A Decision Support Tool for Accommodating Truck Turning Movements at Intersections in Walkable Communities

By

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ABSTRACT

Many North American jurisdictions are creating liveable urban environments with a focus on accommodating the needs of pedestrians. In some cases, this has constrained the mobility and accessibility of goods movement in urban areas despite the essential role goods movement plays in sustaining the liveability of the community. Complete Streets design guidelines recommend restrictive geometric design of roadways through narrower lanes and tighter curb radii to promote pedestrian activity, which can exacerbate the accessibility issues of trucks in urban areas.

In this research, it was found that the typical three-metre curb radius recommended by Complete Streets guidelines is not always conducive to the right-turn maneuver of a truck (combination or single unit vehicle) and the prescriptive limits of curb radii do not consider the diversity of land use and mobility needs in urban areas. Thus, a decision support tool was designed and developed that integrates land use and transportation mobility to guide the selection and design of urban intersection curb radii that allows the safe and efficient accommodation of trucks and pedestrians. The decision support tool relies on the Freight-Walkability relationship that is measured from a novel Walkability Index and the truck turning activity at an intersection. The Walkability Index extends existing planning-oriented indices by introducing a safety indicator measured by the level of compliance of pedestrian crossing control treatments. Both freight activity and walkability are measured to provide a quantifiable classification of intersections that can be replicated in other jurisdictions specific to their land use, transportation system and freight activity context.

The decision support tool provides an integrated engineering and planning solution to address the geometric design trade-offs of trucks and pedestrians in urban areas. This tool can guide transportation engineers and planners to accommodate both pedestrians and trucks through both short-term street-level design changes (e.g., related to curb radius, street connectivity and

pedestrian crossing control compliance) as well as long-term land use transformations (e.g., residential density and land use mix).

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1. INTRODUCTION

1.1. Purpose

The purpose of this research was to develop a decision support tool that enables transportation engineers and planners to better design transportation facilities in urban areas for the safe and efficient accommodation of trucks and pedestrians within the context of a walkable community. The decision support tool was designed and developed relying on:

- an analysis of collisions involving trucks and pedestrians and the characteristics associated with those collisions;
- the Walkability Index, as developed in this thesis, associated with different land use characteristics and transportation system elements of an urban area; and
- the amount of freight activity and the dynamic characteristics of trucks under low-speed off-tracking maneuvers at intersections.

1.2. Background and Need

Many North American jurisdictions are creating liveable urban environments with a focus on accommodating the needs of pedestrians. In some cases, this has constrained the mobility and accessibility of goods movement in urban areas despite the essential role goods movement plays in sustaining the liveability of the community (Williams & Carroll, 2015; Wygonik, Bassok, Goodchild, McCormack, & Carlson, 2015).

While urban liveability follows general principles, there is no consensus on how to define, measure or achieve it (Young & Hermanson, 2013; Appleyard, Ferrell, & Taecker, 2016). The U.S. Federal Highway Administration (FHWA) defines liveability in transportation as being “about leveraging the quality, location, and type of transportation facilities and services available […] to increase transportation choices and access to transportation services […] in order to help achieve broader community goals such as access to a variety of jobs, community services, affordable housing and safe streets" (FHWA, 2014).

There have been numerous initiatives to create liveable communities and implement liveability strategies, all with a common goal of creating compact and walkable environments that provide access to opportunities (FHWA, 2010; Young & Hermanson, 2013; Appleyard, Ferrell, & Taecker, 2016; TAC, 2011; Williams & Carroll, 2015). The Complete Streets design approach is one of these initiatives. This approach focuses on the design of streets and intersections for all users, with priority given to the safe and efficient accommodation of pedestrians and bicyclists. Specific design strategies include tighter turn radii, narrower lanes and curb extensions.

The move towards creating liveable and walkable communities alongside rapid urbanization and the surge of e-commerce have led to higher freight demands in urban areas (Goodchild & Ivanov, 2018). In Canada, e-commerce has increased at an average of approximately 14 percent per year from 2015 to 2018 (Statista, 2019) and is expected to reach 12 percent of all retail sales by 2020, up from 7.5 percent in 2017 (Briggs, 2018). Similarly, in the U.S., e-commerce sales are increasing at an average rate of over 15 percent per year since 2010 (U.S. Department of Commerce, 2018), adding additional vehicles and distance travelled for goods delivery (Goodchild & Ivanov, 2018). Simultaneously, globalization has changed the pattern of goods movement by integrating urban goods transport with long haul transport (OECD, 2003). Since the pick-up and delivery of goods are essential to a vibrant economy and consequently to sustaining a liveable community, the proper accommodation of goods movement has significant impact on the economic growth, quality of life and attractiveness of a community (OECD, 2003).

Trucks are used for the "first- and last-mile" movement of goods in urban areas, due to their accessibility to the origins and destinations of goods (Rhodes, Berndt, & et al., 2012). Accommodation of trucks in urban areas involves planning, design, and operational considerations at all levels: throughout a regional network, along a corridor, and on a street (Lamm

& et al., 2016). Understanding the interrelationship between the broader transportation network and the corridors and individual streets is critical in creating a transportation system that achieves community goals and objectives (ITE, 2010). Designating an adequate truck route network while providing compatible land uses within a jurisdiction through proper regional-level land use planning is key to increasing freight reliability, reducing congestion, improving safety, and reducing truck emissions (Rhodes, Berndt, & et al., 2012). However, it is becoming more common for land around urban industrial areas or truck routes to evolve into liveable pedestrian-friendly areas, which creates conflict between the competing needs of trucks and pedestrians in these areas (Lamm & et al., 2016).

Maintaining or improving truck productivity helps reduce the overall number of truck trips and the transportation costs that carriers pass onto customers (Rhodes, Berndt, & et al., 2012; Lamm & et al., 2016). This is achieved through optimized logistics as well as the utilization of higher productivity vehicles. Five-axle tractor semitrailers (typically equipped with a 53-ft semitrailer) are the most commonly used truck configuration in North America, comprising approximately 43 percent of the U.S. truck fleet and 65 percent of the truck miles travelled (U.S. DOT, 2000; Harwood, et al., 2003). About 42 percent of five-axle tractor semitrailer's travel occur on urban roadways, of which 34 percent are on non-highway road classifications (i.e., urban principal and minor arterials, collectors and local roads) (U.S. DOT, 2011). Most Complete Streets advocates prefer the use of small van-type vehicles for urban deliveries to allow easier access through narrow urban streets and intersections; however, the trade-off is the increase in the number of trucks and distance travelled, which contribute to congestion, emissions, and noise (Rhodes, Berndt, & et al., 2012). In addition, the use of smaller vehicles results in more trucks competing for the limited loading/unloading space, more handling, and additional costs for tolls, fuel and parking fines (Wygonik, Bassok, Goodchild, McCormack, & Carlson, 2015). This trade-off — the positive and negative effects of the division of goods from larger vehicles into multiple smaller van-type delivery vehicles — is rarely discussed in detail in the literature (Giuliano, et al., 2013; Lamm, et al., 2016).

Urban routes expected to facilitate truck activity should be designed to ensure the roadway geometry appropriately accommodates truck maneuverability (Rhodes, Berndt, & et al., 2012). Accessibility and maneuverability of trucks in dense urban environments is one of the key challenges of urban truck accommodation due to restricted geometry (Bassok, et al., 2013). Both the vehicle configuration and the geometric design of an intersection affect the maneuverability of the vehicle, particularly the low-speed offtracking performance and the resulting swept path of a turning truck at an intersection. Generally, a longer vehicle wheelbase (or kingpin to centre of rear tandem axle length— KCRT) and tighter turn increases the extent of offtracking and consequently the swept path width (Harwood, et al., 2003).

The integration of trucks and pedestrians in urban areas presents unique challenges due to their conflicting needs as users of the same transportation system. Pedestrian-friendly Complete Street designs recommend tighter corner radii to reduce vehicle turning speeds and pedestrian crossing distances, which increase the extent of vehicle offtracking. Moreover, smaller intersections with narrower lanes decrease pedestrian crossing distances but also reduce the roadway space available to accommodate the swept path required for turning vehicles (Williams & Carroll, 2015; Wygonik, et al., 2015). These environments may require the driver to make exceptionally wide turns by swinging out into an adjacent lane to prevent the rear trailer from climbing on curbs and hitting pedestrians, curb-side objects or other vehicles (USDOT, 2000). On-street parking and bicycle lanes can increase the effective turning radius of an intersection while curb extensions reduce the curb radius and available turning space; thus these street design elements should be analyzed to determine the effect on turning vehicle swept paths.

There is a need to balance freight accessibility and pedestrian-friendly infrastructure designs in urban areas. Developing an effective decision-making process that reflects community values is a critical success factor in roadway development and geometric design (Neuman, Coakley, Panguluri, & Harwood, 2017), and integrating transportation and land use context is a key strategy towards achieving this balance.

This research develops a decision support tool that relates freight activity to walkability of urban areas to guide the design of urban intersections. The research helped define, characterize, and quantify walkability and urban truck movement to create the Freight-Walkability relationship. This relationship characterizes context zones that guide the design of intersection curb radii by determining the level of truck accommodation based on the truck turning performance suitable for each context zone. A curb radii design domain was developed as part of the research to guide the performance-based design of intersections in different context zones to appropriately balance the competing needs of trucks and pedestrians in walkable communities. Emphasis was given to pedestrian-friendly Complete Street intersection design elements that create challenging environments for truck turning maneuverability, including curb extensions and narrow approaching and receiving lanes.

The methodology developed for this research can be adapted to establish freight-walkability relationships in other jurisdictions. The freight-walkability relationship guides engineers and planners in understanding and quantifying different land use contexts that can influence a context-sensitive and performance-based decision-making process. Understanding this relationship provides guidance in determining suitable operational and geometric design solutions that accommodate the safe and efficient movement of trucks while maintaining the walkability of an urban community.

1.3. Objectives and Scope

The objectives of the research were:

Objective 1: Understand and characterize the magnitude of the safety problem involving truck and pedestrian collisions in Canadian urban areas.

Objective 2: Characterize and quantify walkability in urban areas based on identified land use and transportation system indicators.

Objective 3: Determine the levels of freight activity in urban areas and analyze the dynamic performance of different truck configurations under various intersection design scenarios based on levels of freight accommodation.

Objective 4: Design and develop a decision support tool to accommodate truck-turning movements in walkable urban areas based on the freight-walkability relationship (i.e., amount of freight activity and walkability levels).

The research scope was limited to geometric design considerations at urban intersections. The following specific Complete Street and pedestrian-friendly intersection design elements were analyzed to determine truck turning maneuverability: narrower lanes, curb extensions, on-street parking, and bicycle lanes.

1.4. Methodology

This section describes the methods used to achieve each of the four research objectives. Figure 1 summarizes these methods.

Objectives	Methods/Tools	Description
Objective 1: Understand and characterize truck-pedestrian safety	• Collision Data Analysis	A comprehensive collision analysis was conducted using Winnipeg-specific and Transport Canada data.
Objective 2: Characterize and quantify walkability	• Walkability Indicators Using Land-Use and Transportation Geographic Information System (GIS) Data	Walkability indicators were quantified to develop a Walkability Index. ArcGIS was used to analyze land-use and transportation data.
Objective 3: Characterize urban goods movement and analyze vehicle dynamics	• Vehicle Dynamics Simulation • Truck Turning Volume Data	AutoTURN was used to analyze low-speed off-tracking performance of different trucks at different intersection configurations.
Objective 4: Design and develop a decision support tool to accommodate low speed offtracking in walkable areas	• Design Domain Concept • Freight-Walkability Relationship	A design domain approach was used to develop a curb radii selection tool, based on the level of Freight-Walkability relationship.

Figure 1: Research Objectives and Methods

To meet **objective 1** of this research, an analysis was conducted of truck-pedestrian collisions in urban areas. The collision analysis revealed the safety characteristics of the interaction between trucks and pedestrians sharing the same urban transportation space and supports the development of design solutions that better accommodate their interactions. A nationwide collision analysis was conducted using the National Collision Database (NCDB) provided by Transport Canada to analyze collision-related, person-related and vehicle-related characteristics of collisions between trucks and pedestrians in urban areas across Canada. An analysis of collisions in the city of Winnipeg was also conducted to provide relative collision statistics.

To meet **objective 2** of this research, walkability indicators and their associated metrics were identified to characterize and quantify walkability from a utilitarian transportation perspective. Transportation elements were integrated into currently used land use variables through a transportation systems analysis approach to provide a holistic perspective on walkability. ArcGIS software was used to overlay land use variables and transportation facilities to help quantify walkability indicators and create a composite Walkability Index. The indicator variables included the presence and proximity of trip generators and attractors, type and density of land use, and access to adequate pedestrian transportation infrastructure and services. The Walkability Index provides one component of the Freight-Walkability relationship, which guides the development of the decision support tool. Available land use data from the City of Winnipeg and census data from the Statistics Canada Census Program (2016) were analyzed to develop a continuum of walkability measurements for Winnipeg.

To meet **objective 3** of this research, the levels of freight activity, freight movement needs, and truck dynamic performance were analyzed to determine the varying levels of truck accommodation in urban areas. Simulation of vehicle dynamics was conducted to determine the turning movement performance of different trucks at selected types of urban intersections based on the level of freight accommodation. A comprehensive analysis of low-speed offtracking performance of trucks turning right at different urban intersection configurations was conducted using the AutoTURN turning simulation software program. The right-turn maneuver was analyzed for varying freight-liveability intensities (i.e., context zones) in order to balance the needs of truck mobility and the surrounding community walkability. The trade-off depends on the desired level of accommodation an engineer or planner wants to provide for a particular context zone's characteristics and needs. The Freight-Walkability relationship determines the right-turn maneuver type (i.e., if encroachment in adjacent or opposing lanes is allowed), the vehicle start and end position, and the design and accommodated vehicle.

To meet **objective 4** of this research, a design domain approach was used to guide the selection of curb radii for urban intersections that balance the needs of truck turning maneuverability and community walkability. The Transportation Association of Canada's Geometric Design Guide

(2017) defines the design domain approach as providing a range of values that a design element may take depending on the level of fitness-for-purpose of the design element. This performance-based approach disregards prescriptive thresholds and allows an engineer to consider the impacts of trade-offs throughout the domain and select context-sensitive designs that serve the desired level of fitness-for-purpose (i.e., performance goals) (Neuman, Coakley, Panguluri, & Harwood, 2017).

In this research, the design domain approach provided a range of curb radii based on the trade-offs between the design and accommodated trucks' turning performance and level of walkability based on the surrounding land use. A freight-walkability matrix was developed to create the relationship between freight and walkability levels, which guided the development of the curb radii design domain.

1.5. Thesis Organization

The thesis comprises six chapters, including this introductory chapter.

Chapter 2 presents a review of literature on the concept of liveable and walkable communities and the interaction and trade-offs of pedestrian-friendly urban street designs and urban freight mobility and accessibility. The review included guidelines and reports on creating liveable and walkable environments, Complete Street design guidelines and manuals, and guidelines and best practices on considering trucks in urban roadway design by relating street and land use characteristics to truck activity.

Chapter 3 presents the findings of an analysis of collisions between trucks and pedestrians in Canadian urban areas. The analysis revealed safety issues that arise when trucks and pedestrians share the same urban transportation system. The chapter presents national results and disaggregated findings for Winnipeg, Manitoba.

Chapter 4 presents the design and development of a composite Walkability Index based on land use and transportation infrastructure indicators. The Walkability Index was developed for 158 Census Tracts in Winnipeg and provided one component of the Freight-Walkability relationship, discussed in Chapter 5.

Chapter 5 develops a decision support tool to guide the selection and design of urban intersection curb radii based on the intersection's Freight-Walkability relationship. The Freight-Walkability relationship combines the Walkability Index and truck right-turning volumes to help identify and balance the needs of truck movements and pedestrian crossings in urban intersection design. The Freight-Walkability measurements were estimated for the Winnipeg context and can be transferrable to other urban settings.

Chapter 6 presents conclusions resulting from this research by summarizing key findings and identifying opportunities for further research.

1.6. Terminology

Accessibility: From a pedestrian perspective, accessibility is the availability and ease of access to transportation services and infrastructure (such as sidewalks and transit stops) and destinations (such as schools and stores). From a trucking perspective, accessibility is the ease of access to origin and destination facilities for pick up and delivery of goods.

Accommodated Vehicle: An occasional/infrequent user of a street or network, which is able to operate and maneuver the street or network with some operating constraints.

Decision Support Tool: A documented process that supports and guides the decision-making process.

Design Vehicle: A frequent user of a street or network and must be fully designed-for to allow its operation.

Urban: A metropolitan area with an urban core and its less dense surrounding areas (i.e., suburbs) under the same jurisdiction.

Walkability: The level of safe, accessible and connected transportation facilities and service options provided to pedestrians to reach daily living destinations. This research focuses on walking from a utilitarian perspective, not solely from a commuting or recreational one.

2. LITERATURE REVIEW

2.1. Methodology

A comprehensive literature review was conducted to achieve the following:

- characterize the concept of liveable and walkable communities and how to measure walkability;
- identify pedestrian-friendly design practices in North America by reviewing Complete Streets and urban street design guidelines and policies;
- understand the planning and design needs of trucks in urban areas and characterize truck dynamic performance characteristics;
- understand the interaction and trade-offs of pedestrian-friendly urban street designs and urban freight mobility and accessibility; and
- identify literature that discusses strategies for the accommodation of trucks in liveable and walkable communities.

The literature review included peer-reviewed and non-peer-reviewed publications, government reports and guidelines, consultant reports, and reports and guidelines by special interest groups. The reviewed literature specifically included guidelines and reports on creating liveable and walkable environments, Complete Street design guidelines and manuals, and guidelines and best practices on considering trucks in urban roadway design by relating street and land use characteristics to truck activity. Over 100 documents were reviewed on liveability, walkability and/or truck accommodation, and 40 Complete Street guidelines at varying levels of government were reviewed, including 12 guidelines from Canadian jurisdictions.

2.2. Liveable and Pedestrian-Friendly Urban Design

In North America, there have been numerous initiatives to create liveable communities, with walkability being a key component from a transportation perspective. This section characterizes liveability and walkability and identifies methods of measuring these concepts in the literature. Since creating pedestrian-friendly walkable environments is a key tactic in increasing liveability, the literature review discusses pedestrian-friendly street design principles, with a focus on Complete Streets.

2.2.1. Liveable and Walkable Communities

In North America, there has been an increasing emphasis on creating more sustainable, liveable and walkable communities to improve the quality of life of communities from economic, social, and environmental perspectives. Liveability has been defined in numerous ways in the literature and is commonly used simultaneously or interchangeably with sustainability, with the key difference being short-term versus long-term perspectives, respectively (Miller, Witlox, & Tribby, 2013). Liveability emerged as a more localized, place-based tactic to achieve the broader sustainability goal of meeting the economic, social and environmental needs of the present without compromising the ability of future generations to meet theirs (Young & Hermanson, 2013; Appleyard, Ferrell, Carroll, & Taecker, 2014).

The most commonly used definition of liveability is by the Partnership for Sustainable Communities (PSC), created in 2009 by the U.S. federal government, as a collaboration between the Department of Transportation (DOT), Department of Housing and Urban Development (HUD), and the Environmental Protection Agency (EPA). The Partnership defines six principles of liveability as: (1) providing safe, reliable and economical transportation choices, (2) providing equitable and affordable housing, (3) enhancing economic competitiveness, (4) supporting community revitalization, (5) promoting healthy, safe and walkable neighborhoods in rural, urban or suburban settings and (6) aligning policies and funding to remove barriers from collaboration (Partnership for Sustainable Communities, 2014). Since transportation shapes urban form and travel behaviour, it plays a key role throughout all of the liveability guiding principles (Miller, Witlox,

& Tribby, 2013). Specifically, creating walkable environments to provide a safe and economical transportation option is one of the guiding principles that influences the other liveability principles.

The U.S. Federal Highway Administration (FHWA) defines liveability in transportation as being "about leveraging the quality, location and type of transportation facilities and services available […] to increase transportation choices and access to transportation services […] in order to help achieve broader community goals such as access to a variety of jobs, community services, affordable housing and safe streets" (FHWA, 2014). Furthermore, FHWA (2010) states that liveability in transportation involves making transportation more accessible, efficient and equitable by ensuring that walking, biking and transit are safe, convenient and realistic options.

While liveability and walkability have general principles, there is no consensus on how to define, measure (i.e., indicators, metrics, and weights) or achieve them (Young & Hermanson, 2013; Appleyard, Ferrell, & Taecker, 2016). To measure liveability or walkability, typically indicators are identified to determine the performance objectives and metrics are used to measure the variables for each indicator (Miller, Witlox, & Tribby, 2013). While there are no consistent set of performance measures or indicators that are widely used to monitor community walkability or liveability (Gallivan, Ramsey, & Ang-Olson, 2013), there are a few variables that are commonly associated with them. Generally the focus has been on spatial (i.e., type and density of land use) and physical characteristics of places (Appleyard, Ferrell, Carroll, & Taecker, 2014). Most measurements of walkability include residential density, street connectivity and land use mix (Shashank, 2017).

An "ideal" liveable community is typically moderately dense, diverse, walkable, safe, affordable, accessible, and well-served by public transit systems (Miller, Witlox, & Tribby, 2013; FHWA, 2010). Strategies to increase liveability and walkability generally include increasing developmental densities, mixing land uses, diversifying building types, creating shorter blocks, and connecting the street network (Frost, Appleyard, Gibbons, & Ryan, 2018; Sung, Lee, & Cheon, 2015; ITE, 2010). Walkable distance to fixed-route transit service, number of bus stops within the service areas, and accessible sidewalks to transit stops are also considered indicators of liveability (Brooks, Edrington, & Catala, 2013). Since creating a walkable environment is a key component of enhancing liveability, most of the liveability strategies and indicators also apply to walkability.

One of the most critical strategies that can promote liveability and walkability is integrating transportation and land use since mobility and proximity to services and destinations provides access to opportunities (Appleyard, Ferrell, Carroll, & Taecker, 2014; Appleyard, Ferrell, & Taecker, 2016; Rue, McNally, & Rooney, 2011). Other strategies include increasing multimodal choices through Complete Street design, coordinating housing and transportation investments to address housing location and affordability and access to transportation options, and supporting transit-oriented development (Rue, McNally, & Rooney, 2011; FHWA, 2014).

Transportation planning and health literature over the past two decades has shown the relationship between the built environment and walking/physical activity through various analysis methodologies: surveys/interviews, systematic observations that quantify environmental attributes and geospatial databases that assess walkability indicators (Agampatian, 2014). The literature finds a positive relationship between the built environment (i.e., transportation and land use) and the amount of physical activity (Frank, et al., 2005; Saelens, et al., 2003), with the combined effect of the variables having a more significant impact (Ewing & Cervero, 2010). The five "D's" have been commonly stated in literature as characteristics of the built environment that impact travel behaviour. These are: density, diversity, design, destination accessibility, and distance to transit (Cervero & kockelman, 1997; Ewing & Cervero, 2010; Frost, Appleyard, Gibbons, & Ryan, 2018). Various methods of quantifying liveability or walkability based on combinations of different indicators have been attempted in the literature.

Miller, Witlox, and Tribby (2013) provide a framework for creating and applying multidimensional quantitative liveability and sustainability indicators by defining objectives, identifying indicators and associated metrics, and determining the relative importance of the indicators (i.e., weights). Since the metrics that measure the indicators comprise different scales and units, normalization is essential, typically using the z-score statistical method. The indicators can then be assessed individually or a composite indicator (CI) can be created to determine a liveability score by aggregating the indicators. The normalized indicators/metrics are typically summed to obtain the index (Agampatian, 2014), while Brooks, et al. (2013) provided scores to the equally distributed metric measurements (i.e., percentiles) and Appelyard, et al. (2016) conducted a cluster analysis to develop urban typologies.

Composite measures or indices are commonly used in the literature to develop walkability or liveability indices due to the variety of influencing multi-dimensional indictors (Miller, Witlox, & Tribby, 2013; Agampatian, 2014), and are correlated with physical activity, walking trips, and health indicators (Frank, et al., 2005; Frank, et al., 2010). Composite Indices are considered consistent predictors of walkability or liveability relative to single component measures because they capture the interrelation of various environmental characteristics (Vargo, Stone, & Glanz, 2012).

Frank, et al. (2005, 2010) developed the first composite Walkability Index based on net residential density, land use mix (Entropy Score), intersection density and retail floor area ratio (FAR). The index was calculated by the sum of the four standardized measures (i.e., Z-scores) of urban form, with street connectivity (measured by intersection density) weighted by a factor of two. Street connectivity was given a higher weight due to the evidence regarding the strong influence of street connectivity on non-motorized travel choice (Cervero & kockelman, 1997). However, Frank, et al. (2005) assigns a weight of six to the land use mix variable due to better correlation of the index with moderate physical activity measures.

Frank, et al., (2010) validate the developed Walkability Index using Census Journey to Work travel data for one region (Seattle region) and the Household Travel Survey Data for a different region

(Washington-Baltimore region). Household Travel Survey Data provides a better measure of travel patterns than Journey to Work data since 83 percent of trips taken in the US are for non-work purposes (Frank, et al., 2010). The vehicle miles travelled (VMT) per day were estimated by modelling shortest time path trip assignments for the reported trips divided by the number of vehicle passengers. Field verification was also conducted by informal windshield observations of the urban form characteristics such as the presence of sidewalks, type of retail (malls or smaller stores) and housing type. It was found that areas in the highest decile of walkability had 6.45 times greater number of walking trips and 52 percent lower household VMT than the lowest walkability decile. It was also found that areas with high walkability (high and low income) walked to work more often than those in low walkability neighborhoods.

In the literature, land use mix is commonly measured by an Entropy Index in existing walkability indices (Agampatian, 2014; Frank, et al., 2009; Leslie, et al., 2007). An Entropy index calculates the distribution level of different land use types in an area, where an index of one indicates equal land use mix (i.e., diverse) and an index of zero indicates a very homogenous land use type (i.e., not diverse). However, the Entropy index has many limitations. The main limitation is that the Entropy Score depends on the level of spatial distribution of the different land use types, thus an area can have a low Entropy score if there is an unequal distribution of a variety of land use types, although the land use types contribute to walkability. Brown et al. (2009) states that the presence of a destination is important, not necessarily the number or equal presence of destinations.

Connectivity is typically measured in terms of intersection density in the literature (Frank, et al., 2010; Walk Score, 2011; EPA, 2010; Agampatian, 2014), which is used to represent the number of pedestrian crossing opportunities in an area. However, this metric over-estimates the number of walkable intersections since the presence of an intersection does not imply that there is a pedestrian crossing. Some non-signalized intersections do not provide a pedestrian crossing (such as highway interchanges or on some collector roads), while other areas with signalized intersections do not have a sidewalk network to allow pedestrian crossings. Many new residential neighborhoods are developed with no sidewalks or many cul-de- sacs; therefore, the intersections do not provide a pedestrian crossing or a connected sidewalk network, respectively.

Agampatian (2014) developed a Walkability index, building upon the previously developed Index by Frank, et al. (2010), using six parameters: two measures of density (residential density and retail floor area) and one parameter from each category of diversity, proximity, connectivity, and environmental friendliness. This Index is visually validated to an average obesity rate map.

The Street Smart Walk Score is a commercially used Index that uses walking distance to amenities and road connectivity as the indicators of walkability. The algorithm creates a score for a residence (i.e., an individual address) based on walking distance to a variety of amenities, with a decay function to reduce the score as the distance between the amenity and the home increases. Then the score is penalized by zero to 10 percent based on connectivity levels measured by intersection density and average block length (Walk Score, 2011). Density, land use mix and environmental friendliness are not considered in the Walk Score. Studies have shown a significant positive correlation between the Walk Score and environmental attributes related to walking, specifically with intersection density and the availability and number of local destinations (Koohsari, et al., 2018; Carr, et al., 2011; Duncan, et al., 2011)

The U.S. Environmental Protection Agency (EPA) developed a National Walkability Index that provides relative walkability scores for all Census 2010 block groups in the U.S. based on the four indicators of intersection density, proximity to transit stops, employment mix (using an entropy score), and employment and housing mix (using an entropy score).

Various correlation analyses have been used in the literature to validate Walkability Indices. Most studies have used correlation with physical activity measures (Frank, et al., 2005) and health variables such as obesity (Agampatian, 2014) and Body Mass Index (BMI) (Brown, et al., 2010). A few studies have used commuter data (Frank, et al., 2010) and household origin-destination survey data when available (Frank, et al., 2010; Manaugh & El-Geneidy, 2011). Systematic field observations have been used to help improve the validity of walkability Indices (Frank, et al., 2010); however these can be very laborious, time consuming and costly, and they impose issues with the subjectivity and reliability of the results (Agampatian, 2014).

Table 1 lists the walkability and walk-related liveability indicators and metrics identified in the literature. The indicators are categorized by safety, accessibility and connectivity performance objectives for organizational purposes, however, many of the indicators can overlap between these objectives. In addition to the indicators provided, other metrics are measured in the literature to indicate walkability/liveability, including population demographics such as income levels (EPA, 2011), environmental pollution such as vehicle emissions (EPA, 2011; Gallivan, Ramsey, & Ang-Olson, 2013) and the gas mileage of city fleet (Partnership for Sustainable Communities, 2014), and aesthetics of the area such as the presence of art and entertainment (ITDP, 2018). In addition, Walk Scores or Walkability Indices have been used in a number of studies as indicators of walkability or liveability in conjunction with other walk-related indicators (Frost, Appleyard, Gibbons, & Ryan, 2018; Partnership for Sustainable Communities, 2014; U.S. Environmental Protection Agency, 2018).

Table 1: Summary of Walkability and Walking-Related Liveability Indicators from Literature

Objective	Indicators	Metrics
Safety	Pedestrian safety	• Corridor pedestrian collisions per daily pedestrian *(2)* • Bicycle/pedestrian crashes per 1,000 cyclists/pedestrians *(3)* • Non-occupant fatality rate *(3)* • Crime rate in parks *(5)(8)* • Pedestrian-friendly crosswalk design *(8)*
Accessibility	Land Use Mix/Diversity and Proximity	• Average distance to an activity centre *(1)* • Dwelling density within a walkable distance from each residential address (within 1600 m) (net and gross dwellings per hectare) *(1)* • Access to daily-living destinations including convenience store, public transport stop, and supermarket (as alternative to land use mix) *(1)(10)* • Homes within walking distance to retail, services, parks *(3)* • Diverse mix of employment types and occupied housing (higher values correlate with more walk trips) *(7)* • Mix of employment types (e.g., retail, office, or industrial- higher values correlate with more walk trips) *(7)* • Residential density- ratio of residential units to the land area devoted to residential use per block group *(8)(9)(10)(11)* • Percent of employed persons living and working in the same area *(1)* • Jobs within a 45-min drive *(7)* • Working age population within a 45-min drive *(7)* • Corridor Non-Automobile Internal Capture- measures the number of trips that both begin AND end in the corridor as a proportion of total trips that either begin OR end in the corridor *(2)* • Smart Location Index- indicating location efficiency of a site for worker commute travel *(7)* • Proximity to a variety of daily destinations within a buffer *(8)* • Percent of residential addresses within 400 m of any public open space/recreational land (other variations include within 300 m of Public Open Space, 400 m of local park, 800 m of neighborhood park, and 2 km of district park) *(1)(5)(6)* • Mixed income housing (corridor income diversity) *(2)(4)* • Mixed income housing (percent of income spent for housing) *(2)*

Objective	Indicators	Metrics
		• Jobs per housing unit *(7)* • Employment entropy (a measure of employment diversity) *(7)* • Employment and housing entropy *(7)* • Population density (population/acre) *(2)(4)(6)* • Employment density (employees/acre) *(2)(4)(6)* • Commercial density- retail floor area ratio (ideally less space used for parking lots and shortened distance between retail outlets) *(8)(10)(11)* • Net retail area or retail floor area ratio– a measure of pedestrian friendliness, to determine amount of space dedicated to surface parking (found to not be necessary) *(9)(10)(11)* • Access to retail opportunities (density of retail employees) *(2)* • Access to health care opportunities (density of health care employees) *(2)* • Access to arts and culture opportunities (density of employees in entertainment) *(2)* • Population density to employment density ratio *(6)* • New homes, affordable homes and rental units built in areas well-served by transit *(3)* • New homes, affordable homes and rental units built near employment centres (access to employment by income group) *(3)* • Residential units near employment centres *(3)* • Low income households within a 30 min transit commute of employment centres *(3)* • Low income households within a 20 min driving commute of employment centres *(3)* • Index of population and employment mix in a study area (equation provided) *(3)* • Shared elements of regional transportation, housing, water, and air quality plans tied to local comprehensive land use or capital improvement plans *(3)* • Land consumption (e.g. number of lane miles of roadways, amount of sq. footage of buildings, and number of parking spaces in park and ride lots, acres of land consumed per residential unit, amount of new housing and jobs in greenfield, etc.) • Acres of parks and protected open space per capita *(5)* • Location of new residential units permitted *(5)* • Number of new residential units permitted *(5)* • Mix of housing type permitted for new construction *(5)*

Objective	Indicators	Metrics
		• Land use Mix (LUM)- equation considering residential, commercial, institutional and governmental, resource and industrial, park and recreational and water *(6)* • Entropy Index to determine mix of land use types: residential, commercial, entertainment, mix use, facilities/institutions, industrial, transportation, parking lots, vacant land, open space-outdoor recreational *(8)(9)(10)(11)* • Residential vs non-residential balance *(6)* • Vertical housing type- average number of floors per building *(6)* • Mix of spatial use in terms of activities (by determining whether each places is used daily or not and whether used at night or daylight)- e.g., commercial, nightlife, nightlife density *(6)* • Places where people gather outside of home and work, for eating drinking, organized activities, outdoor and commercial venues- referred to as 3rd places *(6)* • Average block area *(6)* • Boarder vacuums: physical obstacles to pedestrian activities- closeness to parks, railways, highways and water (e.g. parks at night could discourage pedestrian activity) *(6)*
Accessibility	Access to Transportation Options	• High-speed road network density *(7)* • Predicted commute mode split (proportion of workers who carpool) *(7)* • Percent of employed persons aged 15 and over using active transport to travel to work *(1) (3)* • Percent of employed persons aged 15 and over using public transport to travel to work *(1) (3)* • Percent of employed persons aged 15 and over using private vehicles to travel to work *(1)* • Vehicle miles travelled (VMT) per capita *(3)(5)* • Annual household VMT *(4)* • Reduced car space (reduction of physical space for cars) *(8)* • Household transportation costs *(3)* • Combined housing and transportation costs *(5)* • Transportation affordability (annual cost of transportation relative to annual income- or could be calculated for different income groups) *(3)(4)* • Bicycle and pedestrian mode share (for different trip purposes, peak period or average daily, etc.) *(3)(4)*

Objective	Indicators	Metrics
		• Bicycle and pedestrian level of service (grade A-F) (consider auto volumes and perception of safety- Refer to Highway Capacity Manual, 2010) *(3)* • Average vehicle occupancy (AVO) *(3)(4)* • Travel time to work *(5)* • Travel time by mode and income group (work trip travel time, non-work trip travel time, and travel time to key destinations, specific trip types such as shopping, and specific major activity centres) *(3)(4)* • Median commute distance *(4)* • Bike parking spots per capita *(5)* • Percentage of arterial road miles with marked bike lanes *(5)* • Percentage of population living within ¼ miles of a bike lane/trail *(5)* • Bicycle infrastructure- Bike Land and Trail Mileage per square mile *(5)* • Pedestrian Infrastructure- Sidewalk Coverage tracks the percentage of roads with sidewalk or miles of sidewalk in a community *(5)* • Percent of households with no car, 1 car, or 2 or more cars *(7)* • VMT per capita *(3)(5)* • Light-duty VMT per capita *(3)* • VMT per employee *(3)* • VMT per hour per road length of census tract boundary *(4)*
Accessibility	Transit Accessibility	Distance to transit stops *(3)(7)(8)*: • Percent of residential addresses within walking distance of transit (400 m of a bus stop, 600m of a tram stop or 800 m of a train station) *(1)(5)* • Distance to nearest transit stop *(3)(4)(8)* • Corridor transit service coverage (frequency of transit service per square mile) *(2)(4)* • Transit jobs accessible within 45 min via transit *(2)* • Percent of daily/peak period trips (ODs), starting or ending within ¼ mile of transit stop *(3)* • Percent of population and employment within walking distance (0.4 miles) of transit *(3)(5)(8)* • Percentage of jobs within walking distance of transit service *(5)* • Households within five miles of park-and-ride lots or major transit centers *(3)* • Percentage of new homes (housing units) built within walking distance of transit *(5)*

Objective	Indicators	Metrics
		<u>Destinations accessible by transit *(3)*:</u> • Travel time on transit *(3)* • Jobs well-served/accessible by transit (i.e., within a certain travel time; e.g., 45 min transit commute) *(2)(3)(4)(7)* • Transit corridor job density *(2)* • Transit corridor health care opportunities *(2)* • Share of population with good transit-job accessibility (100,000+ jobs within 45 mins) *(3)* • Number of households within a 30 min transit ride of major employment centres *(3)* • Percent of work and education trips accessible in less than 30 mins transit travel time *(3)* • Percent of workforce that can reach their workplace by transit (within 45-mins or one hour with no more than one transfer) *(3)(7)* • Working-age population within a 45-minute transit commute *(7)* • Low wage workers (earning $1250 USD or less per month) and low-medium wage workers (earning $3333 USD or less per month) that can reach the block group within 45-min transit commute *(7)* • Accessibility Index- relative accessibility of a block group compared to other block groups as measured by travel time to working-age population via transit (values closer to 1 are more accessible) *(7)* • Population (total and percent) with access to the block group within a 45-min transit and walking commute *(7)* <u>Transit Productivity *(3)*:</u> • Transit trips per capita (or transit frequency, i.e., total transit trips during a given time period for a community, e.g., afternoon peak period) *(3)(5)(7)* • Average weekday transit boarding per vehicle revenue hour *(3)* • Average transit boarding per vehicle revenue mile *(3)* • Average annual transit boarding per route mile *(3)* • Passenger miles travelled per vehicle revenue mile *(3)* • Transit service density (e.g., during afternoon peak period) *(7)* • Transit service provision by income group (e.g., availability of nighttime service, degree of crowding and number and quality of bus shelters) *(3)*

Objective	Indicators	Metrics
		• Dollars of public and private sector investment in areas well-served by transit or near employment centres *(3)*
Connectivity		• Intersection density (e.g., intersections per sq. mile) *(2)(4)(5)(6)(7)(9)(10)(11)* • Street connectivity (number of intersections of three or more streets per km^2) *(1)* • Pedestrian intersection density *(4)* • Block density (blocks per sq. mile) *(8)* • Ratio of sidewalk coverage to the street-roadbed coverage in sq. metres (environmental friendliness) *(8)(10)*

(1) Arundel, et al. (2017)
(2) Appleyard, Ferrell and Taecker (2016) *and Ferrell, et al.* (2016)
(3) EPA (2011)*; Gallivan, Ramsey and Ang-Olson* (2013)
(4) Frost, et al. (2018)
(5) Partnership for Sustainable Communities (2014)
(6) Nadai, et al. (2016)
(7) U.S. Environmental Protection Agency (2018)
(8) Institute for Transportation and Development Policy (2018)
(9) Mayne, et al. (2013), Leslie, et al. (2007)
(10) Agampatian (2014)
(11) Frank, et al. (2010)

2.2.2. Pedestrian-Friendly Urban Design

There have been numerous initiatives to create liveable communities and implement liveability strategies, including Smart Growth, Complete Streets, Walkable Communities, Safe Routes to School, Transit-Oriented Development, and New Urbanism (Young & Hermanson, 2013; FHWA, 2010). The overarching goal of these initiatives is to create compact and walkable environments that provide various transportation options for accessing opportunities (FHWA, 2010; Young & Hermanson, 2013; Appleyard, Ferrell, & Taecker, 2016; Lamm & et al., 2016). The Complete Streets initiative is unique in the fact that it focuses on the design of streets and intersections for all users, with priority given to pedestrians and bicyclists. This section focuses on Complete Streets as an initiative to increase liveability in order to understand the relationship between street design and liveability.

