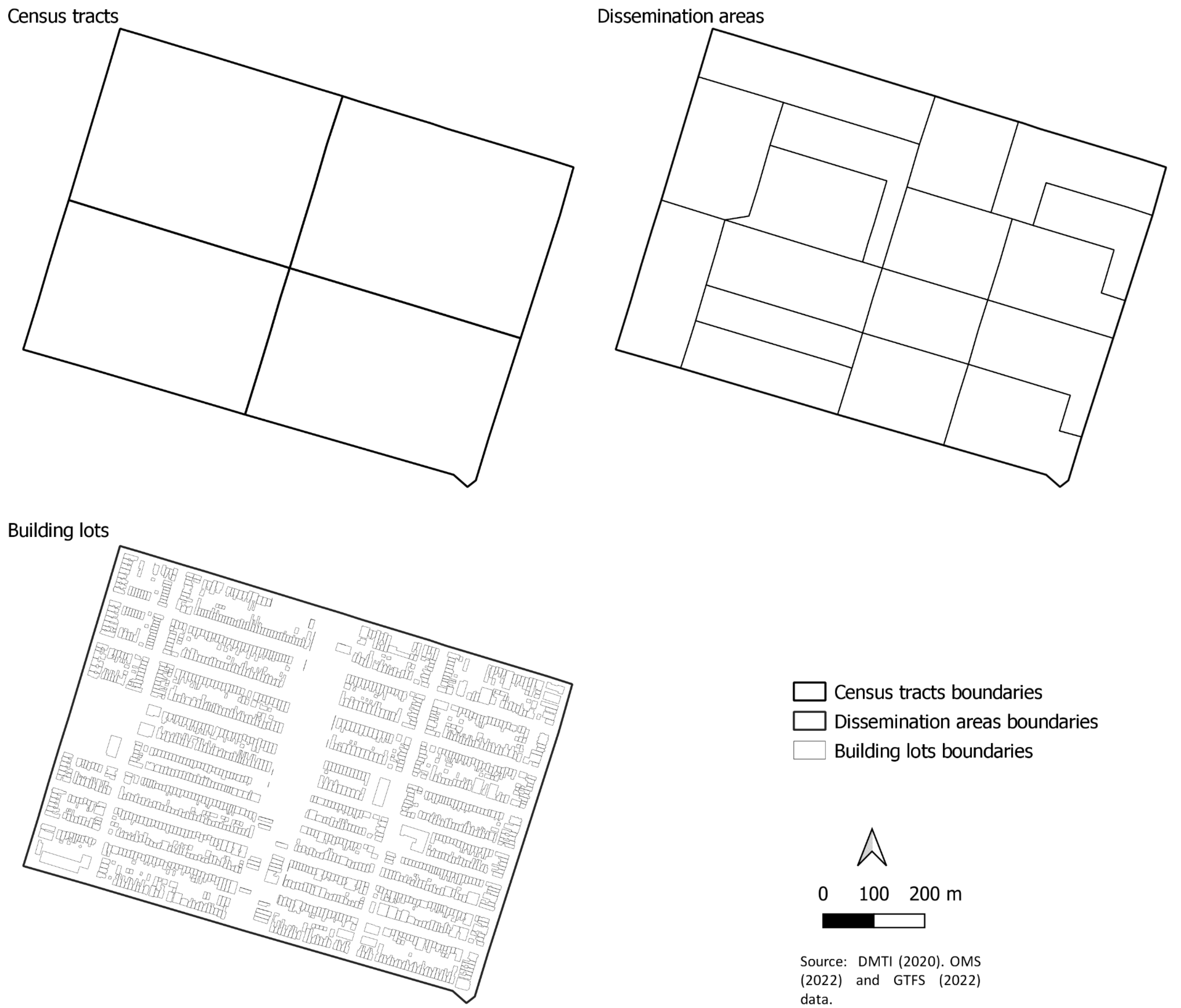

Figure 1.1. Example of the structure of three spatial scales in Montreal

Table 1.1 shows the spatial scale used in various studies of accessibility to different amenities worldwide. Most studies use a spatial scale pre-established by some local authority, such as census tracts, dissemination areas, or dissemination blocks. One of the reasons is that a lot of information and/or data, such as census data, are aggregated at those scales. Traffic analysis zones (TAZ) are frequently used in transportation studies and can be defined as the spatial unit of territory with similar characteristics in transportation attributes. Very often, transportation data (e.g. origin and destination surveys) is aggregated at this scale. However, to our knowledge, only one study in transportation studies measures MAUP in relation to the smallest unit of analysis: building lots (Bryant & Delamater, 2019).

Table 1.1 Spatial scales used in accessibility studies

Spatial scale	**Authors**
Buildings	Bryant and Delamater (2019)
Meshblocks	Mavoa et al. (2012)
Census blocks	X. Zhang et al., (2011); Dony et al., (2015) ;Zhou & Kim, (2013); Nicholls (2001); Mao & Nekorchuk (2013); Karner (2018; Farber et al. (2014);Farber et al. (2016); Owen & Levinson (2015);Fan et al. (2012)
Postal codes	Guagliardo (2004)
Dissemination areas	Reyes et al., (2014);El-Geneidy, Levinson, et al. (2016);Bissonnette et al. (2012)
Census tracts	Boisjoly et al. (2020); Deboosere & El-Geneidy (2018); Grisé et al. (2019); Boisjoly & El-Geneidy (2016); El-Geneidy, Buliung, et al. (2016); Legrain et al. (2016)
Traffic analysis zones	Widener et al. (2015); Manaugh & El-Geneidy (2012); Golub & Martens (2014); Fayyaz et al. (2017); Fransen et al. (2015); Pereira (2019)
Subdistricts	Wei (2017)
Square grid cells	Aslund et al. (2010); Albacete et al. (2017) ; Järv et al. (2018); Tomasiello, Herszenhut, et al. (2022); Ryan et al. (2022)
Hexagons grid cells	Tomasiello, Herszenhut, et al. (2022); Pereira (2019); Liao et al. (2020)

Despite all these studies choosing a spatial scale, they rarely argue the reasons why they choose that specific spatial scale and the respectively effects. From a transportation perspective, MAUP has been studied for predicting travel mode choice (Mitra & Buliung, 2012; M. Zhang & Kukadia, 2005), evaluating transit service (Horner & Murray, 2004), or in accessibility studies (Pereira, 2018). Those studies conclude that aggregating spatial scales impact the results and recommend using more disaggregated spatial scales. However, transport studies have yet to focus on understanding the effects of using different spatial scales with building lots, the finest unit of analysis.

One of the works that focus on understanding MAUP in transportation is Zhang and Kukadia's (2011) work which focused on modeling travel mode choice in Boston, Massachusetts using grid cells of five different sizes, transport analysis zones, census blocks, and block levels. The smaller grid cell was the most robust model for predicting mode choice from all the analyzed spatial scales. Kwan & Weber (2008) examined the relationship between accessibility, land use, and personal and household characteristics with different spatial scales at metropolitan and local levels. They concluded that analyses are sensitive depending on the spatial scales or zonal schemes and that different spatial scales are essential to study accessibility as the results of everyone are complementary to each other. Javanmard et al (2023) measured public transit reliability in Winnipeg, Manitoba at three different spatial scales: route, stop and neighborhood level finding inequities at a stop and neighborhood level and equity at a route level.

Also, the MAUP has been identified to affect accessibility to jobs in Rio de Janeiro, focusing on traffic zones and various sizes of grid cells (.5 km, 1 km, 2 km, and 4 km). The conclusions state to consider spatial scale's effects on spatial analysis as policy recommendations could vary depending on the results (Pereira, 2018) and that it is better to use smaller spatial scales to have more detail and visible details (Pereira, 2018; Wan, 2016).

This problem has been approached in the Canadian context, specifically regarding accessibility to street nodes (intersections) in Windsor, Canada. Six spatial scales were studied: census tracts, dissemination areas, dissemination blocks, and grid cells of .6 km. .3 km and .15 km. However, the study did not approach the smallest unit of analysis (buildings). Instead, the dissemination areas were the smallest unit of analysis. The study found that the bigger the spatial scale, the more the misrepresentation. They mention possible overestimation and underestimation but do not indicate which has a greater effect and do not include the reasons. The paper concludes that it is better to use the most disaggregated data and select zones according to research purposes (Wan, 2016).

Despite studies focusing on understanding the effects of MAUP in transportation studies, many studies still use aggregated spatial scales as a reference (DA, CT, DB) instead of the smallest unit of analysis (residential lots). To our knowledge, only two studies measure accessibility and biases by comparing different spatial scales and residential building lots/individual addresses in transportation. Van Wee and de Jong studied accessibility to medical points and points of interest and inequalities when using several spatial scales: individual addresses, small neighborhoods, 4-digit postal codes and municipalities. They found the Gini index can significantly differ depending on the spatial scale used, which the indices are calculated, with smaller indices at higher spatial scales (2023). Bryant and Delamater (2019) measured accessibility to parks in Alexandria, VA, United States, using the enhanced two-step floating catchment area (E2SFCA) method. They measured travel distance using the centroids of different spatial scales origins: residential buildings, census blocks, census block groups, and census tracts and the parks' entrances as the destinations. Another interesting thing in their research is that they quantify the number of people affected by the election of aggregated spatial scales and also indicate the direction of the misestimation (underestimation or misestimation). They concluded that macro spatial scales produce errors that can result in potentially misleading information regarding the levels of access (Bryant & Delamater, 2019).

This research will focus on understanding the effects of the Modifiable Areal Unit Problem by comparing several spatial scales (census tracts and dissemination areas) to the smallest unit of analysis: building lots.

2.2.3 Zoning effect

The second effect, which is less studied in transportation studies and will not be addressed in this research, is the zoning effect. The zoning effect refers to the analytic differences depending on how the study area is divided. The number of units in the zoning effect remains unchanged, but they change their relative position or structure. For example, the changes in the boundaries or use of different shapes of figures (Jelinski & Wu, 1996). Specifically, the zoning effect plays a significant role in electoral geography, in which the zoning of electoral districts affects voting behavior (Agnew, 1996).

A general approach in transportation studies is to divide the territory into several shapes or forms, such as squares (Järv et al., 2018; Tomasiello, Herszenhut, et al., 2022; Albacete et al., 2017) or hexagons (Pereira, 2019; McKenzie & Romm, 2021; Liao et al., 2020). Figure 1.2 shows several zoning patterns that, despite having the same or similar size, will affect the interpretation of the results (Martinez et al., 2017). Traffic analysis zones can help alleviate these effects in transportation studies because they zone areas based on the location of transportation infrastructure (e.g., public transportation stations and street network). However, this does not solve the spatial effect problem.

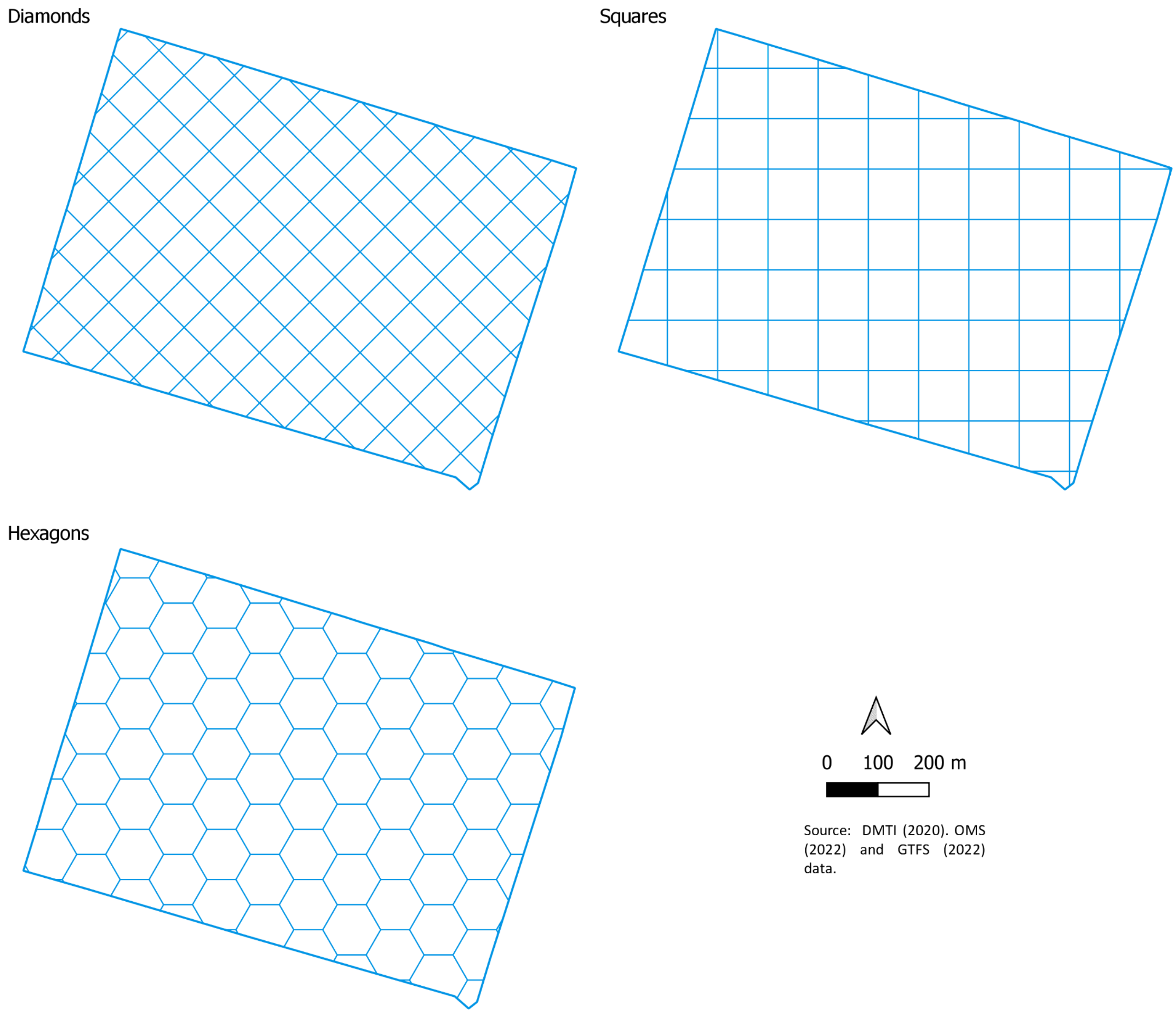

Figure 1.2. Various zoning schemes

2.3 Modifiable Temporal Unit Problem

As mentioned above, the Modifiable Areal Unit Problem (MAUP) has been extensively approached in the literature of transportation studies. However, its temporal counterpart is often ignored or not considered even though it is critically essential in geographic studies (Çöltekin et al., n.d.).

The Modifiable Temporal Unit Problem (MTUP) originates from the idea of temporal granularity, which is the notion that the world is perceived at different grain sizes or granules (Hobbs et al., 1990). As Hornsby & Egenhofer (n.d) and Meentemeyer (1989) mentioned, perceiving different grain sizes or granules can introduce critical issues. For example, temporal and spatial autocorrelation might vary with scale (those grain sizes).

One reason for its recent importance is that data handling has grown enormously in recent years, bringing with it the handling of larger temporal and spatial resolutions thanks to technology; time and money are limited on these spatial scales (Meentemeyer, 1989). At the same time, these technical advances establish new opportunities and challenges that allow cities to be studied in detail and quickly and find new problems, such as the MTUP.

These new technological advances allow us to explore several temporal resolutions in any geographic process. In transport and accessibility studies, advances in the General Feed Transit Specification (GTFS) allow for exploring the calendars and schedules of public transport systems in cities and understanding the different temporal variations present throughout the day, between different days of the week and even seasons of the year. It is important because some events or processes can only be viewed at specific time resolutions when viewing temporal data (Harrower et al., 2000).

Just a few studies have articulated the Modifiable Temporal Unit Problem. One of them is the paper by Cheng & Adepeju (2014) which mentions that the Modifiable Temporal Unit Problem consists of three significant components: aggregation (scales), segmentation (how the temporal dimension is divided), and boundaries (temporal extent).