Providing safe and efficient accommodation of pedestrians and other vulnerable road users is a key initiative towards the goal of liveable and sustainable communities, and the named initiatives (TAC, 2011; Williams & Carroll, 2015). The support for pedestrian (and bicyclist) accommodation in the transportation system was initially brought about by the U.S. Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and was further reinforced in 1998 by the U.S. Transportation Efficiency Act for the 21st Century (TEA-21) (ITE, 2009). With the movement towards prioritizing the inclusion of non-motorized modes in the planning and design of transportation systems, the term Complete Streets was coined by America Bikes in 2003. Subsequently, the National Complete Streets Coalition (NCSC) was founded in 2004 as part of a Smart Growth America Program that promotes the development and implementation of Complete Street policies and professional practices at national, state, regional, and municipal levels (Smart Growth America, 2016). In December 2015, the Fixing America's Surface Transportation (FAST) Act became the first U.S. federal transportation bill to include Complete Streets language, making this approach a formal part of federal policy (Smart Growth America, 2016).

Many North American jurisdictions have implemented towards implementing Complete Street guidelines and policies for planning and designing their urban transportation infrastructure. Over 1200 Complete Streets policies have been adopted in the United States (Smart Growth America, 2017) with increasing adoption in Canadian jurisdictions (e.g., Calgary, Waterloo, Edmonton, Toronto, Ottawa, Ajax, Quebec City, Hamilton, Vancouver and Niagara Region) mainly through high-level policy documents such as Transportation Master Plans (Complete Streets for Canada, 2017). Canadian jurisdictions that have developed standalone Complete Streets guidelines are Edmonton, Calgary, Toronto, Saskatoon, and Niagara Region. In Canada, the concept of Complete Streets is introduced in the newest edition of the Geometric Design Guide for Canadian Roads (TAC, 2017).

There have been many different definitions of Complete Streets by different organizations and jurisdictions. The National Complete Streets Coalition (Smart Growth America, 2016) defines a complete street as "streets designed and operated to enable safe access for all users...a street that works for motorists, bus riders, cyclists and pedestrians, including those with disabilities". The NCSC evaluates and scores the language of Complete Streets policies based on a series of criteria, including the indication of bicyclists and pedestrians as users of the transportation system at minimum (Smart Growth America, 2017), which implies that these two modes take priority in design considerations.

The goal of Complete Streets design specific to the walking mode is to create environments that are safe, attractive, and conducive to walking and crossing the street with ease. Most pedestrian collisions occur when crossing a street and the most common collision type results from conflict between a crossing pedestrian and a turning vehicle at an intersection (TAC, 2009). The two key elements in achieving the goals of Complete Streets are (1) minimizing roadway space dedicated to motor vehicle traffic in order to reduce pedestrian exposure to traffic at crossings and (2) reducing vehicle speeds. With these goals in mind, Complete Street designs may include the following pedestrian-friendly design elements (Transport Canada, 2009; Smart Growth America, 2016; The City of Calgary, 2014):

- Frequent and safe pedestrian crossing opportunities, allowing crossing on all intersection legs, with marked crosswalks at signalized intersections.
- Tighter intersection turning radii to allow the installation of separate and properly aligned pedestrian curb ramps towards each direction of travel, reduce pedestrian crossing distances, reduce vehicle turning speeds, and create smaller and more compact intersections.
- Curb extensions or bulbouts where sidewalks are widened out into the parking lane at intersections or midblock in order to effectively narrow the road and reduce the pedestrian crossing distance, reduce vehicle turning speeds, and improve pedestrian visibility at crossings.
- Raised crosswalks to increase the visibility of pedestrian crossing locations.
- Pedestrian refuge islands to reduce pedestrian crossing distances.
- Median islands to provide access management by limiting left turns into and out of abutting developments and subsequently reduce conflict points, as well as provide a refuge for pedestrians crossing an intersection, especially pedestrians with slower walking speeds such as the elderly or disabled.
- Narrower travel lanes and generally more compact intersections in order to reduce vehicle speeds, especially on urban arterials and in places with limited right-of-way. Lane widths can be reduced from the typical 3.7m (12ft) to 3m (10ft) in liveable communities.
- On-street parking to provide a buffer for pedestrians, help calm traffic speeds, and provide easy access to retail businesses.

- Avoid providing right-turn turning lanes in order to prevent higher vehicle speeds travelling through intersections, minimize pedestrian crossing distance, and avoid safety and comfort implications with pedestrian and cyclist interactions with turning vehicles in the turning lane.
- Smart Channel design for right turn channelization, which reduces the turn angle to 70 degrees in lieu of compound curve right-turn channelization lanes. The discontinuous geometry reduces vehicle turning speeds and increase yielding to pedestrians.
- Lower design speeds to increase driver attentiveness to surrounding activities and increase driver reaction time. Slower vehicle speeds can significantly improve pedestrian safety, where the pedestrian fatality risk at 50 km/h impact speed is greater than five times higher than the risk at 30 km/h (Rosen & Sander, 2009).
- Convenient and accessible crossings at transit stops.
- Accessible pedestrian signals and ramps to guide the crossing of pedestrians with hearing or vision impairments.
- Roundabouts to reduce vehicle speeds travelling through intersections.

2.3. Urban Trucking

Goods movement drives the economy, with transportation industries accounting for 4.5 percent of Canada’s Gross Domestic Product (GDP) in 2016, not including private trucking and the enabling effects of creating jobs and facilitating trade (Transport Canada, 2017). Truck transport is Canada’s dominant freight transportation mode in terms of freight tonnage and value, with 72 percent of domestic goods in Canada (Transport Canada, 2017) and 55 percent of trade between the U.S. and Canada being transported by trucks (Transport Canada, 2014). The demand for truck transport is consistently increasing, outpacing the increase in freight movement by other modes. The freight flow system performance has direct impact on the economy of a nation and the costs of goods and services (Rhodes, Berndt, & et al., 2012).

Motor carriers are used for the “first- and last-mile” movement of goods in urban areas due to their accessibility to the origins and destinations of goods (Rhodes, Berndt, & et al., 2012). Freight transport is a fundamental component of urban life, where goods and services are provided to businesses and residents on a daily basis. Rapid urbanization and the move towards creating vibrant, liveable communities have led to higher freight demands in urban areas, while globalization has changed the pattern of goods movement by integrating urban goods transport with long haul transport (OECD, 2003). The increase in urban truck vehicle-miles traveled (VMT) has outpaced the increase in overall freight-VMT (Bronzini, 2008). In addition to the increasingly dense urban population, the significant growth in e-commerce and the associated changes in customer delivery expectations are exacerbating the challenges with urban goods movement. E-commerce is a major contributor to the increase in urban truck VMT from both deliveries and return of goods (Goodchild & Ivanov, 2018). In the U.S., total e-commerce sales increased by 16 percent from 2016 to 2017, while total retail sales increased by 4.4 percent (U.S. Department of Commerce, 2018). Similarly, in Canada, e-commerce sales have increased by an average of approximately 14 percent per year from 2015 to 2018 and are expected to reach ten percent of all retail sales by 2020, up from 7.5 percent in 2017 (Statista, 2019; Briggs, 2018). Since the pick-up and delivery of goods is essential to the economic success of a community and subsequently to sustaining a liveable community, the proper accommodation of goods movement has significant impact on the economic growth, quality of life and attractiveness of a community (Rhodes, Berndt, & et al., 2012; OECD, 2003).

Accommodation of trucks in urban areas involves planning at the regional, corridor and street levels. Understanding the interrelationship between the broader transportation network and the corridors and individual streets is critical in creating a transportation system that achieves community goals and objectives, by considering modal needs from the start of project development and not only at the street design stage (ITE, 2010). Designating an adequate truck route network that provides access and mobility for trucks to serve major freight origins and destinations while considering other metropolitan functions, such as land use and multimodal systems, is key to increasing freight reliability, reducing congestion, improving safety and reducing truck emissions (Rhodes, Berndt, & et al., 2012).

The selection of truck routes in urban areas is influenced by the origin and destination (OD) nodes of truck trips. The OD nodes are facilities and consumer nodes whose locations are determined by land use and zoning at the local level, which determines the level of economic activity and concentration of residential populations (Gan & Lin, 2010). However, it is becoming more common for land use around urban industrial areas or trucks routes to evolve and convert into liveable pedestrian-friendly areas that attract pedestrian and cyclist activity (Rhodes, Berndt, & et al., 2012). While these areas remain critical OD nodes or connectors to major OD nodes on a regional scale, this can create conflicts with the additional competing localized needs of the evolving land use and activity. These conflicts must be addressed through planning, design and operational strategies at all scales from street design to regional-level land use planning (Lamm & et al., 2016).

For the delivery stage of a goods movement supply chain, carriers are guided by the truck route network and the locations of the delivery destinations, sometimes in relation to the distribution centres (DC), to determine the logistics of the deliveries. A truck will depart a national, regional, or local distribution centre (which can also be the production facility), making a single delivery to one destination or making multiple deliveries in a zone at some distance from the DC or as it works back to the DC, with a shorter empty return distance. Delivery fleet schedules are designed to make as many deliveries in a workday during the required delivery time-window as possible. Maintaining truck productivity is of interest to carriers to reduce the overall number of truck trips and transportation costs which are passed on to customers (Rhodes, Berndt, & et al., 2012; Lamm & et al., 2016)

In addition to optimizing logistics, delivery productivity can be achieved by increasing truck carrying capacity. The 53-ft tractor semitrailer configuration predominates and is often used to make deliveries to retail and restaurant establishments, especially to chain establishments (Lamm, et al., 2016). Most Complete Streets advocates prefer the use of small van-type vehicles for urban deliveries to allow easier access through narrow urban streets and intersections; however, the trade-off is the increase in the number of trucks and vehicle-kilometres travelled (VKT) which contributes to congestion, emissions, and noise (Rhodes, Berndt, & et al., 2012). One 53-ft trailer can carry up to 30 standard pallets (40 by 48 inches), while a 24-ft-long box truck can only carry up to 12 pallets, and a 12-ft-long van can only carry up to four pallets (Lamm & et al., 2016). In some cases, companies are able to transload goods into smaller single-unit trucks or 45-ft or 48-ft semitrailers, while other cases benefit from 53-ft semitrailers (Rhodes, Berndt, & et al., 2012).

Wygonik, et al. (2015) states that the trucking industry finds the move towards smaller trucks challenging, due to the significant daily variation in urban goods demand. This results in higher costs associated with owning and operating a larger fleet of small trucks and drivers relative to a smaller fleet of large trucks. In addition, the smaller vehicles result in more trucks competing for the limited loading/unloading space, more handling, and additional costs for tolls, fuel and parking fines. The higher delivery costs associated with downsizing result in higher costs to the businesses and thus to consumers, which affects smaller businesses to a greater degree (Bassok, et al., 2013). This trade-off in terms of the positive and negative effects of the division of goods from larger vehicles into multiple smaller van-type delivery vehicles is rarely discussed in detail in the literature (Giuliano, et al., 2013; Lamm, et al., 2016; Bassok, et al., 2013).

From a more local planning perspective, a key consideration for truck accommodation, highlighted in the majority of literature on urban trucking, involves providing adequate facility access for loading and unloading (Wygonik, et al., 2015; Giuliano, et al., 2013; Rhodes, et al., 2012). This includes providing sufficient and reliable parking facilities and loading/unloading docks or curbside space as well as adequate regulations enabling sufficient curbside access. Regulations can determine access based on time and/or size and weight restrictions or mandate the implementation of off-street parking through zoning and building ordinances (Giuliano, O'Brien, Dablanc, & Holliday, 2013). Providing proper regulations is crucial for efficient deliveries and reducing congestion caused by trucks circling or blocking traffic while waiting for parking space (Rhodes, Berndt, & et al., 2012).

Subsequent to planning for truck accommodation, routes with truck movement should be designed and operated to accommodate trucks by providing adequate turning radii at intersections and adequate horizontal and vertical clearances, as well as bridge and pavement integrity to handle heavy loads (Rhodes, Berndt, & et al., 2012). Accessibility and maneuverability of trucks in dense urban environments is a challenge due to tight geometric designs. Particularly, low-speed offtracking performance of trucks makes it challenging to negotiate intersections that may be designed specifically with pedestrians in mind (Wygonik, et al., 2015).

When a truck (or any larger vehicle) makes a low-speed turn at an intersection, the rear wheels on the trailer follow a path several metres inboard of the tractor steering axle. The maximum difference in paths of the steering axle and rear trailer axle is referred to as low-speed offtracking, as shown in Figure 2. The overall widest path swept out by the sides of the vehicle is referred to as swept path, which varies depending on the vehicle axle spacing and the turning radius (U.S. DOT, 2000). Both the truck configuration and the geometric design of the intersection affect the amount of offtracking. Generally, a longer vehicle wheelbase (or kingpin to rear tandem axle length- KCRT) and tighter turn increase the extent of offtracking and subsequently the swept path width.

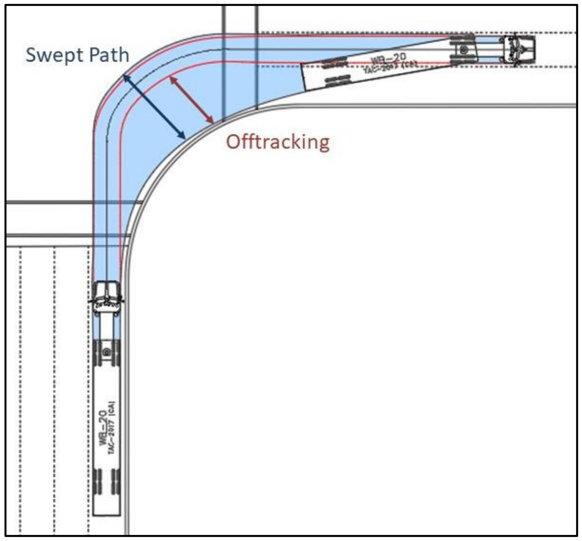


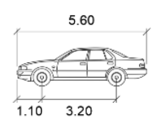
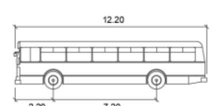
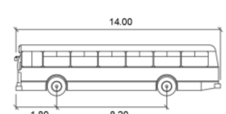
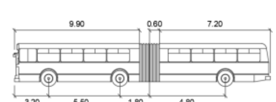
Figure 2: Low-Speed Offtracking and Swept Path of a Tractor Semitrailer

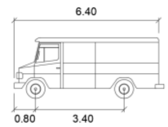
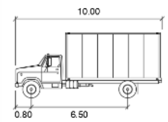
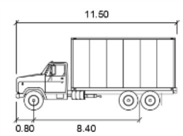
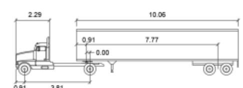
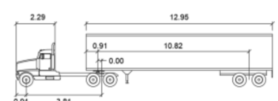
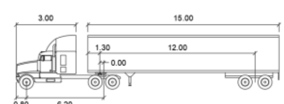
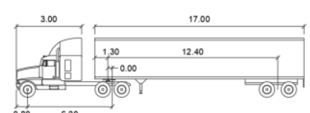
During a turn, the front and rear of the trailer also swing outwards, referred to as the front swingout and rear swingout, respectively. Swingouts are a function of the front and rear overhangs and kingpin to rear tandem axle (KCRT) distance (Harwood, et al., 2003). Increasing the kingpin setback and increasing rear effective overhang are known to reduce vehicle offtracking; however they may have negative safety implications. Increasing the kingpin setback increases the front swing-out and increasing the rear effective overhang increases the rear swing-out of the trailer which can encroach on curbs or other lanes (George, et al., 2014).

The kingpin is the vertical steel pin at the bottom of a semitrailer that connects to the fifth-wheel on the rear of the towing vehicle; in other terms, it is the connection between the tractor and semitrailer. Truck size and weight regulations typically restrict the trailer length, rear overhang distance and any kingpin restrictions, specifically the kingpin to centre of rear axle/tandem (KCRA or KCRT) distance (Harwood, et al., 2003). This indirectly regulates low-speed offtracking and the rear swing out.

Varying design vehicle configurations and dimensions are specified in both current North American roadway design guides: the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads (2017) and AASHTO's Policy on Geometric Design of Highways and streets (2018) (also referred to as the AASHTO Green Book) in the U.S. The design vehicles representing passenger vehicles, buses, single-unit trucks and tractor-semitrailers are shown in Table 2, excluding multi-trailer combination and emergency vehicles. The design vehicles from TAC and AASHTO are mostly similar with a few differences. The AASHTO Green Book specifies one standard single-unit truck (SU-30), while the TAC Guide specifies two additional single-unit trucks: light and heavy. The NACTO Urban Street Design Guide (2012) has introduced the DL-23 design vehicle, a smaller van-type delivery vehicle that resembles the TAC light single-unit truck. This design vehicle is being adopted by some jurisdictions, including the City of Chicago (2013). Three-axle and four-axle single unit trucks make up 30 percent of the truck fleet and nearly 10 percent of the total truck VMT (U.S. DOT, 2000).

Table 2: TAC and AASHTO Design Vehicles

Description	TAC Design Vehicle ID	Total Length	AASHTO Design Vehicle ID	Total Length	Figure
Passenger car	Passenger car	5.6m (18.4ft)	P	5.8m (19ft)	
Buses					
Bus	Standard Single Unit Bus (B-12)	12.2m (40ft)	City Bus (BUS-40)	12.2m (40ft)	
Bus	Intercity Bus (I-BUS)	14m (46ft)	Intercity Bus (BUS-45)	13.7m (45ft)	
Articulated bus	Articulated Bus	18.3m (60ft)	A-Bus	18.3m (60ft)	

Description	TAC Design Vehicle ID	Total Length	AASHTO Design Vehicle ID	Total Length	Figure
Single Unit Trucks					
Light single unit truck	Light Single Unit truck	6.4m (21ft)	*N.A.* *(DL-23, not in AASHTO, 2011 but in NACTO, 2013)*	N.A. (22.6ft)	
Medium single unit truck	Medium Single Unit truck	10m (33ft)	SU-30	9.2m (30.2ft)	
Heavy single unit truck	Heavy Single Unit Truck	11.5m (37.7ft)	N.A.	N.A.	
Tractor-Semitrailers					
33' tractor semitrailer (10.2m)	*N.A.* (WB-12)	*N.A.* *(16.8m, 55.1ft)*	WB-40	13.9m (45.5ft)	
42.5' tractor semitrailer (13.0m)	*N.A.* (WB-15)	*N.A.* *(16.7m, 55ft)*	WB-50	16.7m (55ft)	
48' tractor semitrailer (14.6m semitrailer)	WB-19	20.9m (68.5ft)	WB-62	20.9m (68.5ft) (KCRT 41.0ft)	
53' tractor semitrailer (16.2m semitrailer)	WB-20	22.4m (73.5ft)	WB-65 WB-67	22.4m (73.5ft) (KCRT 43.5ft) 22.4m (73.5ft) (KCRT 45.5ft)	

Source of Schematics: AutoTurn, 2019

The current TAC Geometric Design Guidelines (2017) include two tractor-semitrailer vehicles (not including multi-trailer combination vehicles), the WB-19 and WB-20, which correspond to the AASHTO WB-62 and WB-65 or WB-67 design vehicles, representing a 48-ft and 53-ft tractor semitrailer, respectively. The 48-ft tractor semi-trailer is less common on the road, however the design vehicle WB-19 (WB-62) remains in the guidelines since it represents the offtracking performance of longer trucks with their rear axles pulled forward to meet state KCRT distance requirements, which are typically 12.5m (41 ft) (Harwood, et al., 2003).

The 53-ft tractor semitrailer is the most commonly used vehicle, constituting approximately 43 percent of trucks in the U.S. (U.S. DOT, 2000; Harwood, et al., 2003). The difference between the AASHTO WB-65 and WB-67 design vehicles, representing the 53-ft tractor semitrailer, is the KCRT distance. The rear tandem of the WB-67 is positioned closer to the rear of the truck, making the KCRT distance longer than the WB-65 design vehicle. Therefore, the WB-67 has a greater turning radius, offtracking and swept-path width. The WB-67 design vehicle is not as commonly used as the WB-65 because 19 states limit the KCRT distance to a maximum of about 12.5 m (41 ft). Many truckers prefer to move the rear axle forward to improve maneuverability; however, this would result in a load restriction on a 53-ft trailer due to the reduced wheelbase.

Truck VMT in U.S. urban areas are almost equally split between combination vehicles and single unit vehicles at 54 percent and 46 percent, respectively. Light duty vehicles comprise of 74 percent of urban VMT, however they are used for additional purposes other than goods movement (U.S. DOT, 2015).

In the U.S., about 42 percent of five-axle tractor semitrailer’s VMT are on urban roadway networks. Although the majority of their operation is on urban Interstate Highways, 34 percent of the urban VMT is on non-highway road classifications (i.e., urban principal and minor arterials, collectors and local roads). Majority of single unit trucks (58 percent) operate in urban areas, of which 76 percent operate on urban non-Interstate Highways. (U.S. DOT, 2015)

Selecting an appropriate design vehicle for the land use, level and type of activity, and specific needs of an area can be difficult, specifically in areas with high goods movement activity in combination with high pedestrian activity and limited space. Trucks are also increasing in size and weight in order to increase productivity and reduce the number of trucks on the roadway. For example, Walmart Canada introduced a 60-ft supercube trailer in 2012 that provides a 30 percent increase in cubic capacity relative to a 53-ft trailer (Truck News, 2012). Canadian Tire also introduced a 60-ft trailer in 2016, waiting for approval by provinces and territories (Statistics Canada, 2017).The concept of design and control vehicles to design-for or accommodate different vehicle configurations is recently being adopted by a few jurisdictions and guidelines including the City Portland (2008) and NACTO Urban Streets Design Guide (2013).

2.4. Challenges with the Co-Existence of Trucks and Pedestrians

The integration of trucks and pedestrians in urban areas presents unique challenges due to their conflicting needs and impacts on a community as users of the same transportation system. Accessibility to origins and destinations is one of the greatest challenges in dense urban environments due to limited space for transport and the different infrastructure design requirements by all modes (Bassok, et al., 2013). In terms of geometric design, trucks require wider lanes and turning radii at intersections, while the accommodation of pedestrians favours intersections that are more compact with tighter curb radii to reduce the crossing distance and exposure of pedestrians to traffic and reduce the speed of turning vehicles (Williams & Carroll, 2015).

Due to the substantial difference in the size and maneuverability characteristics of trucks and pedestrians, safety is one of the most important concerns in the interaction of the two modes where a collision would most likely result in pedestrian fatality (ITE, 2009). Transport Canada reports that there are an average of 351 collisions per year involving trucks and pedestrians, of which 27 are fatal (TAC, 2009). Over 50 percent of these collisions occur at or near an intersection. Pedestrian collisions represent a greater risk for young children and seniors (TAC, 2011). Vehicle speed plays an important role in the safety of pedestrians, where the pedestrian fatality risk at the impact speed of 50 km/h is more than twice as high as the risk at 40 km/h and more than five times higher than the risk at 30 km/h (Rosen & Sander, 2009). Reducing vehicle-turning speeds through more restrictive intersection designs such as curb extensions, tight intersection turning radii and narrower lanes can benefit pedestrian safety; however, this creates a difficult environment for truck maneuverability, which in turn can retract from the safety improvements.

With rapid urbanization and the current trend towards creating more vibrant, liveable urban spaces, the emphasis has been placed on planning and designing for passenger movements, and the accommodation of trucks for goods movement has often been ignored (Wygonik, Bassok, Goodchild, McCormack, & Carlson, 2015; OECD, 2003; Bassok, Johnson, Kitchen, Maskin, & Overby, 2013). Freight activity is a derived demand and creating a liveable community can create conditions that increase freight demand by homes and businesses in the area (i.e., first and last mile activity). Although delivering goods to urban areas is essential for maintaining liveable communities by sustaining the economic and social functions of the city, priority is given to passenger movements so freight vehicles encounter the problem of not having the infrastructure necessary to function properly. This raises issues regarding the approach to creating liveable spaces where the inadequate accommodation of freight access can lead to the opposite intended effect given that liveability includes economic prosperity and that freight plays a role in that (Williams & Carroll, 2015).

Complete Streets design recommend even more restrictive geometric design of roadways to promote pedestrian and cyclist activity, which can exacerbate the accessibility issues of trucks in urban areas (Wygonik, Bassok, Goodchild, McCormack, & Carlson, 2015). Pedestrian-friendly Complete Street designs recommend tighter corner radii (typically 3m) which increase the extent of vehicle offtracking, as well as smaller intersections with narrower lanes (typically 3m) and reduced pedestrian crossing distances which reduce the roadway space available to accommodate the swept path required for turning vehicles (Wygonik, et al., 2015). These environments may require the driver to make exceptionally wide turns by swinging out into an adjacent lane in order to prevent the rear trailer from climbing on curbs and hitting pedestrians, curb-side objects or other vehicles (USDOT, 2000). On-street parking and bicycle lanes can increase the effective turning radius of a vehicle at an intersection while curb extensions reduce the curb radius; thus, these street design elements should be analyzed to determine the effect on turning vehicle swept paths. Although the National Complete Streets Coalition (NCSC) promotes a comprehensive policy model that includes the specification of “all modes” and “all users” as one element of the policy, the minimum requirement is the inclusion of bicyclists and pedestrians (Smart Growth America, 2016). Few jurisdictions specify the accommodation of urban goods movement, and of those jurisdictions, only few provide further guidance on how to accommodate truck movements. Complete Streets guidelines have not provided street design guidance on how to balance the geometric design trade-offs based on the land use and mobility demands to accommodate the balance of both modes. The lack of adequate accommodation of freight vehicles can cause disruptions to traffic and increased congestion, environmental effects, and safety problems, which further heightens the negative perception of trucks in urban areas.

Since liveability of an urban community is dependent on the proper movement of goods, appropriate balance must be achieved between the liveability goals of creating a pedestrian-friendly environment and freight movement accessibility, which go hand-in-hand (Williams & Carroll, 2015).

2.5. Key Literature Integrating Transportation and Land Use

Conventional street design is based on the functional classification of streets (e.g., arterial, collector, and local roads), focusing on the mobility and accessibility of passenger vehicles and providing limited consideration to the surrounding context. Once a street is given a class, design standards and guidelines are provided for that specific class and any variation requires a design exception (NACTO, 2013). However, there is a growing understanding that urban intersections have a significant role in place-making in addition to mobility (ITE, 2010). Therefore, jurisdictions are recently moving away from the conventional auto-centric classification of streets and are moving towards more multimodal classification schemes that consider the impact of land use on the transportation system.

The current roadway design guides, both the Transportation Association of Canada (TAC) Geometric Design Guide for Canadian Roads (2017) and AASHTO's Policy on Geometric Design of Highways and Streets (2011) in the U.S., consider context by location (urban and rural), functional classification of streets, and terrain (flat, rolling, mountainous) (Neuman, Coakley, Panguluri, & Harwood, 2017). The current design guides do not adequately cover the variety of contexts and diversity of situations that influence roadway design, as reference to "urban" is not sufficient (Neuman, Coakley, Panguluri, & Harwood, 2017). The recent AASHTO Green Book (2018) provides a further contextual classification of suburban, urban and urban core. Furthermore, the accommodation of freight movement within different land use contexts and the relationship and trade-offs with community liveability are not addressed (FDOT, 2015). However, recent studies have emerged that integrate transportation and the surrounding land use context to meet community objectives and discuss the competing needs of multimodal systems. This section provides a summary of key documents (reports and guidelines) that provide guidance on improving freight mobility and community liveability individually, and the few that address these simultaneously to varying degrees. The summary describes how the documents incorporate land use into the design of transportation systems and the modified classification schemes that they provide. Subsequent to this, a summary of Complete Street Design Guidelines are provided, and a select few that provide classification schemes are discussed.

2.5.1. Summary of Key Literature

- *U.S. DOT (2018) NACTO- Optimizing Large Vehicles for Urban Environments*

The U.S. DOT prepared a report for NACTO that provides vehicle downsizing and advanced driver assistance systems (ADAS) as strategies to address the safety challenge of large trucks operating in urban areas. From the vehicle downsizing perspective, the report recommends using cab-over vehicles to reduce the wheelbase length and rear steer axles on a three-axle tractor to allow tighter turn radii, thus improving maneuverability on narrow streets and intersections with tight curb radii. The report focuses on technological advances that could be made to improve vehicle maneuverability in urban areas, but does not integrate the mobility strategies with land use.

- *Lamm, et al. (2016) NCHRP 844 - Guide for Integrating Goods and Services Movement by Commercial Vehicles in Smart Growth Environments*

The Guide provides a framework for planners and policymakers to assess a community's context and consider strategies to better support goods movement in smart growth environments. When establishing a community's context, the elements that are reviewed are the smart growth classification, environment, transportation users, freight needs and activity, land use, zoning, economy, and transportation infrastructure.

The Guide introduces a Form-Based Code (FBC) zoning system as a tool that promotes smart growth principles by focusing on the physical form of the development (i.e., characteristics of buildings, streets, and open space) rather than on the use (Lamm, et al., 2016; Smart Growth America, 2018). The study identifies six smart growth environment classifications based on the FBC system that fall along a spectrum of development intensities, from rural to urban. The land use development contexts are similar to those presented in ITE (2010). The Guide provides general strategies to integrate goods movement, corresponding to the different smart growth environments.

- *NITC (2015) Integrating Freight into Livable Communities*

The National Institute for Transportation and Communities (NITC) (2015) identifies best practices in improving freight access in liveable communities and provides planning and policy strategies for policy makers. The recommendations are based on a literature review and specific case studies of jurisdictions that are implementing truck accommodation strategies in liveable communities. It is emphasized that the recommended strategies are not prescriptive; rather the community context must be considered. The integration of land use and transportation is not explicitly discussed to guide various levels of truck accommodation within different urban contexts.

- *Florida Department of Transportation (2015) Freight Roadway Design Considerations*

The Florida Department of Transportation's (FDOT) *Freight and Roadway Design Considerations* (FRDC) document (FDOT, 2015) suggests truck-friendly principles and strategies for different contexts that help with the integration of freight mobility needs into the roadway planning and design process while balancing the needs of community livability. This document supplements the AASHTO Green book and other geometric design manuals and does not provide values for the geometric design of roadways and intersections.

FDOT (2015) developed the Freight and Land Use Compatibility (FALUCA) analysis that identifies context zones based on the level of intensity of liveability and freight movement and identifies areas with potential conflict between the two. The analysis uses land use data (uniquely available data sets from individual counties in Tampa Bay) to identify the type and extent of land use and truck traffic statistics to estimate the amount of freight activity. Scores are assigned for different land use features and truck percentages, and the summation of scores determines the freight-liveability score (i.e., context zone).

FDOT (2015) identifies four general context areas: Low Activity Areas, Community Oriented Areas, Freight Oriented Areas, and Diverse Activity Areas. Diverse Activity Areas are the most challenging context zones with high potential for conflict between the two elements of freight movement and liveability, since they have high freight activity as well as relatively dense residential and/or office uses. The report states that in Diverse Activity Areas, a modal emphasis on larger vehicles, such as trucks and transit buses is appropriate and that the design decisions in these diverse areas are not binary; rather they lean towards community or freight orientation depending on the localized context.

- *The City of Toronto (2015) Curb Radii Guideline*

The City of Toronto (2015) developed curb radii guidelines to complement the current TAC Geometric Design Guideline and provide more context sensitive designs for urban settings. This is the only document that provides specific design guidelines to accommodate trucks at intersections. However, this guideline does not consider land use characteristics and the interaction of trucks with other modes.

Intersections are classified into five types based on the conventional road classification system; however, they are categorized further by the volume of large trucks turning at a specified intersection corner. The road classification for an intersection corner is the road classification with the lower annual average daily traffic (AADT). The intersection corner types are major/minor arterial, collector, local, collector, and local, and these are further subcategorized by the frequency of truck-turning volumes. The Guideline provides curb radii design tables for the design and control vehicles selected based on the intersection corner type and the truck route, using vehicle tracking software.

- *NACTO (2013) Urban Street Design Guide*

The NACTO Guide provides guidance on urban street design that balances the needs of movement and place making, with safety as the driving factor. The Guide moves away from using functional or other classification schemes, but rather provides urban street contexts such as Downtown, Neighborhood Street, Boulevard, and Transit Corridor. Recommendations on street design principles and elements are provided.

The Guide addresses trucks as users of the system and briefly discusses trade-offs in accommodating them in intersection design; however, it leans towards segregating large vehicles from urban streets through rerouting of truck routes. The Guide recommends the adoption of a new design vehicle- the delivery truck (DL-23)- as specified in the Chicago Complete Street Guidelines (2013).

- *Bassok, et al. (2013) NCFRP 24 - Smart Growth and Urban Goods Movement*

NCFRP report 24 discusses and models the relationship between the transportation of goods in urban environments and land use patterns, specifically in smart growth environments. Policy and planning considerations are provided based on a comprehensive stakeholder survey to better accommodate goods movement in smart growth environments. Smart growth scenarios that can impact transportation are identified and inputted into an urban freight demand forecasting model to assess the impacts of smart growth land use patterns on truck miles of travel, truck hours of travel, truck delay, truck trip, length and travel times, and emissions. It was found that when a smart growth land use scenario was coupled with corresponding transit and non-motorized transportation investments, overall travel distances and hours on the road were reduced. However, longer trip lengths and travel times were found for goods movement between goods-dependent analysis zones and smart growth analysis zones. The models did not account for truck mode choice.

- *ITE (2010) Designing Walkable Urban Thoroughfares- A Context Sensitive Approach*

ITE (2010) provides a framework on how context sensitive solutions (CSS) can be applied in the planning and designing of walkable urban thoroughfares (i.e., arterials and collectors) in pedestrian places, pedestrian-supportive areas and pedestrian-tolerant areas. Although this guide does not specifically focus on freight movement, it addresses the balance between motorized (including trucks) and non-motorized traffic in walkable communities.

The report uses context zones, thoroughfare types (i.e., boulevard, avenue, and street), and functional classifications to select design parameters and criteria for walkable urban thoroughfares. This allows the thoroughfare type to be integrated with the surrounding land use. The term "context zones", introduced in this report, describes the physical form and character of a place. Context zones are characterized by land use, density, and design features such as building placement, frontage type, typical building height, and type of public open space. The guide presents six context zones, with four being considered urban*: natural zone, rural zone, suburban zone, general urban zone, urban center zone, urban core zone,* and *assigned district*. This context zone concept is also adopted by Lamm et al. (2016).

Guidelines for selecting a context zone include considering existing and future development plans, assessing community goals, assessing residential densities and commercial floor-area ratios, and identifying current and future levels of pedestrian and transit activity based on land use type and mix. An urban thoroughfare can pass through several different context zones.

There is some discussion on the accommodation of large vehicles throughout the report, specifically in selecting the design vehicle and design elements, with no specified engineering measurements. General considerations are provided in the design of curb radii. The report recommends that truck routes be outside of or on only a minimum number of walkable streets. However, the curb radii at locations with a high number of truck turning movements should be designed to adequately accommodate trucks to avoid mounting on curbs and pedestrian waiting areas.

- *City of Portland (2008) Designing for Truck Movements and Large Vehicles in Portland*

The City of Portland (2008) guideline provides design guidance and best practices on how to accommodate truck access and mobility in street design, including multimodal locations where trade-offs are required to balance the needs of different users. The guideline incorporates adjacent land use characteristics in addition to the safety, mobility, and access requirements found in engineering standards. The guide addresses various road design elements to accommodate trucks alongside other modes (i.e., pedestrians, transit, bicycles) in four types of areas: Freight Districts, Centers and Main Streets, Residential Areas, and Infill Development and Redevelopment within Historic Districts. The advantages and disadvantages of various design elements within each area type are discussed without providing specific direction on when to use them and how to modify them for various contexts.

The City's Transportation System Plan (TSP) establishes the street classifications for freight and other modes, which is different from the FHWA functional classification scheme. This is the only document that identifies street classification based solely on the freight perspective. Each street may have multiple street classifications that need to be considered in design including freight, transit, bicycle, and pedestrian street designations. The TSP establishes the following street classifications for freight that match the designated land uses along these streets: Regional Truckway, Priority Truck Street, Major Truck Street, Truck Access Street, Local Truck Street and Freight District Street.

In designing intersections, the guideline presents the approach of "design for" versus "accommodate" of large trucks, defined as follows:

- “Design for”: intersections are designed such that a design vehicle remains entirely within its travel lane or lanes as it completes a turn.
- “Accommodate”: intersections are designed such that a selected vehicle will use all available lanes moving in their direction and encroachment on opposing lanes to complete a turn. This strategy is used when accommodating truck movements in relatively tight street environments.

The recommended design vehicle for Regional Truckways, Priority Truck Streets, Major Truck Streets, and Freight District Streets is the AASHTO WB-67 (53-ft tractor semitrailer). The recommended design vehicle for Truck Access Streets with frequent bus service is at minimum a standard bus, while depending on the businesses that front the street, a WB-50 or WB-40 may be appropriate. For local Service Truck Streets a SU-30 design vehicle is recommended.

- *BESTUFS (2007) Good Practice Guide on Urban Freight Transport*

The European Coordination Action on Best Urban Freight Solutions (BESTUFS) (Allen, Thorne, & Browne, 2007) was funded by the European Commission to identify best practices to improve the sustainability of urban freight transportation systems. Planning and policy strategies are provided that address issues in accommodating trucks in urban areas for the European context, including general guidance on the implementation of urban consolidation centres. However, the integration of land use and transportation is not explicitly discussed to guide various levels of truck accommodation within different urban contexts.

- *Strausse-Wieder, et al., (2003) NCHRP 320- Integrating Freight Facilities and Operations with Community Goals*

NCHRP 320 (2003) was one of the first documents to consider the relationship of freight movement and facilities with its surrounding communities. It covers all types of freight movement: air, truck, rail, and maritime. Higher-level policy solutions are provided that focus on long-distance freight movement instead of urban movements and encourage the separation of freight facilities and operations from neighborhoods, either physically or temporally. No specific road design guidance is provided. The land use solutions provided in this report are creating buffer zones to transition from freight/industrial areas to residential and requiring developers to make highway access improvements for trucks.

2.5.2. Summary

Table 3 provides a summary of key reports and guidelines that discuss urban street design with consideration towards community liveability/walkability and/or freight accommodation. Table 4 provides a summary of key Complete Street design guidelines from Canadian and U.S. jurisdictions. Table 4 lists all 12 existing Canadian and 28 select U.S. Complete Street Design Guides, comprising city, county, regional and state levels, totalling 40 reviewed documents. The U.S. Guides were identified from the Smart Growth America inventory of Complete Streets policies (Smart Growth America, 2018b) as well as through an online search.

The summary tables, Table 3 and Table 4, indicate whether the document develops or discusses land use and/or street typology that is different from the traditional functional classification of roadways (i.e., arterial, collector, local, etc.) that only focus on vehicle mobility and accessibility. The table also indicates whether freight accommodation and curb radii design with consideration for freight accommodation are comprehensively considered and discussed in the street planning and design process. Documents that provide a statement simply stating that special consideration should be given to truck movements without elaborating further on how that should be conducted are not considered positive for “freight accommodation” or “curb radii design”.

Table 3: Key Urban Street Planning and Design Guides and Reports

Guidelines and Reports	Land Use/ Street Typology	Freight Accommodation	Curb Radii Design
U.S. DOT (2018) NACTO- Optimizing Large Vehicles for Urban Environments	✗	✓	✓
Lamm, et al. (2016) NCHRP 844 - Guide for Integrating Goods and Services Movement by Commercial Vehicles in Smart Growth Environments	✓	✓	✗
NITC (2015) Integrating Freight into Livable Communities	✗	✓	✗
Florida DOT (2015) Freight Roadway Design Considerations	✓	✓	✗
The City of Toronto (2015) Curb Radii Guideline	✗	✓	✓
NACTO (2013) Urban Street Design Guide	✓	✗	✗
Bassok, et al. (2013)NCFRP 24 - Smart Growth and Urban Goods Movement	✗	✓	✗
ITE (2010) Designing Walkable Urban Thoroughfares- A Context Sensitive Approach	✓	✓	✗
City of Portland (2008) Designing for Truck Movements and Large Vehicles in Portland (2008)	✓	✓	✗
BESTUFS (2007) Good Practice Guide on Urban Freight Transport	✗	✓	✗
Strauss-Wieder, et al. (2003) NCHRP 320 Integrating Freight Facilities and Operations with Community Goals	✗	✓	✗

Key findings from the review of the reports summarized in Table 3 on the accommodation of trucks and liveable/walkable communities, either separately or inclusively, follow:

- None of the reviewed literature covers all three categories of the integration of land use into the transportation system, the accommodation of trucks and providing curb radii design guidance.

- The FDOT Freight Roadway Design Considerations (2015), NCHRP 24 (2013), and NCHRP 844 (2016) are the only three documents that address the relationship of freight mobility and accessibility with community liveability.
- Although NCHRP 320 (2003) considers the relationship of freight movement and facilities with its surrounding communities, it focuses on long-distance freight movement and encourages the separation of freight facilities and operations from neighborhoods, either physically or temporally.
- Although the ITE (2010) design guide focuses on creating walkable communities, it does address the balance between motorized (including trucks) and non-motorized traffic in these communities and provides some discussion on the accommodation of large vehicles throughout the report, specifically in selecting the design vehicle and design elements.
- City of Portland (2008) is the only guide that develops a street classification scheme specifically for truck activity, while considering the multimodal trade-offs in urban areas. Additional street classifications are also developed specific to other modes.

Table 4: Key Complete Street Design Guides

Jurisdiction's Complete Street Guidelines	Land Use/ Street Typology	Freight Accommodation	Curb Radii Design
Canada			
City of Calgary (2014)	✓	✗	✗
City of Edmonton (2018)	✓	✓	✓
City of Fredericton (2016)	✗	✗	✗
Grey and Bruce Counties (2015)	✗	✗	✗
City of Kingston (2015)	✓	✗	✗
City of London (2018)	✓	✓	✗
City of Niagara Region (2017)	✗	✗	✗
City of Ottawa (2015)	✓	✓	✓

Jurisdiction's Complete Street Guidelines	Land Use/ Street Typology	Freight Accommodation	Curb Radii Design
City of Saskatoon (2017)	✓	✗	✗
City of St. Albert (2018)	✓	✗	✗
City of St. Thomas (2016)	✗	✗	✗
City of Toronto (2017)	✓	✗	✗
U.S.A.			
City of Albany, NY (2016)	✓	✗	✗
City of Alexandria, VA (2016)	✓	✓	✗
City of Boston, MA (2013)	✓	✗	✗
City of Charlotte, NC (2007)- *awarded Smart Growth Achievements by EPA*	✓	✗	✓
City of Chicago, IL (2013)	✓	✗	✗
City of Cleveland, OH (2013)	✓	✗	✗
City of Deerfield Beach, FL (2013)	✓	✗	✗
City of Jaffrey, NH (2017)	✓	✗	✗
City of Lancaster, CA	✗	✗	✗
City of Los Angeles, CA (2014)	✓	✗	✓
City of Mankato, MN (2015)	✗	✗	✗
City of New Haven, CT (2010)	✓	✗	✗
City of Northampton, MA (2017)	✗	✗	✗
City of Philadelphia, PA (2009)	✓	✗	✗
City of Tacoma, WA (2009)	✓	✗	✗
Alameda County, CA (2016)	✓	✗	✗
Miami-Dade County, Miami, FL (2017)	✓	✗	✓
Lancaster County , PA (2015)	✓	✗	✗
Oakland County, Detroit, MI (2012)	✗	✗	✗

Jurisdiction's Complete Street Guidelines	Land Use/ Street Typology	Freight Accommodation	Curb Radii Design
Passaic County, New Jersey (2012)	✓	✗	✗
Region of Farmington, NM (2016)	✓	✗	✗
Region of Knoxville, TN (2009)	✗	✗	✗
Region of South Nevada, NV (2012)	✓	✗	✗
State of California (2010)	✗	✗	✗
State of Florida (2018)- *recognized as one of Smart Growth America's best Complete Streets Initiatives of 2017*	✓	✓	✓
State of New Jersey (2017)	✓	✗	✗
State of North Carolina (2012)	✓	✗	✗

Complete Street guidelines place emphasis on considering land use context in the planning and design of the roadway network, with the majority of the guides developing or utilizing an existing street typology that integrates land use context into the street or area classification. However, few guidelines mention trucks or provide guidance on the accommodation of trucks in street design and specifically in curb radius design in these areas. The few guidelines that consider truck accommodation in the curb radii design guidance do not utilize the land use/street typology utilized/developed within the guide to select an appropriate curb radius; rather, prescriptive curb radii or a general range is provided based on the modal presence.

Most Complete Streets guidelines recommend minimizing the curb radius in urban areas, typically with a range of three to 4.8 metres (10-15ft). Some Complete Streets guidelines mention considering trucks at intersections for curb radii design, however, they only simply state that their occasional movement should be accommodated by allowing encroachment on multiple lanes, or a maximum curb radius is prescribed for areas with high truck movements while land use and multimodal needs are not considered. For example, the Tacoma guide (2009) recommends implementing a 12-metre (40-ft) curb radius in areas with high truck or bus traffic, and the Knoxville guide (2009) recommends a range of 4.8 to 12 metres (15-40 ft) where there is a presence of vehicles larger than passenger cars.

From Table 4, it is evident that of the 12 existing Canadian Complete Streets Design guidelines and manuals, Edmonton and Ottawa are the only two jurisdictions with Complete Streets documents that address all three components of creating an integrated street and land use typology, discussing truck accommodation and providing guidance on curb radii selection. The Edmonton Complete Streets Design Standards (2018) is the most comprehensive Complete Streets document within the scope of this research. It uses the design domain approach to provide street design guidance and design parameters based on the area's context. However, although street typologies are developed in this guide based on land use type, the functional classification system of arterial, collector and local are used in combination with the designation of a truck route when determining an intersection curb radius, rather than the land use context, with the exception of industrial areas. The WB-20 truck (53 ft- tractor semitrailers) is designated as the design vehicle for industrial areas only. In contrast, although the St. Albert Complete Street Guide does not address freight accommodation as a component of Complete Street Design, it does require large trucks to be accommodated at all road typology types (i.e., crosstown, connector, neighborhood and local) and land use types (i.e., commercial, residential and employment), except local residential and lane typologies.

The City of Ottawa created a Multimodal Level of Service (MMLOS) tool alongside its Complete Street Framework, which evaluates the LOS for each travel mode using a series of performance metrics. Although this tool satisfies all three criterion in this research, it provides an evaluative tool and not guidance on Complete Streets design. This tool uses effective turning radius and number of receiving and departing lanes as the metrics for truck LOS (TkLOS) at signalized intersections. Pedestrian LOS (PLOS) at intersections is measured by the street width, corner radius, crosswalk treatment, and traffic signal timing while PLOS on segments is measured by vehicular operating speed, sidewalk width, boulevard width, vehicle volume and presence of on-street parking. Minimum desirable MMLOS targets are provided for different land use designations such as Central Area, Developing Community, Mixed-use Centre and Arterial Main Street. However, specific guidance on system planning or street design is not provided to address the trade-offs associated with multimodal design.

The City of Quebec and Montreal also have Complete Street guidelines; however, they are written in French and thus not included in the summary. In addition, a number of Complete Streets guidelines (e.g., in Cambridge and Guelph) have been developed for specific neighborhoods (e.g., a downtown area or town centre) and not on a municipality-wide basis; these are not included in the summary.

Of the 28 American Complete Streets guidelines, the Florida DOT Design Manual (2018) was the only one that met all three criteria, and was recognized as one of the best Complete Streets initiative of 2017. Although this guide provides truck consideration in various street design elements, including curb radii selection, it does not integrate land use in the selection of curb radii. However, the Florida DOT Freight Roadway Design Considerations (2015) report does address curb radius design within land use context, as discussed in Section 2.5.

3. ANALYSIS OF COLLISIONS BETWEEN TRUCKS AND PEDESTRIANS IN URBAN AREAS

This chapter presents the findings of an analysis of collisions between trucks and pedestrians in Canadian urban areas. The objective of the analysis was to better understand the safety issues that arise when trucks and pedestrians share the same urban transportation system. The chapter presents national results and disaggregated findings for Winnipeg, Manitoba. The analysis examines: (1) the historical trends of the number and severity of truck-pedestrian collisions, (2) the temporal distribution of truck-pedestrian collisions, (3) truck-pedestrian collisions by weather condition (4) truck-pedestrian collisions by roadway characteristics, (5) collision configurations and vehicle maneuvers prior to truck-pedestrian collisions, (6) pedestrian actions prior to truck-pedestrian collisions and (7) the contributing factors to truck-pedestrian collisions. This analysis provides an overall depiction of truck-pedestrian collision characteristics in Canadian urban centres but does not provide exposure and collision rate information.

3.1. Methodology

The collision analysis involved reported collisions between trucks and pedestrians in urban areas across Canada as well as for the city of Winnipeg. The analyzed truck types, as defined by the City of Winnipeg's Traffic Accident Report and the National Collision Database (NCDB) Data Dictionary (CCMTA, 2006), were as follows:

- Single unit truck over 4,500 kg (unit chassis): includes all straight trucks with a gross vehicle weight of 4,500 kg and over on the vehicle registration. This excluded truck tractors with a fifth wheel assembly.
- Road tractor (power unit for semi-trailer): truck tractors used for the movement of cargo in or on a trailer by means of a fifth wheel connection, with or without a semitrailer. This excluded pickups equipped with a fifth wheel.

This analysis made use of the following two data sources: (1) Transport Canada's National Collision Database and (2) the City of Winnipeg's Collision database.

Transport Canada's National Collision Database

The National Collision Database (NCDB) provided by Transport Canada contains individual collision records reported annually to Transport Canada by the 13 Canadian provincial and territorial jurisdictions: Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick, Quebec, Ontario, Manitoba, Saskatchewan, Alberta, British Columbia, Northwest Territories, Yukon Territory, and Nunavut. Although jurisdictions use different Motor Vehicle Collision Forms (also known as Traffic Accident Reports-TAR), the NCDB provides a national format for provision of collision data to the national database. The dataset provides information on the following categories:

- Collision-related variables include when the collision occurred, severity of the collision, collision configuration, number of vehicles involved, traffic control type, road surface condition, road alignment, road configuration, road classification, and weather condition.
- Vehicle-related variables include vehicle types and vehicle maneuvers.
- Person-related variables include the type of road user, pedestrian action, injury severity (medical treatment required) and contributing factors.

The NCDB does not provide information on the collision location. For this research, the database was filtered to include urban collisions only. The boundaries of urban locations are defined in the relevant legislation of each jurisdiction providing the collision data.

The database provides fatal, injury and property damage-only (PDO) collisions exceeding $2000. The analysis was conducted for the years 2011 to 2015, inclusive, the most recent available years of consistent data that correspond to the City of Winnipeg data and the change in data collection criteria by the Manitoba Highway Traffic Act in 2011.

City of Winnipeg Collision Database

The City of Winnipeg collision database provides individual records of reported collisions occurring within the municipal boundaries of the city of Winnipeg, which are all considered urban collisions. In addition to the collision-related, vehicle-related and person-related data, the City of Winnipeg collision database provides the location of collisions (i.e., intersection street names).

This research analyzed data for the six-year period of 2011 to 2016, inclusive. The data analysis was from the year 2011 onwards due to a change in the collision reporting criteria in the year 2011 as specified by the Highway Traffic Act where law enforcement personnel no longer need to record minimal injury and PDO collisions, as well as a change in the source of data. Therefore, the two datasets post and pre- 2011 are known to be inconsistent and not comparable.

Since 2011, the City of Winnipeg received its collision data from Manitoba Public insurance (MPI). The collision database includes data from two sources: (1) fatal, major injury and minor injury collision data obtained from Traffic Accident Reports (TAR) completed by law enforcement personnel at the scene of the incident and (2) minimal injury (i.e., requiring no hospital admittance or treatment) and property damage-only (PDO) collisions reported directly to Manitoba Public Insurance (MPI) for insurance claims that required no police presence on site. Therefore, the Winnipeg collision database post 2011 does not include data that resulted in minimal injuries (i.e., requiring no hospital admittance) and PDO collisions that were not reported directly to MPI for insurance claims. This resulted in the number of injury and PDO collisions involving pedestrians being less post 2011 than prior to 2011.

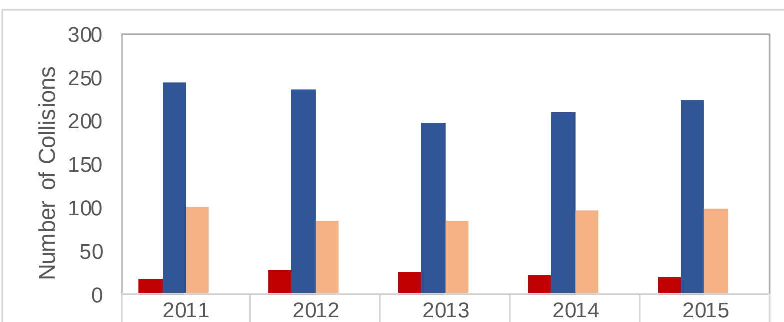
3.2. Urban Truck-Pedestrian Collision Analysis

In Canada, urban areas account for 90 percent of reported collisions involving pedestrians, of which two percent are fatal, 85 percent are injury and 13 percent are PDO collisions. Of the pedestrian collisions that involve trucks, the majority (78 percent) occur in urban areas.

Between the years 2011 and 2015, there were 1686 reported collisions between pedestrians and trucks (single unit and tractor-semitrailer trucks) in Canadian urban centres, or 337 collisions per year, on average. These collisions accounted for: (1) three percent of all urban pedestrian collisions, (2) two percent of all urban injury collisions involving pedestrians, and (3) 10 percent of all urban fatal collisions involving pedestrians. Therefore, a higher proportion of fatal pedestrian collisions were with trucks relative to the proportion of all pedestrian collisions that occurred with trucks. A total of 1982 pedestrians were reported to be involved in the 1686 reported collisions with trucks in Canadian urban centres.

3.2.1. Severity of Truck-Pedestrian Collisions

Figure 3 shows the number of reported urban collisions between trucks and pedestrians across Canada by severity type for the years 2011 to 2015. A total of 111 fatal collisions (seven percent), 1112 injury collisions (66 percent) and 463 property damage-only (PDO) collisions (27 percent) were reported in Canadian urban centres during this five-year period. These collisions represented 113 fatalities and 1237 injuries reported over the five-year period. There was an average of 23 fatalities and 247 injuries reported per year from urban truck-pedestrian collisions.



	2011	2012	2013	2014	2015
Fatal	18	27	26	21	19
Injury	244	236	198	210	224
PDO	100	84	84	96	99
Total	362	347	308	327	342

Figure 3: Distribution of Truck-Pedestrian Collisions by Severity in Canadian Urban Centres (2011-2015)

Figure 4 shows the total number of reported collisions between trucks and pedestrians per year in Canadian urban centres by truck type and Table 5 shows the severity distribution of these collisions. There were 1705 trucks involved in the 1686 truck-pedestrian collisions in Canadian urban centres. The majority of truck-pedestrian collisions in Canadian urban centres occurred with single unit trucks (an average of 285 collisions per year), followed by truck tractors (an average of 56 collisions per year). Although truck tractors accounted for a lower number of collisions with pedestrians than single unit trucks, they accounted for a higher proportion of fatal collisions, with 14 percent (39 of 279) of the pedestrian collisions with truck tractors being fatal compared to five percent (74 of 1426) of pedestrian collisions with single unit trucks.

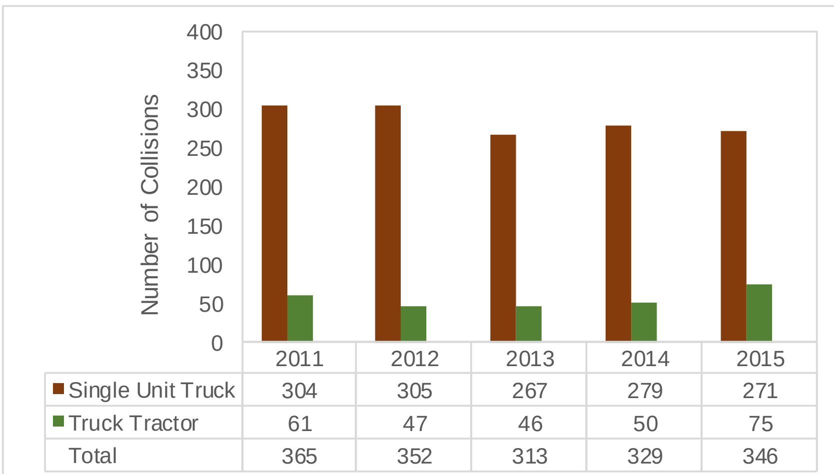


Figure 4: Number of Truck-Pedestrian Collisions by Vehicle Type in Canadian Urban Centres

Table 5: Severity of truck-pedestrian collisions in Canadian urban centres by truck type (2011-2015)

	Number of Collisions			
Vehicle Type	**Fatal**	**Injury**	**PDO**	**Total**
Single Unit Truck	74	926	426	1426
Truck Tractor	39	199	41	279
Total	113	1125	467	1705

The City of Winnipeg reported 10 collisions between trucks and pedestrians over the six-year study period from 2011 to 2016, or 1.7 collisions per year, on average. While this figure resulted in approximately 0.8 percent of total collisions involving pedestrians, it accounted for 14 percent of fatal pedestrian collisions in Winnipeg, which is higher than the national rate of 10 percent. Of the 10 reported collisions, four were fatal, four were injury, and two were PDO collisions. The proportion of fatal collisions (four out of 10 collisions) is higher than the national proportion of fatal collisions (seven percent); however, this is based on very low numbers of truck-pedestrian collisions in Winnipeg.

Single unit trucks were the most frequently involved truck type in collisions with pedestrians in Winnipeg, accounting for seven out of 10 truck-pedestrian collisions, followed by tractor-semitrailers accounting for three out of ten collisions, as shown in Table 6. Although tractor-semitrailers were involved in a lower number of truck-pedestrian collisions, all of the collisions were fatal.

Table 6: Collision severity for truck-pedestrian collisions by truck type in Winnipeg (2011-2016)

Truck Type	Fatal	Injury	PDO	Total
Truck Over 4500 kg (Single Unit Truck)	1	4	2	7
Power Unit for Semi-Trailer (Truck Tractor)	3	0	0	3
Total	**4**	**4**	**2**	**10**

3.2.2. Temporal Distribution of Truck-Pedestrian Collisions

Figure 5, Figure 6, and Figure 7 show the temporal distribution of pedestrian collisions with trucks in Canadian urban centres as a function of month-of-year, day-of-week and time-of-day, respectively. In terms of the month-of year distribution, the monthly proportion of collisions was relatively consistent, with each month accounting for an average of eight percent of yearly collisions. However, October had the highest proportion of yearly collisions, accounting for an average of 9.4 percent of yearly collisions. September, October and March together accounted for one-third of fatal collisions in Canadian urban centres. December had the lowest collision proportion accounting for an average of seven percent of pedestrian-truck collisions.

In terms of the day-of-week distribution, the majority of collisions occurred on weekdays, accounting for an average of 85 percent of weekly collisions. On average, each weekday accounted for approximately 17 percent and each weekend day accounts for eight percent of truck-pedestrian collisions.

In terms of the time-of-day distribution, three-quarters of truck-pedestrian collisions in Canadian urban centres occurred during the daytime hours of 8:00 to 18:00, with a peak in proportion of daily collisions at 10:00-11:00 (accounting for 10 percent), followed by 14:00-15:00 (accounting for nine percent). The morning hour of 10:00-11:00 also accounted for the highest proportion of fatal collisions (13 percent), followed by the hour from 7:00 to 8:00 (11 percent). The period between midnight and 6:00 accounted for the lowest proportion of collisions.

In Winnipeg, the truck-pedestrian collisions were distributed consistently amongst of the months of the year, with the highest number of collisions (two out of 10 collisions) occurring in August. Almost all of the collisions (nine out of 10 collisions) occurred during weekdays, with only one collision occurring on a weekend (Sunday). Monday and Tuesday accounted for the highest number of collisions, with six out of 10 collisions occurring on these days. In Winnipeg, all of the truck-pedestrian collisions occurred during the daytime hours between 7:00 and 15:00. The highest number of collisions (three out of 10 collisions) occurred from 12:00-13:00, followed by 8:00-9:00 (two out of 10 collisions).

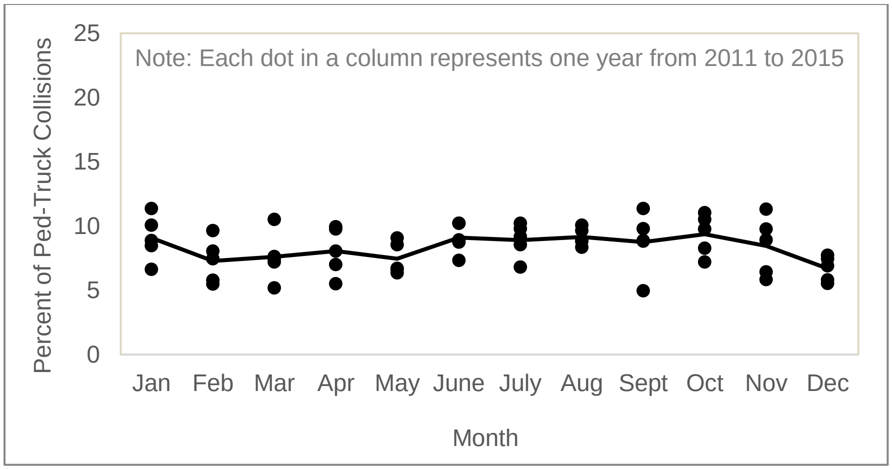


Figure 5: Percent of Urban Truck-Pedestrian Collisions in Canada by Month of Year (2011-2015)

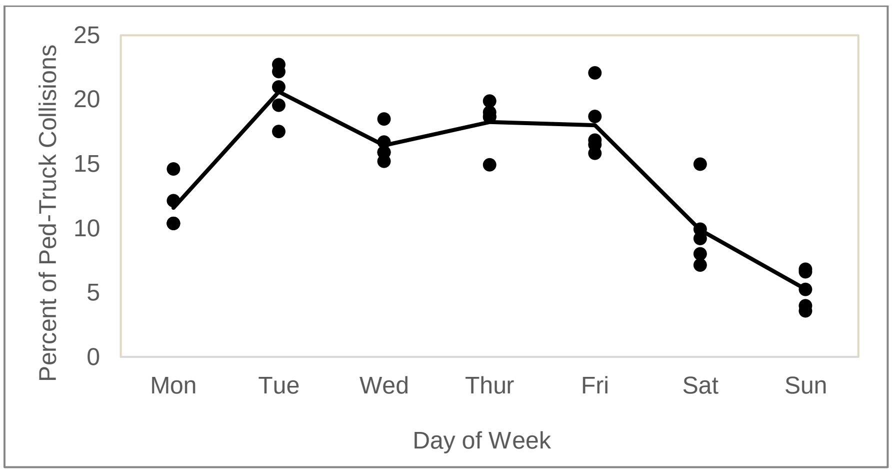


Figure 6: Percent of Urban Truck-Pedestrian Collisions in Canada by Day of Week (2011-2015)

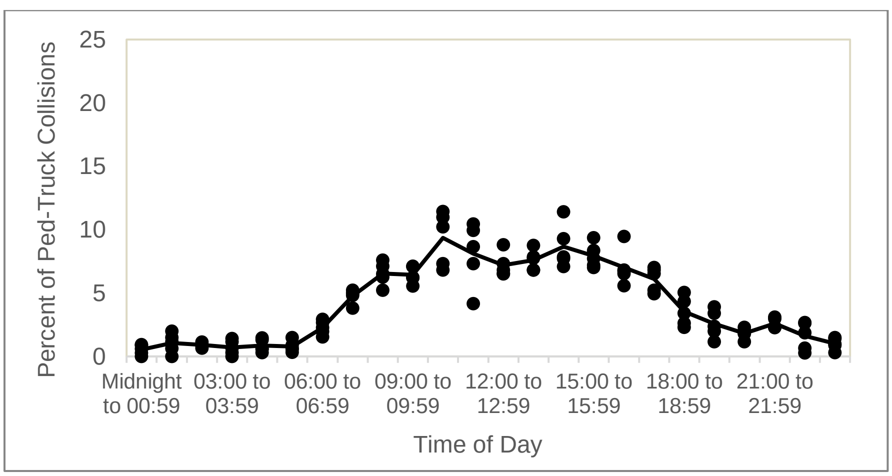


Figure 7: Percent of Urban Truck-Pedestrian Collisions in Canada by Time of Day (2011-2015)

3.2.3. Truck-Pedestrian Collisions by Weather Condition

Table 7 shows the weather conditions during truck-pedestrian collisions in Canadian urban centres. The majority of these collisions occurred during clear weather conditions. Adverse weather conditions (rain, snow, sleet, hail, and bad visibility due to fog, smoke, smog or drifting snow) were present for 29 percent of the collisions. In Winnipeg, eight out of 10 collisions occurred during clear weather conditions and one collision occurred during snowy conditions.

Table 7: Weather conditions for truck-pedestrian collisions in Canadian urban centres (2011-2015)

Weather	Fatal	Injury	PDO	Total	% of Total Known
Clear and Sunny	77	813	281	1171	71
Cloudy	18	123	98	239	14
Rain	8	82	50	140	8
Snow	4	45	16	65	4
Bad Visibility	1	12	7	20	1
Sleet, Hail	0	6	5	11	1
Wind	2	3	0	5	<1
Other	0	8	0	8	<1
Total Known	**110**	**1092**	**457**	**1659**	**100**
Unknown	1	20	6	27	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows weather condition information for 1659 of 1686 reported collisions.

3.2.4. Truck-Pedestrian Collisions by Roadway Characteristic

Table 8 shows the roadway condition and alignment at locations where truck-pedestrian collisions took place in Canadian urban centres. The road condition describes the construction and/or maintenance condition of the road. The road condition categories identified in the National Collision Database are good road conditions (i.e., no signs of adverse road conditions), roads under repair/construction, potholes and ruts, uneven pavement surface, worn pavement (i.e., low coefficient of friction), and obscured or faded pavement markings. The road alignment describes the visual alignment of the roadway the vehicle was travelling on at the time of the collision. The road alignment configurations include straight roadway (i.e., no horizontal curvature) either with a level vertical alignment or with a gradient, a curved roadway (i.e., with a horizontal curvature) either with a level vertical alignment or with a gradient, top of a hill or a gradient (i.e., crest curve), and the bottom of a hill or gradient (i.e., a sag curve). The database identified road conditions for 1430 collisions and road alignments for 1541 collisions of the 1686 national collisions. Of the known data, the majority of collisions occurred on straight and level road alignments (79 percent) and good roadway conditions (94 percent). The City of Winnipeg collision database does not report road condition or road alignment data.