2.3.1 Temporal aggregation

Temporal aggregation can be considered as the counterpart spatial aggregation effects in the MAUP and refers to the regularly spaced unit of time observation, which can be a second, minute, hour, day, week, year, etc. Temporal aggregation is a process that converts observations from a fine interval into a coarse interval (Cheng & Adepeju, 2014). Pereira (2018) explains this in accessibility and transportation terms. Pereira states that accessibility level will vary depending on when a person departs, relative to when a public transit vehicle arrives, and how transfers are coordinated given a service timetable. To take this variation into account, the levels of accessibility would be averaged or used as the median across a sample of various departures during a specific time interval (Pereira, 2018). Having said this, the temporal aggregation directly depends on the sample size, which will affect the results obtained. Figure 3 shows different sample sizes: every minute, every 10 minutes, every 15 minutes and every 30 minutes. Each of those sample sizes will have different results when averaging. The larger the sample, the more accurate it will be in accounting for temporal variation. The smaller the sample, the less certainty of the temporal variation

Figure 1.3. Temporal aggregation

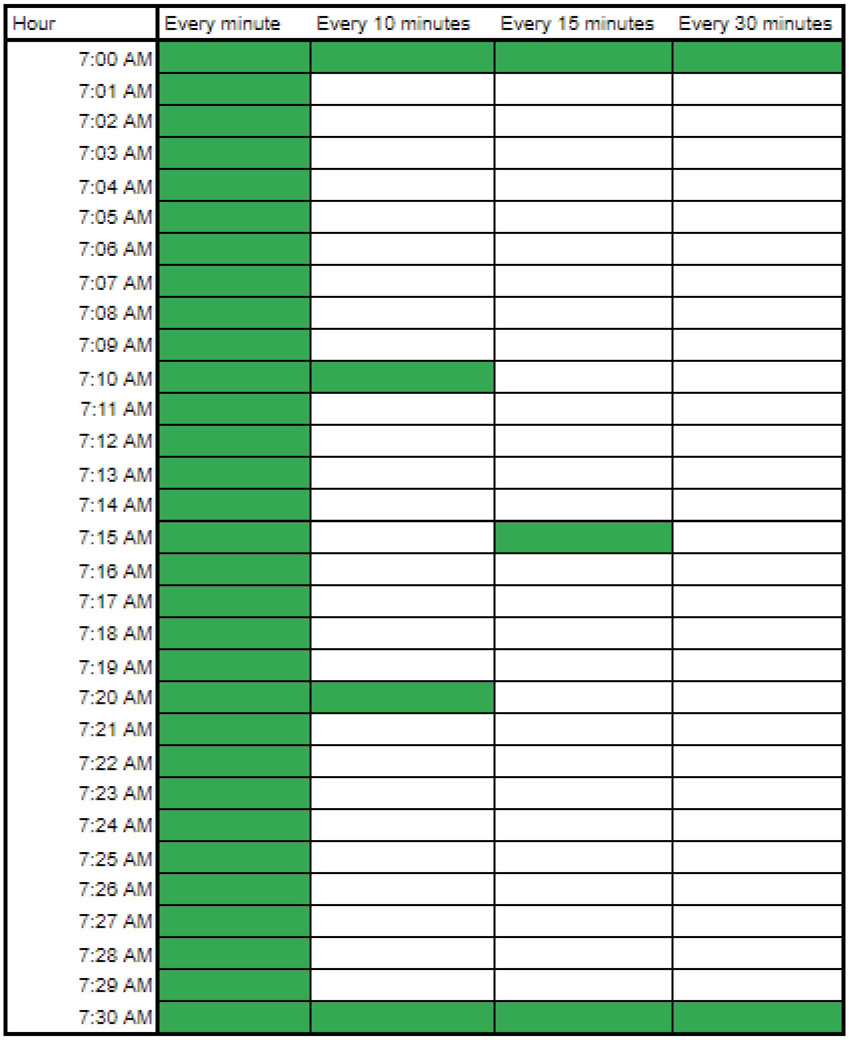

Table 1.2(end of the chapter) shows some studies that have calculated accessibility at different temporal aggregations. These focus only on accessibility in public transport, which is the only mode of transport with data about the variation through the day. Many studies only consider a single departure time (El-Geneidy, Levinson, et al., 2016); (Widener et al., 2015); (Boisjoly et al., 2020)(Grisé et al., 2019); other studios samples every hour (Boisjoly & El-Geneidy, 2016); another study, such as Järv et al., (2018) that do not choose regular resolutions, but use

irregular or random resolutions throughout the day. Karner et al. (2018) calculate accessibility every 5 minutes. Finally, some studies sample every minute (Tomasiello, Pereira, et al., 2022, Farber, 2014), considered the finest temporal resolution available to date.

Although many studies choose a spatial resolution, this selection is usually arbitrary, and many of them have not measured the bias or effects of this. One of the studies that have approached this is Stępniak et al., 2019 which studied the effects of the aggregation problem on accessibility to various amenities in Warsaw, Poland, using several temporal resolutions: every minute, every five minutes, every 10 minutes, 15, 20, and 30 minutes. Considering every minute of a specific period as the baseline, they found that the precision decreases when using coarser temporal resolution. They stated that the difference between every minute and every five minutes is negligible, recommending not using resolutions coarser than 5 minutes.

The temporal aggregation will be the main focus of this research by using eight different resolutions: every minute, every five minutes, every 10 minutes, every 20 minutes, every 30 minutes, and every 60 minutes.

2.3.2 Segmentation effect

The segmentation effect could be analogous to the zoning effect in the MAUP. This happens when the continuous time frame is divided into chunks of temporal segments. If a single frame time is considered, let's say a travel time matrix for 17 hours of the day, a series of segmentations from a single time frame by varying the starting point can be generated. In transportation or accessibility studies, it is prevalent to choose several departure periods, such as peak and off-peak hours or all day (Figure 1.4).

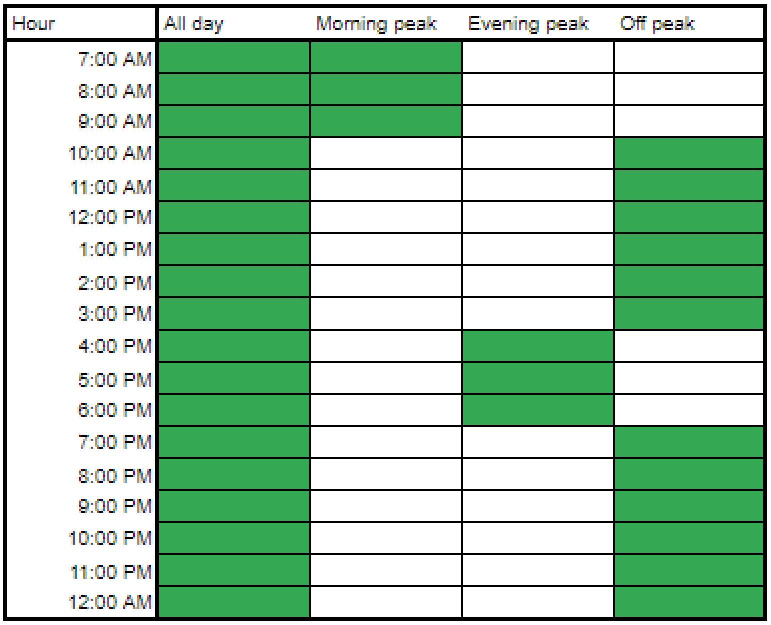

Figure 1.4. Temporal segmentation

This component is prevalent in transport studies. However, it is not explicitly mentioned. Having information in a GTFS format allows for knowing the frequency of public transport throughout the day. Due to the nature of public transport, it has high and low-frequency peaks.

Many studies compare accessibility in the hours of high frequency, or peak hours, with the hours of less frequency, off-peak, indicating that accessibility changes drastically. Depending on the context of the city, usually, the morning peak is between 6 am and 10 am, the afternoon peak is between 4 pm and 7 pm, while the off-peak is usually between 11 am to 4 pm and from

7 pm to 6 am (Legrain et al., 2016; Liao et al., 2020; Manaugh & El-Geneidy, 2012; Fransen et al., 2015; Liao et al., 2020).

However, the best temporal segmentation to study accessibility should be the closest to reality, or in other words, the hour in which the highest concentration of trips to the destination is made. Regarding shopping trips in Montreal, the hour corresponds to the off-peak hour, specifically between 10:00 am and 11:00 am, with around 14% (Origin-Destination Survey, 2018).

This research will use only two segmentations: 10:00 am to 11:00 am, our baseline segmentation, and 8:00 am to 9:00 am. For both segments, several temporal resolutions (aggregations) are used. It is essential to mention that time aggregation and segmentation are closely related. Aggregation refers to the change of the scale (from fine to coarse: every minute of the day to only one minute of the day). However, segmentation refers to the partitioning of the data during the process of change of scale (Cheng & Adepeju, 2014).

2.3.3 Temporal boundary effect

Finally, the boundary effect refers to the start and end points of the time series as its temporal boundaries. The variance and mean of the results will be altered if the temporal boundary is altered. Regarding transportation, this could refer to the duration of the trip or the time threshold in the cumulative opportunities method (Figure 1.5). The results are going to change depending on the time threshold chosen. The higher the threshold, the higher the number of opportunities that can be reached. The choice of a time threshold depends on many factors, many times depending on the political agenda of the cities in wanting a large part of the population to have access to a certain number of facilities in a specific travel time. In other cases, it directly depends on the desired travel time of the populations in the cities depending on the type of amenity and the mode of transport used.

Figure 1.5. Temporal boundary

In accessibility studies, the most common threshold used are 15 minutes (Dony et al., 2015; Reyes et al., 2014), 30 minutes (Tomasiello, Herszenhut, et al., 2022; Manaugh & El-Geneidy, 2012), 45 minutes (Golub & Martens, 2014; Grisé et al., 2019; Boisjoly et al., 2020) and 60 minutes (Mavoa et al., 2012; Liao et al., 2020). Although it is known that the choice of results varies depending on the threshold, just a few studies have analyzed the differences in the choice of different thresholds. One of those studies is Tomasiello, Herszenhut, et al. (2022) in which they calculate accessibility using several time thresholds. They found no difference between two-time thresholds when the time between them is less than 10 minutes (e.g., 10 and 20 minutes), but the difference is essential when the time between them is greater than 10 minutes (e.g. 10 and 30-minute thresholds) (Table 1.2).

Table 1.2. Temporal resolutions in accessibility studies

Authors	**Aggregation**	**Segmentation**	**Boundary**
Boisjoly et al. (2020)	10 am		Threshold: 45 minutes
Widener et al. (2015)	5 pm		Threshold: 120 minutes
Deboosere & El-Geneidy (2018)			Threshold: 20 minuteS
Aslund et al. (2010)			Threshold: 5km
Wei (2017)			Threshold: 800 mts/ 10 min walk; 5 min bike
Dony et al. (2015)			15 min threshold
Reyes et al., (2014)			Threshold: 15 min walk
Zhou & Kim (2013)			Threshold: 300 mts
Nicholls (2001)			Threshold: 800 mts
Albacete et al. (2017)			Threshold: 38 min
Mavoa et al. (2012)			Threshold: 10, 20, 30, 40, 50 >60 min

Deboosere & El-Geneidy (2018)	8 am		Threshold: 30 min
Mao & Nekorchuk (2013)			Threshold: 30 minutes
Bissonnette et al. (2012)			Threshold: 3 km
Guagliardo (2004)			Threshold: 30 min
Grisé et al. (2019)			8 am. 45 min threshold
El-Geneidy, Levinson, et al. (2016)	7 am		
Widener et al. (2015)	5 pm		
Boisjoly & El-Geneidy (2016)	Every hour	Five periods: 6 am, 7 am, 8 am (single departure times), 9 am-12 pm and 12 pm-5 am (mean travel time)	•
El-Geneidy, Buliung, et al. (2016)		Periods: 5-6 am, 6-7 am, 7-8 am, 8-9 am (single departure times) 9 am – Noon (mean travel time)	
Legrain et al. (2016)		Two periods: peak (6-9 am) and peak-off (9 am 5 am)	
Järv et al. (2018)	Quasi temporal resolution (irregular resolution): departure times		

	selected according to Golomb ruler (7 to 8)		
Fayyaz et al. (2017)	Every 10 minutes	4 am to 10 pm	
Fayyaz S. et al. (2017)	5 minutes	5 am to 8 pm	
Fransen et al. (2015)		Periods: peak hours (6–9 am, weekday), peak-off hours (11 am-2 pm, weekday) and weekend (11 am-2 pm	Multiple thresholds
Karner (2018)	quasi temporal resolution (irregular resolution): departure times randomly selected for each of 24 5-min periods)	7 to 9 am	
Farber et al. (2014)		From 7 am to 9 pm.	Threshold 10, 20 min.
Owen & Levinson (2015)	Every minute	7 to 9 am	
Tomasiello, Herszenhut, et al. (2022)	Every minute	6 to 8 am	Threshold: 30 and 60 min by public transit and 15 and 30 min by car
Tomasiello, Pereira, et al. (2022)	Every minute	peak period (between 6 am and 8 am)	
Ryan et al. (2022)	Every minute	Peak, pre peak and post peak	

Liao et al. (2020)		Midnight = 0:00–7:00, Morning peak = 7:00–10:00, Off peak = 10:00–16:00, Afternoon peak = 16:00–19:00, Night = 19:00–0:00.	
Pereira (2019)	Every 15 min	Between 7 a.m. and 9 a.m.	Threshold 30, 60, 90, 120
Manaugh & El-Geneidy (2012)		AM peak	Threshold: 30 mins
Golub & Martens (2014)			Threshold: 45 min
Fan et al. (2012)	Every hour	From 5 am to 9 pm	Threshold: 30 min

In summary, the Modifiable Areal Unit Problem (MAUP) refers to the variations in research outcomes that arise when studying a phenomenon at different spatial resolutions, such as spatial scale and zonings. Similarly, the Modifiable Temporal Unit Problem (MTUP) is the temporal counterpart of the MAUP, which pertains to the variations in results due to the selection of temporal configurations. The MTUP consists of three main components: aggregation, segmentation, and boundary.

While the MAUP has been extensively studied in the literature, the MTUP has often been overlooked, resulting in a significant research gap. There is a lack of comprehensive investigation into the combined effects of these problems, which is known as the Modifiable Spatio-Temporal Unit Problem (MSTUP), particularly in the context of accessibility studies.

To address this gap, the objective of this study is to simultaneously tackle the MAUP and MTUP. By examining the interplay between spatial and temporal resolutions, this research endeavor aims to fill the existing research gap and contribute to the advancement of knowledge in the field.

3. Methodological design and methods

3.1 Montreal context

The population of the Greater Montreal metropolitan area is 4.43 million inhabitants distributed among 91 municipalities. The most populous are Montreal, Laval, and Longueuil. Greater Montreal's public transportation is administered by several transportation agencies, including the Montreal Transportation Society (STM), the Laval Transportation Society, Réseau de transport de Longueuil, and the Metropolitan Transportation Agency. The public transport system has its backbone in the Montreal Metro, administered by the Montreal Transport Society, which consists of four Metro lines and 68 stations with a length 69 km. It concentrates on the island of Montreal, with some stations in Laval and Longueuil.

Additionally, it has extensive train systems covering many areas in Longueuil, Laval, the North Shore, and the South Shore, and it has more than 100 local and metropolitan bus routes (Figure 2.1). It is essential to understand the transportation systems one of its main functions is to provide accessibility to the population (Manaugh & El-Geneidy, 2012)

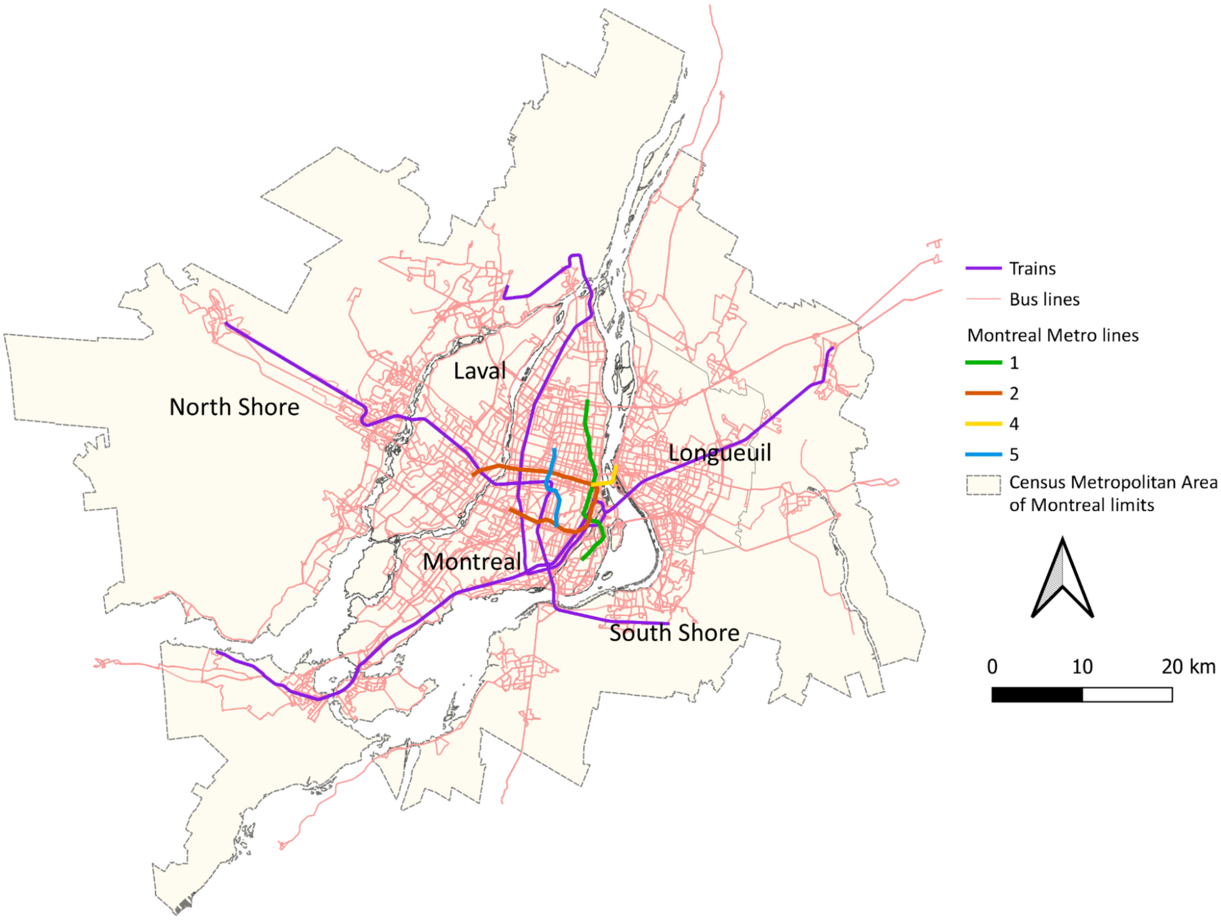

Figure 2.1: Geographic Context and Transport Network

The location of supermarkets in Montreal was obtained from the DMTI (2020) database, which contains the location and characteristics of economic activities in Montreal and its metropolitan area. The database was cleaned by searching keywords with the words "supermarket," "supermarche" and other combinations of those words in English and French, as well as the name of well-known supermarket chains such as Metro, IGA, Provigo, Walmart, Super C, and others. The supermarkets were used as a proxy for providing various food options. Other food stores, such as small markets, convenience stores, or "depanneur", were not considered as these establishments predominantly sell foods of low nutritional value and offer just a few options that do not meet the basic diet requirements. 480 supermarkets were identified in the whole Census Metropolitan Area of Montreal (Figure 2.2). Most supermarkets are concentrated on Montreal's main island, and a small portion is located on the North and South Shore.