Table 8: Road condition and alignment at truck-pedestrian collision locations in Canadian urban centres (2011-2015)

Road Condition	Fatal	Injury	PDO	Total	% of Total Known
Good	79	845	422	1346	94
Under Repair, construction	1	27	7	35	2
Ruts, Potholes	1	9	7	17	1
Uneven Pavement	0	2	0	2	<1
Worn	0	1	0	1	<1
Obscured or faded pavement markings	0	0	1	1	<1
Other	0	27	1	28	2
Total Known	**81**	**911**	**438**	**1430**	**100**
Unknown	4	73	19	96	
Not Provided	26	128	6	160	
Total	**111**	**1112**	**463**	**1686**	

Road Alignment	Fatal	Injury	PDO	Total	Percent
Straight and level	84	823	300	1207	78
Straight with gradient	13	78	58	149	10
Curved and level	5	48	20	73	5
Curved with gradient	4	27	30	61	4
Top of hill	0	9	6	15	1
Bottom of hill ("sag")	0	13	14	27	2
Other	0	8	1	9	1
Total Known	**106**	**1006**	**429**	**1541**	**100**
Unknown	5	106	34	145	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows road condition information for 1430 collisions and road alignment information for 1541 collisions of the 1686 reported collisions.

Table 9 shows the design classification of the roadways where the truck-pedestrian collisions occurred in Canadian urban centres. The road classification provides information on the geometric design of the roadway, which includes one-way roads, undivided and divided roadways, with two lanes or multiple lanes. The type of median is identified for divided roadways, specifically whether they are divided with a traversable median (such as painted medians or flush medians) or with a physical non-traversable barrier (such as a raised concrete curb, concrete barrier, or grass median). About two-thirds of collisions in Canadian urban centres occurred on undivided roadways, with the majority of these collisions occurring on two lane roadways. Divided roadways accounted for 19 percent of collisions and one-way roadways accounted for 14 percent of collisions. On divided roadways, barrier medians accounted for a higher proportion of collisions than traversable (i.e., no barrier) medians. The City of Winnipeg collision database does not report road classification data.

Table 9: Road classifications at truck-pedestrian collision locations in Canadian urban centres (2011-2015)

Road Classification	Fatal	Injury	PDO	Total	% of Total Known
Undivided, 2 way, 2 lanes	45	465	141	651	47
Undivided, 2 way, >2 lanes	19	115	74	208	15
1-way, 1-2 lanes	12	90	45	147	11
1-way, >2 lanes	3	31	13	47	3
Divided with barrier median	2	34	77	113	8
Divided, with median, no barrier	6	33	32	71	5
Divided (not specified)	11	61	7	79	6
Other	2	62	5	69	5
Total Known	**100**	**891**	**394**	**1385**	**100**
Unknown	11	221	69	301	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows road classification information for 1385 of 1686 reported collisions.

Table 10 shows the roadway design configuration at the truck-pedestrian collision locations, which describes the location where the collision occurred. The roadway configurations where collisions occurred are identified by the NCDB as at intersections (with public or private roads), at non-intersections (i.e., midblock locations), on a bridge (or overpass or viaduct), on an express lane of a freeway system, on a ramp, in a traffic circle, at a railroad crossing, in a tunnel or underpass, and on a passing or climbing lane. Of the known road configurations across Canada, the majority of collisions (52 percent) occurred at intersections, with 46 percent occurring at intersections with public roads and six percent occurring at intersections with private roads (i.e., parking lot entrance/exit, private driveway or laneway). Non-intersection collisions accounted for 32 percent of collision locations. In Winnipeg, the collision locations were almost equally split between public intersections (five out of 10 collisions) and non-intersection locations (four out of 10 collisions), with one unknown roadway configuration.

Table 10: Roadway configuration at truck-pedestrian collision locations in Canadian urban centres (2011-2015)

Roadway Configuration	Fatal	Injury	PDO	Total	% of Total Known
Intersection with public road	67	500	147	714	46
Non-intersection	30	305	160	495	32
Intersection with private road	2	42	46	90	6
Bridge or overpass	2	9	34	45	3
Express lane of a freeway system	1	6	19	26	2
Ramp	0	5	11	16	1
Traffic circle	0	4	4	8	1
Railroad crossing	0	6	1	7	<1
Tunnel or underpass	0	1	4	5	<1
Passing or climbing lane	0	1	0	1	<1
Other*	4	120	5	129	8
Total Known	**106**	**999**	**431**	**1536**	**100**
Unknown	5	113	32	150	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows road configuration information for 1536 of 1686 reported collisions.
*Other includes back lanes, parking lots or off-road locations.

Table 11 shows the predominant traffic control device or measure present at the truck-pedestrian collision sites in Canadian urban centres. The traffic control types identified in the NCDB are no traffic controls present, traffic signals present (either fully operational or in flashing mode), stop signs, yield signs, warning signs (i.e., yellow diamond shape sign), roadway markings (e.g., no passing), reduced speed zone, pedestrian crosswalk, school guard or flagman, police officer, railway crossings (with signals or with signs only), and school bus stopped (with or without bus signals flashing). Of the collisions with known traffic control types across Canada, almost half of the collisions occurred at sites with no traffic control devices, followed by 36 percent of collisions occurring at properly working signalized intersections. Locations with no traffic control measures are reported to be between intersections (which includes jaywalking) and at intersections (mostly in residential areas). Seven percent of collisions occurred at intersections with stop signs and five percent of collisions occurred at pedestrian crosswalks or crossings with school guards or flagmen. In Winnipeg, the majority of collisions (6 out of 10) occurred at properly working signalized intersections, with one collision occurring at an intersection with a stop sign. The "no traffic control" option that is reported in the NCDB is not available in the Winnipeg TAR and collision database.

Table 11: Traffic control device present at truck-pedestrian collision location in Canadian urban centres (2011-2015)

Traffic Control	Fatal	Injury	PDO	Total	% of Total Known
No traffic control present	42	530	138	710	47
Traffic signals fully operational	46	331	161	538	36
Stop Sign	11	70	23	104	7
Pedestrian crosswalk	1	38	4	43	3
School guard, flagman	1	19	3	23	2
Yield Sign	0	13	6	19	1
Markings on the road (e.g., no passing)	1	2	9	12	1
Traffic signals in flashing mode	0	2	3	5	<1
Warning Sign	0	1	2	3	<1
Reduced speed zone	0	1	1	2	<1
No passing zone sign	0	0	1	1	<1
Railway crossing with signals, gates	0	0	1	1	<1
Control device not specified	0	4	0	4	<1
Other	1	34	7	42	3
Total Known	**103**	**1045**	**359**	**1507**	**100**
Unknown	8	67	104	179	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows traffic control information for 1507 of 1686 reported collisions.

Table 12 and Figure 8 show the distribution of posted speed limits at the truck-pedestrian collision sites in Canadian urban centres. The majority of collisions with known speed limits (69 percent) and the majority of fatal collisions with known speed limits (62 percent) occurred on roadways with 50 km/h posted speed limits. The proportion of fatal collisions rose with an increase in the posted speed limit, up to a 60 km/h speed limit. For example, of the collisions occurring at 50 km/h posted speed limits, about seven percent were fatal, and of the collisions that occurred at 60 km/h posted speed limits, 15 percent were fatal. Since posted speed limits in urban areas are commonly 60 km/hr or less, the frequency of collisions on roadways with speed limits greater than 60 km/h were low. Roadways with 60 km/h posted speed limits accounted for 11 percent of truck-pedestrian collisions while accounting for 20 percent of fatal truck-pedestrian collisions. Therefore, the proportion of fatal collisions occurring on a 60 km/h speed limit roadway is greater than the associated proportion of total collisions (i.e., a collision on a 60km/h road is more likely to be fatal). Seven percent of collisions occurred on streets with less than 40 km/h speed limits.

Table 12: Speed limit at truck-pedestrian collision locations in Canadian urban centres (2011-2015)

Speed Limit (km/h)	Fatal	Injury	PDO	Total	% of Total Known
<40	5	45	27	77	7
40	5	60	3	68	6
50	58	494	238	790	69
60	19	92	12	123	11
70	1	15	17	33	3
80	2	7	6	15	1
90	1	4	3	8	1
100	2	18	8	28	2
110	1	4	1	6	1
Other	0	1	1	2	0
Total Known	**94**	**740**	**316**	**1150**	**100**
Unknown	6	183	126	315	
Not Provided	11	189	21	221	
Total	**111**	**1112**	**463**	**1686**	

Note: The NCDB shows speed limit information for 1150 of 1686 reported collisions.

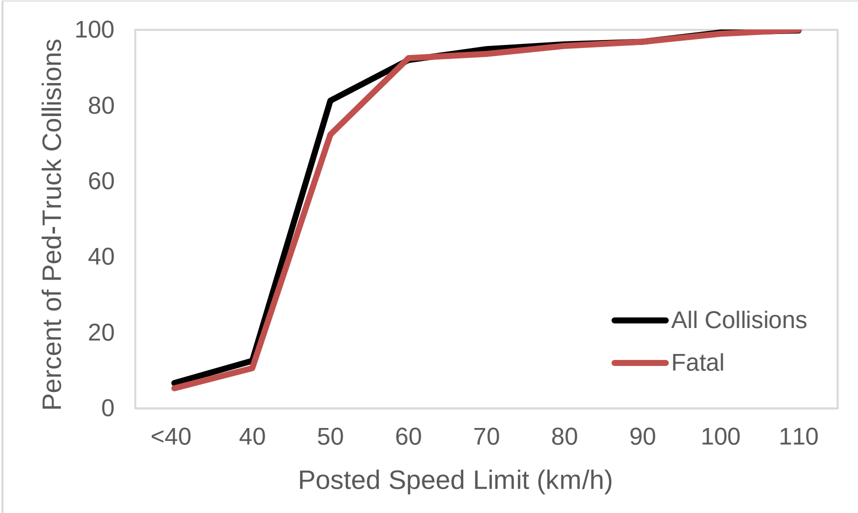


Figure 8: Percent of Truck-Pedestrian Collisions in Canadian Urban Centres by Posted Speed Limited

Figure 8 shows that 81 percent of truck-pedestrian collisions and 72 percent of fatal truck-pedestrian collisions occurred on roads with 50 km/h or less posted speed limit. It is also evident that a significant increase in the total number of collisions as well as fatal collisions occurred from a 40 km/r speed limit to a 50 km/h speed limit. From a 50 km/h to a 60 km/h speed limit roadway there is a higher proportion of increase in fatal collisions (28 percent increase) than total collisions (13 percent increase).

3.2.5. Vehicle Maneuver of Truck-Pedestrian Collisions

Table 13 shows the distribution of vehicle maneuver types just prior to a collision for the trucks involved in pedestrian collisions in Canadian urban centres. The vehicle maneuver descriptions are listed in Table 13. Of the 1705 trucks involved in collisions with pedestrians in Canadian urban centres (some collisions had more than one truck involved), 1443 vehicle records reported a vehicle maneuver configuration. For the trucks for which the vehicle maneuver is known, the table shows that the highest number of collisions occurred when the vehicle was travelling straight ahead (38 percent), followed closely by right and left turn vehicle maneuvers together accounting for 35 percent (about 18 percent each). Approximately 11 percent of vehicles were reversing when they collided with pedestrians.

In Winnipeg, 11 trucks were involved in the 10 reported truck-pedestrian collisions. The collision maneuver patterns are similar to the national statistics, however the proportions of maneuvers are relatively higher, with the majority of trucks (five out of 11) travelling straight ahead just prior to the collision and right and left turn maneuvers accounting for four out of the 11 vehicles (three vehicles turning left and one vehicle turning right).

Table 13: Vehicle maneuver configurations of trucks involved in pedestrian collisions in Canadian urban centres (2011-2015)

Vehicle Maneuvers	Fatal	Injury	PDO	Total	% of Total Known
Going Straight Ahead	40	331	173	544	38
Turning Right	23	154	82	259	18
Turning Left	25	162	53	240	17
Reversing	6	117	40	163	11
Stopped/Parked Legally	3	39	5	47	3
Changing Lanes	1	14	24	39	3
Slowing or Stopping in Traffic	0	19	11	30	2
Starting in Traffic	1	18	5	24	2
Negotiating a Curve	0	10	11	21	1
Leaving Roadside	2	12	2	16	1
Merging into Traffic	0	1	9	10	1
Passing, Overtaking	0	4	4	8	1
Stopped/Parked Illegally	0	5	1	6	<1
Making a U-Turn	0	2	1	3	<1
Run-Away Vehicle	0	0	3	3	<1
Other	1	26	3	30	2
Total Known	**102**	**914**	**427**	**1443**	**100**
Unknown	0	14	3	17	
Not Applicable (e.g. parked car)	0	6	16	22	
Not Provided	11	191	21	223	
Total	**113**	**1125**	**467**	**1705**	

Note: The NCDB shows vehicle maneuver information for 1443 of 1705 vehicles involved in pedestrian collisions.

When looking at the truck-pedestrian collisions occurring at intersections-only in Canadian urban centres, as shown in Table 14, the proportion of left and right turn vehicle maneuvers are more exaggerated. Right and left turn maneuvers account for the majority of collisions at intersections, with right turns accounting for 30 percent and left turns accounting for 28 percent of vehicle maneuvers.

Table 14: Vehicle maneuver configurations during truck-pedestrian collisions at intersection locations only in Canadian urban centres (2011-2015)

Vehicle Maneuvers- at intersections	Total	% of Total Known
Right Turn	218	30
Straight Ahead	205	29
Left Turn	202	28
Reverse	35	5
Stopped/Parked Legally	11	2
Changing Lanes	9	1
Slowing/Stopping in Traffic	13	2
Start in Traffic	13	2
Curve	0	0
Leave Roadside	1	<1
Merge	1	<1
Passing	6	1
Stopped/Parked Illegally	0	0
U-Turn	1	<1
Run away Vehicle	0	0
Swerving to Avoid Collision	0	0
Unspecified	0	0
Other	3	<1
Total Known	**718**	**100**
Unknown	7	
Not Applicable (e.g., parked vehicle)	6	
Not Provided	77	
Total	**808**	

Note: the NCDB shows vehicle maneuver information for 718 of 808 vehicles involved in pedestrian collisions at intersections.

3.2.6. Pedestrian Action at the Time of Collision with Trucks

Table 15 shows the action of pedestrians just prior to or at the time of the collision with a truck or multiple trucks in Canadian urban centres. A total of 1982 pedestrians were reported to be involved in the 1686 collisions, of which 710 pedestrian records had a known pedestrian action. The pedestrian action types reported by the NCDB are crossing an intersection with or without the right of way, crossing an intersection with no traffic control, crossing between intersections, crossing crosswalks, working construction on a roadway, getting on/off a school bus or other vehicle, walking alongside a roadway with or against traffic, walking on the travelled portion of the roadway with or against traffic, coming from behind a parked or moving car, running into a roadway, playing, working, or lying on a roadway, and riding in a wheelchair on a road.

As Table 15 shows, the majority of pedestrians (55 percent) were crossing an intersection when struck by a truck, either with right of way, without right of way, or with no traffic control. In over half of these pedestrian records (52 percent), pedestrians were crossing with the right of way, in 14 percent, pedestrians were crossing without the right-of-way and in 34 percent, pedestrians were crossing at intersections with no traffic control. About six percent of pedestrian records involved the pedestrian crossing the roadway between intersections and about three percent involved the pedestrian crossing at a crosswalk.

Analyzing collisions at intersections only, pedestrians being involved in collisions while crossing an intersection was an even greater proportion of pedestrian actions (72 percent of pedestrian records). Pedestrians involved in collisions while crossing controlled intersections with the right of way was the most common scenario at 40 percent, followed by intersections with no traffic control at 24 percent, and controlled intersections without right of way at eight percent. It is also evident that 12 percent of all urban truck-pedestrian collisions and eight percent of collisions at intersections occurred while the pedestrian was on the sidewalk, median, or safety zone. In these collisions, the truck would have mounted the curb and collided with the pedestrian on the sidewalk/median. The City of Winnipeg dataset was missing all data on pedestrian action and pedestrian condition for truck-pedestrian collisions.

Table 15: Pedestrian action at truck-pedestrian collisions in Canadian urban centres (2011-2015)

Pedestrian Action	Fatal	Injury	PDO	Total	% of Total Known
Crossing intersection with traffic control, with ROW	22	173	8	203	29
Crossing intersection with no traffic control	28	106	1	135	19
On sidewalk, median, safety zone	1	81	0	82	12
Crossing intersection with traffic control, w/o ROW	8	46	0	54	8
Crossing Between Intersections	5	37	0	42	6
Working on roadway (i.e. construction worker)	1	29	2	32	5
Crossing a crosswalk	5	19	0	24	3
Getting on/off vehicle (other than school bus)	1	12	2	15	2
Pushing vehicle on roadway	1	14	0	15	2
Walking along roadway with traffic	2	11	1	14	2
Walking along roadway against traffic	0	5	0	5	1
Coming from behind parked car on roadside	0	10	0	10	1
Running into roadway	1	7	0	8	1
Working on vehicle on the side of the road	0	7	0	7	1
Walking on roadway with traffic	2	2	0	4	1
Playing on roadway	0	1	0	1	<1
Other	12	45	2	59	8
Total Known	**89**	**605**	**16**	**710**	**100**
Not Applicable	19	144	563	726	
Unknown	31	484	31	546	
Total	**139**	**1233**	**610**	**1982**	

Note: The NCDB shows pedestrian action information for 710 of 1982 reported pedestrian records.

3.2.7. Contributing Factors to Truck-Pedestrian Collisions

There are four categories of contributing factors collected by jurisdictions to describe the variables that appear to have contributed to the collision: (1) *human/driver condition*, such as driver inattentiveness, loss of consciousness, and impairment by alcohol or drugs, (2) *driver action*, such as failure to yield to the right of way, improper passing or turning and driving too closely, too fast or too slow (3*) vehicle condition,* such as overloads, loads shift, and defective brakes, lights or tires and (4) *environmental condition*, such as weather, obstructions on the roadway and wildlife. Although the contributing factors collected are similar amongst jurisdictions, the data recording methodology can be different, since some jurisdictions are required to select one factor from each category while others prioritize the contributing factors in order of entry and can select any four from all four categories with a possibility of multiple selections from the same category.

Table 16 provides the number of collisions the contributing factors (CF) from each category were reported on for truck-pedestrian collisions in Canadian urban centres. Since more than one factor from a contributing factor category can be listed for one collision, the total represents the number of times a CF category was listed in the collision database.

Driver action was listed most frequently (894 times) as a contributing factor to collisions. Driver action was also reported as a contributing factor in the most number of collisions (45 percent of collisions), where of the 1686 reported collisions, 758 had a driver action listed at least once as a contributing factor. This was followed by environmental conditions reported at least once in 119 collisions (seven percent of collisions), vehicle conditions reported at least once in 63 collisions (four percent of collisions) and human/driver condition reported at least once in 50 collisions (three percent of collisions).

Of the 52 times human conditions were listed as contributing factors (sometimes more than once for a collision), alcohol impairment was identified the most frequently at 31 percent. Of the 894 times driver action was listed as a contributing factor, inattention/distraction was identified the most frequently at 42 percent, followed by failure to yield at 28 percent. Of the 63 times vehicle condition was listed as a contributing factor, obstructed visibility (e.g., from wipers, defrosters, mirrors, or tinting) was identified the most frequently at 32 percent followed by defective brakes and overloads at 14 percent each. Of the 124 times environmental conditions were listed as contributing factors, obstructed view from glare or reflection was identified the most frequently at 20 percent, followed by weather conditions at 19 percent.

Table 16: Contributing factors to truck-pedestrian collisions in Canadian urban centres (2011-2015)

Human Condition (HC)	No. of Records/Collisions	Percent
Alcohol	16	31
Sudden Illness, lost consciousness	8	15
Drugs	3	6
Fatigued, fell asleep	2	4
Other Driver Condition	23	44
Total Number of HC Records	**52**	**100**
Driver Action (DA)		
Inattentive, Distraction	374	42
Fail to Yield	248	28
Improper Turning or Passing	122	14
Reversing Unsafely	57	6
Disobey Traffic Control Device or Officer	47	5
Too Fast	20	2
Too Close	17	2
Wrong Direction	4	<1
Wrong Side of Road	3	<1
Lost Control	2	<1
Total Number of DA Records	**894**	**100**
Vehicle Condition (VC)		
Visibility Obstructed (e.g. wiper, defrosting)	20	32
Defective Brakes	9	14
Oversized Load, Overload	9	14
Unsecured Load	4	6
Defective Lights	3	5
Other Vehicle Defects	18	29
Total Number of VC Records	**63**	**100**
Environmental Condition (EC)		
Obstructed View (glare or reflection)	25	20
Weather	23	19
Road Condition (including road construction)	11	9
Road Obstruction	10	8
Animal on Road	1	1
Other Environment CF	54	44
Total Number of EC Records	**124**	**100**

From the contributing factor options, driving properly, normal human conditions or no apparent vehicle defects were the ones listed in the City of Winnipeg truck-pedestrian collision records. From the limited available data, it is evident that similar to the national statistics, driver/human action was identified most frequently (four times). The driver/human actions reported in four separate collisions were careless driving, failure to yield right of way, leaving stop sign before safe to do so, and pedestrian error/confusion. The collision involving pedestrian error/confusion resulted in a fatality from a truck tractor colliding with an elderly pedestrian at an intersection, with all other conditions being seemingly normal.

Driver distraction/inattention was the only driver condition reported as a contributing factor, which was from a single unit truck driver turning left at a signalized intersection, failing to yield to the right of way, and resulting in a fatal pedestrian collision. Two of the three pedestrian collisions with trucks turning left were due to either careless driving or inattention/distraction from the driver. Slippery road surface was the only environmental condition reported as a contributing factor, which resulted in two single unit trucks colliding at a midblock location and involving a pedestrian. No vehicle defects were identified as a contributing factor in any of these collisions.

3.3. Limitations of the Analysis

The limitations of the collision data and analysis follow:

- Collision data from 2011 onwards was used for the collision analysis due to the change in the collision reporting criteria by the Manitoba Highway Traffic Act and source of data in 2011. Prior to 2011, the Highway Traffic Act required collisions resulting in a fatality, injury or property damage greater than $1000 to be reported by a law enforcement agency. Amendments to the Highway Traffic Act in 2011 changed the definition of reportable collisions and now require collisions to be reported by law enforcement personnel if the collision involves a fatality or an injury requiring admittance to a hospital for observation or treatment (i.e., major and minor injuries, but not minimal injuries). Therefore, minimal injury and property damage-only (PDO) collisions do not require a Traffic Accident Report (TAR) by law enforcement. A fatal collision is defined as a collision in which at least one person is killed as a result of the collision, with the death occurring within 30 days of the collision. An injury collision is defined as a collision in which at least one person has been recorded as sustaining some level of personal injury that is not fatal. The injury levels include: “major” (admitted to the hospital), “minor” (treated and released from the hospital), and “minimal” (no hospital treatment required). (Manitoba Public Insurance, 2016)

Since 2011, the City of Winnipeg has received its collision database records from Manitoba Public Insurance (MPI), rather than directly from the police. The collision database post 2011 includes fatal and major and minor injury collision data obtained from Traffic Accident Reports (TAR) completed by law enforcement personnel at the scene of the incident as well as minimal injury and property damage-only (PDO) collisions reported directly to Manitoba Public Insurance (MPI) for insurance claims that required no police presence on site.

Although the retrieval of data form MPI since 2011 provides the opportunity of capturing more PDO and minimal injury collision records in the collision database, the reporting of these collisions is optional and depends on those involved in the collisions. Therefore, the overall effect of the change in the Manitoba Highway Traffic Act data collection requirement by law enforcement personnel is lower PDO and injury pedestrian collision records in the database post-2011 compared to pre-2011.

- The lack of accurate location descriptors is a limitation with the collision database. Many collision sites are not investigated by law enforcement personnel, therefore, the TAR relies on the location descriptors provided by those involved in the collision and the MPI representative that is inputting the descriptors into the TAR. The lack of quality control in providing accurate and detailed location descriptions as well as accurate data transfer to the database can result in incomplete, inaccurate, or missing information in the database. In addition, the database does not allow the transfer of additional location descriptors (if provided) from the TAR to the database. Therefore, if a collision occurred between a pedestrian and a vehicle at an intersection or at midblock, it is not evident which leg of the intersection or which approach to the intersection the pedestrian was crossing.

- The reporting of collision data in Traffic Accident Reports (TAR) or Motor Vehicle Accident (MVA) reports is not completely consistent amongst jurisdictions. The data categories or the options within the categories can vary slightly. For example, the road category/classification can have varying levels of detail, where the Manitoba TAR specifies the number of lanes while the Saskatchewan MVA does not. Another example is that the Saskatchewan MVA has a "no control present" option under the Traffic Control category, while the Manitoba TAR does not.

  In addition, the method of inputting data varies amongst jurisdictions. For example, although the contributing factor categories are similar amongst jurisdictions, the data recording methodology can be different, since some jurisdictions are required to select one factor from each category while others prioritize the contributing factors in order of entry and can select any four from all four categories with a possibility of multiple selections from the same category.

  The selection of collision characteristic options on the TAR is also subjective. The TAR form is completed based on how law enforcement of insurance personnel interpret the collision characteristics based on their personal judgement of the collision characteristics or the description/interviews provided by those involved.

- The research provides a collision frequency analysis to provide an overview of truck-pedestrian collision characteristics. Collision rates are not analyzed as the analysis does not account or adjust for exposure data.

3.4. Summary of Findings

A summary of findings from the urban truck-pedestrian collision analysis follows:

- From 2011 to 2015, inclusive, an average of 337 collisions occurred per year involving pedestrians and trucks in Canadian urban centres, with seven percent of these collisions being fatal. Pedestrian collisions with trucks accounted for 10 percent of all fatal pedestrian collisions in Canadian urban centres. Winnipeg had a significantly higher percentage of fatal collisions between pedestrians and trucks (four out of 10 collisions) relative to the National statistic; however, this finding is based on low numbers of 10 total collisions over a six-year period.
- The majority of trucks involved in pedestrian collisions were single unit trucks (84 percent), followed by truck tractors (i.e., tractor-semitrailers combinations). Although truck tractors accounted for a lower number of trucks in collisions with pedestrians, they accounted for a higher proportion of fatal collisions, with 14 percent of collisions resulting in a fatality.
- The majority of truck-pedestrian collisions in Canadian urban centres (approximately 52 percent) occurred at intersections. Non-intersection collisions accounted for about 32 percent of collision locations.
- Left and right turn truck movements together accounted for 35 percent of known vehicle maneuvers at truck-pedestrian collisions (approximately 18 percent each). Left and right turns were the most common vehicle maneuver at intersection collisions, with right turns accounting for 30 percent and left turns accounting for 28 percent of vehicle maneuvers.
- The majority of pedestrians were involved in collisions with trucks while the pedestrian was crossing an intersection, with the pedestrian having the right-of way in over half of these records and not having the right of way in 14 percent. Analyzing collisions at intersections only, pedestrians crossing intersections accounted for an even higher proportion of pedestrian actions during collisions at 72 percent.

- Approximately 12 percent of all urban truck-pedestrian collisions and eight percent of collisions at urban intersections occurred while the pedestrian was on the sidewalk, median or safety zone. These collisions resulted from a truck mounting the curb onto the sidewalk/median.
- Driver action was reported as a contributing factor at least once in 45 percent of collisions. This was followed by environmental conditions (seven percent), vehicle conditions (four percent) and human/driver condition (three percent).
- Of the human condition contributing factors, alcohol impairment was identified the most frequently at 31 percent. Of the driver action contributing factors, inattention/distraction was identified the most frequently at 42 percent, followed by failure to yield at 28 percent. Of the vehicle condition contributing factors, obstructed visibility (e.g., from wipers, defrosters, mirrors, or tinting) was identified the most frequently at 32 percent. Of the environmental condition contributing factors, obstructed view from glare or reflection was identified the most frequently at 20 percent.

4. DESIGN AND DEVELOPMENT OF A WALKABILITY INDEX

This Chapter defines, characterizes and quantifies walkability as it relates to utilitarian transportation in urban areas. The relative Walkability Indices of urban areas within a jurisdiction can guide engineers and planners to plan and design transportation infrastructure and land use characteristics suitable to the needs associated with existing or desired walkability levels, identify priority areas for redevelopment to enhance walkability levels and monitor changes in urban form and walkability measures over time. The Walkability Index provides one component of the freight-walkability relationship, discussed in Chapter 5, which will guide the development of the urban freight-walkability decision support tool.

Figure 9 shows the process followed for the development of the Walkability Index in this research. First, walkability was defined and the performance objectives were identified specific to this research. Second, the spatial boundaries were selected for the measurement of walkability indicators. Third, walkability indicators and their associated metrics to measure walkability were selected. Indicators identify the performance objectives and track the performance towards these objectives and goals, while metrics measure the variables for each indicator. ArcGIS software program was used to overlay land use and transportation infrastructure spatial data associated with the selected walkability indicators. Fourth, the design and development of a composite Walkability Index based on the identified indicators was developed and a continuum of relative Walkability Indices were measured for 158 Census Tracts in Winnipeg. Available land use and infrastructure data were obtained from the following City of Winnipeg departments: 1) Planning, Property, and Development, 2) Winnipeg Transit, and 3) Public Works. Readily available Census data was obtained from the Statistics Canada Census Program (Statistics Canada, 2016). Finally, the validation of the Walkability Index was conducted. Each step is described further in this Chapter.

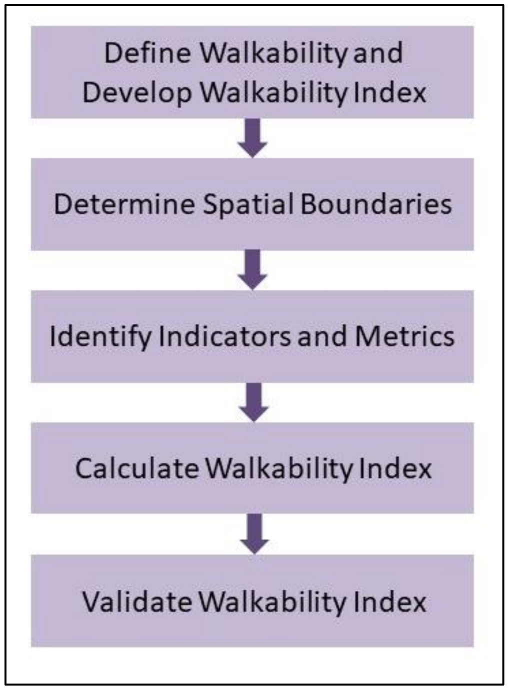


Figure 9: Walkability Index Development Methodology

4.1. Define Walkability and Develop a Walkability Index

Creating urban walkability means providing safe, accessible and connected transportation facilities and service options to pedestrians to reach daily living destinations. This research focused on walking from a utilitarian perspective, not solely from a commuting or recreational one. Walkability from a utilitarian perspective refers to the level of accessibility by foot or transit to every-day destinations based on necessity, such as work, shopping (grocery and retail), restaurants, entertainment, and schools. Therefore, in this research, although the traditional walkability ideology of a vibrant and active mixed land use area is still valid, areas that provide adequate pedestrian access to daily destinations such as grocery stores and schools were also considered walkable. Parks were not included in this analysis as they are solely recreational and were considered to skew the walkability index due to their large spatial area.

The composite Walkability Index developed as part of this research was quantified as a function of the identified performance objectives, as follows:

$$Walkability\ Index_n = w_1(\ Safety) + w_2(Accessibility) + w_3(Connectivity)$$

Where *n* is the spatial boundary (e.g., Census Tracts) and w_1, w_2 and w_3 are the designated weights for each performance objective, depending on the relative importance placed on the objectives by jurisdictions. The performance objectives were measured based on identified indicators and their associated metrics.

For the purpose of this research, the performance objectives of walkability were defined as follows:

- Safe referred to the urban environment creating safe interactions between pedestrians and other modes on the roadway. This was achieved through consideration of adequate pedestrian crossing designs and treatments suitable to the traffic characteristics and exposure time of pedestrians to vehicular traffic.
- Accessible referred to the availability and ease of access by pedestrians to daily services and destinations. This was based on the proximity of destinations within a reasonable walking distance or transit commute from trip origins.
- Connected referred to adequate infrastructure and service coverage to allow users to reach their destinations within a reasonable amount of time. This included well-connected and well-designed pedestrian infrastructure that provided shorter walking distances.

A composite index is a mathematical aggregation technique used for multidimensional concepts that do not have a common measurement unit across indicators (Miller, Witlox, & Tribby, 2013). Developing a composite Index involves standardizing the indicators into Z-scores to create unit-free measures prior to aggregating them. Composite measures of walkability are expected to provide a more consistent predictor of walking behavior than single component measures (Frank, et al., 2005; Agampatian, 2018). In addition, using composite indices reduces collinearity between indicators in a multidimensional concept (Feng, et al., 2010, Frank, et al., 2005; Brownson, et al., 2009).

Weights can be applied to the standardized indicators prior to aggregation to represent the relative importance of the indicators within the Index. Selecting appropriate weights can be challenging since some walkability indicators can reflect more than one performance objective, although they are categorized to represent one objective. In addition, some objectives may have more than one indicator, which, if simply added, would have a greater weight in the Index. Selecting relative importance of indicators also involves reaching a consensus of individual stakeholder perspectives, which could change over time due to contextual factors (Miller et al, 2013). In this research, all three walkability performance objectives represent equal contribution to the Walkability Index.

In order for the three performance objectives of safety, accessibility and connectivity to be equally weighted in the developed Walkability Index, the three accessibility indicators were averaged to provide one measurement of accessibility. Simply adding the three indicator measurements of accessibility in the Index would result in a greater contribution of the accessibility indicator, while safety and connectivity contributed one indicator measurement each. The composite Walkability Index was then calculated as follows:

$$Walkability\ Index_n = w_1\ (Safety\ Z\ Score) + w_2(Average\ Accessibility\ Z\ Score) + w_3(Connectivity\ Z\ Score)$$

Where n is a Census Tract (or any selected spatial boundary) and w_1, w_2 and w_3 are the designated weights for each objective, which are designated as one in this research.

The Walkability Index was developed based on the transportation systems analysis approach, which involves a holistic view of the interactions between various elements within a system. This approach brings together the dynamic interrelation between the transportation systems supply and existing demand and the resulting level of service, and resources consumed in the accommodation of the transportation task. The transportation systems supply composes the transportation services and infrastructure provided to facilitate the movement of pedestrians, while the demand composes the activity features of the urban form that determine where people and destinations are located, created by the socioeconomic and political characteristics of the environment. The choice of travel options (i.e., whether to walk to a destination) is influenced by the urban form (land use patterns and transportation options) and external economic and political factors.

The transportation systems supply and demand, individually and interrelated, determine the flow patterns and resources consumed. In turn, the flow pattern causes changes in the supply and demand over time. Changes in the supply and demand elements can also be imposed to purposefully create changes in the flow system, for example exogenously through land use and zoning policies and regulations or endogenously through infrastructure changes.

Studies show that both land use patterns and transportation systems design are consistently related to walking (Frank, et al., 2005; Saelens, et al., 2003; Ewing and Cervero, 2010), however, existing Walkability Indices in the literature and in practice have been developed from a planning perspective, focusing primarily on the system demand (i.e., land use variables). Literature uses proximity to destinations (accessibility variables) as the key factor in influencing the decision to use non-motorized transport (Leslie, et al., 2007). Planning measures such as density, diversity (land use mix), and walking distance to destinations are the indicators commonly used in existing Walkability Indices, which all ultimately represent proximity to destinations. Connectivity of the pedestrian network is the most commonly used supply-related variable in existing Walkability Indices; however, it is commonly measured by intersection density. This metric can be misleading since the presence of an intersection does not imply that it is a pedestrian crossing opportunity. Some areas (for example many new residential neighborhoods) are developed with no sidewalks;

therefore, the intersections do not provide a pedestrian crossing. The Walkability Index developed by the U.S. Environmental Protection Agency uses proximity to transit stops, intersection density, and land use diversity (employment and housing density) to determine walkability levels (EPA, 2010). The commercially-used Walk Score measures the walk time to amenities, intersection density, block length and population density to determine walkability levels (Walk Score, 2011).

The Walkability Index developed in this research provides a more holistic approach by incorporating transportation system supply elements in addition to the currently used demand elements. The transportation system supply elements include traffic signals, sidewalks, crosswalks, and transit service (ITDP, 2018). By incorporating transportation system supply elements in the analysis, the Walkability Index developed in this research provides a more engineering-oriented perspective to the existing planning-focused Walkability Indices by relating the safety and connectivity of pedestrian infrastructure design to the level of walkability. In addition, these transportation system supply elements provide street-level variables that can be physically changed by engineers in the short-term to influence walkability levels, while land use patterns and the spatial pattern of population and economic activity are long-term transformations.

4.1. Spatial Boundaries

Census Tracts were selected as the spatial boundary to assess relative walkability levels. Census Tracts are small and relatively stable geographic subdivisions in metropolitan areas with a population between 2500 and 8000 persons as specified by Statistics Canada and local specialists. Census Tract boundaries follow physical geographic features of the environment and are typically homogenous in terms of socioeconomic characteristics (Statistics Canada, 2015).

Similar to the Walkability Index developed by Agampatian (2014), a hybrid approach was used in the analysis where buffered spatial units were also used as an integration into the pre-defined spatial units (i.e., Census Tracts). In the literature, measures of the built environment are commonly analyzed either for pre-defined spatial units such as Census Tracts, blocks, or neighbourhoods or for set buffers around geocoded locations at a given distance (Agampatian, 2014). This research integrated both methods by using the buffered spatial units to determine the proximity of residents within a set walking distance to specific daily destinations, and subsequently overlaid the Census Tract boundaries onto the buffers to provide a measure of proximity for each Census Tract. The hybrid method provides a more accurate representation of the proximity indicator because it accounts for residents within walking distance of daily destinations that are not in the same Census Tract.

The City of Winnipeg has survey data at a neighbourhood level; however, Census Tracts were selected for this research due to their smaller areas, the availability of Census data by Statistics Canada, and the consistency of the analysis zones and transferability of the methodology to other Canadian jurisdictions. The walkability measures were calculated and a relative Walkability Index was determined for all 158 Census Tracts in Winnipeg. The Walkability Indices represented the distribution of walkability levels of Census Tracts relative to each other.

4.2. Walkability Indicators and Metrics

Once the performance objectives of walkability were determined, indicators were selected to identify and track the progress towards these objectives. Metrics were then identified for each indicator to measure the performance relative to an objective based on the indicator, as per Miller, Witlox, and Tribby (2013). Indicators of walkability can be measured with subjective or objective metrics. Subjective measures of walkability such as the pedestrian friendliness and attractiveness of an area, aesthetics, and perceived safety and comfort based on lighting, existence of graffiti and presence of loitering, alcohol and drugs can be perceived differently by different individuals (Agampatian, 2014; ITDP, 2018). This research measured walkability within an objective framework, where the analysis was based on tangible data and objective measures that could be assessed based on the physical features of the urban form, land use, and transportation infrastructure, not judgement and perceptions. Although the perceived subjective measures can be influencers on a person's decision to walk to a destination, this research focused on utilitarian transportation and the use of reliable, objective, measurable and readily-available metrics allows the Index to be easily transferrable and applied to other jurisdictions.

The literature identifies an extensive variety of walkability indicators and metrics, as summarized in Table 1 (in Chapter 2), with a focus on accessibility metrics. The indicators and metrics used in this research were selected based on the following:

- Intensity of use in the literature- the indicators and metrics were frequently stated in the literature as an influencing factor to walkability.
- Applicability- the indicators and metrics were applied in existing Walkability Indices and not just stated in the literature as an influencing variable to walkability.
- Data availability- the indicators and metrics could be measured based on available and readily-accessible data that are reliable and objective.
- Existing knowledge gap- the engineering-based indicators and metrics would close a knowledge gap in the literature and practice where Walkability Indices are commonly developed from a planning perspective.

The literature states that while composite measures of walkability are expected to provide more consistent predictors of walking behavior than single component measures (Frank, et al., 2005; Agampatian, 2018), they can be misleading by covering up the failures in some dimensions (Miller, Witlox, & Tribby, 2013). In addition, arguments have been made that some environmental features naturally co-exist; however, it is shown that no one indicator can represent every aspect of walkability (Krizek, 2003). For example, although land use mix typically exists in dense residential areas, there are areas with clusters of high residential density that have no walkable access to key destinations.

Therefore, in this research, five metrics were selected to represent the multidimensional nature of walkability while not losing sight of the contribution of the different variables; however, future applications of this research could see the use of additional or substitute metrics to develop an Index. Due to the various indicator measurements, the indicators were standardized to create unit-free measures prior to aggregating them in the composite Walkability Index. As previously stated, the measurements of each indicator were converted into Z-scores, which represent the distance of the measurement from the mean, in units of the standard deviation. Therefore, a positive value implies the value is above the mean and a negative value implies the value is below the mean in that data set. The Z-score is calculated as follows, where Z is the Z-score, X is the measured value, μ is the mean and σ is the standard deviation of the measurements of all Census Tracts:

$$Z = \frac{X - \mu}{\sigma}$$

Table 17 lists the objectives and the associated indicators and metrics used to calculate relative walkability levels in Winnipeg. Five indicators were selected to determine the performance of the listed performance objectives. The measurement methodology of each indicator is further discussed in the following section and maps representing the results of each indicator are presented to provide insight into the contributions of each variable to the final Walkability Index.

Table 17: Walkability Objectives and Associated Indicators and Metrics

Objectives	Indicators	Metrics	Data *(Source)*
Safe	Adequate pedestrian crossing infrastructure	Compliance rate of pedestrian crossing control types with the TAC Pedestrian Crossing Control Guide (2018) based on the ADT, posted speed limit, and total number of lanes	Pedestrian crossing control types and locations *(City of Winnipeg Public Works Department)*
Accessible	Land use density	Residential density	Number of households and Census Tract area *(2016 Statistics Canada Census Survey)*
	Proximity to daily destinations (land use diversity)	Percent of residential area within walking proximity to a variety of daily destinations (within a 400	Land use GIS data

Objectives	Indicators	Metrics	Data *(Source)*
		m buffer to destinations including: grocery stores, retail stores, food outlets, schools, and entertainment)	*(City of Winnipeg Planning, Property and Development)*
	Proximity to transit stops	A weighted transit score as a function of the number of transit stops per square km with headways 10 mins or less, between 10 and 20 mins, between 20 and 30 mins, and greater than 30 mins	Transit stop locations and bus frequency GIS data *(City of Winnipeg Transit Department)*
Connected	Connected pedestrian sidewalks	Percent of roads with adequate sidewalks (greater or equal to 1.5m)	Sidewalk and road network GIS data *(City of Winnipeg Planning, Property and Development)*

4.2.1. Safety Indicators and Metrics

Safety is inherently important to walking and crossing control treatments are a critical component of pedestrian safety (TAC, 2018). However, the adequacy of pedestrian crossing control treatments has never been used as an indicator in a Walkability Index. ITDP (2018) is the only known document that identifies safe crosswalks as an indicator to pedestrian safety and accessibility, measured by the percent of intersections with adequate crosswalks. This metric, however, does not assess the suitability of the crosswalk for the traffic and street design characteristics and has not been used in a Walkability Index. To overcome this knowledge gap, this research used *adequate pedestrian crossing infrastructure* as the indicator to determine the performance of safety of an urban environment in a composite Walkability Index and developed a new metric to assess the adequacy of pedestrian crossing infrastructure.

The safety indicator was determined by assessing the compliance of existing crossing control treatment types with the Transportation Association of Canada's Pedestrian Crossing Control Guide (TAC, 2018). The safety metric was the percent of compliant pedestrian crossing control treatments in each Census Tract. This pedestrian crossing control compliance metric was selected since it can be used to evaluate the safety of all crosswalk treatments, not only those at intersections, and ensure the suitability of the crossing treatment to the context.

The TAC Pedestrian Control Guide (2018) provides a decision support tool for determining both the need for a crossing treatment and the type of treatment. This research assessed the compliance of existing crossing control treatments, but not whether a site was indeed a candidate for a crossing control treatment. The reason for this was that the City had already established a need for pedestrian crossing control at each site, however, the adequacy of the provided treatment did not always match the recommendation in the TAC Guide.

Assessing the absence of crosswalks across a jurisdiction is time-consuming and difficult. However, once a crossing is installed, the crossing control treatment type must be suitable for the location's cross section and vehicular exposure to provide a safe crossing for pedestrians. Thus, this research examined the suitability of existing crossing control treatment types to the street design and traffic context to provide safe pedestrian crossings. The TAC (2018) decision support tool guides the selection of a crossing control treatment type based on Average Daily Traffic (ADT), posted speed limit and cross section design (in terms of number and direction of lanes and existence of a raised refuge). The crossing control treatment types, in the order of least advanced to most, are ground mounted systems (GM), enhanced ground mounted systems (GM+), rectangular rapid flashing beacons (RRFB), overhead flashing beacon system (OF), and traffic signals (TS).

In this research, every existing pedestrian crossing in Winnipeg was assessed, excluding crossings at channelized turning lanes as they were all deemed compliant with a GM treatment type, as per the TAC Guide. The location of each crossing was geocoded in ArcGIS along with the traffic characteristics (i.e., ADT and speed limit), street design (i.e., lane configurations, presence of raised refuge or curb bulbout, etc.) and crossing control treatment characteristics (treatment type and compliance status). The ADT along the roadway of the location of the crossing was obtained from the City of Winnipeg's Traffic Flow map (2015) which provides Average Weekday Daily Traffic (AWDT) on major streets. Residential streets with no available AWDT were assumed to have volumes between 1500 and 4500 vehicles per day, which is the lowest ADT interval provided in the TAC decision support tool that would require a crossing control device. These residential streets require a ground mounted sign at crossings with a posted speed limit of 50 km/h regardless of the cross-section design.

The compliance rate metric was calculated for each Census Tract as the ratio of the number of compliant pedestrian crossings to the total number of pedestrian crossings. Since Census Tract boundaries follow major roadways, pedestrian crossings that are located on Census Tract boundaries were assigned to both Census Tracts. Figure 10 shows the relative safety levels of Winnipeg Census Tracts, measured by the compliance rate of pedestrian crossing control treatments with the TAC Pedestrian Crossing Control Guide (2018). The compliance metric was converted to Z-scores for inclusion in the Walkability Index analysis.

A total of 364 crossings with ground mounted signs (standard GM or enhanced GM+), 184 pedestrian corridors (i.e., overhead flashing beacon systems, OF), and 660 traffic signals in Winnipeg were assessed. All traffic signals were deemed compliant. Of the pedestrian crossing control treatments (GM, GM+, and OF), 143 crossing treatments (approximately 26 percent) were found to be non-compliant and required a more enhanced crossing control treatment. On average, the treatment compliance rate in the Census Tracts was 0.02. Figure 11 shows that most of the Census Tracts located in the outskirts of the city have higher compliance rates. This is because these Census Tracts have few or no pedestrian crossings and therefore they are considered fully compliant. The majority of non-compliant pedestrian crossing control treatments were overhead flashing beacon systems (OF) requiring an upgrade to a traffic signal along St. Mary's Rd, St. Anne's Rd, Pembina Hwy and Henderson Hwy, which are all major arterials in the city.

The compliance rates shown on the map can seem contradicting to the expected walkability characteristics of a city where typically downtown areas are considered more walkable while suburbs and surrounding areas are considered less walkable. However, based on the distribution of the compliance Z-scores shown in Figure 11, it is evident that the majority of Census Tracts are fully compliant and therefore the data is highly skewed. Therefore, Census Tracts with 100 percent compliance receive a slight boost of 0.8 in the Walkability Index, while those that have non-compliant pedestrian crossing control treatments may receive a reduction in the Index up to -4.6. Therefore, the safety indicator mainly reduced the Walkability Index in areas with non-compliant pedestrian crossing control treatments while not significantly affecting other areas with few or no pedestrian crossings or with many fully compliant pedestrian crossings.

Figure 10: Safety Map of Winnipeg based on Pedestrian Crossing Control Compliance Rate

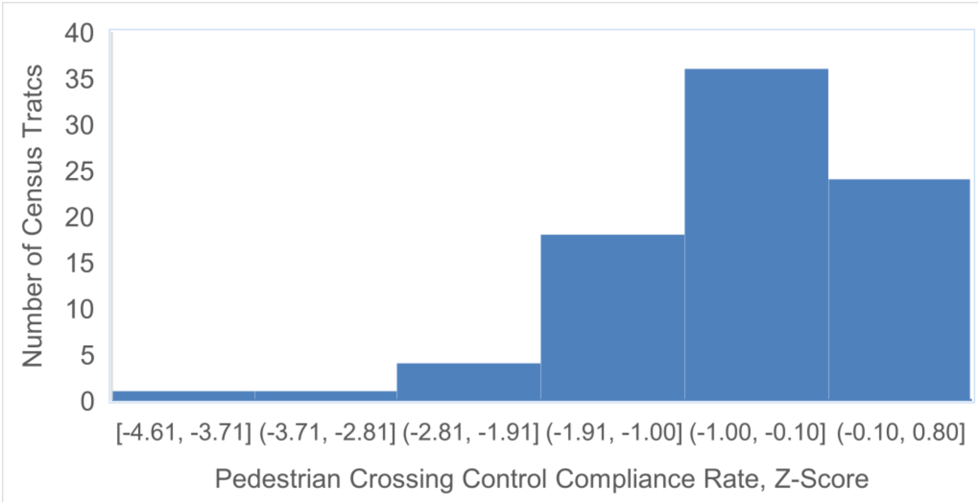


Figure 11: Pedestrian Crossing Control Compliance Rate (Z-scores) for Winnipeg Census Tracts

4.2.2. Accessibility Indicators and Metrics

Residential density, proximity to daily destinations and proximity to transit stops were the indicators selected to measure accessibility of an urban environment as it relates to walkability. Accessibility was calculated from the mean of the three measured indicators. The three accessibility indicators and their associated metrics are individually mapped and discussed in this section, followed by results of the final accessibility measurement.

Land Use Density

Density is considered an essential measure of walkability as it implies compact land use and reduced distances to destinations (Feng, et al., 2010). Residential density was the metric selected to calculate land use density. Residential density is the ratio of the number of households per square kilometer of each Census Tract. Net residential density is commonly used in the literature, which is a division by the residential area, not Census Tract area, in order to exclude other land uses. However, this measure provided misleading results because areas with a small portion of high density residences (e.g., a few apartment or condo buildings in close proximity to each other) provided high net residential density, while in reality, the Census tract was observed to be relatively low density as the rest of the area did not have dense residential zones or any residential areas at all. Therefore, gross residential density was used in this research as it provided a more accurate representation of the residential characteristics in the Census Tracts.

Figure 12 shows the residential density of Winnipeg Census Tracts as a function of the number of households per Census Tract area. Generally, Winnipeg's residential land use is mostly single detached dwellings, which results in low residential density. The urban centre of Winnipeg is the densest with a maximum of 6506 households per square kilometre, with the density decreasing moving away from the city centre.

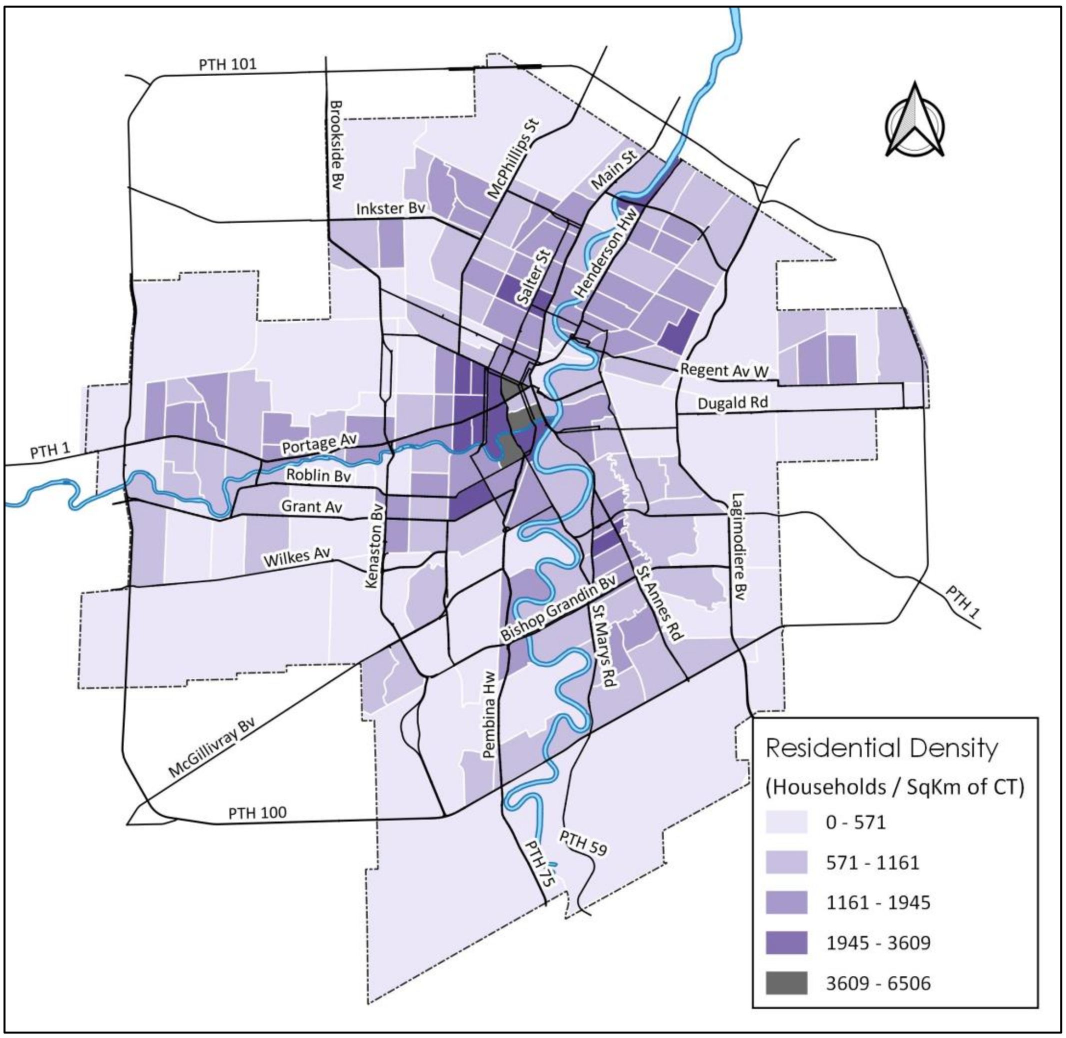


Figure 12: Residential Density Map of Winnipeg based on Number of Households per Census Tract Area

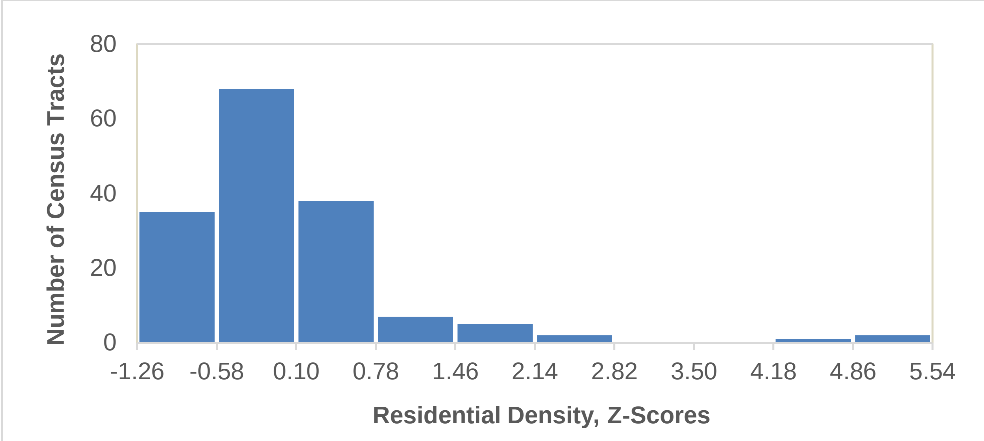


Figure 13: Residential Density (Z-Scores) for Winnipeg Census Tracts

Figure 13 shows the distribution of the residential density for Winnipeg Census Tracts in Z-score format. The distribution is normal with a significant positive skew, where the majority of the Census Tracts (93 of 158) have below average residential density. Since the average residential density was 1206 households per km^2 of Census Tract, any measurement below the average resulted in a decrease in the accessibility measurement. Therefore, Census Tracts with above average residential density had a greater impact on the accessibility measurement (an increase of up to 5.54) than those with below average densities (a decrease of up to -1.26).

Proximity to Daily Destinations

The percent of residential area within walking proximity to daily destinations was the metric selected to calculate proximity to destinations. The considered daily destinations were grouped into five categories: grocery stores, retail, restaurants, educational facilities (universities, schools, libraries), and entertainment. While travel to employment destinations is considered a daily utilitarian destination, it was not analyzed in this proximity indicator due to lack of access to employment data.

A 400-metre straight-line walking distance buffer was used around each facility within each destination category to determine the residential area within the buffer. The literature identifies 400 metres as a reasonable distance that a person will walk rather than drive (Atash, 1994;

Ontario Ministry of Transportation, 2012), which results in a 6.7-minute walk based on a design walking speed of 1.0 m/s as specified by the TAC Pedestrian Crossing control Guide (2018). An average of the proximity measures for the five destination categories provides the measure for the proximity indicator for each Census Tract, as follows:

Proximity to Daily Destinations Score=

(% residential within proximity to retail + % residential within proximity to grocery stores + % residential within proximity to restaurants + % residential within proximity to education + % residential within proximity to entertainment) / 5

Proximity to daily destinations also indicates land use diversity, which is a commonly used indicator of land use mix. Diverse land use offers a variety of services within a near vicinity, thereby reducing trip distances and providing a more attractive option to pedestrians. Proximity to destinations was measured to determine land use mix in this research instead of an Entropy Index due to the limitations of an Entropy Index, described in Chapter 2. Brown et al. (2009) found that the presence of a destination is important, not necessarily the number or equal presence of destinations. Entropy score depends on equal land use area distribution, whereas the proximity measure depends on the presence of a destination within walking distance. Having a greater number of destination facilities increases the percentage of residents within walking distance to these destinations; however, the presence of one destination can still be impactful. Similar to an Entropy Score, the proximity measure also evaluates the land use type mix where access to a destination in each category provides a higher proximity score relative to access to only one or two destinations. Therefore, the direct measure of proximity to destinations utilized in this research can be a more suitable measure of walkability relative to the implied proximity result of an Entropy Score.

Figure 14 shows the relative proximity levels of Census Tracts in terms of the standardized percentage of residential land use area within walking distance of 400 m to daily destinations. As shown in Figure 14, areas in the city centre provide more destinations and amenities within walking distance to residents. City centre areas have higher proximity levels due to the mixed and dense land use, allowing a higher number of residents access to nearby destinations. The proximity levels to daily destinations decrease moving away from the city centre. Notably, Census Tracts with only destination land use types (e.g., a major commercial area or University campus) and no residential land use show low proximity levels; however, the surrounding Census Tracts with residential areas show higher proximity levels as they are within walking distance to the destination Census Tracts. Areas with mixed land use types (i.e., residential and commercial) and with access to a variety of daily destinations provide the best scenario for high proximity levels. If a high percentage of residents are within walking distance of grocery stores but not schools or retail, the proximity average would be lower relative to an area with a high percentage of residents within walking distance to destinations within all five categories.

Figure 15 shows the Z-score distribution of proximity measurements based on the average percent of residential within walking proximity to different destination categories. The mean percent of residential proximity of Census Tracts was 45.2 percent. Thus, any measurement below the average resulted in a decrease in the accessibility measure and consequently in the Walkability Index. The proximity measurement distribution is relatively normal with a slight positive skew (81 Census Tracts below average and 77 Census Tracts above average).

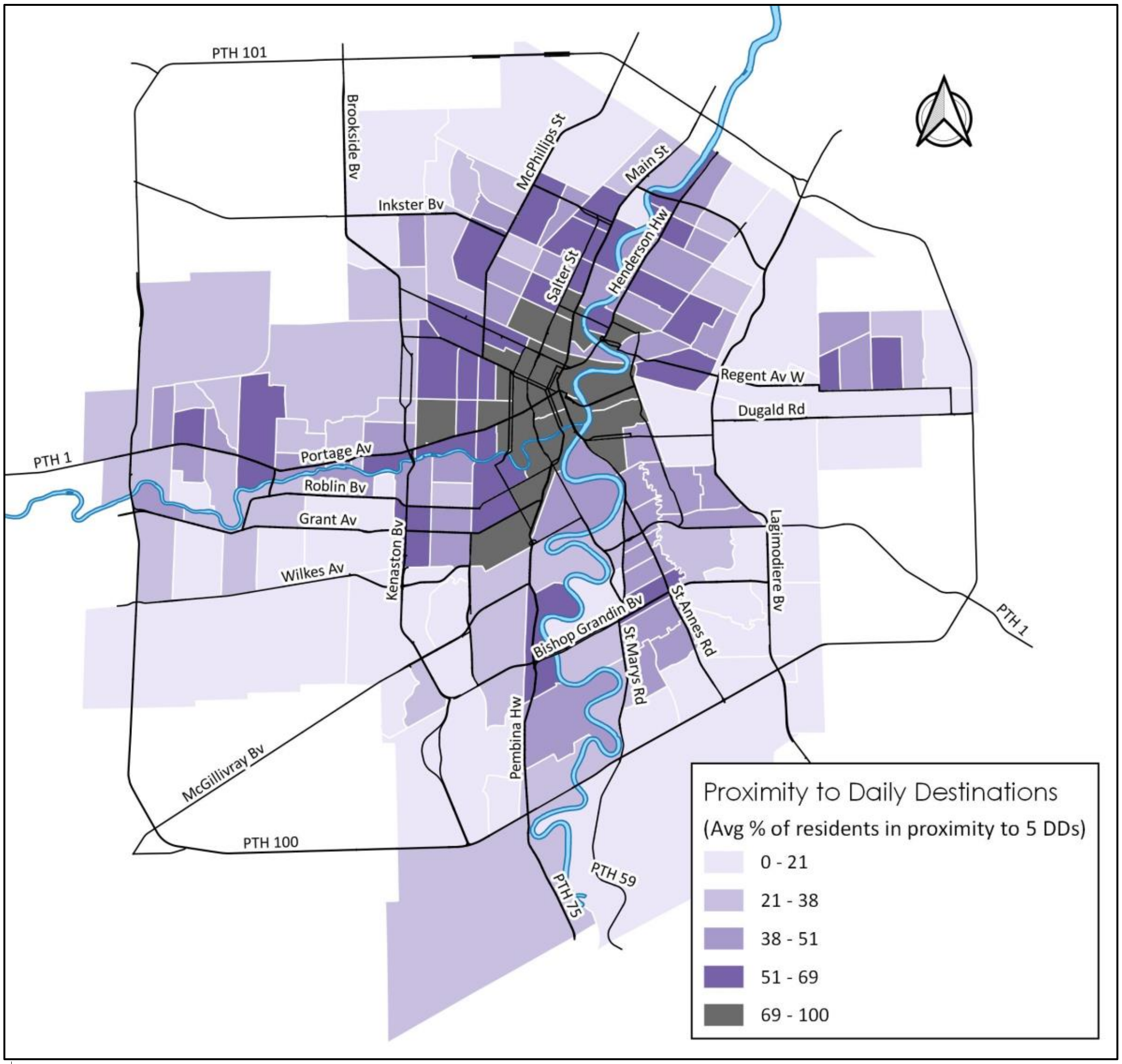


Figure 14: Percent of Residents within Walking Distance of 400m to Grocery Stores, Retail, Restaurants, Educational Facilities, and Entertainment in Winnipeg per Census Tract

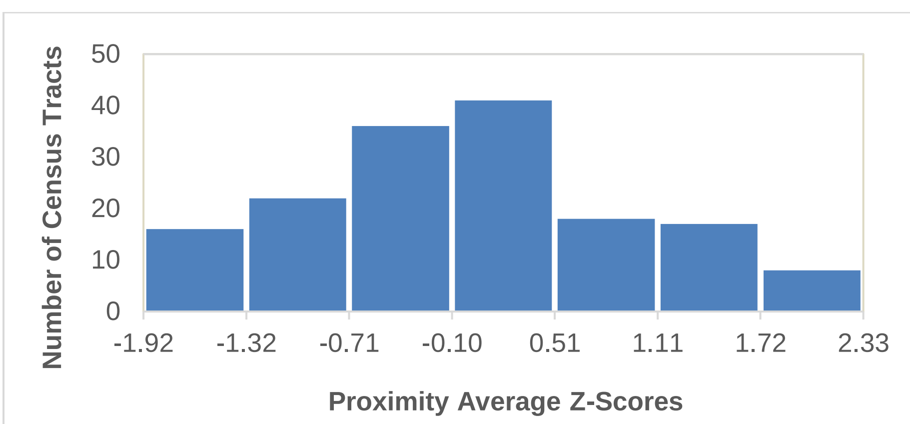


Figure 15: Average Proximity of Residents to Daily Destinations (Z-Scores) for Winnipeg Census Tracts

Proximity to Transit Stops

Access to frequent transit stops provides pedestrians access to destinations within the city and thus increases pedestrian transportation (ITDP, 2018). The presence of transit stops attracts residents who prefer walking and provides them opportunities to act on their preferences (Brown, et al., 2010). Studies have shown that transit/rail commuters walked 30 percent more steps per day than car commuters (Wener & Evans, 2007). A transit score based on the number of transit stops per square kilometre was the metric selected to calculate proximity to transit stops. The transit score is a weighted calculation of the number of transit stops per square kilometre. The highest weight of 1.5 was given to stops with bus headways of 10 min or less, followed by 0.7 to stops with headways between 10 and 20 min, 0.3 to stops with headways between 20 and 30 min, and 0.2 to stops with headways greater than 30 min. The weights were obtained from a multivariable regression analysis between the transit stops with different headway categories and the percent of employed persons walking or taking transit to work from the Census Canada 2016 Journey to Work Data. The correlation of the transit stops with Journey to Work data was based on the assumption that locations with higher frequency of transit results in higher pedestrian activity and transit ridership, and vice-versa.

The frequency of buses stopping at each stop in Winnipeg was provided by Winnipeg Transit. The headways were calculated based on the assumption of a 20-hour daily bus operation. From the 4700 analyzed transit stops, those with only peak hour bus operations or school charters were removed from the analysis. The transit score was calculated as follows, where *h* is the headway between buses stopping at each transit stop:

$$\begin{aligned}\textit{Transit score} = {} & 1.5\,(\text{No. of transit stops per km}^2 \text{ with } h \leq 10 \text{ min}) \\ & + 0.7\,(\text{No. of transit stops per km}^2 \text{ with } 10 < h \leq 20 \text{ min}) \\ & + 0.3\,(\text{No. of transit stops per km}^2 \text{ with } 20 < h \leq 30 \text{ min}) \\ & + 0.2\,(\text{No. of transit stops per km}^2 \text{ with } h > 30 \text{ min})\end{aligned}$$

Figure 16 shows the 1528 transit stop locations by bus headway in Winnipeg. Transit stops with buses stopping every 10 minutes or less account for approximately 11 percent of transit stops; these are located mainly along the main north-south arterial (Pembina Hwy and Main St) and the main east-west arterial (Portage Ave). Approximately 33 percent of bus stops in Winnipeg have bus headways of between 10 and 20 min, 24 percent have headways between 20 and 30 min, and 32 percent have headways greater than 30 min.

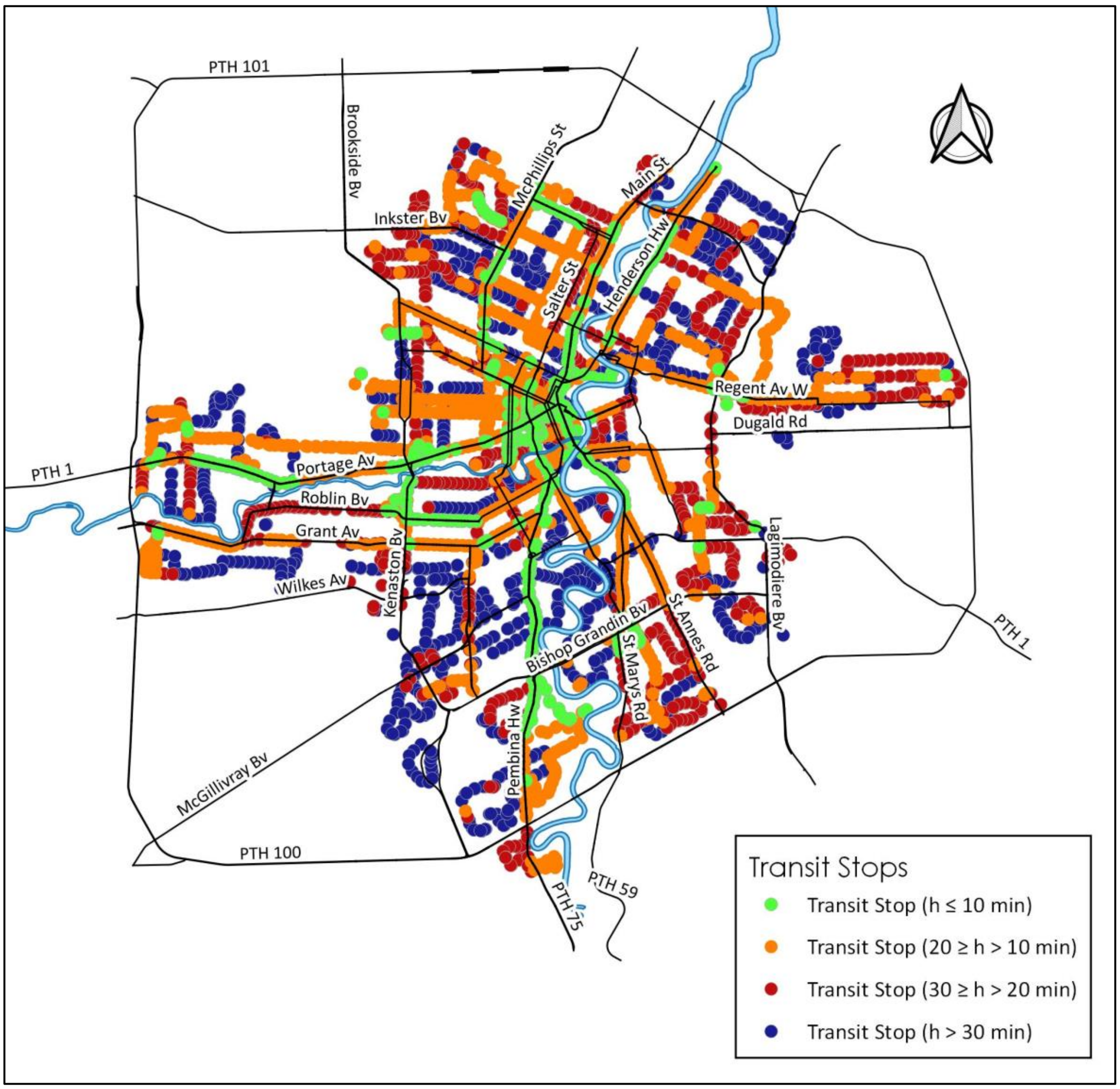


Figure 16: Transit Stop Locations in Winnipeg by the Average Daily Bus Headways (h= bus headway)

Figure 17 shows the Transit Score map of Winnipeg. The city centre has the highest Transit Score due to the highest number of transit stops per square kilometre and the highest number of stops with headways of 10 min or less. The top three Census Tracts with the highest Transit Scores (shaded in gray in Figure 17) have 72, 58 and 52 transit stops per square kilometre, which include 30, 20, and 32 transit stops per square kilometre with headways of 10 min or less, respectively. Some Census Tracts with a high number of transit stops with short headways (e.g., along Pembina Hwy and Portage Ave) have lower Transit Scores than the city centre because they have stops along the main arterial but few stops or stops with poor headways within the remaining area of the Census Tract.