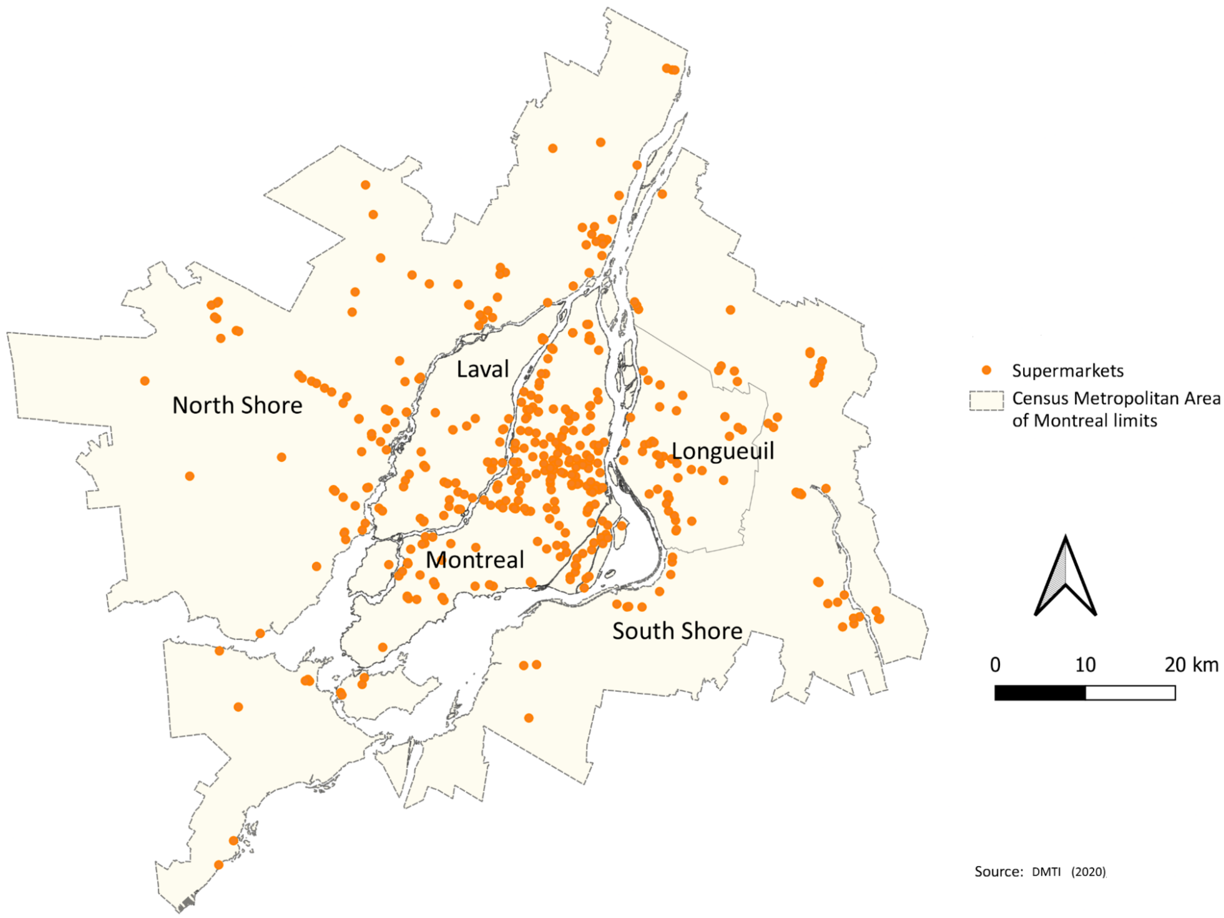

Figure 2.2. Distribution of supermarkets in Montreal, Canada

3.2 Spatial scales

To quantify the effects of the Modifiable Areal Unit Problem, I measured the accessibility to supermarkets at census tract (CTs) and dissemination areas (DAs) scale and then compared with the finer area of analysis, which are the building lots.

The total number of residential buildings in the CMA is about 870,000 (OSM, 2021). However, only those buildings estimated as apartments or housing or located in residential land use were used as the reference OpenStreetMap for the analysis. The total number of residential buildings used is around 780,000. I obtained information on the 6469 dissemination areas and 970 census tracts of the CMA of Montreal from StatisticsCanada (2016). A dissemination area comprises one or more neighboring dissemination blocks and is the smallest standard geographic area for which all census data are released. Census tracts (CTs) are relatively stable geographic areas with a population between 2,500 and 8,000 people (Statistics Canada, 2016).

The area size of each of these areas shows that, on average, a dissemination area is 4,500 times larger than a building. At the same time, a census tract is around 29,000 times larger than a building and about 6.5 times larger than a dissemination area (See Table 2.1). The average number of buildings in a census tract is 809, and the average number of buildings in a dissemination area is 121.

Table 2.1. Description of different spatial scales

Spatial scale	Description	No. of units	Average no. of buildings	Avg. area (sq. km)	Source
Residential buildings	estimated as apartments or housing or located in residential land use were used for the analysis	780,000		0.00016	OpenStreetMap (2021)
Dissemination areas	are small, relatively stable geographic areas with a population between 2,500 and 8,000 people	6,469	121	0.72	Statistics Canada (2016)
Census tracts	an area composed of one or more neighboring dissemination blocks and is the smallest standard geographic area for which all census data are released	970	809	4.7	Statistics Canada (2016)

Figure 2.3 shows an example of the geographies composition in Montreal, including the street network, localization of the supermarket, and centroid of each geography. The position of the centroid of the dissemination areas and the census tracts to the centroid of the buildings can be observed. Its importance will be explained in the following subsection.

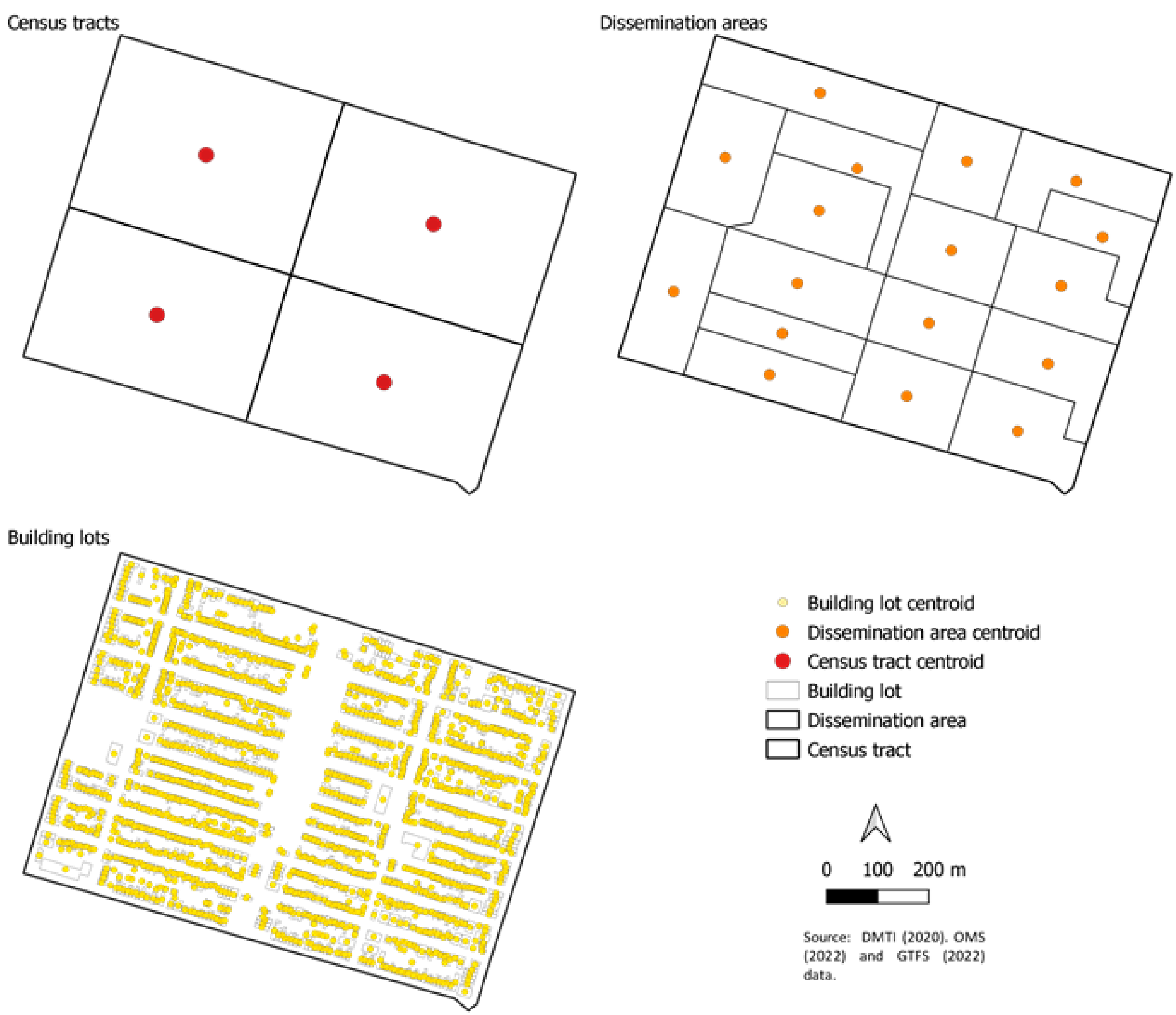

Figure 2.3. Composition of different geographies in Montreal

3.3 Travel time matrices

Several travel time matrices between multiple origins and destinations were generated using Rapid Realistic Routing with R5 in R (r5r), an R-based package based on Java. This is done by building a multimodal transport network using the OpenStreetMap street network and the information of public transit in Montreal in a General Feed Transit Specification (GTFS) data format.

Figures 2.4 and 2.5 show the different ways travel time matrices were calculated: one for census tracts and dissemination areas and another for residential buildings. Regarding travel time matrices for census tracts and dissemination areas (Figure 2.4), the travel time matrix was calculated using the centroid of each geography as origin and destination. For buildings (Figure 2.5), the travel time was calculated using the centroid of the building as the origin and the location of the supermarkets as the destination.

Regarding the temporal resolution, I measure the travel time matrices every minute from 7:00 am to 9:00 pm on a weekday (Wednesday) as it is considered a day of typical demand in the city. All the trips calculated could be made by only walking or the combination of walking + public transit, depending on which route is fastest. Regarding the combination of walking + public transit, I set the maximum walkable distance from the origin to the first public transit stop and from the public transit stop to the destination as 1,500 meters. The computed walking speed chosen was 3.6 km/h and was chosen by considering that around 50% of the population that made shopping trips are aged 60 years and 3.6 km/h maximum average speed for adults over 65 years old who can walk independently (Julius et al., 2012) and the minimum average speed for healthy individuals (Nadeau et al., 2013) and which also coincides with the default speed in r5r.

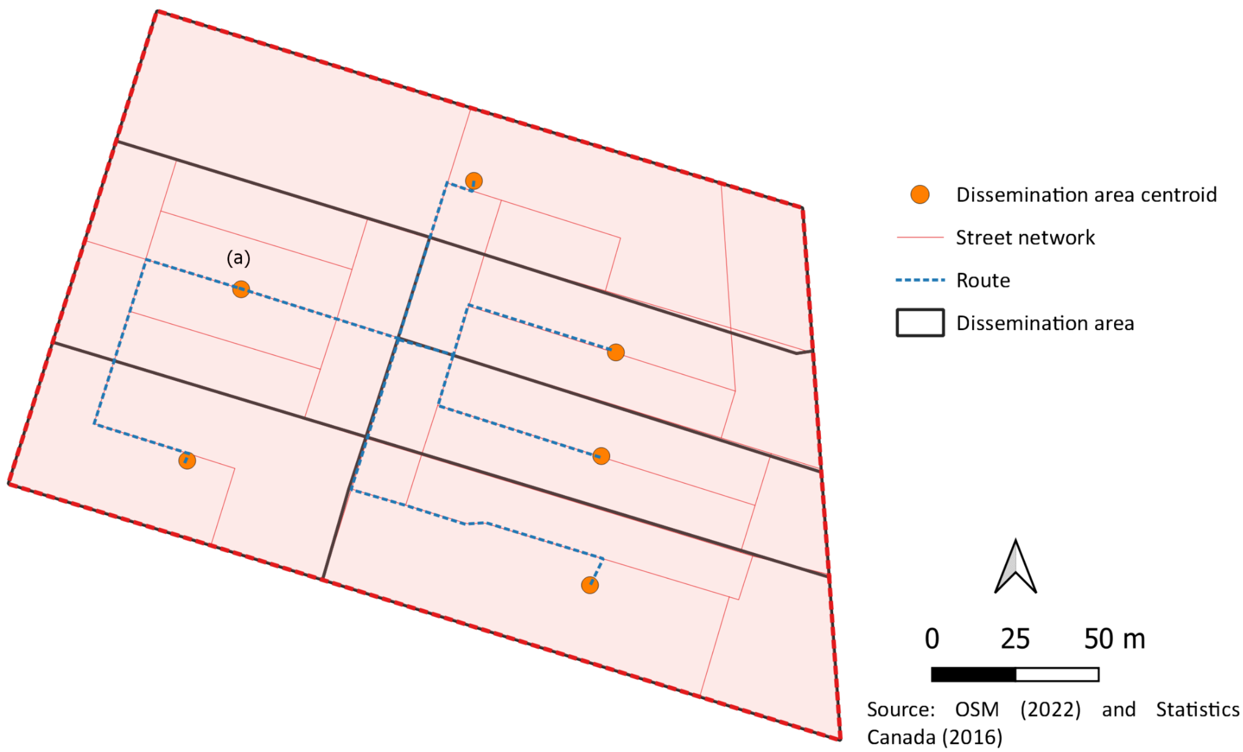

Figure 2.4: Comparison of Spatial scale and boundaries

Figure 2.5. Comparison of spatial scale and boundaries (sample of three buildings)

3.4 Cumulative opportunities measure

The second part of the methodology consists of measuring accessibility using the cumulative opportunity methods using a 30-minute threshold. The cumulative opportunities method counts the number of opportunities that can be reached within a travel time or distance. Unlike the gravity model, this model does not calculate the impedance of the destination, so all opportunities are considered equally.

The formula is

$$Ai = \sum_{j=1} OjBj$$

Where:

- Ai is the accessibility at zone i
- Bj is a binary value equal to 1 if zone j is within the predetermined time threshold and 0 otherwise, and;
- Oj are the opportunities in zone j.

I calculated accessibility at census tracts levels, dissemination areas and building lots using the average of every minute for both periods (from 10:00 am to 11:00 am, out baseline, and from 8:00 am to 9:00 am; 60 observations for each temporal segmentation), every five minutes (10:00, 10:05, 10:10… to 11:00 am; and 8:00, 8:05, 8:10 to 9:00 am. 12 observations for each temporal segmentation), every 10 minutes (six observations for each temporal segmentation), every 20 minutes (three observations), every 30 minutes (two observations) and every 60 minutes (one observation).

3.5 Descriptive analysis

The descriptive analysis consisted of the absolute and relative quantification of the number of building lots that are misestimated when different temporal and spatial resolutions are used. The combination that was used as a base was the average accessibility of each minute of the day on a scale of building lots.

The basic formula is the following:

$$\frac{(Geography_{itime} - Building_{ij\,min})}{Building_{ij\,min}}$$

Where:

$Building_{i\,j\,min}$ = Which is the baseline and indicates the average accessibility number of opportunities using every minute from 10:00 am to 11:00 am in the building i in the Geography j

$Geography_{j\,time}$ = Which is the average accessibility of several opportunities in the Geography j at a specific temporal resolution and segmentation.

In this case, there are 12 temporal combinations if I consider the segmentation and aggregation components. Six for every temporal segmentation (10:00 am to 11:00 am and 8:00 am to 9:00 am): every minute, every five minutes, every ten minutes, every 20 minutes, every 30 minutes and once during the period. On the side of the aggregated spatial scales, it could have two: dissemination areas and census tracts. In other words, I did this for all the buildings in the city for every combination mentioned above (35 different combinations). Table 2.2 shows a sample of the combinations of this formula.

Table 2.2: Formulas to calculate the difference in accessibility depending on spatial and temporal scales

	Spatial scale		
Temporal scale	**Building lots**	**Dissemination areas**	**Census tracts**
Every minute	BASELINE	$\frac{(AccDA_{i\,min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$	$\frac{(AccCT_{i\,min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$
Every 5 min	$\frac{(AccBld_{i\,5min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$	$\frac{(AccDA_{i\,5min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$	$\frac{(AccCT_{i\,5min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$
Every 60 minutes	$\frac{(AccBld_{i\,60min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$	$\frac{(AccDA_{i\,60min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$	$\frac{(AccCT_{i\,60min-10am} - AccBld_{i\,j\,min})}{AccBld_{i\,j\,min}}$

Now, let’s explain the formula with some real examples using Figure 2.6. Figure 2.6 shows three maps: accessibility measured at a building lot level every minute from 10:00 am to 11:00 am (1), census tracts from 10:00 am to 11:00 am (2) and the percentage difference between both scales (3).

Let's start with building “a”, which on a building lot scale has an accessibility of 14 supermarkets, while on a census tract scale (every minute from 10:00 am to 11:00 am), the same building has an accessibility of 25. If I use the mentioned formula, this indicates that measuring accessibility at the census tract scale overestimates accessibility by 81% (positive number)

$(\frac{(25-14)}{(14)}) * 100$ = 81%

If I now take building "b" as a reference, I can identify that it has access to 29 supermarkets. In the case of census tracts, the accessibility of said buildings is still 16. In this case, the difference would be -44% (negative number), so measuring at the census tract scale underestimates the value.

$(\frac{(16-29)}{29)}) * 100$ = -44%

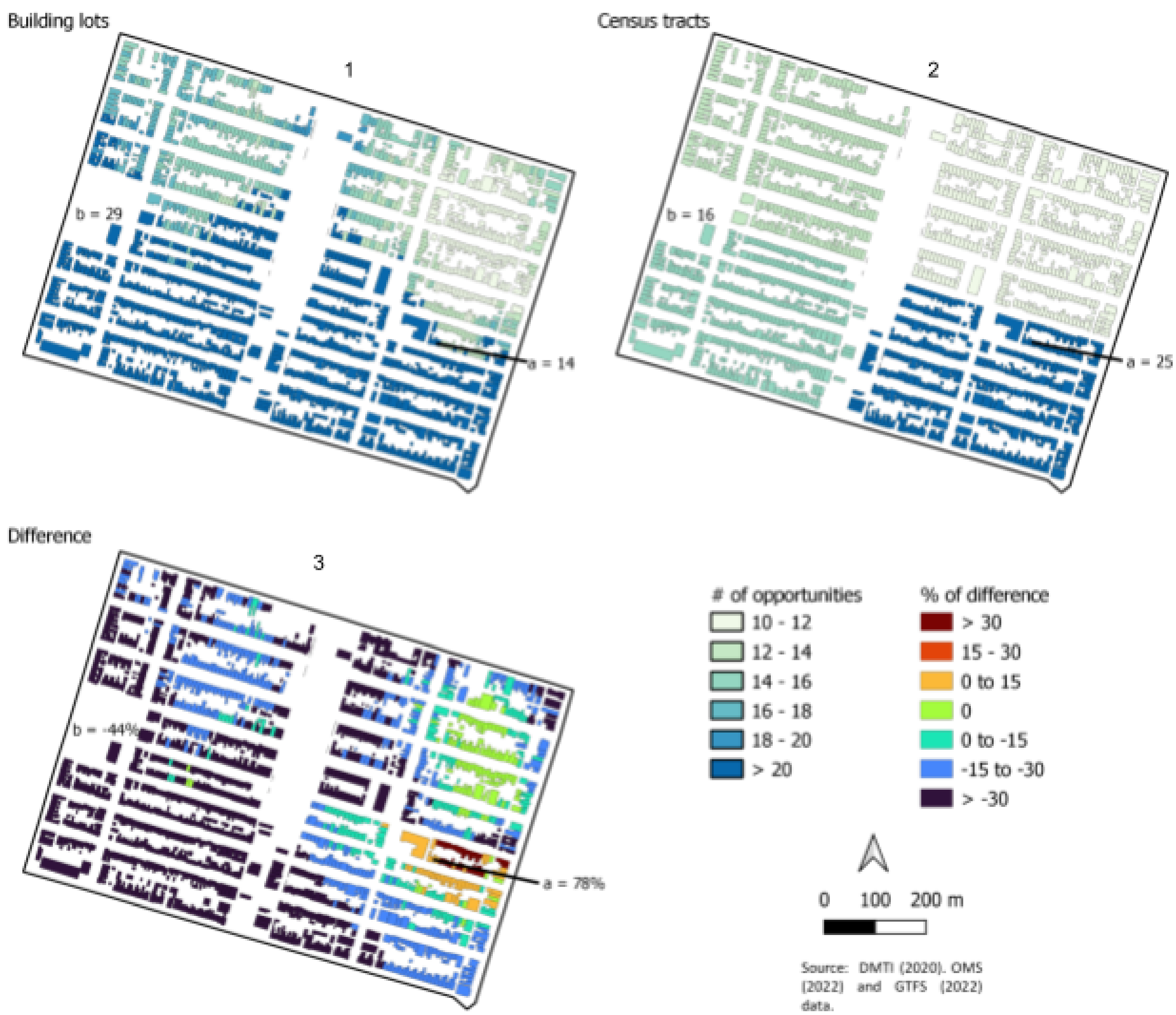

Figure 2.6: Example of how the misestimation levels were calculated using various combinations of spatial resolutions and temporal resolutions and segmentations

After this, I quantified how many buildings are misrepresented in every 35 combinations and identified the direction of the misestimation, either underestimated or overestimated.

Finally, I compared the information on accessibility overestimation and underestimation with various socioeconomic variables such as median household income (Statistics Canada, 2016).

This is useful for analyzing which population groups are affected by the choice of a given spatial and temporal resolution. An income threshold of $40,000 or less as a low-income group and > $40,000 as a high-income group we used, as has been a threshold used in some transportation studies (Manaugh & El-Geneidy, 2012).

4. Results

The results section is divided into four subsections. The first section shows the results when I measure accessibility at a building level. The second one shows the results of the MAUP on the accessibility to supermarkets; the third subsection shows the results of the MTUP, and the fourth one shows the results of both the MTUP and MAUP.

4.1 Accessibility to supermarkets

Figure 3.1 shows the average accessibility (number of opportunities/supermarkets) every minute between 10:00 am and 11:00 am at every building lot in Greater Montreal within a 30-minute threshold. The highest accessibility is located in the center of the island of Montreal (more than 50), where the highest density of supermarkets and the Subway system are located.

Outside the center of the island of Montreal, accessibility levels are still relatively high. However, accessibility decreases in the outskirts. In some areas, accessibility is zero (represented by red buildings), meaning that these areas lack access to any supermarket within a 30-minute threshold by public transit. The locations where these red buildings are situated are the ones requiring intervention in terms of land use or public transit.

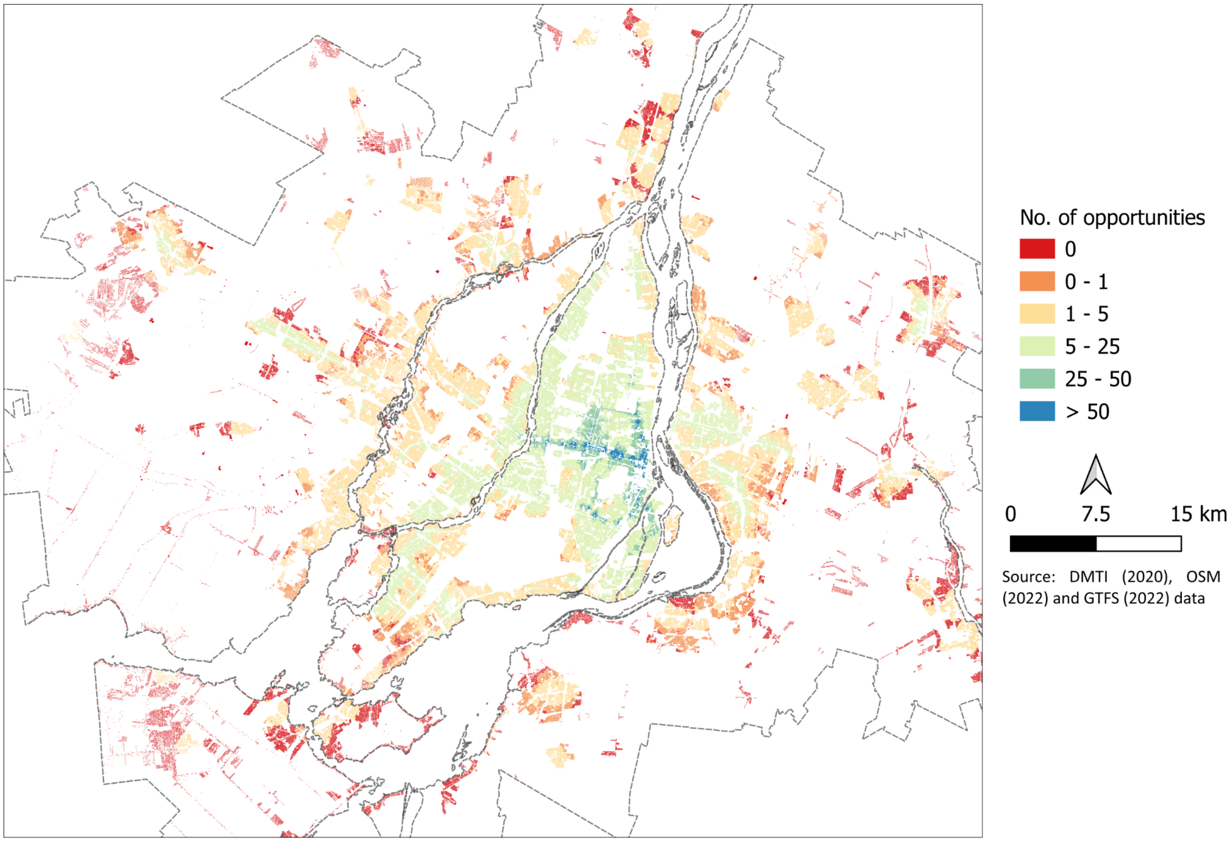

Figure 3.1. Average accessibility (no. of opportunities) at every minute from 10:00 am to 11:00 am at a building lot scale within a 30-minute threshold

Calculating accessibility at a scale of building lots every minute between 10:00 am and 11:00 am should be considered the best spatial and temporal resolution and temporal segmentation. Regarding the spatial resolution, the building lot is the smallest unit of analysis and is the de facto origin of most of the trips, and the centroid of a DA or CT is not the origin of the trips. In this case, only residential building lots were used in this analysis because it is where people live. Sometimes people can go to the supermarket after work, but people will always have to return home as it is because it is where they live.

On the other hand, 10:00 am to 11:00 am was chosen because it is the hour of the day in which most of the shopping trips are made, and the resolution of every minute during this period was chosen because it captures transit variation; coarser resolutions do not capture this transit variation.

However, as previously mentioned, the accessibility computation times at this scale are very high, so it is decided to add the spatial scales and choose the lowest temporal resolution (fewer minutes). Calculating the travel time matrices for the buildings of each minute of the day took around 123 computing hours. In the case of dissemination area matrices, it took about 1 hour, while for census tracts, it took about 10 minutes. To create those travel time matrices, I used an online R Server from McGill University's Department of Geography, which has 256 GB of Random-access memory (RAM) and has 24 central processing units (CPUs) to create the matrices quickly for Windows 11.

4.2 Modifiable Areal Unit Problem

Figure 3.2 quantifies the misestimating building lots when measuring accessibility at a dissemination area and census tract scale. In general, census tracts misestimate 88% of the buildings and dissemination areas 84%. Most buildings that are not misestimated are located in the same position as the centroid of the polygon or around the centroid. At the same time, the misestimated buildings are usually farther from the centroid. However, misestimation has two different directions: underestimation and overestimation. This research focuses on the levels of overestimation, which is more relevant in terms of urban planning because if a DA or CT overestimates accessibility, this might imply that the buildings have high, or at least enough accessibility and do not need any type of intervention (land use or transportation infrastructure). In contrast, if accessibility is measured at a building lot scale, accessibility is lower, and some areas would need some kind of intervention not seen at a DA or CT scale. Having said this, I found that dissemination areas overestimate 9.1% of the buildings, and census tracts overestimate 21% (Figure 3.2).[1]

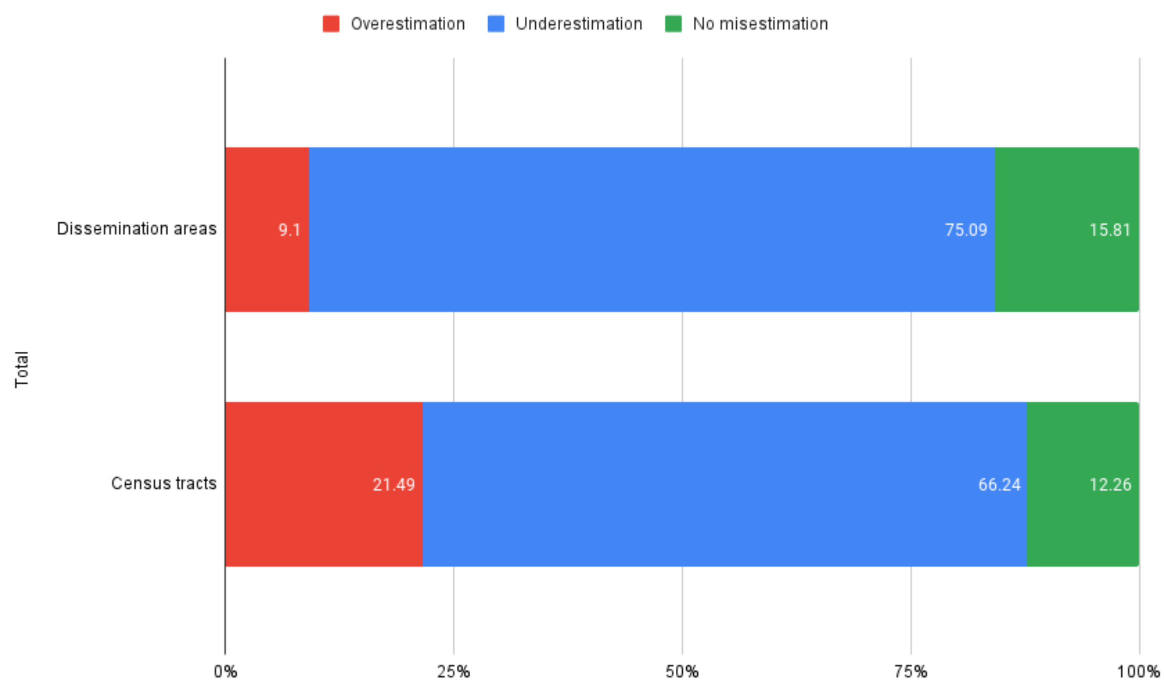

Figure 3.2. % of misestimation of dissemination areas and census tracts

[1] Another way to represent those results is in terms of population instead of building lots. However, there is not information about the population in every building.

Figure 3.3 shows the % difference between the average accessibility at every minute of the day at every residential building versus the centroid of census tracts and dissemination areas. The warm colors mean census tracts or dissemination areas overestimate accessibility, while cold colors mean underestimation; green colors mean no difference.

When comparing building lots and dissemination areas, most buildings on Montreal Island are underestimated by 5% to 25%. This underestimation increases in buildings outside the island with values between 25% and 50%. Those effects increase when comparing building lots and census tracts, in which the levels of misestimation increase in Greater Montreal and are higher than those found at a dissemination area level, and again the levels of underrepresentation and overrepresentation are higher in buildings located outside the island of Montreal, which are the areas in which the geographies are more prominent. The Modifiable Areal Unit Problem effects are higher in census tracts than in dissemination areas.