Figure 18 shows the distribution of the Transit Scores in Z-score format. Any Census Tract with a Transit Score below the average Transit Score of 11.03 resulted in a decrease in the Walkability Index. The majority of Census Tracts (97 out of 158) resulted in a below average Transit Score; however, the above average Transit Scores had a larger variance. Therefore, Census Tracts with a high Transit Score had a greater impact on the accessibility measurement than those with a low Transit Score.

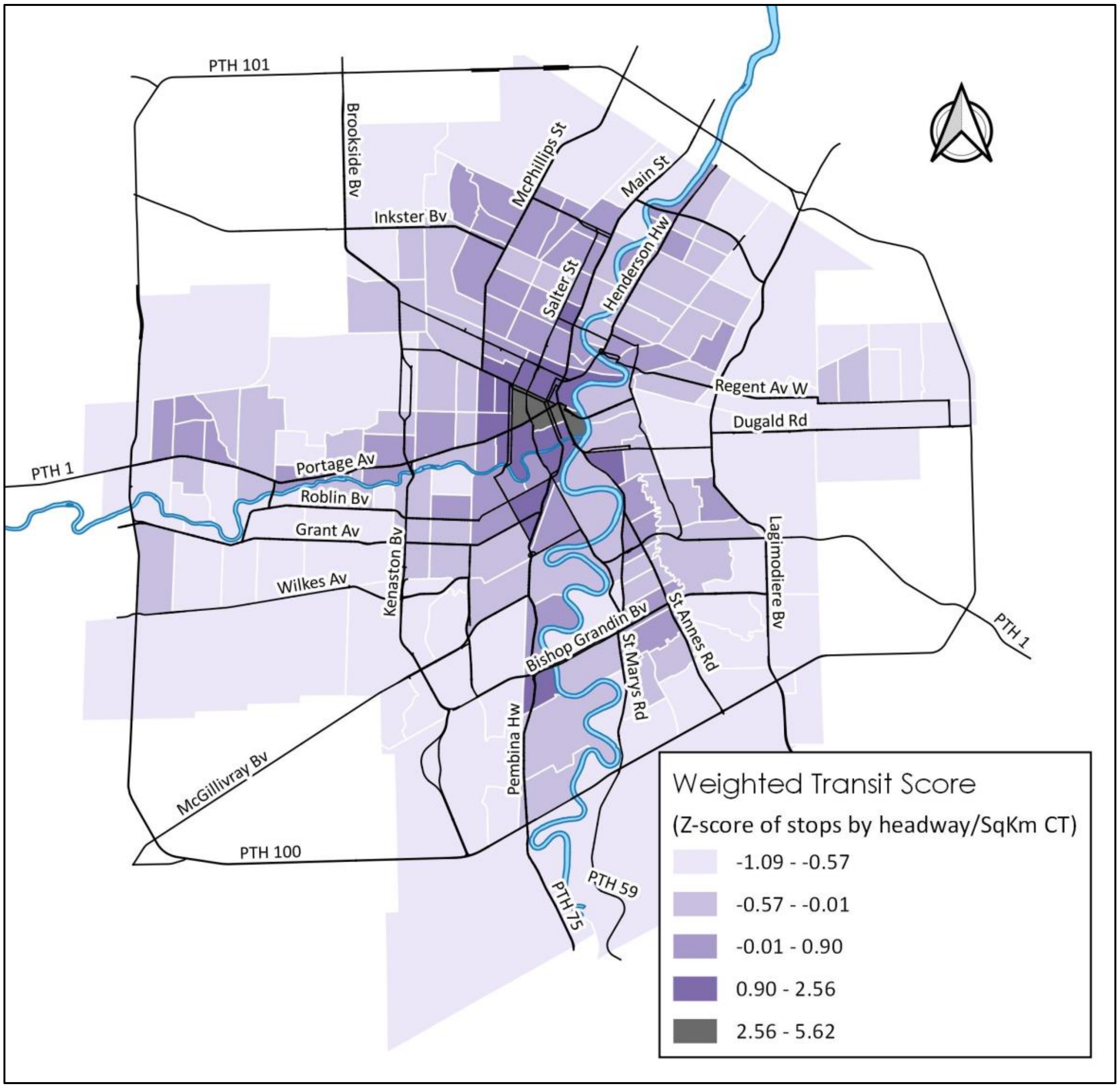


Figure 17: Weighted Transit Scores based on the Number of Transit Stops per Km^2 per Headway Category by Census Tract

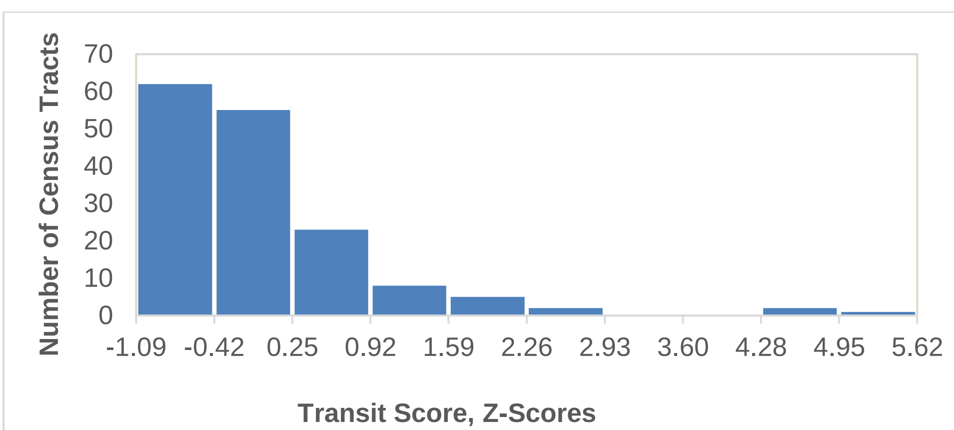


Figure 18: Transit Scores (Z-Scores) for Winnipeg Census Tracts

Overall Accessibility Indicator

The standardized results from the three indicators of residential density, proximity to daily destinations, and proximity to transit stops were averaged to achieve the final accessibility measurement for each Census Tract. Figure 19 shows the relative accessibility levels of Winnipeg Census Tracts based on the average of the three accessibility indicators. The three indicator measurements were each standardized to Z-scores to allow their aggregation. The city centre area received the highest accessibility scores due to high residential density, walking proximity to a variety daily destinations and access to many bus stops with frequent buses. The accessibility variable increased the Walkability Score in these areas by a maximum of 4.36, while areas with poor accessibility reduced the Walkability Index by up to -1.42.

Figure 20 shows the distribution of the accessibility Z-scores amongst the Census Tracts. As the Figure shows, the data is a positively skewed normal distribution, which implies that the majority of the Census Tracts have a below average accessibility score. The average accessibility measurement of the Census Tracts was zero (since it is an average of standardized values); thus, any measurement below zero resulted in a lower than average Walkability Index and any measurement above zero resulted in a higher than average Walkability Index. The Census Tracts with above average accessibility scores are fewer; however, they have a wider distribution from the accessibility score mean.

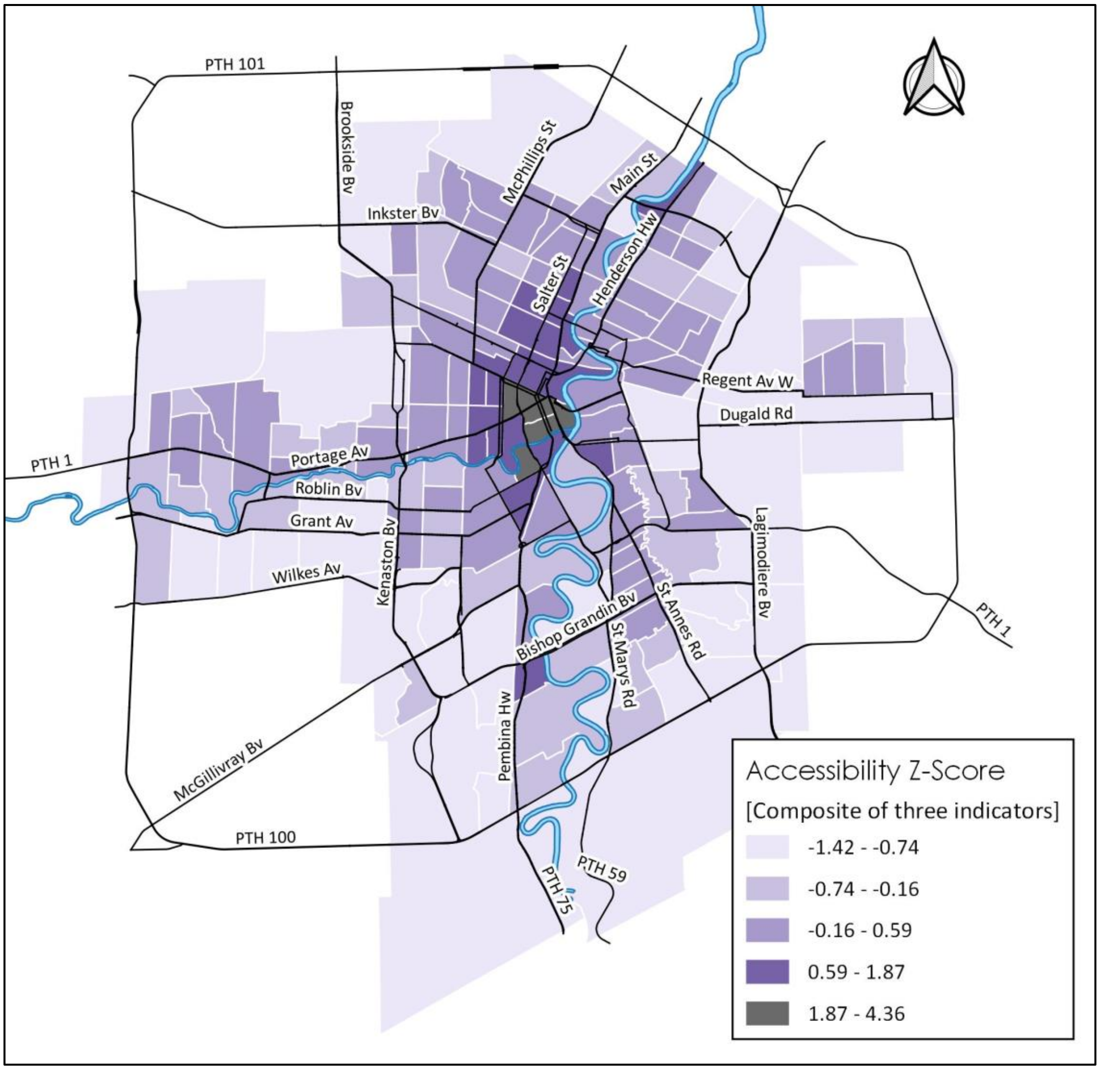


Figure 19: Accessibility Map of Winnipeg based on the Average Z-Scores of Three Accessibility Indicators (Residential Density, Proximity to Destinations and Transit Score)

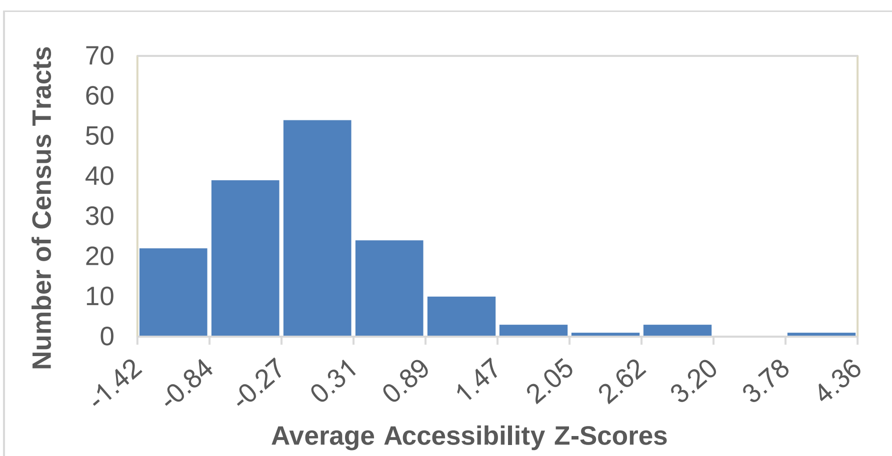


Figure 20: Accessibility Z-Scores for Winnipeg Census Tracts

4.2.3. Connectivity Indicators and Metrics

Providing a complete and continuous sidewalk network for pedestrians, including those with disabilities, contributes to urban walkability by providing shorter and alternate routes for pedestrians (ITDP, 2018). Some literature assesses connectivity using intersection density to measure the number of crossing opportunities in an area. As indicated in Chapter 2, however, this metric may over-estimate connectivity for pedestrians since not all intersections facilitate pedestrian crossings. Consequently, the ratio of sidewalk coverage was selected as the measure of connectivity because it represented the extent of availability of an adequate sidewalk network within an area. In addition, the adequacy of pedestrian crossings was assessed by the safety indicator.

Sidewalk coverage was measured by the ratio of kilometres of roads with adequate sidewalks (on one or both sides of the roadway) to the total kilometres of roads within the network. Adequate sidewalks have a minimum width of 1.5 metres, as this is the specified practical lower limit for sidewalks by the Transportation Association of Canada's Geometric Design Guide for Canadian Roads (2017). A width of 1.5 metres allows the passing of two pedestrians or for a wheelchair user to turn around.

Figure 21 shows the roads in Winnipeg with adequate sidewalks (i.e., with widths greater or equal to 1.5 m) and those with no sidewalks (including those with poor sidewalk widths). More than half (56 percent) of roads (by length) in Winnipeg have adequate sidewalks on at least one side of the road, while the other 44 percent have no sidewalks or have sidewalks with poor widths (i.e., narrower than the recommended minimum 1.5 m by TAC, 2017).

Figure 22 shows the relative connectivity measurement per Census Tract as a function of the percentage of roads with adequate sidewalks per Census Tract. As the Figure shows, the central city areas have high sidewalk coverage while the surrounding city areas have lower coverage.

The surrounding areas comprise mainly industrial or residential land use, which do not have sidewalk infrastructure implemented. Many new residential neighborhoods such as those in the northeast portion of Winnipeg (i.e., North and East Kildonan) and in the southwest portion of Winnipeg (i.e., Bridgwater, Waverley West and Wilkes South) are developing without adequate sidewalk coverage.

Figure 23 shows the distribution of connectivity measurements in Z-score format for Winnipeg Census Tracts. The average ratio of adequate sidewalk coverage amongst the Census Tracts is 65 percent. The distribution of sidewalk coverage is not normal, but there are almost equal number of Census Tracts with sidewalk coverage above-average and below-average (81 Census Tracts above average and 77 below average). However, the Census Tracts with below-average connectivity scores can have a greater impact on the Walkability Index (up to -2.29 for those Census Tracts with zero percent sidewalk coverage) than those with positive connectivity scores (up to 1.24 for those with 100 percent sidewalk coverage).

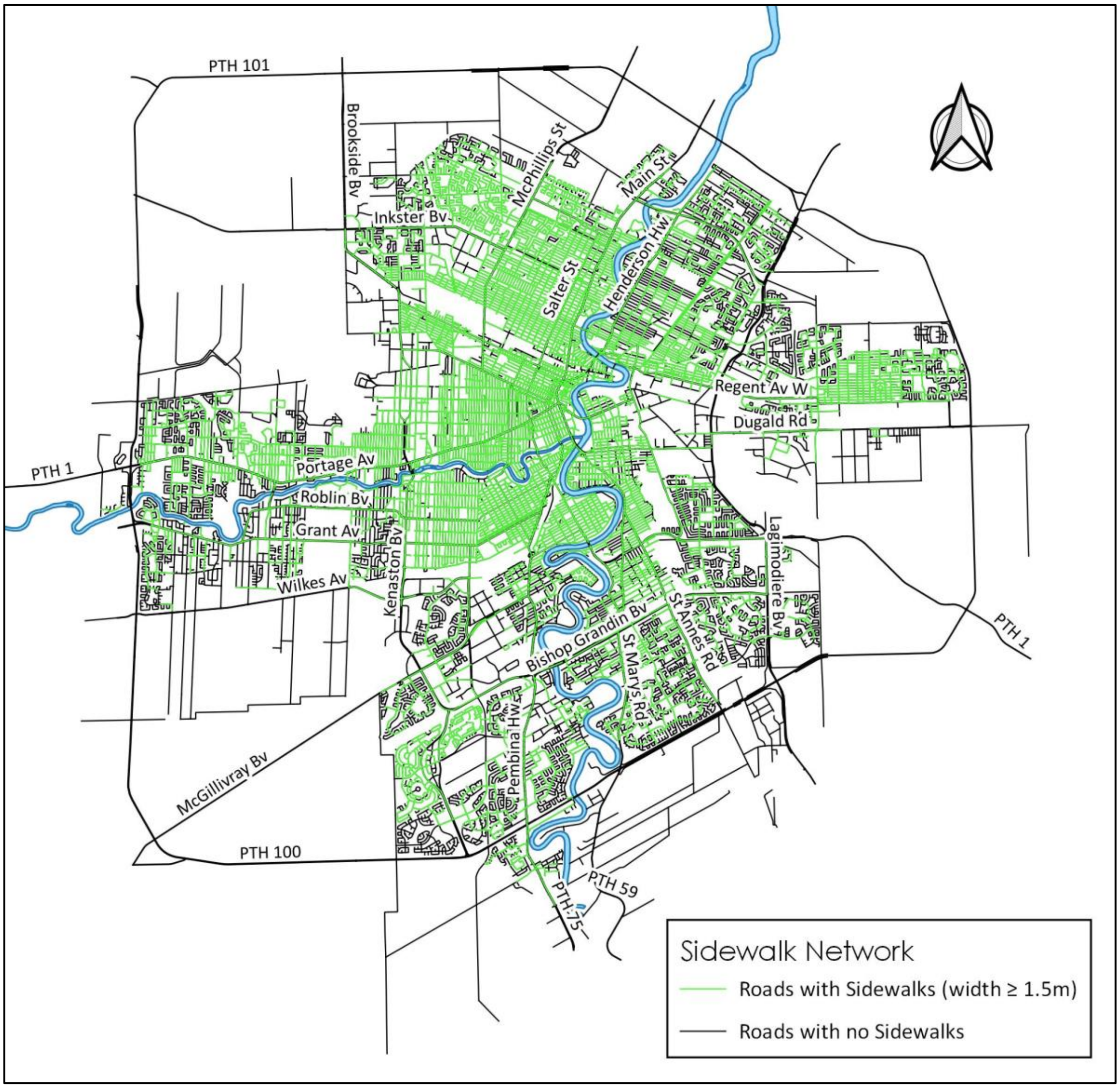


Figure 21: Winnipeg's Roadway Network with Adequate Sidewalks (widths≥1.5m) and no Sidewalks

Figure 22: Connectivity Map of Winnipeg based on Sidewalk Coverage Measurement
(i.e., ratio of km of roads with sidewalks to km of roadway per Census Tract)

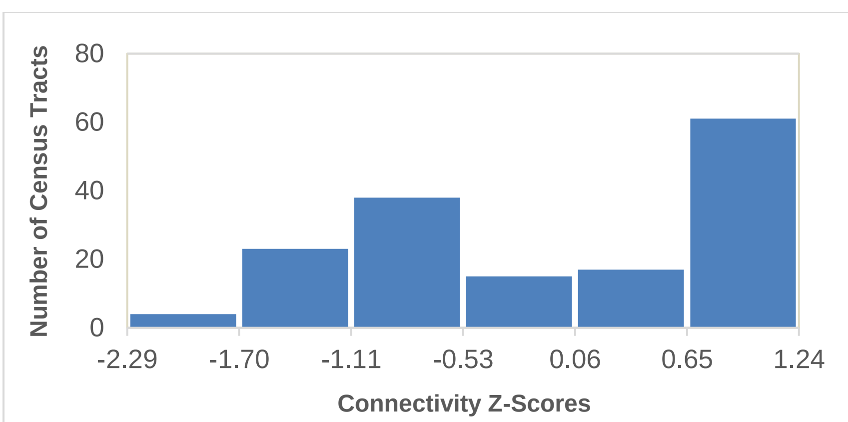


Figure 23: Connectivity (Raw Scores and Z-Scores) for Winnipeg Census Tracts

4.3. Walkability Index

The fourth step in the methodology to develop a Walkability Index is the calculation of the Index. This section presents the results of the composite Walkability Index developed in this research for Winnipeg. By including the indicators/metrics (in Z-score format) used to measure each of the walkability objectives, the Walkability Index can be further expressed as follows:

$$Walkability\ Index_n = Z_{Crossing\ Control\ Compliance} + \frac{Z_{Residential\ Density} + Z_{Proximity} + Z_{Transit\ Score}}{3} + Z_{Sidewalk\ Coverage}$$

Figure 24 shows the relative composite Walkability Index map of Winnipeg Census Tracts based on the aggregation of the measured indicators. Similar to the evaluated indicators, the city centre area has the highest walkability levels with generally reduced walkability levels moving outwards. Figure 25 shows the Walkability Index distribution amongst the Census Tracts. The Figure shows that the Walkability Indices have a normal distribution with a slightly positive skew, which implies that there are a few more Census Tracts with Walkability Indices below average than there are above (71 Census Tracts with above average Walkability Indices and 87 Census Tracts with below average Walkability Indices). The Walkability Indices range from – 4.18 to 5.69.

Most of the residential areas have lower Walkability Indices (below average) due to the lower residential density, limited number of destinations within walking distance and lack of adequate sidewalk infrastructure. This includes residential developments in North and East Kildonan (East of Henderson Hwy) and along South Kenaston Blvd. Census Tracts along McPhillips St and Arlington St have unexpectedly higher Walkability Indices (above average) despite having low density development land use with divided six lane highways. However, access to transit and the variety of destinations (contributors to accessibility), adequate sidewalk coverage (connectivity) and compliant pedestrian crossing treatments (safety) counter the lower density development.

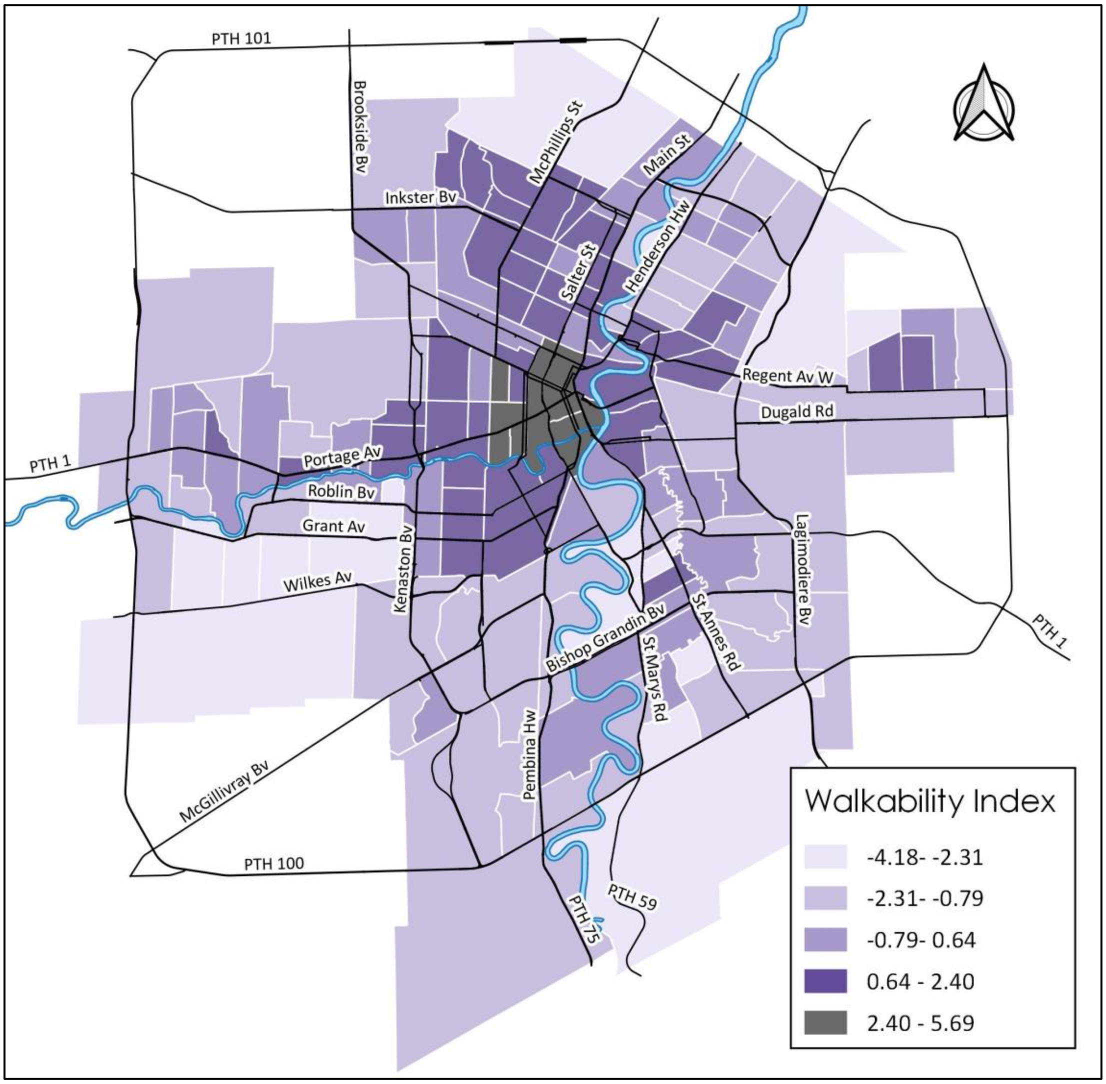


Figure 24: Walkability Index Map of Winnipeg

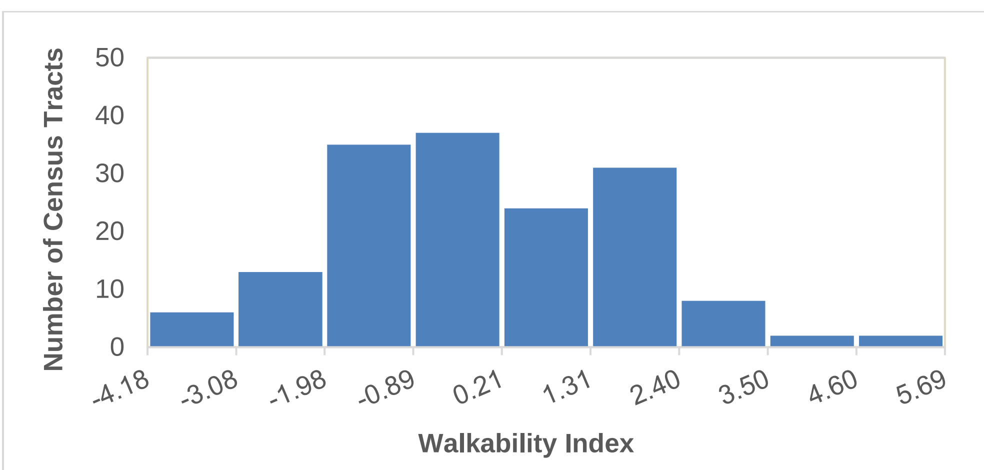


Figure 25: Walkability Index Z-Scores for Winnipeg Census Tracts

4.4. Validation of Walkability Index

The Walkability Index was validated through a correlation analysis with the percent of employed persons aged 15 years or over that walk or take transit to commute to work. Transit commuter data was included since access to transit is an important contributor to walkability as it expands the reach of pedestrians and allows them to access citywide services, not just those within walking distance. The commuter data was obtained from the 2016 Journey to Work survey from Statistics Canada's Census Program. The data represents a 25 percent sample size, as the survey was conducted from a random sample of one in four private dwellings.

The literature states that correlation analysis or visual GIS map comparisons are typically used to validate Walkability Indices and find associations between specific urban form characteristics and walkability levels. Most studies have used physical activity measures (Frank, et al., 2005) and health variables such as obesity (Agampatian, 2014) and Body Mass Index (BMI) (Brown, et al., 2010) to validate Walkability Indices or indicators. A few studies have used commuter data (Frank, et al., 2010) and household origin-destination travel survey data when available (Frank, et al., 2010; Manaugh & El-Geneidy, 2011). Household travel survey data is a better representation of travel behaviours as it considers all household trips, which are more likely to be impacted by local conditions than work trips only (Manaugh & El-Geneidy, 2011). Systematic field observations have also been used to help improve the validity of walkability Indices (Frank, et al., 2010; Leslie, et al., 2007); however, they can be very laborious, time consuming and costly, and pose issues with the subjectivity and reliability of the results (Agampatian, 2014).

This research used Journey to Work commuter data since household travel survey data on a Census Tract level was unavailable. The correlation analysis provides general insight into the validation of the Walkability Index; however due to its limitations, it does not determine the accuracy of the Index.

Spearman's rank order correlation was used due to the non-normal distribution of the variables. Table 18 presents the Spearman's correlation coefficients (*r*) for the different variable combinations. The correlation analysis shows that the accessibility measure was found to have a strong positive correlation with the percent of walking and transit commuters (r=0.84, p<0.0001). The three individual accessibility indicators—residential density, proximity to destinations and transit score—also were found to have moderate to strong positive correlations with the percent of walking and transit commuters with correlation coefficients of 0.63, 0.81 and 0.85 (p<0.0001), respectively. The results are comparable to other studies showing that higher population density, presence of daily destinations (diverse land use) and access to transit (higher transit density) are positively correlated with pedestrian activity and with Walkability Indices (Frank, et al., 2010; Brown, et al., 2010; Koohsari, et al., 2018).

Table 18: Correlation (*r*) between Walkability Indices and Associated Indicator Measurements and Journey to Work Census Data

	Accessibility	*Connectivity*	*Safety*	*% Walk Commute*	*% Transit Commute*	*% Walk+Transit Commute*	*Walkability Index*
Accessibility	1.00						
Connectivity	0.75***	1.00					
Safety	-0.33***	-0.24*	1.00				
% Walk Commute	0.60***	0.48***	-0.16	1.00			
% Transit Commute	0.83***	0.66***	-0.26**	0.52***	1.00		
% Walk+Transit Commute	0.84***	0.67***	-0.25**	0.74***	0.92***	1.00	
Walkability Index	-	-	-	0.48***	0.60***	0.63***	1.00

*p<0.01
** p <0.001
*** p <0.0001

The connectivity measure was found to have a moderately strong positive correlation with the percent of walking and transit commuters (r=0.67, p<0.0001). This result suggests that greater adequate sidewalk coverage correlates with more pedestrian and transit activity and a higher

Walkability Index. Koohsari, et al. (2018) found that connectivity measured by intersection density is positively correlated to the Walk Score. This research found a correlation between a different measure of connectivity (i.e., sidewalk coverage) and walkability levels.

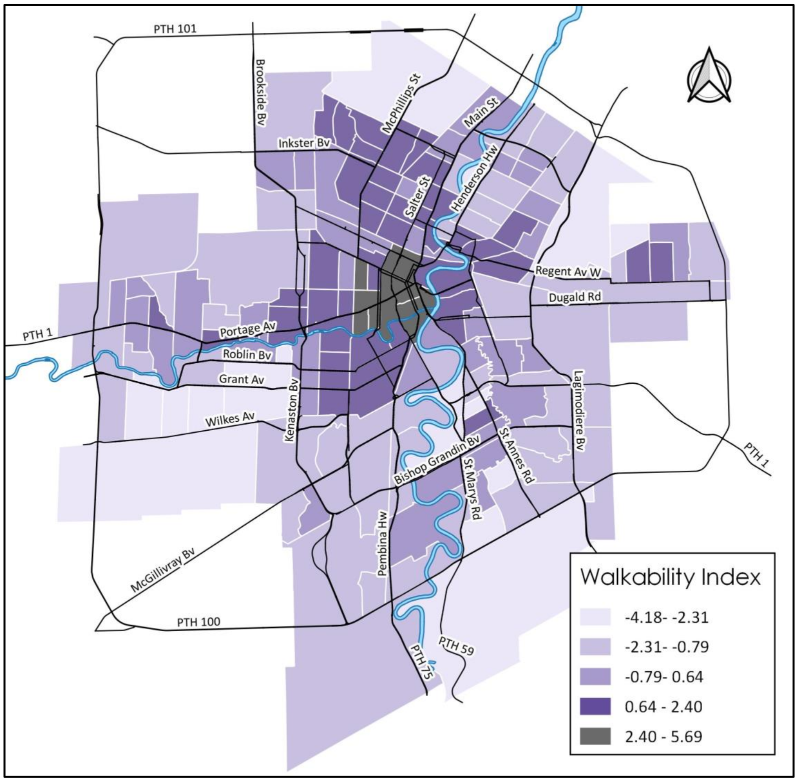
The safety measure was found to have a weak negative correlation (r=-0.25, p<0.001) with the percent walking and transit commuter data. A negative safety correlation was not expected with the percent walking and transit commuters, because it suggests that the presence of non-compliant crossing control treatments may result in greater pedestrian and transit activity, or vice versa. However, this was a weak correlation, which implies that no correlation exists between crossing control treatment types and a person's choice to walk. This result is reasonable because regardless of the crossing control treatment type, pedestrians will continue to cross at crossings that are below the design standards, either out of necessity to reach their destination or without realizing the crossing treatment is unsuitable for the context hence receiving a false sense of safety. Locations with non-compliant crossing control treatments will continue to see pedestrians crossing, while locations with compliant crossing control treatments with low necessity for crossing may not see pedestrian crossing activity.

Although the crossing control compliance metric does not indicate pedestrian activity, it represents the level of walkability of an urban environment from a normative perspective. Safety is inherently important to walking and providing suitable crossing control treatments to the urban context enhances the safety and, consequently, the walkability of an area. Non-compliant crossings that do not meet the required minimum standard of TAC Pedestrian Crossing Control Guideline (2018) may provide a false sense of safety to crossing pedestrians. This normative metric is important to consider from an engineering design perspective, as it is an initial step to providing a transportation supply-based variable into walkability measurements. This metric provides practitioners with actionable items (i.e., upgrade crossing control treatments) through an objective approach, to help improve pedestrian safety and hence walkability of an area, regardless of the impact it may or may not have on pedestrian activity.