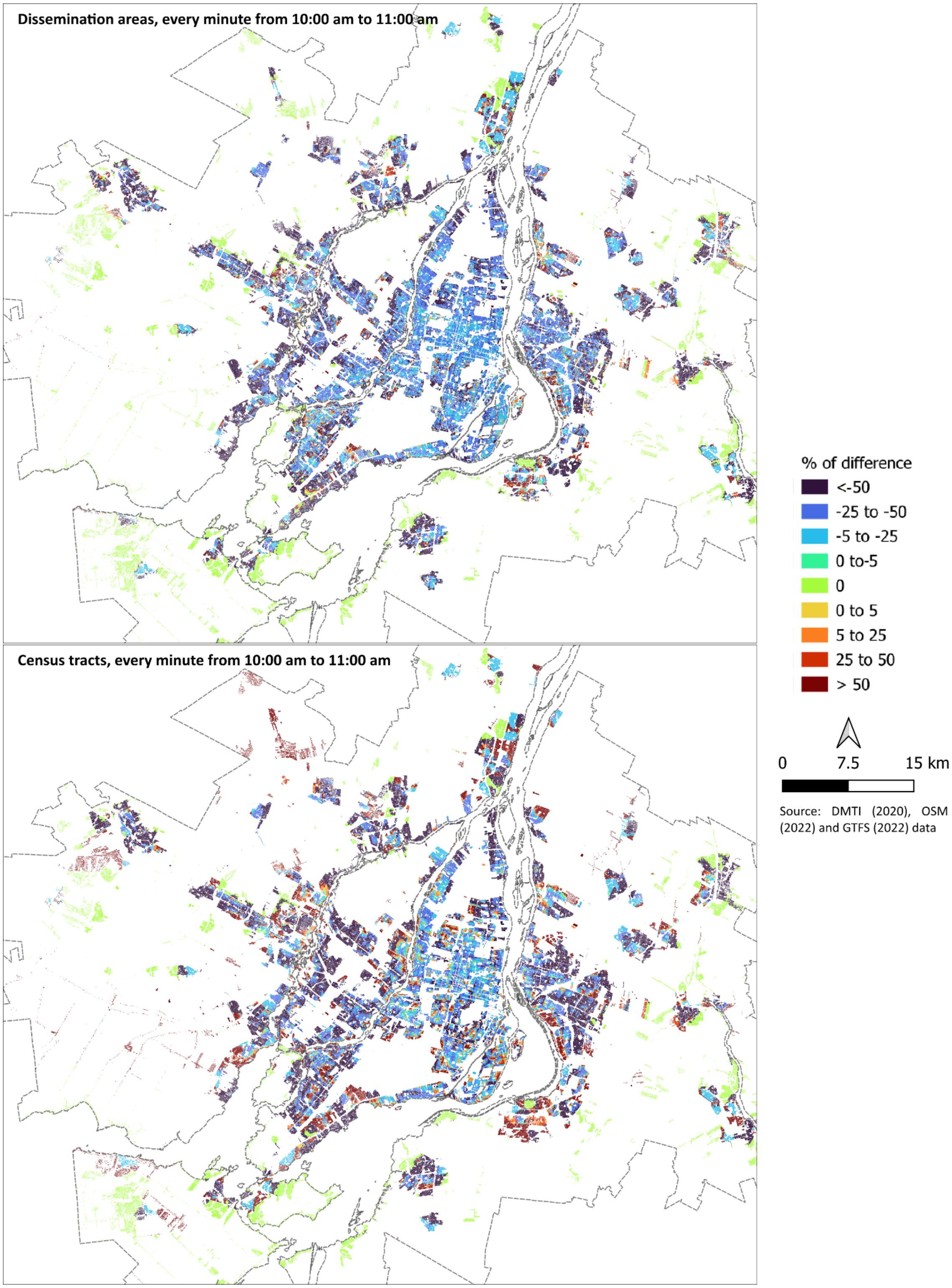

Figure 3.3. Accessibility difference between every minute at a building lot scale and every minute at a census tracts and dissemination scale from 10:00 am to 11:00 am

The level of misestimation varies depending on socioeconomic groups. Figure 3.4 shows the levels of overestimation in low-income and high-income groups. High-income groups are more overrepresented than low-income groups at both scales. Dissemination areas overestimate 9% of building lots in high-income areas and 4% in low-income areas. On the other hand, census tracts overestimate 22% of building lots located in high-income areas and 9% in low-income areas. As expected, DAs overestimate fewer building lots in low-income areas than in CTs. This is good news regarding equity because low-income groups are less overrepresented than the high-income group. However, still, there are 4% (dissemination areas) and 9% (census tracts) of buildings located in low-income areas, which are overestimated.

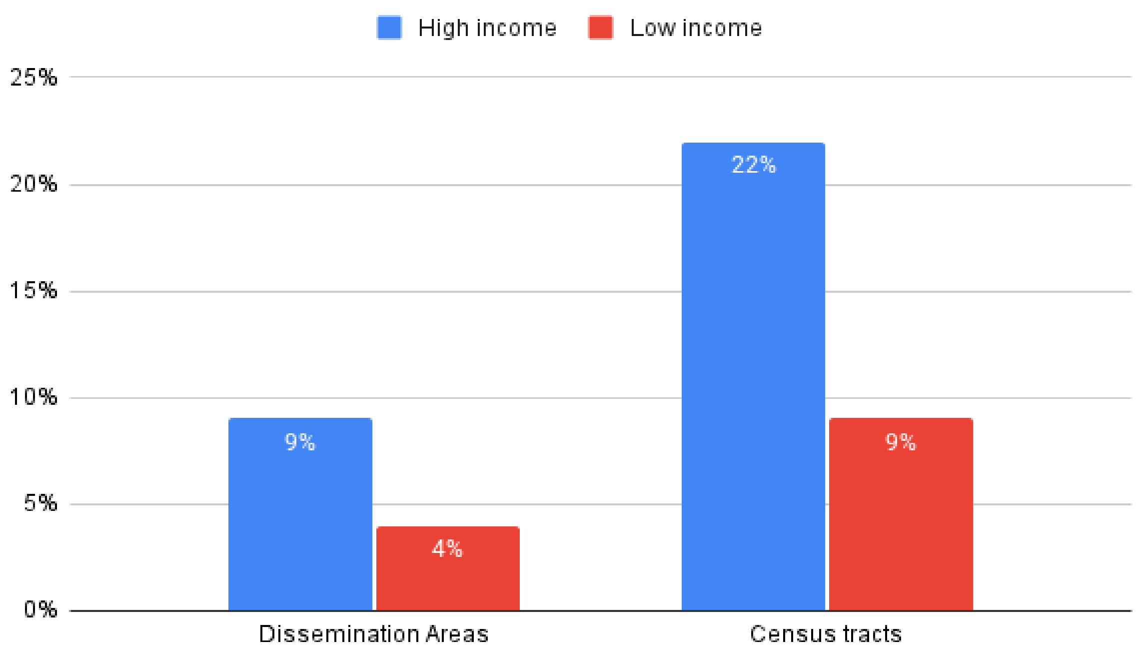

Figure 3.4. Overestimation of Montreal residential buildings when measuring accessibility at different spatial scales per socioeconomic group

4.3 Modifiable Temporal Unit Problem

I mentioned that aggregated spatial resolutions misestimate accessibility. This subchapter also found that using different coarse spatial resolutions and segmentation schemes misestimate accessibility in relation to the base combination (every minute from 10:00 am to 11:00 am at a building lot level).

The ‘x’ labels in Figure 3.5 are coded as follows and apply to the entire document. The first letters, 'bld,' 'ct,' or 'da,' indicate the spatial scale: building lots, census tracts, or dissemination areas, respectively. The next characters indicate the temporal segmentation, which can be either 10:00-11:00 am or 8:00-9:00 am, representing the time period being compared. The final characters indicate temporal granularity. For example, 'bld_10am_every5' means that the combination is compared to our baseline is every five minutes from 10:00 am to 11:00 am at a building lot scale.

Figure 3.5 shows the quantification of the misrepresentation of buildings lots when I compare several temporal resolutions using the same temporal segmentation (10:00 am to 11:00 am). The results indicate that the lowest percentage of misestimation is at every five minutes (66%), which is the finest resolution (after every minute). The misestimation increases as coarser temporal resolutions are used. Also, after the temporal resolution of every ten minutes, the temporal resolution with the highest misestimation level is the coarsest (sampling only one minute), with 82.15%.

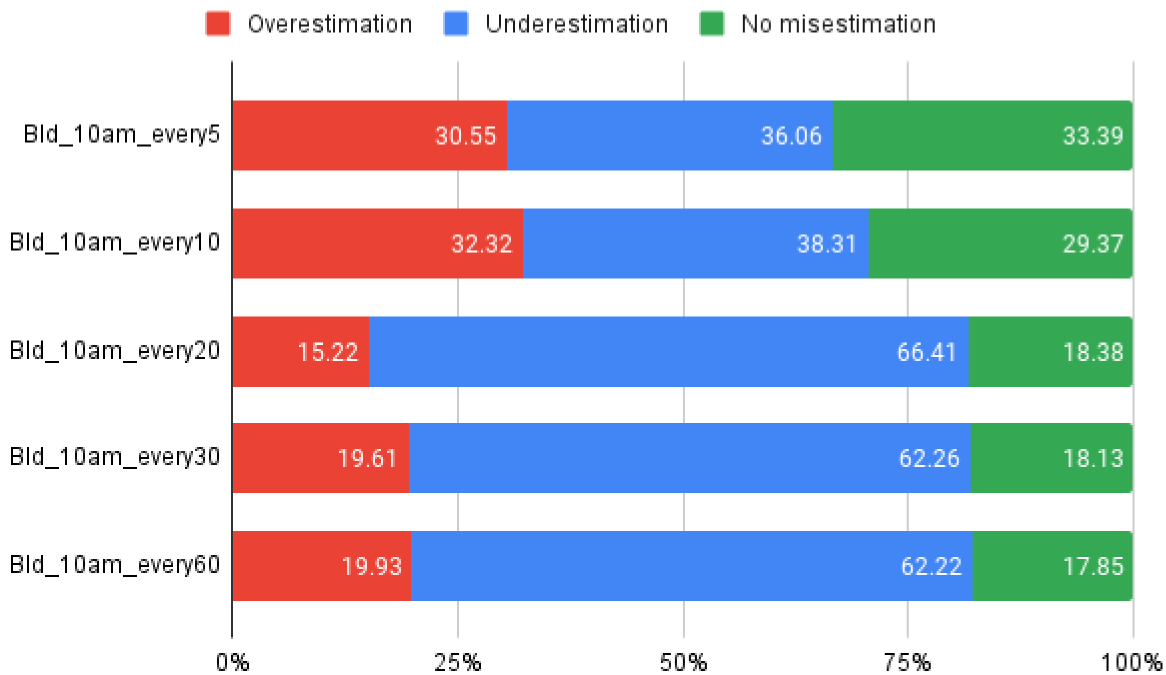

Figure 3.5. Percent of misestimation of temporal resolutions (10:00 am to 11:00 am)

Figure 3.6 shows the average percentage of underestimation and overestimation and indicates that the average percentage of underestimation and overestimation increases a coarser temporal resolutions are used, being every 60 minutes, the resolution with the highest average and every five minutes with the lowest average.

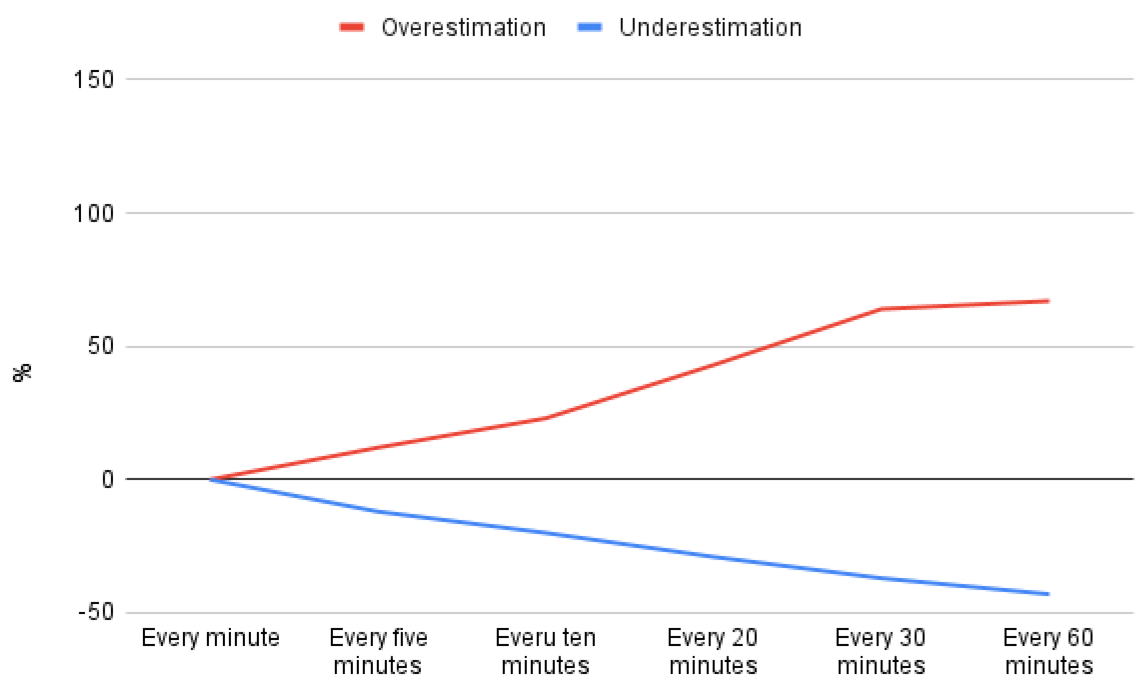

Figure 3.6. The average percentage of overestimation and underestimation (10:00 am to 11:00 am)

Figure 3.7 shows the misestimation levels in Montreal when calculating accessibility every five minutes and every 60 minutes from 10:00 am to 11:00 am at a building lot level. The resolution every five minutes shows small levels of misrepresentation, and if the building is misrepresented, it is usually smaller than 25%. In terms of every 60 minutes, the levels of misestimation, specifically underestimation, increase in the entire metropolitan area, with the highest values outside the main island of Montreal, which are areas with low frequency and only a few options for public transport.

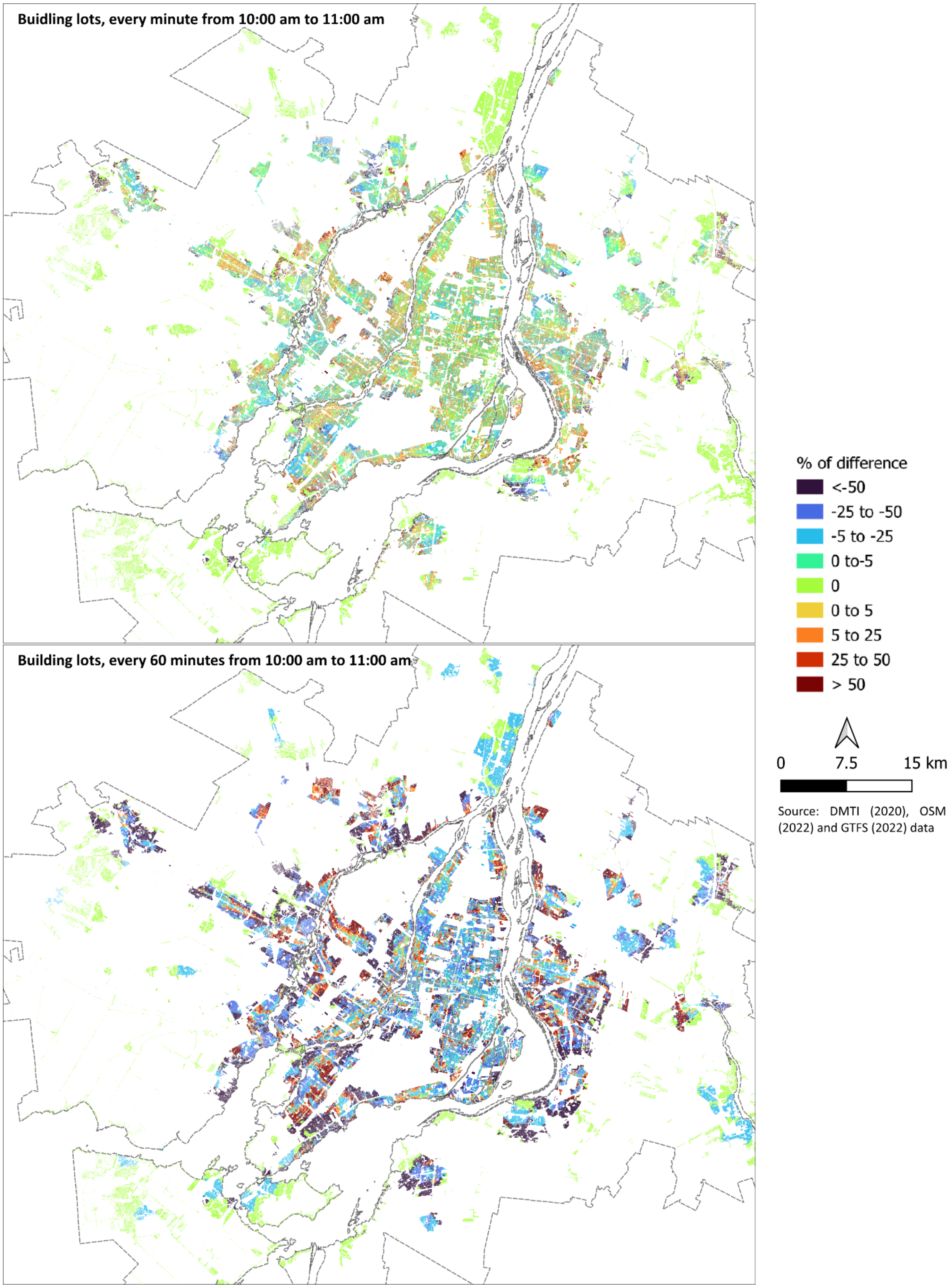

Figure 3.7 Accessibility difference between every minute and every five and 60 minutes from 10:00 -11:00 am at a building lot scale

Figure 3.8 shows what happens when I compare every minute from 10:00 am to 11:00 am to various temporal resolutions from 8:00 am to 9:00 am. The overall level of misrepresentation remains stable for all the temporal resolutions with around 81%-83%, which also are similar to most of the values from 10:00 am to 11:00 am. Also, the levels of overestimation are higher and remain stable for all the temporal resolutions at around 35%, which are higher or similar to the overestimation levels for the temporal resolutions from 10:00 am to 11:00 am.

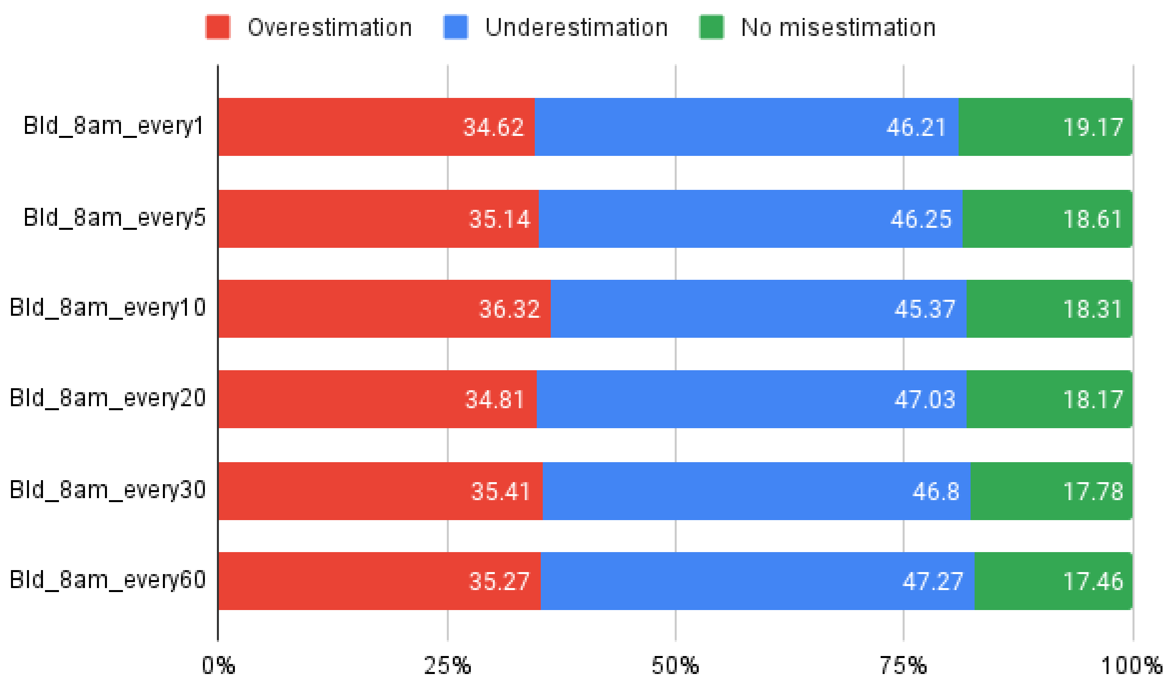

Figure 3.8. % of misestimation of temporal resolutions (8:00 am to 9:00 am)

However, Figure 3.9 shows differences in the % average of overestimation (Figure 3.9), the average of overestimation increases as I move through the temporal resolutions. This has the same effect as seen when compared to the temporal resolutions from 10:00 am to 11:00 am but the overestimation average is higher in this case. The underestimation average also increases as moving throughout temporal resolutions but remains slightly lower than the average calculated for temporal resolutions from 10:00 am to 11:00 am.

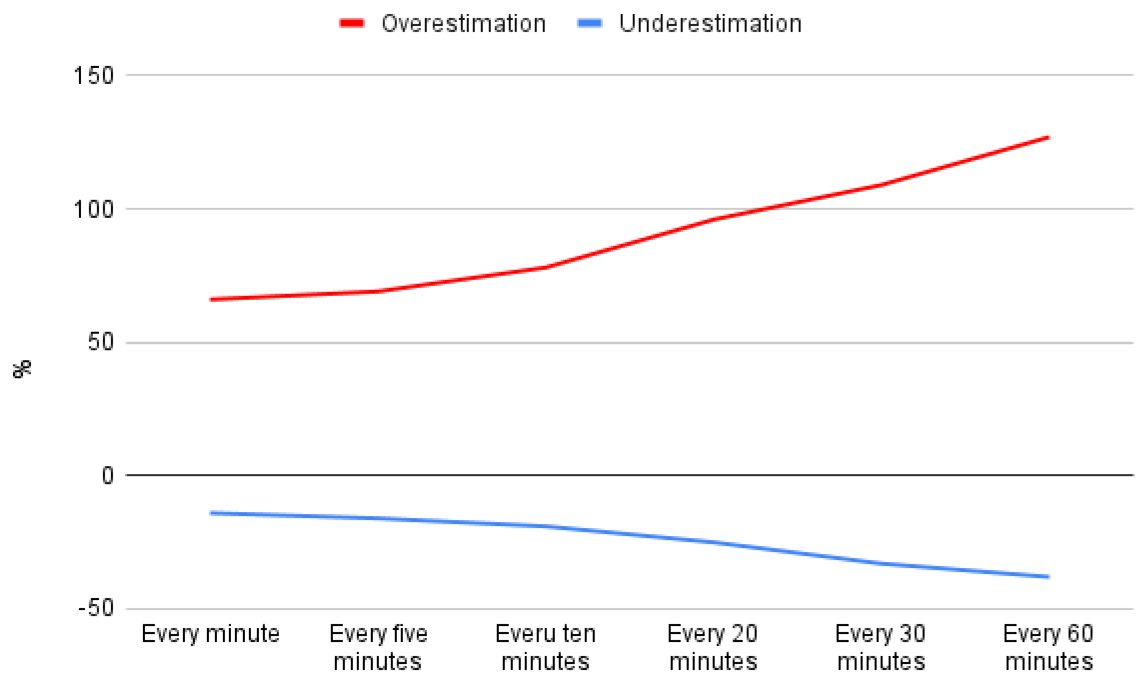

Figure 3.9. Average percentage of overestimation and underestimation (8:00 am to 9:00 am)

Figure 3.10 shows the misestimation levels of building lots using every minute and once during the period (every 60 minutes) from 8:00 am to 9:00 am at a building lot level. At every minute of the day, the overestimation levels are high overall (in comparison to the same temporal segmentation). It is smaller than 25% on the main island of Montreal and with values higher than 50% in some areas outside the island, such as Longueuil. However, using the every 60 minutes resolution, the overestimation higher than 50% increases in the city, specifically in Longueuil, Northern Ring, and the southwest portion of the main island of Montreal.

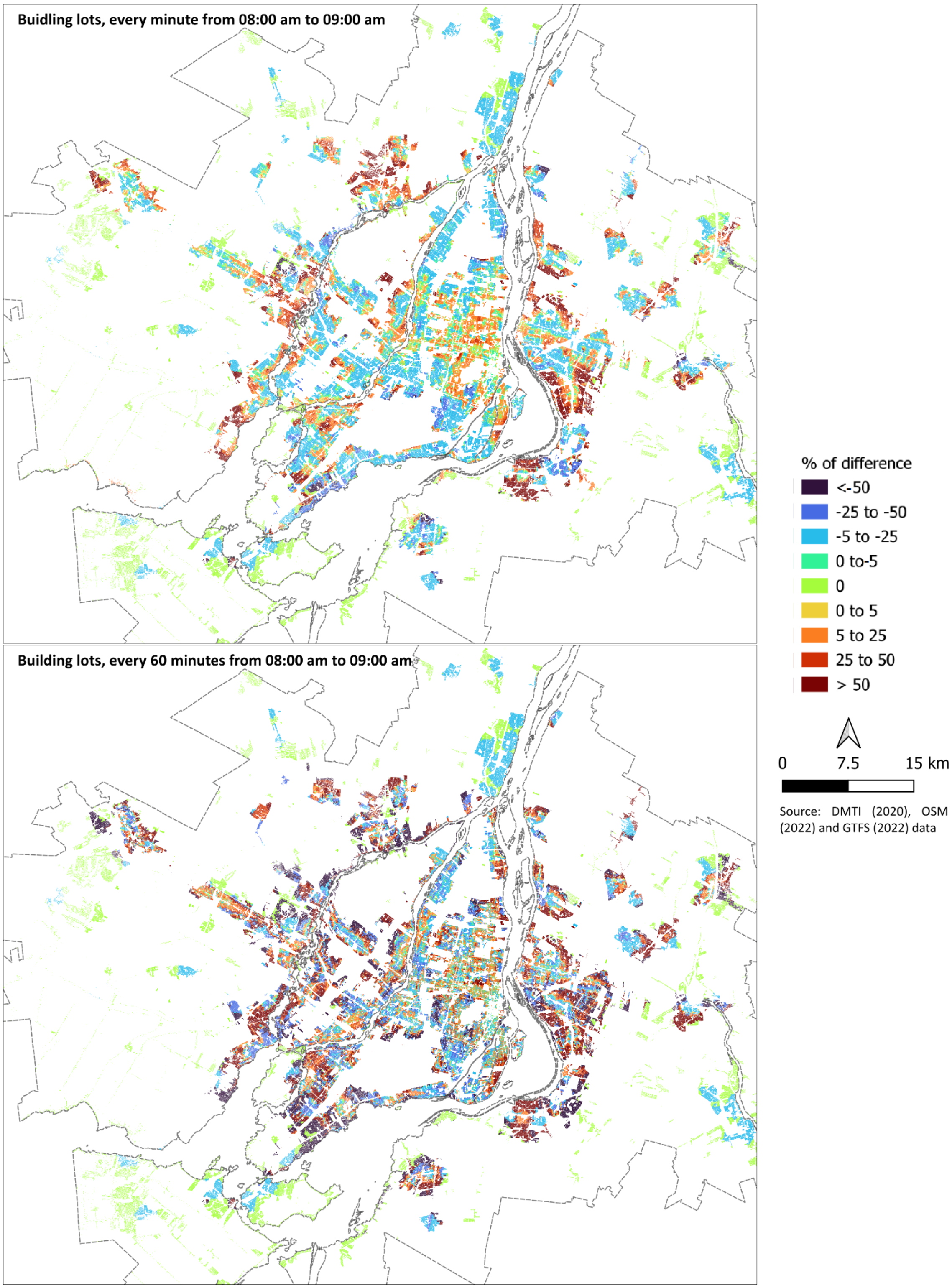

Figure 3.10 Accessibility difference between every minute at a building lot scale from 10:00 am to 11:00 am and every minute and every 60 minutes from 8:00 am to 10:00 am at a building lot scale

Understanding how the public transit schedule works are essential to understand those effects. If we consider that most of the trips to supermarkets are made during off-peak hours (10 am in the case of Montreal), using temporal segmentation between 7:00 am to 9:00 am (peak hours) or with public transport data that does not account for the changes in frequency service, as many studies do will overestimate the levels of accessibility and will not reflect the levels of accessibility that are closer to reality. For those temporal segmentations, the best thing to do is to use the average of every minute to account for the variation. The results indicate that the larger the sample, the greater the accounts for the variation and the lower the misestimation. The smaller the sample, the lesser it accounts for the variation and the higher the misestimation.

Figure 3.11. Shows the differences in using several temporal resolutions and segmentations between high-income and low-income groups regarding overrepresentation levels. Regarding the differences using the temporal resolutions from 10:00 am to 11:00 am, buildings in low-income groups are more overrepresented when measuring every five minutes and every 10 minutes. However, for coarser resolutions in this temporal segmentation. Now, if it is compared to our baseline (every minute from 10:00 to 11:00 am at a building lot level) but now to several temporal resolutions from 8:00 am to 9:00 am. The opposite happens, as low-income groups are more overrepresented in coarser temporal resolutions. This is not the end of the story. Some areas, mainly in the central part of the island of Montreal, where the accessibility is higher, and low-income groups live, the level of overestimation could be more prominent in absolute terms but not in relative terms.

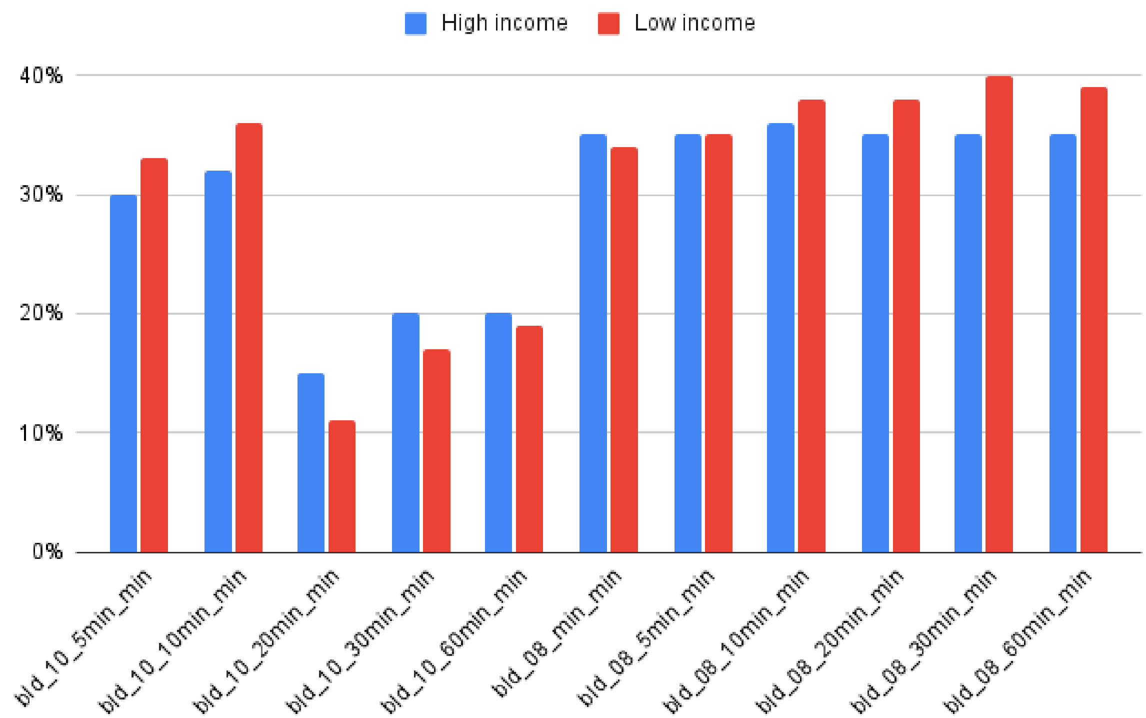

Figure 3.11. Overrepresentation of Montreal residential buildings when measuring accessibility at different spatial scales per socioeconomic group

4.4 Modifiable Spatio-Temporal Unit Problem

In the last two subsections, the results indicated that when moving through a spatial resolution and a temporal resolution and segmentation. However, the effects were studied separately. Now, this subsection shows what happens when moving through both spatial and temporal resolutions and temporal segmentation.

Figure 3.12 shows the difference in the average accessibility means between all the possible combinations. The average accessibility increases when moving from one spatial resolution and temporal segmentation to another with some exemptions. The lowest absolute value corresponds to a building lot scale every 20 minutes (6.3). Also, In general, dissemination areas at 10:00 -11:00 am have the lowest accessibility (6.6), which is lower than the building lot level at every minute at 10:00 am, our baseline. After dissemination areas from 10:00 am to 11:00 am, the next group in terms of the average accessibility is at a building lot level from 10:00 to 11:00 am and then from 8:00 am to 11:00 am, which is expected. Then there is an increase in the average accessibility as using coarser spatial resolutions and temporal segmentations: dissemination areas from 8:00 am to 9:00 am, census tracts from 10:00 am to 11:00 am, and then census tracts from 8:00 am to 9:00 am, which would be the least ideal combinations.