The correlation analysis showed that the Walkability Index has a significantly positive correlation (r=0.63, p<0.0001) with the percent of commuters that walk or take transit. This implies that areas with higher Walkability Indices correlate with greater pedestrian and transit activity.

Figure 26 shows the Walkability Indices and the percent of walking and transit-riding commuters per Census Tract, side by side. The data intervals are shown with natural breaks through the ArcGIS software, where the data is clustered into intervals based on maximizing the variance between intervals and minimizing the variance within intervals. The figure shows that city centre areas have higher Walkability Indices and higher pedestrian and transit ridership activity, while the surrounding areas of the city have lower Walkability Indices and lower pedestrian and transit ridership activity.

Furthermore, Figure 27 shows the relationship between the deciles of Walkability Indices and the associated average percentage of walking and transit commuter ridership data. A relatively high coefficient of determination (R^2) of 0.74 was found, which shows a high goodness-of-fit for a linear regression relationship between the two variables. This correlation suggests that the Walkability Index and, consequently, the measured urban form variables may be a reasonable indicator of walkability levels.



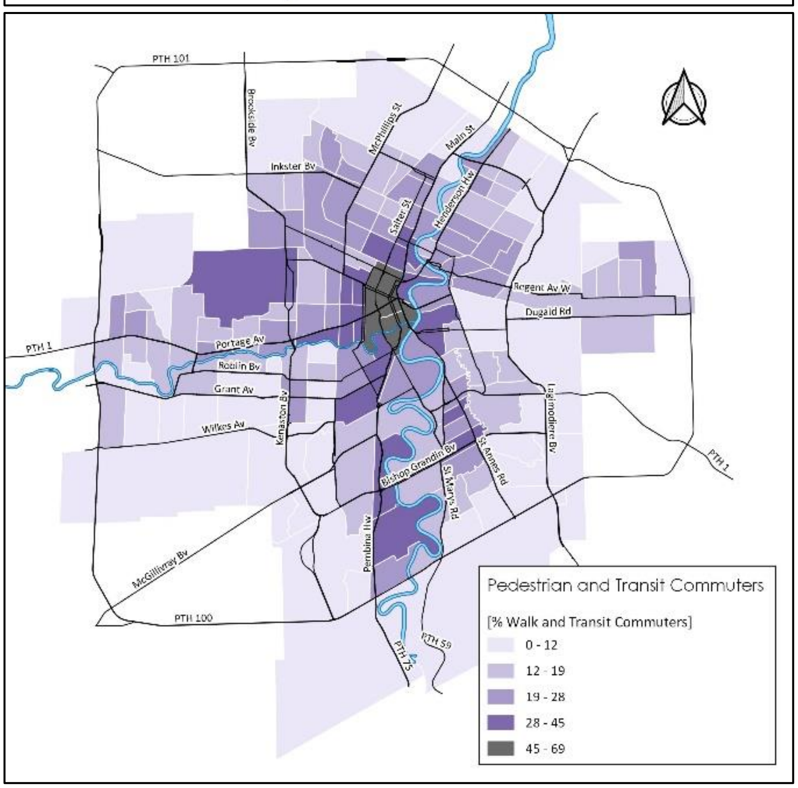


Figure 26: Walkability Indices (top) and Percent of Commuters that Walk or take Transit (bottom) amongst Winnipeg Census Tracts (Natural Breaks)

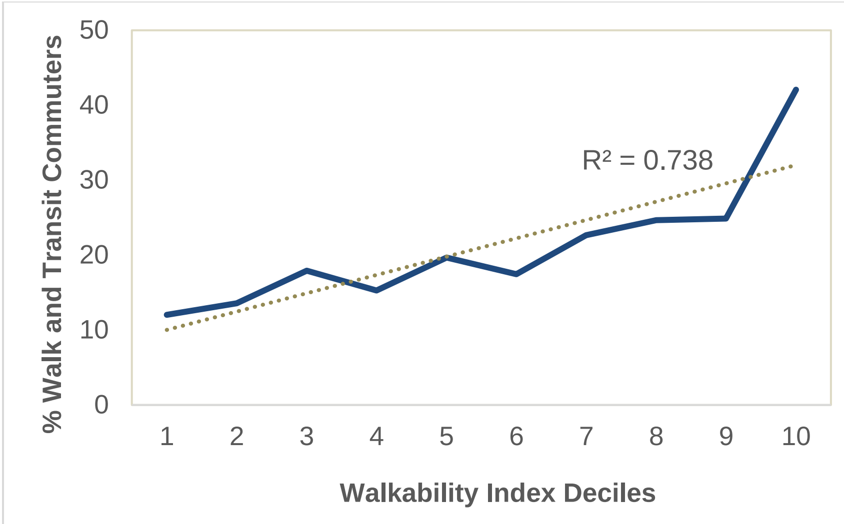


Figure 27: Percentage of Walking and Transit Commuters by Deciles of Walkability Indices

Although a correlation analysis is a commonly used method to test the validity of a Walkability Index, there are limitations to this approach:

- Pedestrian and transit ridership activity does not necessarily provide an accurate representation of the level of walkability of an urban environment. The choice to utilize a particular mode of transport varies not only by the time, distance and degree of convenience, but also by the characteristics of the decision maker, the household type and the trip purpose (Manaugh & El-Geneidy, 2011). The literature finds that income levels and availability of a vehicle significantly impact the decision to walk (Manaugh & El-Geneidy, 2011). Areas may have high pedestrian and transit activity but they may not be walkable areas in terms of the urban form; rather people walk based on necessity (i.e., lower income or no access to other transportation options). Wealthier neighborhoods are more responsive to changes in the urban environment to improve walking, although their pedestrian activity may never equal those in lower income neighborhoods (Manaugh & El-Geneidy, 2011). Therefore, pedestrian volumes or commuter data do not necessarily validate the Walkability Index, but they do provide general insight in the Walkability Index's representation of walkability through urban form characteristics.

- Commuter data was used for correlation in this research, which can be influenced differently by the urban environment for travel decisions than other trip-purposes. Non-work trips should be the focus as they are more likely to be affected by local conditions than work trips (Manaugh and El-Geneidy, 2011). Although considering all household trips (or retrieving specific trip purposes) is preferred, commuter data is still valuable since variables such as proximity to the workplace (density) and access to transit are variables could impact work-trip modal choice decisions. Winnipeg's travel survey data (WATS, 2007) on travel origins and destinations would be a better correlation resource because it includes all trip purposes. However, the data is collected for neighborhood boundaries which differ from Census Tracts that were used in this study.
- Commuter Census data represents the Census Tract with the place-of-work address and not the location of residence, unless the resident and employment location are in the same location. Therefore, the correlation analysis may show lower correlation due to some Census Tracts with mainly industrial land use and high pedestrian/transit commuters correlating with a lower Walkability Index.

4.5. Limitations of the Walkability Index

The limitations of the Walkability Index designed and developed in this research follow:

- The Walkability Index is a relative measure, providing the distribution of walkability levels across a jurisdiction above and below average walkability levels specific to that jurisdiction's urban form dataset. Therefore, the Walkability Indices from one jurisdiction cannot be compared to those of another jurisdiction, as they show the distribution amongst the utilized datasets. Due to the relative nature of the Index, urban form improvements made in one area can reduce the walkability measure in another untouched area. The relative Walkability Index is beneficial for prioritization of urban areas within a jurisdiction that require walkability improvements, and the walkability rank distribution amongst all Census Tracts can change as urban form improvements are made.

- Equal weights were given to the Walkability Index objectives of safety, accessibility, and connectivity; thus they each equally contributed to the level of walkability in an area. Stakeholder consultation and surveys can be conducted by a jurisdiction to determine the level of importance of each of the walkability objectives.
- Only objective indicators were included in the measurement of walkability. Subjective measures, such as pedestrian friendliness and the attractiveness of an area, have an influence on walkability, however, utilizing objective measures allows the transferability of the Walkability Index to other jurisdictions. The Index could also be calibrated to the socio-economic and demographic characteristics of an area (e.g., income level).
- The measurement of the pedestrian crossing control compliance rate was a first attempt to introduce and include safety within a walkability index. Although compliance is not necessarily a direct indicator of safety, non-compliant crossing control treatments can provide a false sense of safety to pedestrians in locations where the treatment is unsuitable for prevailing traffic conditions and street design characteristics. In addition, this metric was introduced as a normative measure of the treatments that should be implemented to provide adequate urban form for pedestrians, since treatment compliance does not necessarily influence a person's decision to walk. Future research is required to assess alternative safety surrogates as indicators of walkability.
- In addition to the assessment of existing pedestrian crossing control treatments, further analysis can be conducted to assess locations where a pedestrian crossing control treatment is required, but does not currently exist. The inclusion of these locations would reduce the

safety Z-score of those Census Tracts that received a one hundred percent compliance rate while having no crossing control treatments.

- Due to lack of access to data, employment data was not included in the walkability analyses. Spatial employment data by Census Tract would be beneficial to include in the Walkability Index to determine the proximity of residents to employment locations as an indicator of accessibility.
- Intersection density was not used an indicator of connectivity because it overrepresented the number of crossing opportunities, since many intersections did not have sidewalk access. The sidewalk coverage metric introduced in this research represents the extent of the sidewalk network within an area; however, the inclusion of a refined intersection density metric that only includes intersections with sidewalks would also be beneficial as it would represent the number of available pedestrian crossing opportunities.

5. URBAN INTERSECTION DESIGN BASED ON THE FREIGHT-WALKABILTY DECISION SUPPORT TOOL

This chapter discusses the development of a decision support tool to guide the selection and design of urban intersection curb radii based on the intersection's Freight-Walkability relationship. The Freight-Walkability relationship combines the Walkability Index, developed and measured in Chapter 4, and the level of freight activity, discussed in this Chapter, to help identify and balance the needs of truck movements and pedestrian crossings in urban intersection design.

5.1. Freight- Walkability Relationship

This research developed a Freight-Walkability relationship, shown in Figure 28, by combining the two aspects of freight movement and walkability levels. The Freight-Walkability relationship characterizes the context of an area to guide the balance of goods movement needs and pedestrian walkability needs. The Freight-Walkability context identifies the modal priority (either truck or pedestrian activity) that should be considered in an area, or whether both modes should be considered in a more balanced manner.

The Freight-Walkability relationship is generic in nature, thus the freight and walkability axes can be quantified differently depending on the application context of the relationship and the parameters being measured. The relationship can be utilized to guide the context-sensitive design strategies of the transportation system ranging from a broader planning level (e.g., land use and zoning) to street design elements (e.g., lane widths, right-turn treatments, and curb bulbouts), to operational considerations (e.g., traffic control devices and signal phasing), and to management considerations (e.g., parking and access management) (FDOT, 2015). The Freight-Walkability context zones can be applied to existing freight movement and walkability conditions, predicted future conditions, or desired conditions which can be reflected by the freight and walkability measurements of the area.

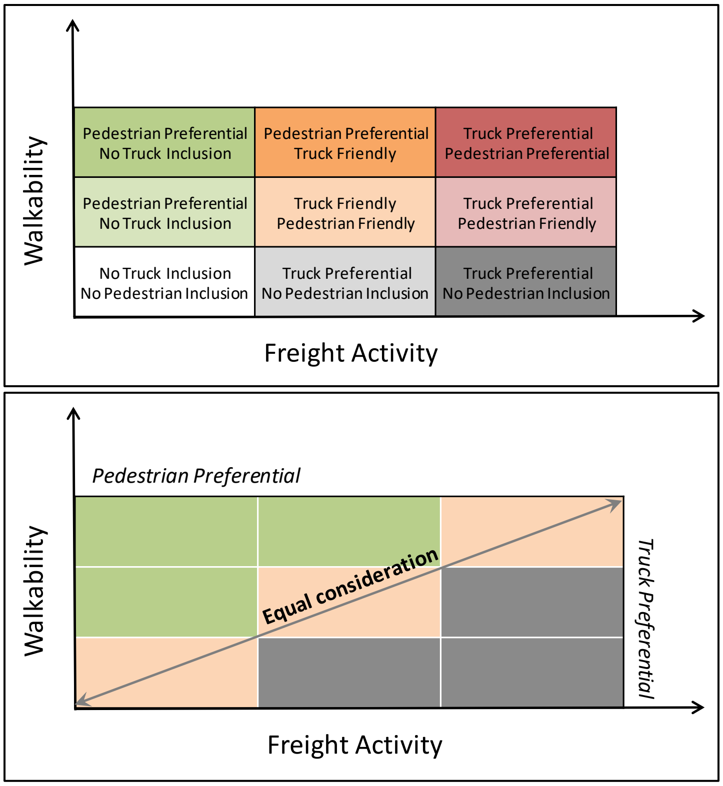


Figure 28: Freight-Walkability Modal Priority Matrix

The developed Freight-Walkability relationship builds off of the Freight Activity and Land Use Compatibility Analysis (FALUCA) developed by the Florida Department of Transportation's (FDOT, 2015) which relates and characterizes freight activity and liveability. The FDOT report (2015) characterizes four general areas based on the freight-liveability relationship: low activity areas, community oriented areas, freight oriented areas and diverse activity areas. The Tampa Bay Regional Strategic Freight Plan (2012) provides a scoring system to measure the level of liveability and freight activity separately, based on a series of planned land uses (liveable future land uses, existing or future transit stations, community redevelopment areas, and activity centres) and freight activity (percent truck traffic, industrial future land uses, and regional freight activity centres). This research followed the FDOT (2015) FALUCA characterization of context zones; however, it focused on walkability instead of the broader liveability concept and it provides a more robust measurement scheme of the two elements of freight activity and walkability rather than a scoring (points) system.

The freight activity and walkability axes in the Freight-Walkability relationship, shown in Figure 28, individually range from low to medium to high levels. The level of emphasis on freight or pedestrian movement in the planning, design, operation and management of the transportation network reflects the level of current or future/desired freight activity or walkability, with treatments ranging from preferential to friendly to no inclusion for the given mode. The combination of the freight activity level and walkability level determines the level of treatment that should be provided based on the modal priority. The three levels of treatments in the Freight-Walkability relationship are further described:

- *Preferential Treatments:* Areas with higher levels of freight activity than walkability require truck-preferential treatments, where the roadway network is planned and designed with trucks as the modal priority. Similarly, areas with higher levels of walkability than freight activity require pedestrian-preferential treatments, where the infrastructure is designed with pedestrians as the modal priority. Areas with both high freight activity and walkability would require a compromise of the truck-preferential and pedestrian-preferential treatments to balance the needs of the two modes. These are mixed-used areas with significant multimodal presence.
- *Friendly Treatments*: Areas with medium levels of freight activity where pedestrians are the modal priority require truck-friendly treatments, where freight movement is accommodated but not designed-for. This means that although large trucks are not the modal priority in these areas, they are able to operate in the network with some operational or regulatory constraints. Similarly, areas with medium walkability levels where pedestrians are not the modal priority require pedestrian-friendly treatments, where the infrastructure accommodates pedestrian movements. These areas would typically be designed to the recommended limits of design standards, while not exceeding standard limits. Areas with medium levels of both freight activity and walkability would require a

compromise of the truck-friendly and pedestrian-friendly treatments to balance the needs of the two modes. These are mixed-use areas with moderate multimodal presence.

- *No inclusion:* Areas with low levels of freight activity typically do not require the accommodation of large freight vehicles, as they do not operate on these roadways, which can be considered non-truck inclusive. Rather these areas may require the operation of smaller single unit trucks or delivery vehicles to deliver goods; therefore, the network is designed to allow the operation of these smaller freight vehicles. Similarly, areas with low walkability levels have a lower level of accommodation of pedestrians in the network where they are able to maneuver the system through infrastructure designed to the practical lower limits of the design domain of street design parameters. Non-pedestrian inclusive treatments would be considered in areas with no walkability, where pedestrians are either prohibited or minimal support is provided. Areas with low freight activity are typically designed for medium single unit trucks (City of Toronto, 2017) or passenger vehicles (FDOT, 2015) as the modal priority which would accommodate the operation of smaller delivery vehicles as well. An area with both low freight activity and low walkability is either a non-developed area or an area that is not adequately designed for pedestrians or trucks. In this case, the infrastructure and land use design should be modified to either increase walkability or freight activity or both.

An important element of this research with respect to the Walkability-Freight activity matrix was the application of this relationship to the design of intersection curbs to allow the safe right-turn maneuver of trucks while aiming to reduce the crossing distance of pedestrians. Within the scope of urban intersection design, a truck preferential treatment would be to design an intersection with a wider curb radius that allows the simple right-turn maneuver of a large truck (tractor-semitrailer) from the curb lane without requiring encroachment onto adjacent/opposing lanes or oversteering of the vehicle. However, a wider curb radius results in an increased crossing distance for pedestrians and the placement of intersection ramps that are not aligned squarely with the crossing, which would make this design lean towards a more non-pedestrian inclusive treatment.

A pedestrian-preferential treatment would be to minimize the curb radius to reduce the crossing distance of a pedestrian and consequently their time of exposure to vehicular traffic. This treatment would be considered truck-ignorant as trucks would have difficulty completing a curb lane right-turn maneuver without mounting the curb or making multiple maneuvers at the intersection. Truck-friendly and pedestrian-friendly curb radii would be along a spectrum depending on the intersection context characteristics and intersection configuration.

5.2. Truck Configurations

This research analyzed two truck configurations specified by TAC (2017) (Figure 29): heavy single unit trucks (HSU) and tractor-semitrailer trucks with 53-ft semitrailers (WB20).

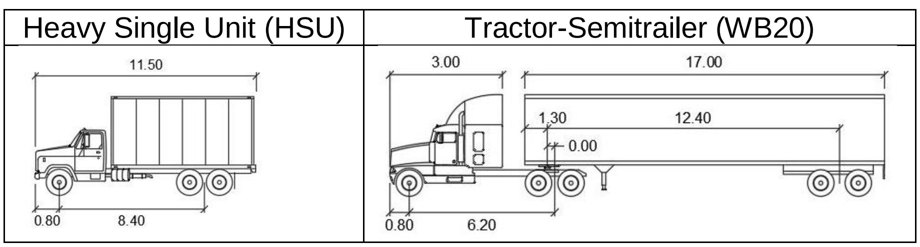


Figure 29: TAC (2017) Heavy Single Unit (HSU) and Tractor Semitrailer (WB20) Truck Configurations *(Source: AutoTurn software)*

Five-axle tractor semitrailers are the most common truck configuration in North America, followed by three-axle and four-axle single unit trucks (U.S. DOT, 2000). Truck vehicle-miles-travelled (VMT) in U.S. urban areas is almost equally split between combination vehicles and single unit vehicles at 54 percent and 46 percent, respectively (U.S. DOT, 2015).

The TAC Geometric Design Guide (2017) specifies two single unit truck configurations: Medium Single-Unit (MSU) and Heavy Single-Unit (HSU). The MSU is a 2-axle straight truck with a 6.5m wheelbase, while the HSU is a three or four axle straight truck with an 8.4m wheelbase. The HSU was the selected design vehicle because the turning configuration of an HSU better represents the full spectrum of large vehicles that may need to be accommodated in urban areas, including transit buses (specifically TAC's standard and intercity transit design vehicles) and emergency vehicles such as fire trucks.

The turning characteristics of single unit vehicles and combination vehicles are different. The vehicle characteristics that affect the turning maneuver of a vehicle follow (AutoTurn, 2019):

- Steering lock angle: The maximum angle of the steered axle direction relative to the front of the vehicle. This variable affects the circular portion of the turning path.
- Lock to lock time: The time it takes the driver to turn the steering from the maximum angle in one direction to the maximum angle in the opposite direction in a single continuous turn. Auto Turn's default value is six seconds for low speed turns. This variable affects the transition portion of the turn.
- Articulation angle: The angle of the trailer/semitrailer direction relative to the tractor that occurs as the trailer/semitrailer rotates around the articulation point. Single unit vehicles do not have any articulation points.

Generally, the default low-speed turning maneuver characteristics of AutoTurn were used for HSU and WB20 vehicles, shown in Table 19.

Table 19: Low-Speed Turning Characteristics of WB20 and HSU Vehicle Configurations

Low Speed Turning Variables	WB20	HSU
Steering Angle (degrees)	28.2	40
Lock to Lock Time (seconds)	6	6
Articulating angle (degrees)	70	n.a.

5.3. Freight-Walkability Decision Support Tool for Intersection Curb Radii Design

This research developed a decision support tool to determine the urban intersection curb radius required to accommodate the trucks discussed in section 5.2 and pedestrians based on their level of modal priority determined by the Freight-Walkability relationship. The Freight-Walkability relationship was applied to the design of intersection curb radii, where walkability was measured by the Walkability Index (developed in Chapter 4) and freight activity was measured by the peak-hour truck turning volumes. Figure 30 shows the steps to follow when using the decision support tool to select a curb radius that is suitable to the Freight-Walkability context, considering the vehicles discussed in section 5.2. A detailed description of each step follows.

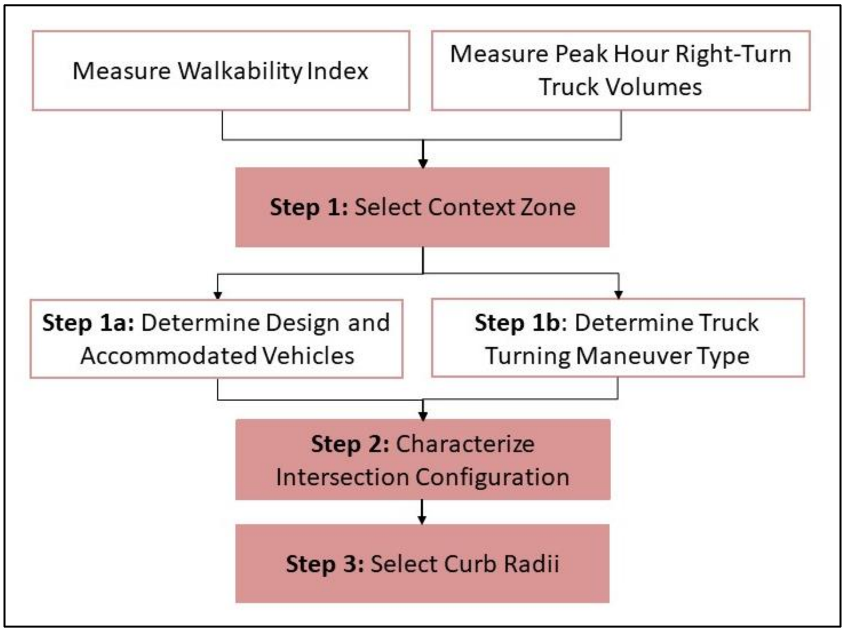


Figure 30: Decision Support Tool Methodology Flow Chart

Step 1: Select the context zone

The context zone (labelled 1 to 9 in Figure 31) of an urban intersection is determined based on the level of walkability and freight activity. Figure 31 shows the Freight-Walkability relationship developed in this research as a component of the developed decision support tool to select an intersection curb radius. The walkability level is measured by the Walkability Index developed in Chapter 4, while freight activity is measured by the peak-hour right-turning truck volumes at the intersection of interest. Truck traffic does not follow standard vehicular peak hours thus peak-hour right-turning truck volume was selected as the freight activity metric since it represents the maximum amount of right-turning truck activity at any four consecutive 15-minute intervals in a day. The axis scales will vary by jurisdiction depending on the relative levels of freight activity and walkability across the jurisdiction.

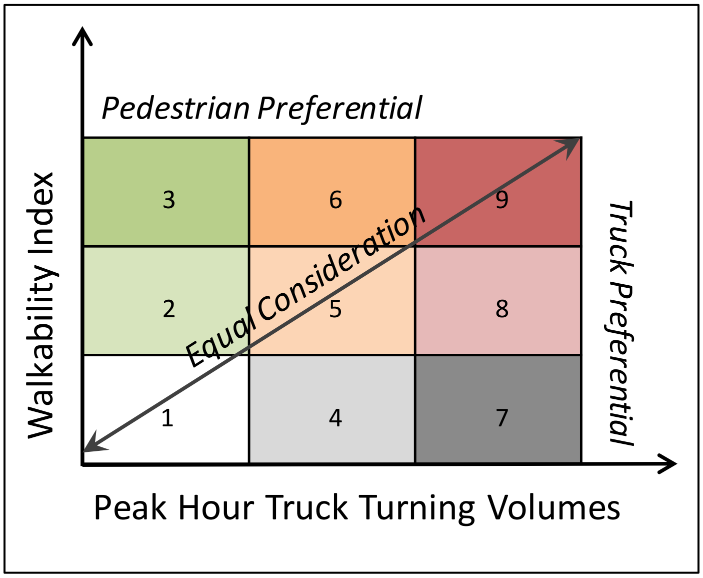


Figure 31: Freight-Walkability Relationship as a component of the Decision Support Tool for Curb Radii Selection

The context zone characterizes the urban environment surrounding the intersection to guide the prioritization of modal needs in street design and in cases of equal prioritization, determine the compromise in street design to accommodate the needs of both. The selection of the Freight-Walkability context zone determines the next two steps (steps 1a and 1b) in the decision support tool, where it defines:

- the design and accommodated vehicles that must be able to complete a right-turn maneuver at an intersection depending on the level of truck treatment (i.e., truck-preferential, friendly or non-inclusive),
- the maximum number of receiving lanes that the design and accommodated vehicle can occupy once the right-turn is complete, and
- the truck right-turn maneuver type (i.e., oversteer or no oversteer) based on the level of walkability at the location of interest.

Step 1a: Determine the design and accommodated vehicle and truck-turning configuration

The design and accommodated vehicles and their turning configurations are selected based on the associated Freight-Walkability context zone. The level of freight activity and walkability associated with each context zone determine the required level of accommodation of each mode at the intersection of interest. The combination of the accommodation levels of the two modes determines the modal priority and guides the balance required to accommodate the needs of both trucks and pedestrians at the intersection. The balance of modal needs determines: (1) the types of vehicles that should be able to maneuver a right-turn at the intersection (i.e., design and accommodated vehicles); and (2) the amount of space the vehicle can occupy during the turn (i.e., the start and end positions of the vehicles in the approach and receiving legs, respectively). In general, the higher number of lanes a turning vehicle occupies in both the approach and receiving legs, the less space the vehicle will occupy at the intersection curb, which would allow more curb space for pedestrians.

The level of freight activity in combination with the modal priority associated with the context zone determines the required level of accommodation of trucks in terms of truck-preferential, truck-friendly or non-truck inclusive design (refer to Figure 28), which subsequently guides the selection of a design and accommodated vehicle. A design vehicle is a frequent user of a street or network and must be fully designed-for to allow its operation. An accommodated vehicle is an occasional/infrequent user of a street or network, which is able to operate and maneuver the street or network with some operating constraints (NACTO, 2013). This research used the heavy single unit trucks (HSU) and tractor-semitrailer trucks with 53-ft semitrailers (WB20) specified by the Transportation Association of Canada Geometric Design Guide (2017) as the design/accommodated vehicles, depending on the context zone.

In this research, the design and accommodated vehicles determined the truck-turning configurations in terms of the vehicle's starting position in the intersection approach leg. The design vehicle was required to be able to complete a right-turn starting from the lane closest to the curb, while the accommodated vehicle should be able to complete a right-turn starting from the second lane closest to the curb, thus providing more space in the intersection for the vehicle to turn and reducing the curb radii. Figure 32 shows the truck turning configuration of a WB20 design and accommodated vehicle in the approach lane.

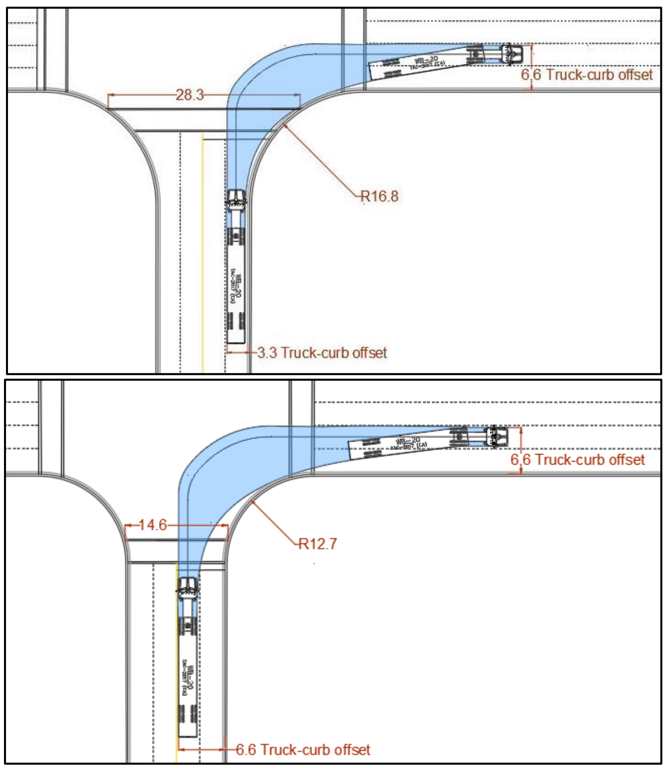


Figure 32: Curb Radius and Pedestrian Crossing Distance at an Intersection with WB20 as the design vehicle (top) and accommodated vehicle (bottom) ***(all measurements in metres)***

Within the context of this research:

- Context zones 4, 7, 8, and 9 in Figure 31 require truck preferential treatments as they are areas with moderate to high truck activity where freight is the modal priority. Thus, the tractor-semitrailer truck (WB20) is the design vehicle. This means that the curb radius is designed to allow a tractor-semitrailer truck complete a right-turn starting from the first lane closest to the curb.

- Context zones 5 and 6 in Figure 31 require truck friendly treatments, as they are areas with moderate truck activity where freight is the modal priority or has equal modal priority. Thus, the heavy single unit vehicle (HSU) is the design vehicle and the WB20 vehicle is the accommodated vehicle. This means that the curb radius is designed to accommodate a tractor-semitrailer truck by allowing the truck to maneuver a right-turn starting from the second lane closest to the curb, while smaller freight vehicles (i.e., HSU) would be able to complete a right-turn from the curb lane.
- Context zones 1, 2, and 3 in Figure 31 require non-truck inclusive treatments as truck activity is low to non-existent and trucks are not the modal priority. This means larger vehicles are not considered in the intersection design, rather the intersection would be designed for other modal priorities (e.g., pedestrians in walkable areas or passenger cars elsewhere), hence providing the minimum curb radius. The minimum curb radius would allow the right-turn maneuver of smaller delivery vehicles (e.g., light single unit-LSU) from the curb lane (i.e., design vehicle) at these intersections.

While the design and accommodated vehicles, based on the level of freight activity and modal priority, determined the starting position of a vehicle in the approach leg, the level of walkability determined the maximum number of receiving lanes the vehicle can occupy in its final position (i.e., target receiving lane). A high walkability context zone would require pedestrian-preferential treatments, which can be achieved by allowing the design and accommodated vehicles to occupy a higher number of receiving lanes to reduce the curb radius and the pedestrian crossing distance. A low walkability context zone would prioritize other modes thus the design and accommodated vehicles would be able to complete a right-turn into the receiving curb lane.

Therefore, the overall truck-turning configuration of different truck types can be determined by the combination of the two levels of freight activity and walkability. Table 20 outlines the truck-turning maneuver configurations specified in this research for the design and accommodated vehicle in each context zone from the vehicle's starting position in the approach leg to the final position in the receiving leg, up to a maximum number of available lanes.

Table 20: Truck Turning Configurations of Design and Accommodated Vehicles Based on Context Zones

Context Zone	WB20	HSU
Context Zone 1* *No Truck Inclusion* *No Pedestrian Inclusion*	n.a.	n.a.
Context Zone 2* *Pedestrian Preferential* *No Truck Inclusion*	n.a.	n.a.
Context Zone 3* *Pedestrian Preferential* *No Truck Inclusion*	n.a.	n.a.
Context Zone 4 *Truck Preferential* *No Pedestrian Inclusion*	*Design Vehicle:* Curb lane- Curb lane (no oversteer)	n.a. *(WB20 governs)*
Context Zone 5 *Truck Friendly* *Pedestrian Friendly*	*Accommodated Vehicle:* 2nd lane – Up to 2 lanes (no oversteer)	*Design Vehicle:* Curb lane- Up to 2 lanes (no oversteer)
Context Zone 6 *Pedestrian Preferential* *Truck Friendly*	*Accommodated Vehicle:* 2nd lane – Up to 2 lanes (oversteer)	*Design Vehicle:* Curb lane- Up to 2 lanes (oversteer)
Context Zone 7 *Truck Preferential* *No Pedestrian Inclusion*	*Design Vehicle:* Curb lane- Curb lane (no oversteer)	n.a. *(WB20 governs)*
Context Zone 8 *Truck Preferential* *Pedestrian Friendly*	*Design Vehicle:* Curb lane- Up to 2 lanes (no oversteer)	n.a. *(WB20 governs)*
Context Zone 9 *Truck Preferential* *Pedestrian Preferential*	*Design Vehicle:* Curb lane- Up to 2 lanes (oversteer)	n.a. *(WB20 governs)*

**Provide minimum curb radius for context zones 1, 2 and, 3 because there is no truck activity*
Note: n.a. means that the turning movement of that vehicle is not being considered for that context zone because either the design vehicle governs or there is no truck activity in that context zone

For example, an intersection in a context zone with high freight movement and low walkability (e.g., context zone 7) should be designed to prioritize truck movements by allowing the maneuver of a larger truck (WB20) from the approach curb lane to approach receiving lane. These areas of low to no pedestrian activity either prohibit pedestrian crossings or provide pedestrian refuge islands or medians to reduce the pedestrian crossing distance. If this high freight area also had moderate pedestrian activity (e.g., context zone 8), trucks would still have modal priority, however, a compromised design would be required to allow the right turn of a WB20 from the approach curb lane while still aiming to reduce pedestrian crossing distance by allowing the vehicle to occupy two receiving lanes. Conversely, a context zone with medium freight movement and high walkability (e.g., context zone 6), where pedestrians are the modal priority, should have a compromised design. This context zone should allow the maneuver of a smaller vehicle (e.g., single unit truck) and only accommodate the maneuver of a larger truck (WB20) with some operating constraints (i.e., start from second approach lane) while allowing both vehicles to occupy up to two receiving lanes, thus reducing the intersection crossing distance for pedestrians. Figure 32 shows the reduced curb radius and pedestrian crossing distance of an intersection with a WB20 accommodated vehicle relative to a WB20 design vehicle.

Step 1b: Determine the truck turning maneuver type

In addition to accommodating vehicles and/or allowing the occupation of a greater number of receiving lanes, an additional method of reducing an intersection curb radius is to oversteer a vehicle. If the context zone requires designing-for or accommodating truck movements (context zones 4 to 9), the type of turning maneuver (i.e., with or without oversteer) must be selected depending on the walkability levels of the context zone. A truck maneuvering a turn could be oversteered by making a wider turn into the intersection. This would occupy more space within the intersection and the vehicle could encroach on adjacent lanes in both the approach and receiving lanes. An oversteered turn allows the vehicle to make a more compact turn by shifting its swept path away from the curb, which allows a tighter curb radius at the intersection, thus reducing the crossing distance for pedestrians. Figure 33 shows a truck turning swept path with and without oversteering and the resulting curb radii for the same intersection configuration.