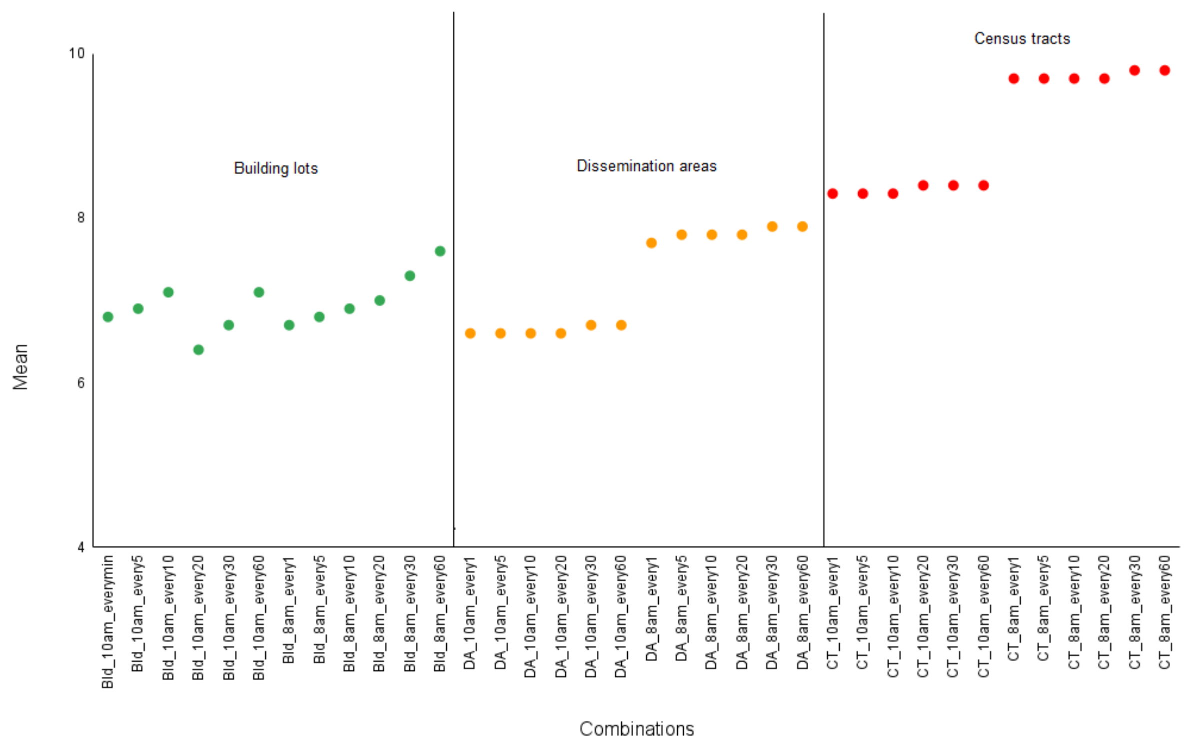

Figure 3.12. Mean accessibility of all the possible temporal and spatial combinations[2]

[2] All the means are different in relation to building lot at every minute (p-value < .05) except for building every 12 hours.

Figure 3.13 shows the misestimation of buildings for all the combinations of temporal and spatial resolutions for both temporal segmentations (10:00 am to 11:00 am and from 8:00 am to 9:00 am).

The results indicate that the misestimation increases as moving throughout spatial scales and temporal segmentations and resolutions. It was noticed that the combination with the lowest level of misestimation is every minute of buildings from 10:00 am to 11:00 am with around 66%. The highest levels of misestimation belong to census tracts from 8:00 am to 9:00 am, specifically when calculated at every 20, 30 and 60 minutes with around 88%. Figure 3.13 also shows that the highest levels of overrepresentation are higher for temporal segmentations from 8:00 am to 9:00 am in relation to the same spatial and temporal resolutions from 10:00 am to 11:00 am.

Also, the higher levels of representation are at a building lot scale, followed by census tracts and dissemination areas. One of the reasons for this effect could be that the differences between the resolutions are small in absolute terms at the same spatial scale (building lot) but are small at coarser spatial scales (CTs and DAs).

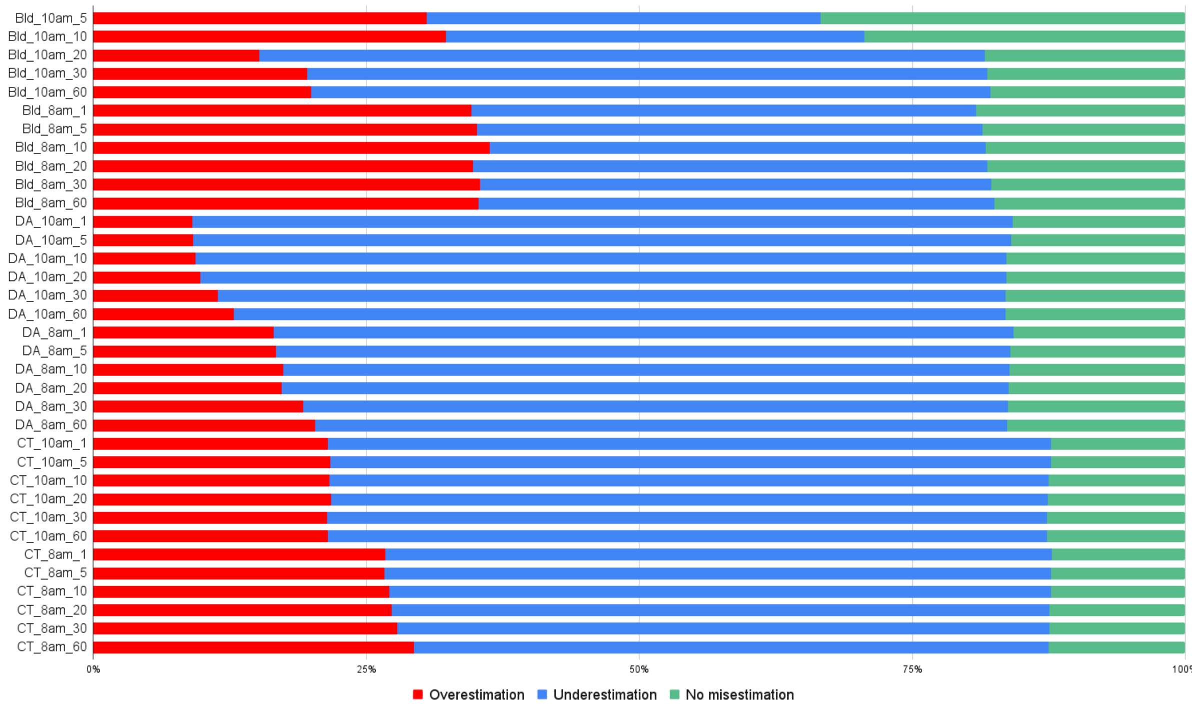

Figure 3.13. misestimation of buildings using several spatial and temporal resolutions

Figure 3.14 shows the average levels of overestimation and underestimation, which helps us understand how strong those levels are. The average percentage of overestimation and underestimation increases as moving to coarser spatial scales, temporal resolutions, and segmentations. The highest average overrepresentation of buildings is at a census tract scale, measured only once between 8:00 am and 9:00 am, which is the coarser temporal and spatial resolution and the not optimal temporal segmentation. The lowest average of overrepresentation is every 5 minutes from 10:00 am to 11:00 am at a building lot level, which is also the finest (after our baseline) spatial and temporal combination and the optimal temporal segmentation. Regarding underestimation, the highest average is every 30 minutes from 10:00 am to 11:00 am at a census tract level, followed by once from 8:00 am to 9:00 am at a census tract level, which is the least ideal combination. The lowest underestimation average is again every 5 minutes from 10:00 am to 11:00 am at a building lot level. Those results show that calculating the % of buildings being overrepresented is one of many things to consider. It is also essential to consider how strong is this overrepresentation or underrepresentation.

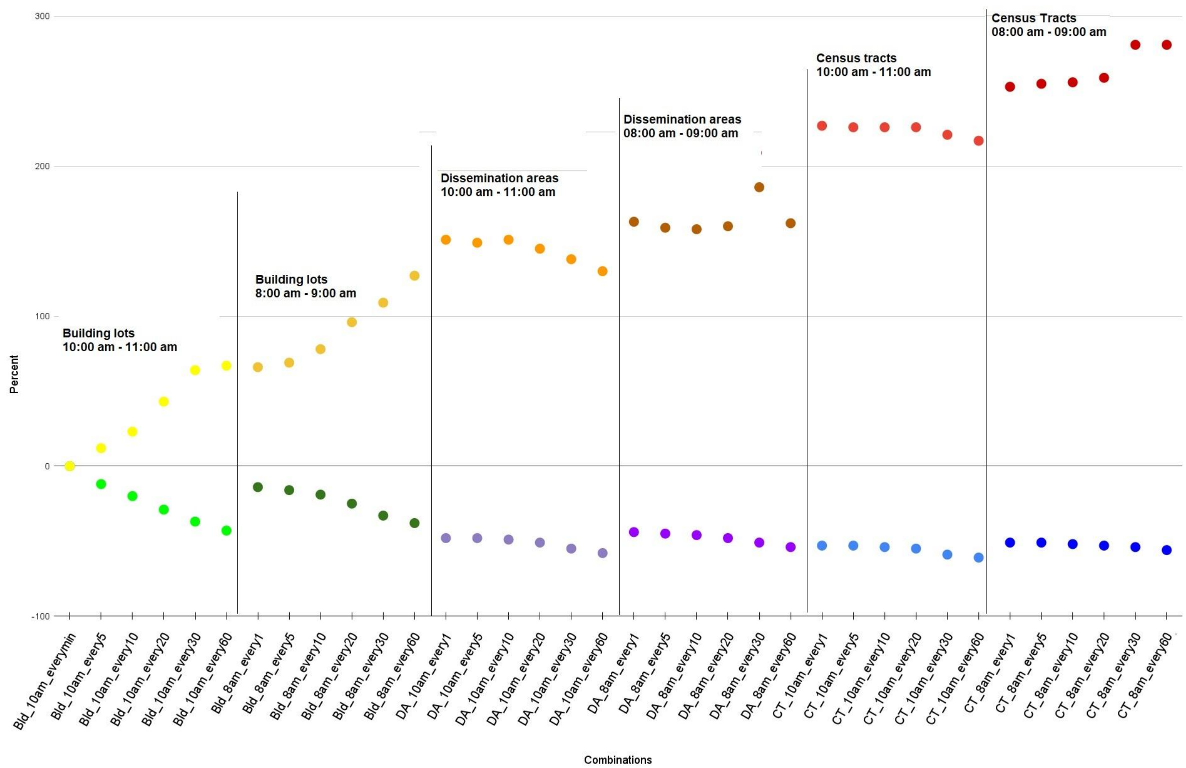

Figure 3.14 Average percentage of accessibility misestimation for all the possible temporal and spatial combinations

Figure 3.15 shows the levels of misestimation every 60 minutes from 8:00 am to 9:00 am at a dissemination area and census tract level. Those combinations were chosen because they are the coarsest temporal and spatial resolutions during the peak hour. The levels of misestimation at a dissemination area level are lower than those at a census tract level in the entire city.

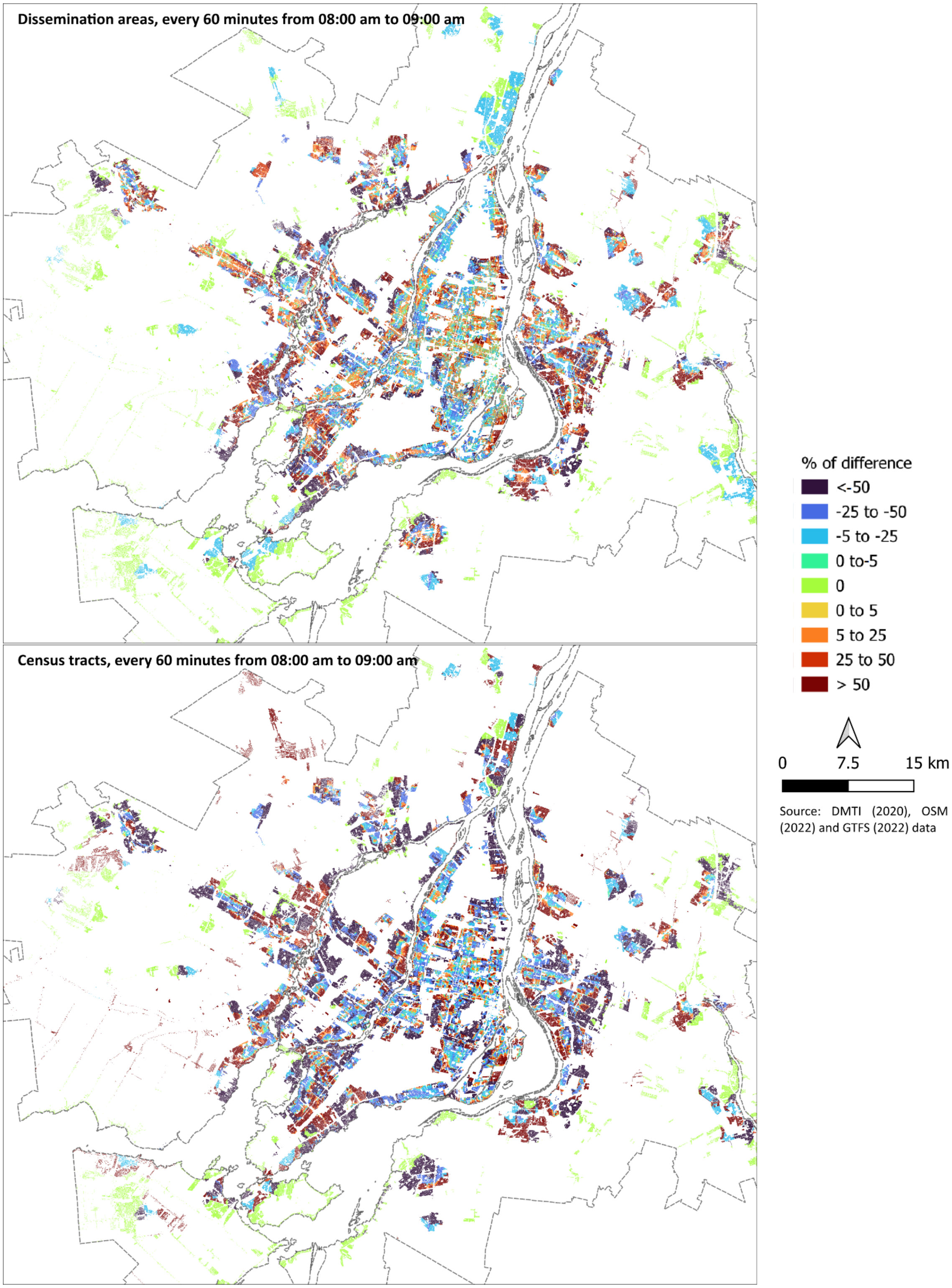

Figure 3.15. Accessibility difference between every minute at a building lot scale from 10:00 am to 11:00 am and every 60 minutes from 8:00 am to 10:00 am at a dissemination area and census tract level

Looking at all the possible combinations, the overestimation levels are higher for high-income groups in most combinations, specifically at a dissemination area and census tract scale (Figure 3.16).

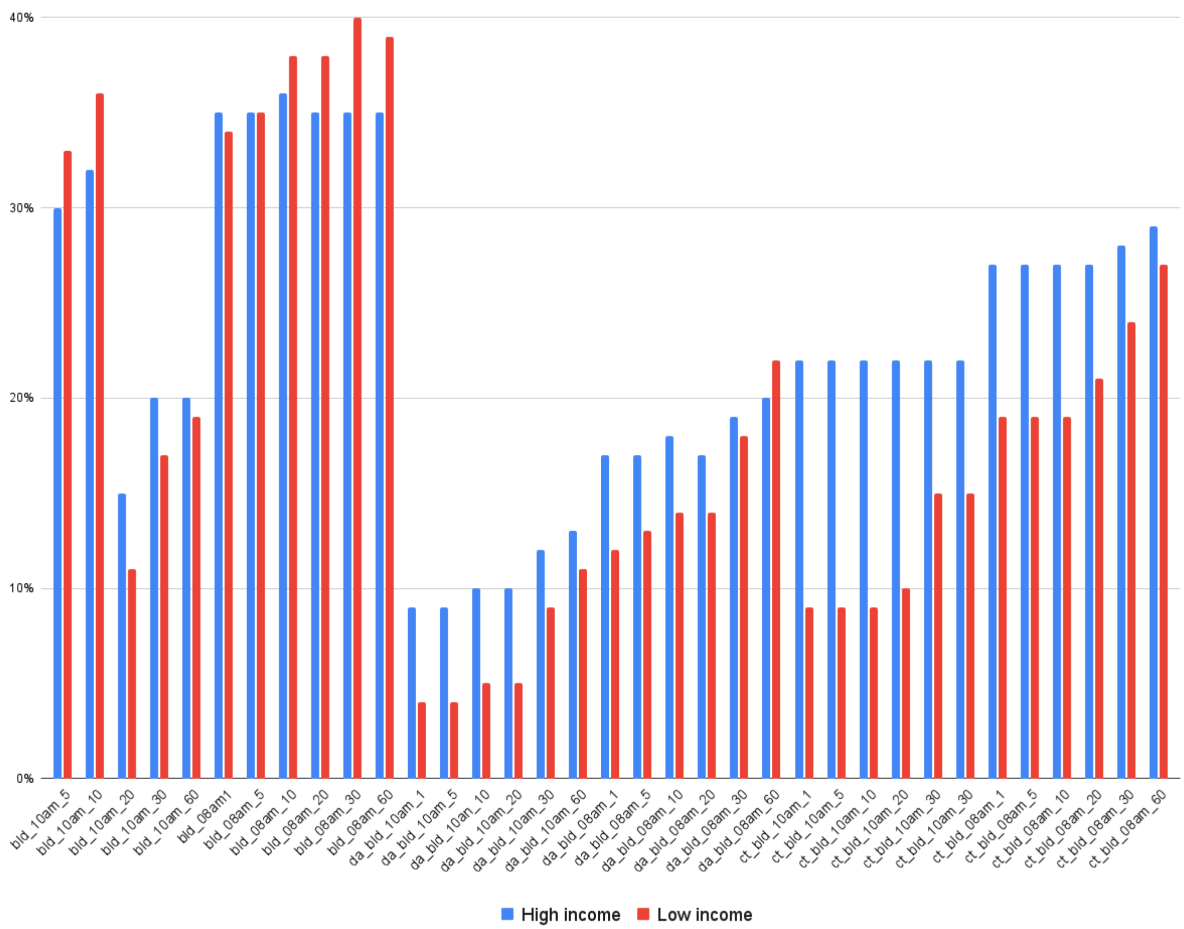

Figure 3.16. Overrepresentation of Montreal residential buildings when measuring accessibility at different spatial scales and resolutions per socioeconomic group

5. Discussion

The Modifiable Areal Unit Problem and the Modifiable Temporal Unit Problem affect accessibility measurements to supermarkets in Montreal, Canada, when studied separately but also interact and make the effects more pronounced. This effect is called the Modifiable Spatio Temporal Unit Problem.

Firstly, I measured accessibility at a building lot scale every minute between 10:00 am and 11:00 am, the finest scale of analysis and the hour of the day with the highest share of shopping trips. Performing this type of analysis has its pros and cons. Among the pros is that it shows a result closest to reality. I can identify exactly where people that do not have access to supermarkets live and can help in terms of transport and land use planning to implement the infrastructure. I identify where residential building lots cannot access supermarkets in urban planning. One of the disadvantages is the displaying of the information. Mapping building lots on a map showing the entire metropolitan area could be challenging to read. To plan efficiently, it is necessary to zoom in on the areas of interest. In terms of computing times, it could take more than 750 times more than measuring this at a census tract scale. One of the most important disadvantages is that the Census Canada data is only aggregated at a DA and CT scale, with no information at a building lot level. In this research, every building is given the same values for socioeconomic variables as the DA in which it is located. This, of course, is another problem that can be explored in the future, and it is essential to consider. Also, in some instances, the General Transit Feed Specification (GTFS) does not have information regarding the variation throughout the day, considering that the transportation frequency remains constant throughout the day, mostly using the frequency of the morning peak. Due to these disadvantages, most studies use coarse temporal and spatial resolution, or inadequate temporal resolution, which brings errors or biases such as MAUP and MTUP.

Regarding the Modifiable Areal Unit Problem, I found that when using coarser spatial scales, accessibility levels are misestimated: the coarser the spatial scale, the higher the underestimation and the overestimation of the results. I found that dissemination areas misestimate 84% of the buildings, of which 9% are overestimated and 75% underestimated; census tracts misestimate 88% of the buildings, of which 21% are overestimated and 67% are underestimated. This statement has important implications for urban planning. When aggregating spatial scales, it means some building lots have more accessibility than they do when measuring at a building lot scale, meaning that the buildings in those areas do not require land use or transport interventions. One of the reasons for this misestimation is that when using the centroid of a DA or CT, it means that all the building lots in that area are assumed to have accessibility levels as the accessibility in the center of the area. However, this is different because the buildings are distributed within the area. So the further the building lot is from the centroid of the polygon, the higher the misestimation. To mitigate the effects of MAUP, some researchers use the weighted population centroid to measure accessibility instead of the actual centroid (as I did in this research). The logic behind this idea is that regular centroids can fall in an area without connection to the street network, public transit stops, or population centers. This causes the misestimation to increase. Using the population-weighted centroid can reduce this effect in most cases because the centroid will be near the population. However, it will reduce overestimation in populations near the centroid and increase overestimation in places further from the weighted population centroid. The best way to reduce those effects is to use building lots as the unit of analysis; if it is not possible, use less aggregated spatial scales and acknowledge the MAUP effects.

The Modifiable Temporal Unit Problem is more complex to interpret. I examined temporal segmentation and aggregation. Taking into account that the highest share of trips to shopping is between 10:00 am and 11:00 am (off-peak), measuring accessibility at this hour of the day is the most precise or representative time to measure accessibility to supermarkets. Most studies choose a temporal segmentation between 7:00 am and 9:00 am, which is peak hour. In this case, I selected a temporal segmentation from 8:00 am to 9:00 am to compare to 10:00 am and 11:00 am. The results indicate that measuring from 8:00 am to 9:00 am overestimates accessibility as it is the hour of the day with the highest transportation frequency. This means that some building lots have more access to supermarkets during that period, but studying accessibility at this time does not represent the real behavior (in terms of the hour people are likely to go to the supermarkets). Regarding temporal aggregation, the coarser (smaller sample of minutes), the higher the misestimation; the finer (bigger sample of minutes), the lesser the misestimation. In this research, our baseline was accessibility at every minute, accounting for the period's variation. Using smaller samples increases the misestimation. The direction of the misestimation (underestimation or overestimation) will depend on which sampled minutes are used. For example, Figure 3.17 shows the variation of accessibility at a building level throughout the day and the daily mean. Choosing any minute of the day above the mean line, overestimation levels will increase, but if choosing a minute below the mean, underestimation will increase. Small sampling has a considerable impact, so it is recommended to make large samples to account for this variation. So the results indicate that if coarser temporal resolutions are used, along with the most appropriate temporal segmentation, the misestimation levels (overestimation and underestimation) will increase.

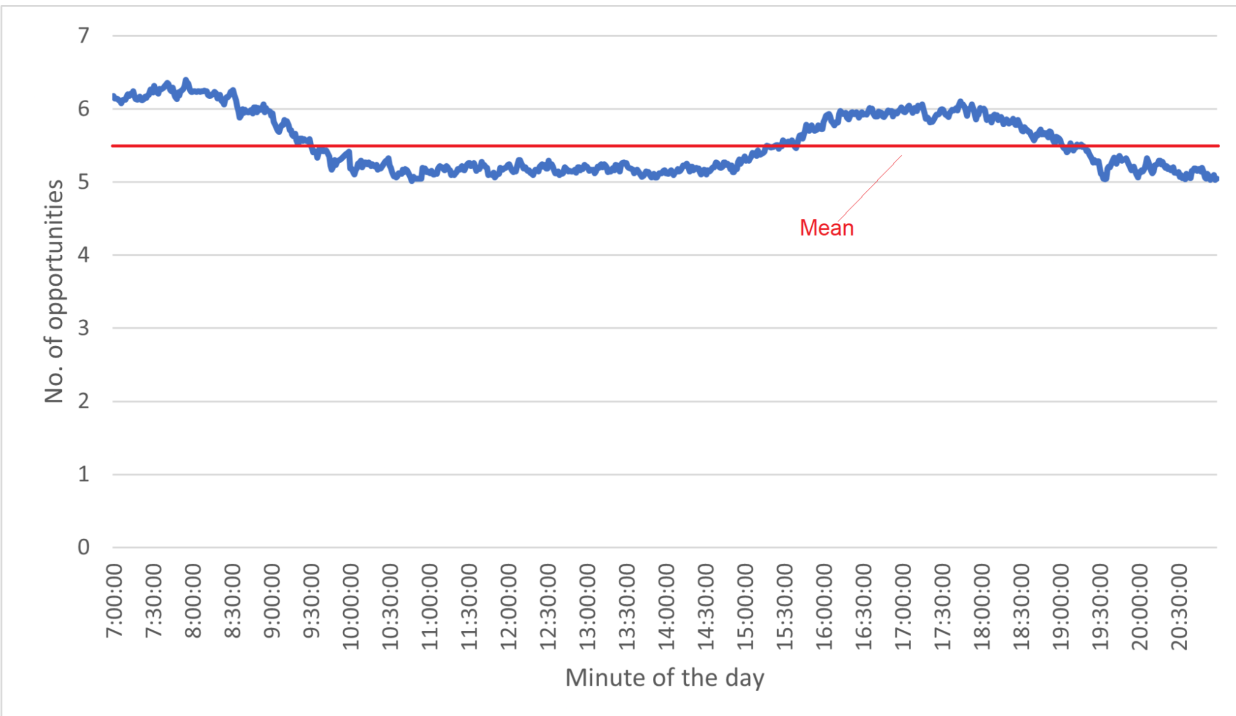

Figure 3.17. Accessibility variation throughout the day

I found that MAUP and MTUP have effects on accessibility separately, but I also found that both problems interact. The coarser the temporal and spatial resolution and the choice of not the most optimal temporal segmentation, the higher the misestimation and the stronger the underestimation and overestimation. For example, the second best combination (after every minute from 10:00 am to 11:00 am at a building lot scale) is every five minutes from 10:00 am to 11:00 am at a building lot scale. I found that it only misestimates around 66% of the buildings, and looking at the average misestimation, it is only 12% for both overestimation and underestimation. Let's consider the least optimal combination, which is only one sample from 8:00 am to 9:00 am at a census tract level. The results will show that the average overestimation of buildings is 281% and 56% for underestimation (the highest level of misestimation is every 30 minutes from 10:00 am to 11:00 am at a census tract level).

These results indicate that the temporal segmentation has a more significant effect on the overestimation of buildings; to a greater extent, it could be because sampling minutes correspond to the period with the highest frequency of public transport. In terms of the temporal resolution, the misestimation will increase when using coarse temporal resolutions. The overestimation or underestimation will depend on whether the sampling average is higher or smaller than the average of every minute.

On the other hand, the spatial component also affects the misestimation of accessibility. This is mainly due to the location of the building to the centroid of the area (census tract or dissemination area), the street network, and the public transport stations. The further away it is from the centroid, the greater the misestimate. The direction of the misrepresentation will depend on the location relative to public transport stations. For example, if the building is closer to a public transportation station than the centroid, the building will have more accessibility than the area, causing the area to underestimate. On the other hand, if the centroid is closer to a public transport station than the building, the centroid will have more accessibility so that will overestimate accessibility.

Also, I found that building lots in high-income areas are more overestimated in most temporal and spatial combinations. One of the reasons is that low-income groups are located in areas with many transportation options during the day, while high-income groups do not have access to many options or transportation is not frequent. The low-income groups have higher levels of absolute misestimation but lower relative misestimation.

Although it is necessary to be aware of the effects of choosing a specific spatial and temporal resolution in any geographic study, no literature studies the effects of using aggregated spatial and temporal resolutions simultaneously or a Modifiable Spatio-Temporal Unit Problem (MTSUP). The first resource that mentions the Modifiable Spatio-Temporal Unit Problem is a blog by Jacquez (2011) stated, "MSTUP arises as the intersection of MAUP and MTUP, it considers not only that the spatial sampling frame may be changing, but that the temporal sampling frame is also changing. What happens to mean and variance estimates when one goes from county to zip code, and from weekly to annual sampling frames?". The author mentions that in 2011 he googled the term "Modifiable Spatio Temporal Unit Problem" on the Internet and it returned zero results. By the day of the publication of this thesis, when I googled the term it returns four results.

The second one is by Martin et al. (2014). They argue that it is necessary to have finest temporal and spatial representations in population modeling to address the modifiable spatiotemporal unit problem, citing Jacquez (2011) as a pioneer of this term. Although they research to analyze differences in outcomes, they do not quantify the effects of using coarse spatiotemporal representations.

The third one is a dissertation thesis by King (2018) credits Jacquez's blog (2011) and mentions that the MAUP can be mitigated using the finest possible spatial resolution, the MTUP using the finest possible temporal resolution and the MTSTUP can be mitigated using the finest spatial and temporal resolution. Despite the above, he only mentions the three problems in the research without measuring the effects.

Finally, Mordian (2022) only examines the effects of the spatial scale in the monitoring of drought and early warning systems; and, without performing any analysis, mentions that there is literature that shows similar effects depending on the temporal scale on monitoring drought studies. Therefore, the author mentions evidence of a spatiotemporal scale interaction in the results of drought monitoring and acknowledges Martin et al. (2015) as one of the studies that have approached the MSTUP. Mordian (2022) also concludes that “These interactions between spatial and temporal scaling effects must be studied further to elucidate their effects on the results of drought monitoring and early warning systems.” However, this study does not consider which is the most accurate temporal and spatial component in order to measure the effects.

Although Modifiable Spatio Temporal Unit Problem exists, most of these hints only mention the importance of considering the effects of spatial and temporal resolutions. There is no study in geography, or specifically in transport or accessibility studies that quantifies both effects and there is no literature that structures the MTSUP either. This research measures the Modifiable Spatio Temporal Unir Problem effects on accessibility to supermarkets using the coarsest temporal and spatial resolution and adequate temporal segmentation.

This study does have some limitations; for example, to better understand the effects of the MTSUP it is essential to measure accessibility to more facilities (e.g. parks, jobs, hospitals) to see if the results are similar. Also, it is essential to understand the effects of using more temporal and spatial combinations not only from the components used (temporal aggregation and temporal scale) but to incorporate the rest of the components of both problems (temporal boundary and spatial zoning).

An additional constraint of this study is the lack of census data at the level of individual building lots, including population, total number of floors, and overall area for each residential building. Possessing this dataset would significantly enhance our comprehension of the extent to which the population is impacted by the MAUP, MTUP, and MSTUP. Quantifying the number of people affected instead of building lots could bring different results.

The only way to estimate the population in each building using the available data is by dividing the total population of each geography (CT or DA) by all the buildings in that geography.

However, this methodology introduces more bias, assuming that all buildings within specific areas have identical populations— which is not true. Further investigation is necessary to understand those effects.

Likewise, these results indicate that there is an opportunity to articulate the Modifiable Temporal Unit Problem (MTUP) by combining the three components of the MTUP (aggregation, segmentation and boundary) and the two components of the MAUP (scale and zoning) that are not have explored in the literature. This structure of the Modifiable Spatio-Temporal Unit Problem, plus the calculation of misestimation using these components, are the next steps after this thesis.

6. Conclusions

In this thesis, I answered the four research questions. First, choosing coarser spatial resolutions will misestimate the accessibility to supermarkets. Second, choosing coarser temporal resolution and non-optima temporal segmentation will misestimate accessibility. The effects of these misestimations vary across different socioeconomic groups. Finally, temporal and spatial resolution interact, making the misestimation of accessibility even more significant.

Choosing coarser spatial or temporal resolutions or not adequate temporal segmentations that are not fine can cause various problems regarding bias and interpretation of results. In the case of the spatial resolution, specifically of the scale, results that align with the literature: the larger the spatial scale, the larger the misestimation. Specifically, the overestimation of buildings is greater in census tracts than in dissemination areas. However, one of the additions of this research in transportation studies is the quantification of the misestimation of buildings and the direction of the same, which also compares the effects in different socioeconomic groups. For this reason, it is essential to use lots as the finest scale of analysis, and if it is not available, use the next smallest scale, but keep in mind the possible misestimation levels. In this research, dissemination areas could be the best option, followed by census tracts. However, more spatial scales could be used, such as dissemination blocks or Canadian postal codes, smaller than dissemination areas.

In terms of temporal component, specifically temporal aggregation and segmentation, the coarser the temporal aggregation (smaller the sample), the greater the misestimation and, thus, the more extreme. Also, choosing an inadequate temporal segmentation, specifically somewhere between 7:00 am and 9:00 am, usually used in the literature, will increase the misestimation and overestimation levels. In contrast, the overestimation will depend on which minutes are sampled. For example, suppose the sample (or most of the samples) is above the mean. In that case, the temporal resolution will have higher levels of overestimation, while if the majority are below the mean, the levels of underestimation will increase. However, the misestimation will be more remarkable because it will not account for the temporal variation. To have accessibility measures close to reality, it is essential to use the hours of the day most of the trips to the destination are made. In the case of supermarkets in Montreal, this is from 10:00 am to 11:00 am. It is essential to consider the average of every minute within this period to account for the transit variation.

High-income groups are more affected by the Modifiable Temporal Unit Problem and the Modifiable Areal Unit Problem. This is because most of these groups live outside the center of the island of Montreal, where the census tracts and dissemination areas are larger. Likewise, there are few public transport options in these areas and the frequency is lower than in central areas, so they are more affected by choice of a specific temporal resolution or segmentation. Regarding equity, the good news is that low-income groups are less overestimated in accessibility levels; however, it is essential to mention that they are still affected by these effects.

Finally, I found that temporal and spatial resolutions interact and affect accessibility to supermarkets in Montreal. I found that the coarser the temporal and spatial resolution, and an inadequate temporal segmentation, the higher and more potent the misestimation and overestimation of buildings in Montreal. This is important in accessibility studies using public transport as the mode of transport, as certain levels of bias must be considered when using coarse temporal and spatial resolutions. A transportation researchers, we do not have to only look at the effects of either MAUP or MTUP, but also focus on both issues as misestimation levels increase.

These results are essential not only in theoretical terms but also in practical terms, specifically in terms of urban planning. These results indicate that certain temporal and spatial resolutions overestimate buildings, so these spatial and temporal resolutions indicate that the buildings are fine in terms of accessibility. However, in reality, this may not be the case, and they need some kind of transportation intervention or land use to lessen these effects.

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8. Appendices

All of the R code used for calculating the travel time matrices, accessibility measures and the variables related to the levels of misestimation used in this thesis, as well as future updates, are available at: https://github.com/ArturoJasso2256/MSTUP