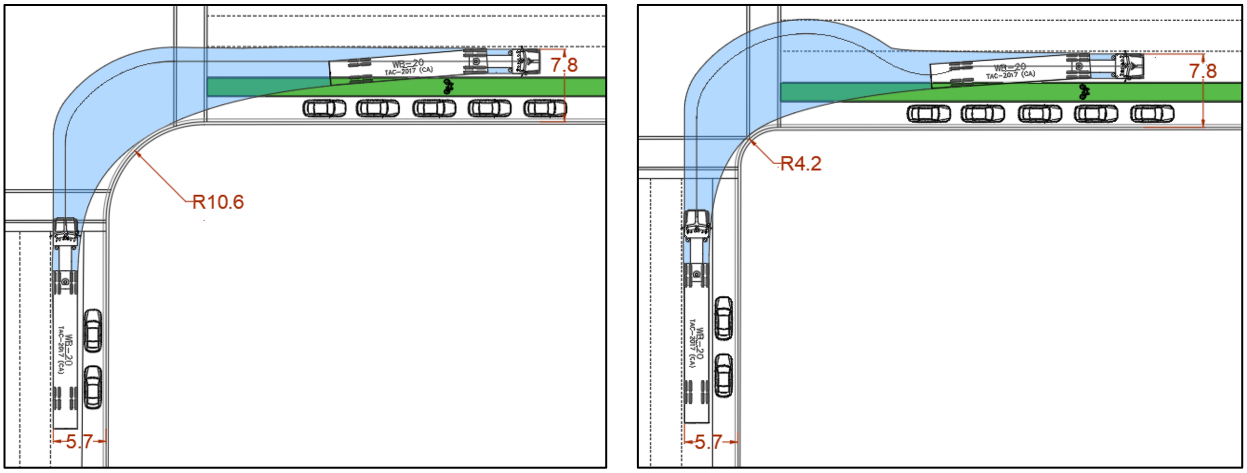


Figure 33: Truck Right-Turning Maneuvers with (right) and without (left) Oversteering

In this research, the walkability level of a context zone determines whether oversteering of a design or accommodated vehicle is preferred while completing a right turn. Neighborhoods with higher walkability levels (context zones 6 and 9) require more compact intersections, thus a WB20 or HSU design or accommodated vehicle are required to make a wider turn with encroachment in an adjacent/opposing receiving lane (i.e., oversteer) to shift back the vehicle swept path further into the intersection. The designer would be required to ensure that the vehicle is safely able to encroach on additional space through the presence of an adjacent lane or mountable curb. For encroachment on an opposing lane, common design elements include a set-back stop bar, set-back median or re-shaped median nose to conform to the truck swept path.

In the analysis for this part of the research, the vehicles were oversteered with exit offsets only (i.e., no entry offsets). This means that oversteering commences in the receiving lane and not in the approach lane, as shown in Figure 33, thus there is no encroachment on additional lanes in the approach lane. A WB20 vehicle was allowed an exit offset of 3.24 m that is larger than its minimal offset width of 1.76 m to allow the vehicle to encroach on the entire width of an adjacent lane. Similarly, the HSU vehicle was allowed the minimal offset of 3.24 m, which is its minimal offset ability, to limit the vehicle encroachment to only one adjacent lane.

In contrast, neighborhoods with lower walkability (context zones 4 and 7) do not require compact intersections and thus a WB20 and HSU design or accommodated vehicle can make a simple turn with no oversteering, which would require a relatively wider curb radius. The design and accommodated trucks in context zones with medium walkability levels (context zones 5 and 8) are also not expected to oversteer as they are allowed to occupy up to two lanes of the receiving leg.

Step 2: Determine the intersection configuration

Prior to selecting a curb radius, the amount of roadway space available for a truck to complete a right turn maneuver must be determined. This is dependent on the roadway configuration characteristics. The number of lanes and lane widths on the approach and receiving intersection legs determine the amount of roadway space available to a turning vehicle. Additional street design elements that determine the available roadway space are buffered or unbuffered bike lanes, parking lanes, curb bulbouts, or different combinations of the street elements. The distance from the face of the curb to the outer wheels of the vehicle at its start and end position determines the intersection approaching and receiving leg widths available to a vehicle to complete a turn. The effective turning radius of the vehicle (i.e., the turning radius of the inner axles) guides the determination of the curb radius required to allow a truck turn.

Wider curb lanes or the addition of bike lanes and/or parking lanes provides more space between the vehicle and the curb, thus increasing the effective radius of the turning vehicle. This allows the designer to provide a smaller curb radius while allowing the vehicle to complete a right-turn with minimal or no constraints (TAC, 2017).

Curb bulbouts or curb extensions are a pedestrian-preferential treatment recommended by Complete Street Guidelines used to narrow the roadway at pedestrian crossings. However, curb bulbouts reduce the available roadway space for a truck's swept path as it maneuvers a right-turn. Although the truck-curb offset is greater due to the additional extension, a larger curb radius is required to accommodate truck turns. The benefits of a curb bulbout must be weighed against the benefits of providing a smaller curb radius. Curb bulbouts that reduce the pavement width can range from a minimum of 1.2 metres to a preferred 2.0 metres from the face of the curb. Curb bulbouts with dedicated parking lanes can extend from 2.0 metres to 2.8 metres with a preferred width of 2.4 metres (City of Toronto, 2017). This research used a curb bulbout width of 2.4 metres with a dedicated parking lane to determine required curb radii.

Step 3: Select the curb radius required based on the correct graph

An intersection curb radius must accommodate both the design and accommodated vehicle turning movements; therefore, the larger curb radii of the two scenarios governs. The curb radius is determined based on the turning configuration (i.e., vehicle starting and ending position) and the effective turning radius of the design and accommodated vehicles as they complete a right-turn. The combination of the street design elements, the start and end lanes of a turning vehicle and the walkability level of the area, determine the distance from the face of the curb to the outer axles of the vehicle (i.e., left side of the vehicle) in both the approach and receiving legs of the intersection. The truck's position in the starting lane in the approach leg and ending lane in the receiving leg maintains a 0.3 metre buffer between the axles on the left side of the vehicle and the outer lane (i.e., lane marking on the left side of the vehicle). In addition, a minimum buffer of 0.3 metres is maintained between the inner axles of the vehicle (i.e., right side of the vehicle) and the face of the curb throughout the entire turning maneuver. The City of Toronto Road Engineering Design Guidelines (2017) use a 0.3-metre distance from the curb and the TAC Geometric Design

Guide (2017) specifies a minimum distance of 0.25 metres. Figure 34 shows the buffers maintained during a vehicle's right-turn maneuver.

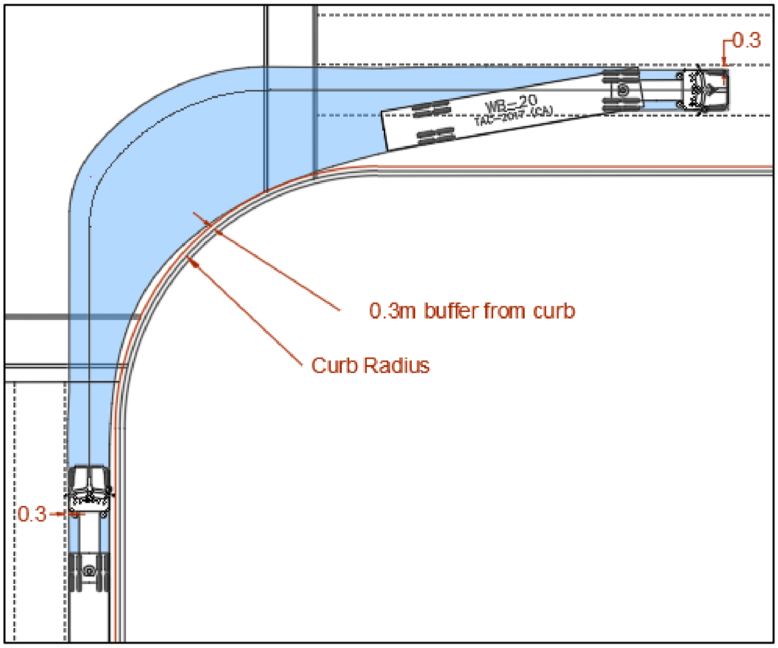


Figure 34: Buffers Maintained during a Truck Right-Turn Maneuver

In cases where the 0.3 metre offset from the left lane marking could not be maintained simultaneously with the 0.3 metre offset from the curb on the right side of the vehicle, the 0.3 metre offset from the curb must be maintained while the 0.3 metre offset from the left lane was reduced.

Figure 35, Figure 36, Figure 37 and Figure 38 define the curb radius design domain developed through this research and determine the minimum curb radius required to allow the right-turn maneuver of a design or accommodated truck. The provided curb radii are single curve radii, which are most commonly used in urban areas (TAC, 2017). AutoTurn software was used to conduct the swept path and curb radii analysis, with a set turning speed of 5 km/h.

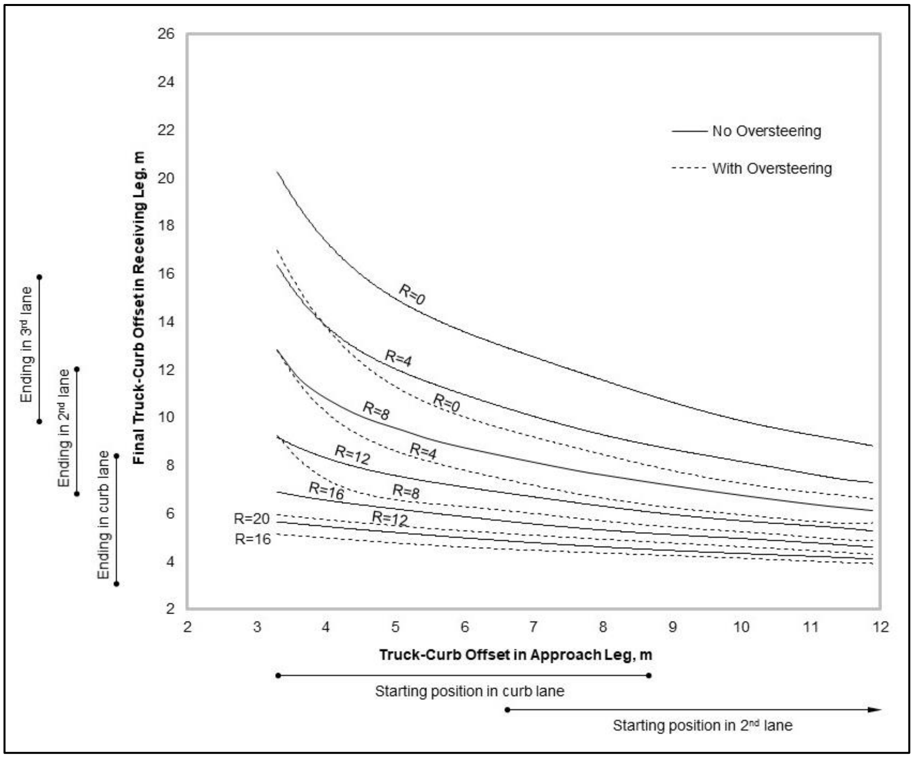


Figure 35: Minimum Curb Radii for a WB20 Design or Accommodated Vehicle at a Standard Intersection

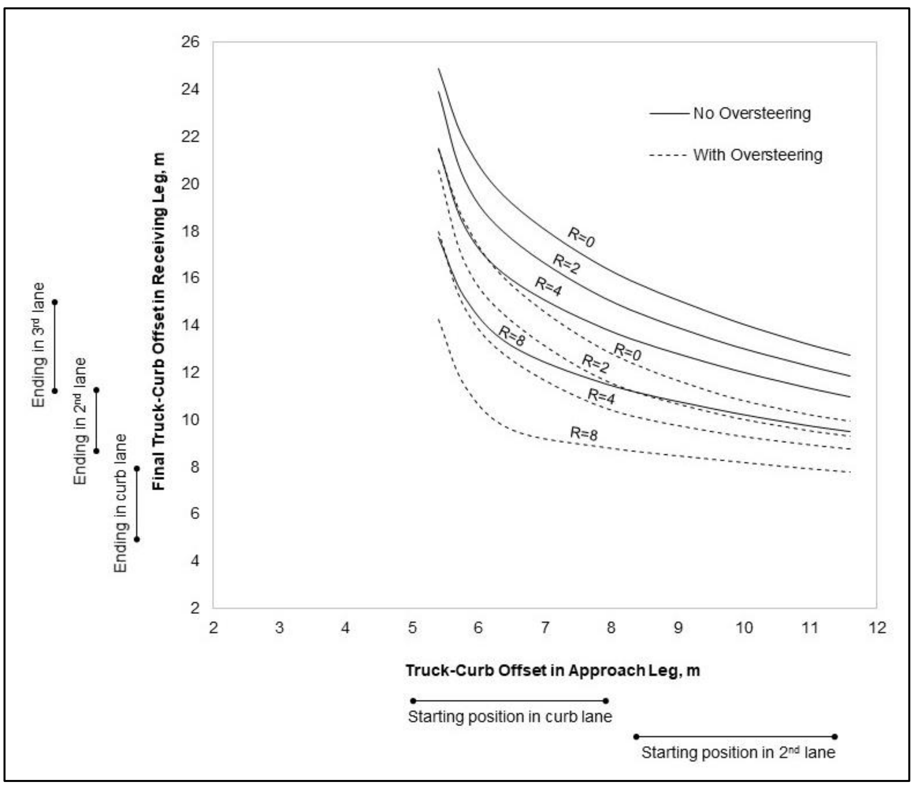


Figure 36: Minimum Curb Radii for a WB20 Design or Accommodated Vehicle at an Intersection with a Curb Bulbout/Extension

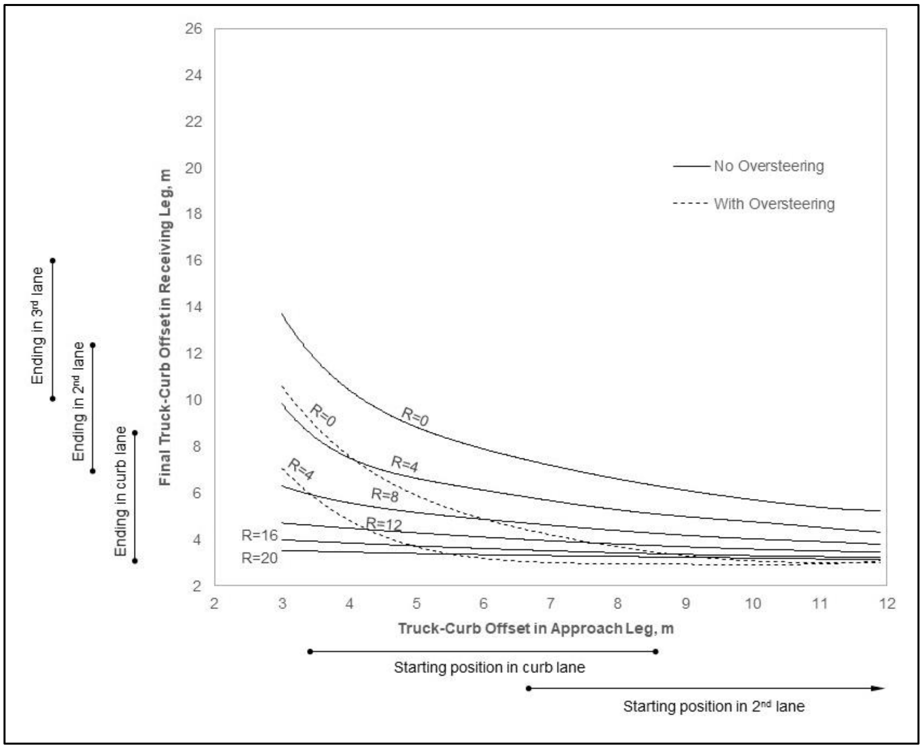


Figure 37: Minimum Curb Radii for a Heavy Single Unit (HSU) Design or Accommodated Vehicle at a Standard Intersection

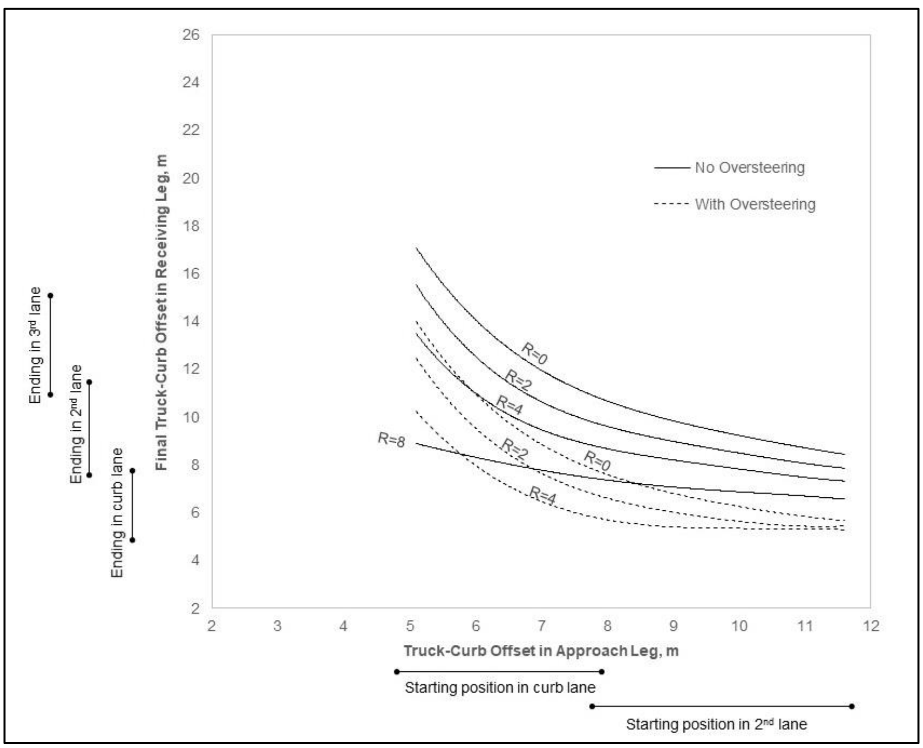


Figure 38: Minimum Curb Radii for Heavy Single Unit (HSU) Design or Accommodated Vehicle at an Intersection with a Curb Bulbout/Extension

The design domains shown in Figures 35-38 were developed to assist designers with the decision-making process based on the combination of walkability and truck activity present or desired at an intersection. A designer can select the curb radius from the design domain based on the following four variables:

- **Truck to curb offset in the approach leg:** The distance from the face of the curb to the outer truck axles (i.e., left side of the vehicle) in the approach lane determines the truck-curb offset in the approach leg. Figure 39 shows the approach leg truck-curb offset distance. This distance depends on whether the vehicle is maneuvering a turn from the curb lane (i.e., design vehicle) or second lane (i.e., accommodated vehicle). It also depends on the street design elements. The presence of a bike lane, parking lane, or combinations of the elements increases the distance between the vehicle and the curb. For example, the truck-curb approach offset for a design vehicle can range from a minimum of 3m for a narrower curb lane (3m) to 8.6m for a wide curb lane (3.7m) with a wide parking lane (2.8m) and buffered bike lane (2.1m.). The truck-curb approach offset for an accommodated vehicle can range from a minimum of 6m for narrower curb lanes (two-3m lanes) to 12.3m for wide curb lanes (two-3.7m lanes) with a wide parking lane (2.8m) and buffered bike lane (2.1m.). It is recommended that the minimum lane width of 3m not be provided in locations with tractor-semitrailer operations (TAC, 2017). The offset at an intersection with a curb bulbout can range from a minimum of 4.7m to 7.9m with a bike lane for a design vehicle and 7.7m to 11.6m for an accommodated vehicle. The width measurements are obtained from the recommended lower and upper limits from the TAC Geometric Design Guide (2017).
- **Truck to curb offset in the receiving leg:** The distance from the face of the curb to the outer truck axles (i.e., left side of the vehicle) in the receiving lane once the turn is complete determines the final truck-curb offset in the receiving leg. Figure 39 shows the receiving

leg truck-curb offset distance. This distance is dependent upon the final position of the vehicle in the target receiving lane and does not include the additional encroachment space required if the vehicle is oversteering. The receiving lane position of the vehicle is determined by the Freight-Walkability context zone, where high walkability neighborhoods would allow a vehicle to occupy more receiving lanes to create a more compact intersection while low walkability neighborhoods would enable the vehicle to end in a curb lane which would increase the curb radius. In addition, similar to the truck-curb offset in the approach leg, the street design elements impact the available space, where the presence of a bike lane, parking lane, or combinations of these elements increase the distance between the vehicle and the curb.

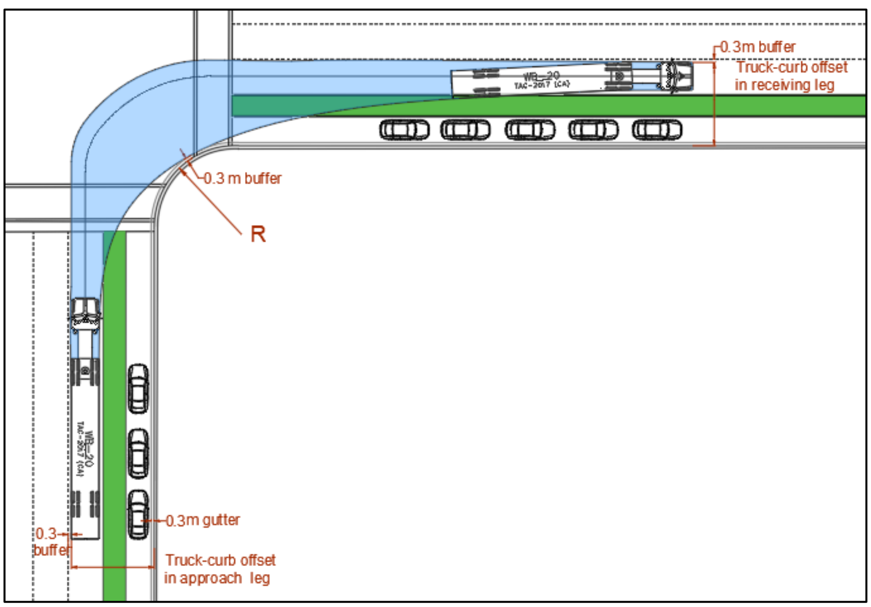


Figure 39: Offset and Buffer Distances for a Right Turning Vehicle (all measurements in meters)

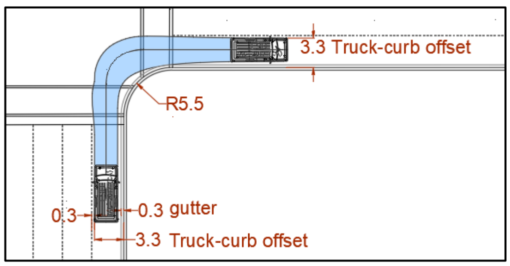
- **Intersection design elements:** Different street design elements can affect the amount of space available for a truck to complete a maneuver. Elements such as buffered or unbuffered bike lanes and parking lanes are considered in the approach and receiving leg offset distances. The presence of a curb bulbout reduces the space available for the swept path of a vehicle but increases the distance between the vehicle and the original face of the curb (i.e., truck-curb offset). Figure 35 and Figure 37 provide minimum curb radii for WB20 and HSU vehicles, respectively, at standard intersections and Figure 36 and Figure 38 provide minimum curb radii for WB20 and HSU vehicles, respectively, at intersections with curb bulbouts.

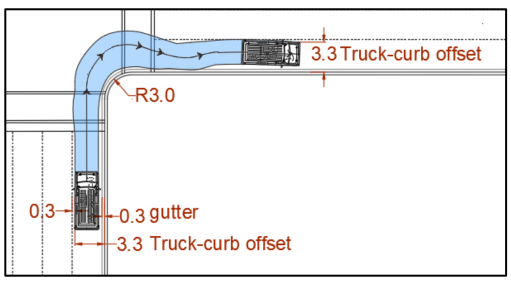
- **Truck maneuver type:** Oversteering of a vehicle shifts the vehicle turning swept path further back into the intersection, away from the curb. Oversteering reduces the curb radius and subsequently the pedestrian crossing distance. Figure 35, Figure 36, Figure 37, and Figure 38 provide curb radii measurements for both oversteering and non-oversteering vehicles.

Table 21 provides a summary of the Freight-Walkability context zones and the truck turning characteristics of their associated design and accommodated vehicles. The designer can modify the intersection design elements to allow the right turn of the design and accommodated vehicles. The table identifies additional intersection design options for further consideration based on the context zone.

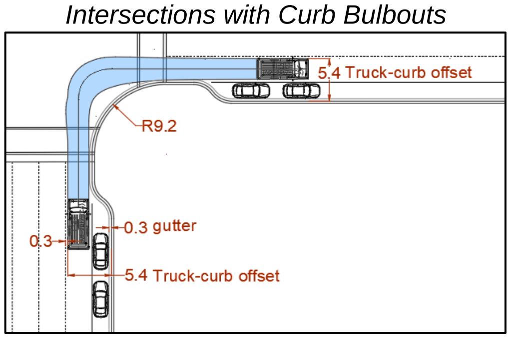
Table 21: Truck Turning Characteristics of Design and Accommodated Vehicles for each Context Zone

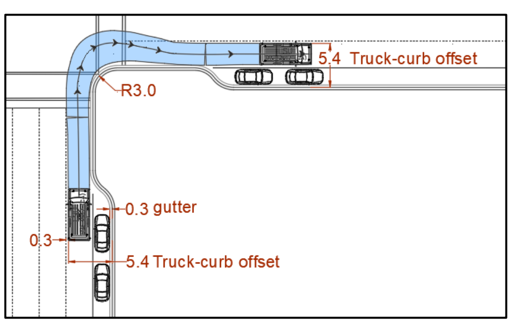
<table>
<tr><th></th><th colspan="3">Design Vehicle</th><th colspan="3">Accommodated Vehicle</th></tr>
<tr><th>Context Zones</th><th>Type</th><th>Turning Configuration</th><th>Maneuver Type</th><th>Type</th><th>Turning Configuration</th><th>Maneuver Type</th></tr>
<tr><td>1, 2, 3</td><td>LSU</td><td><u>Approach leg:</u>
Curb lane
<u>Receiving leg:</u>
Curb lane</td><td>No Oversteer</td><td>N.A.</td><td>N.A.</td><td>N.A.</td></tr>
<tr><td>Context zone 3
Context zone 2
Walkability: Pedestrian Preferential Context zone 1
Freight Activity: No Truck Inclusion</td><td colspan="3">Standard Intersections





Intersections with Curb Bulbouts





</td><td colspan="3"></td></tr>
</table>

Note: All measurements are in metres

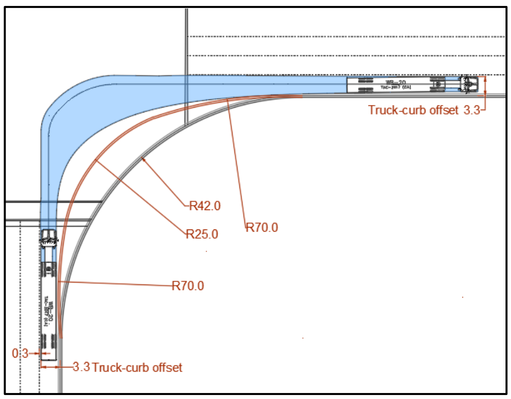
Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

	Design Vehicle			Accommodated Vehicle		
Context Zone	**Type**	**Turning Configuration**	**Maneuver Type**	**Type**	**Turning Configuration**	**Maneuver Type**
4	WB20	Approach leg: Curb lane Receiving leg: Curb lane	No Oversteer	N.A.	N.A.	N.A.

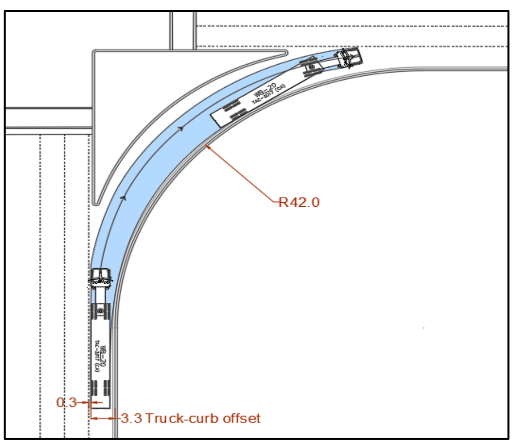
Freight Activity: Truck Preferential

Walkability: No Pedestrian Inclusion

Standard Intersection
(single curve or compound curve)



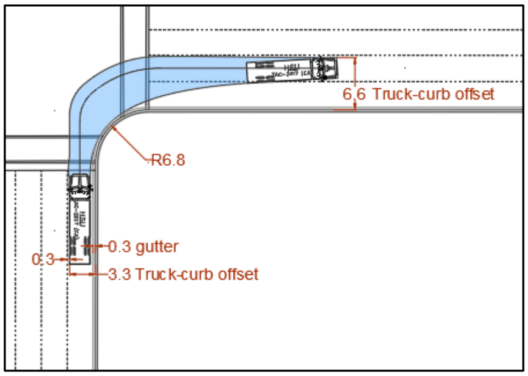
Standard Intersection
(with pedestrian refuge)

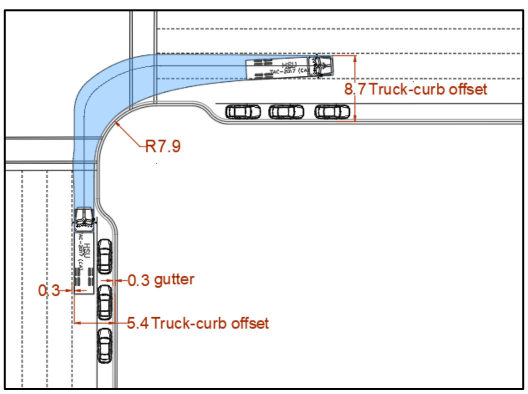
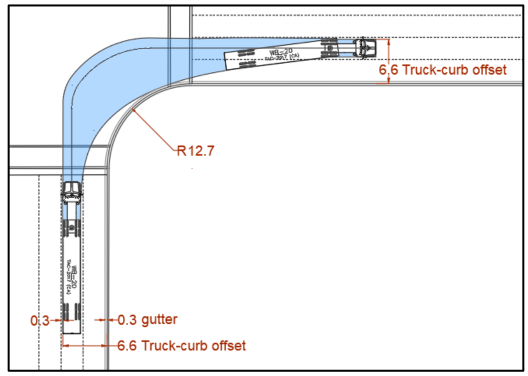


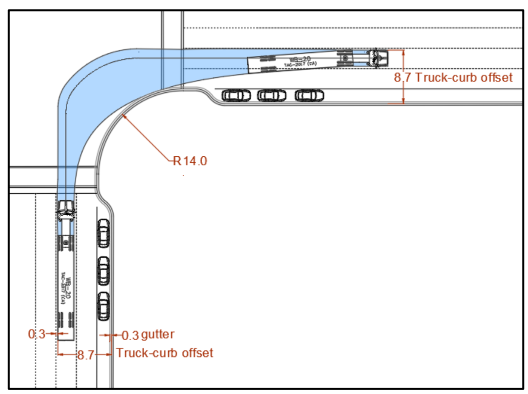
Intersection with Curb Bulbouts

N.A. (low walkability)

Note: All measurements are in metres
Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

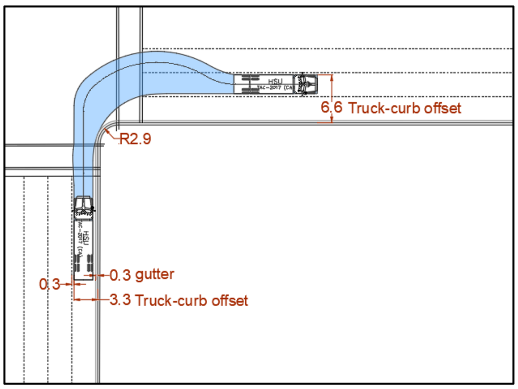
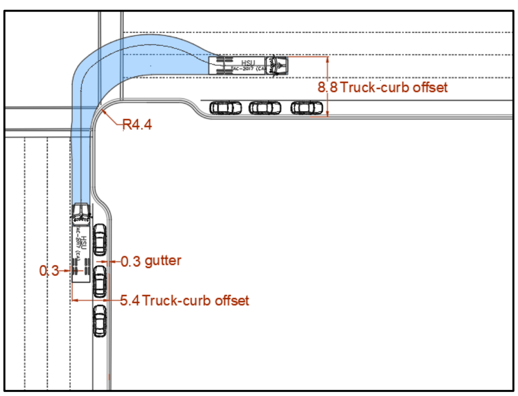
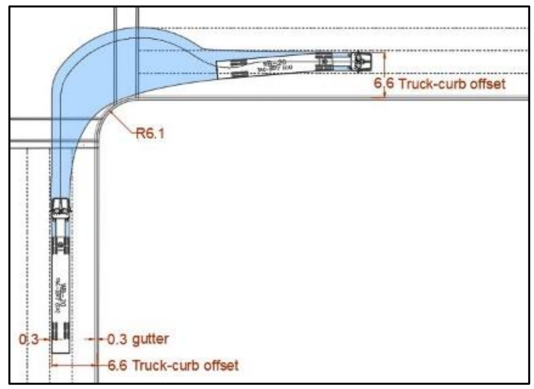
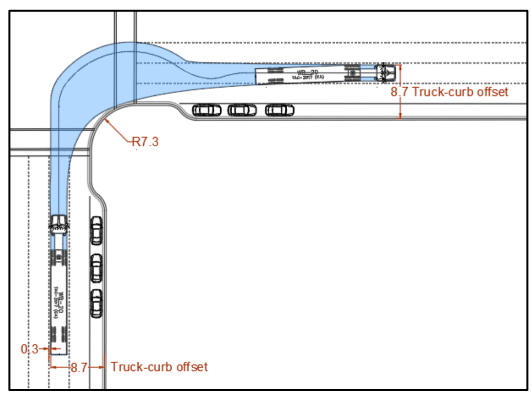
<table>
<tr><th></th><th colspan="3">Design Vehicle</th><th colspan="3">Accommodated Vehicle</th></tr>
<tr><th>Context Zone</th><th>Type</th><th>Turning Configuration</th><th>Maneuver Type</th><th>Type</th><th>Turning Configuration</th><th>Maneuver Type</th></tr>
<tr><td>5</td><td>HSU</td><td>Approach leg:
Curb lane
Receiving leg:
Up to 2 lanes</td><td>No Oversteer</td><td>WB20</td><td>Approach leg:
2nd lane
Receiving leg:
Up to 2 lanes</td><td>No Oversteer</td></tr>
<tr><td>Freight Activity: Truck Friendly
Walkability: Pedestrian Friendly</td><td colspan="3">Standard Intersection


Intersection with Curb Bulbouts

</td><td colspan="3">Standard Intersection


Intersection with Curb Bulbouts

</td></tr>
</table>

Note: All measurements are in metres

Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

	Design Vehicle			Accommodated Vehicle		
Context Zone	**Type**	**Turning Configuration**	**Maneuver Type**	**Type**	**Turning Configuration**	**Maneuver Type**
6	HSU	<u>Approach leg:</u> Curb lane <u>Receiving leg:</u> Up to 2 lanes	With Oversteer	WB20	<u>Approach leg:</u> 2^{nd} lane <u>Receiving leg:</u> Up to 2 lanes	With Oversteer
Freight Activity: Truck Friendly Walkability: Pedestrian Preferential	*Standard Intersection*  *Intersection with Curb Bulbouts*  			*Standard Intersection*  *Intersection with Curb Bulbouts*  		

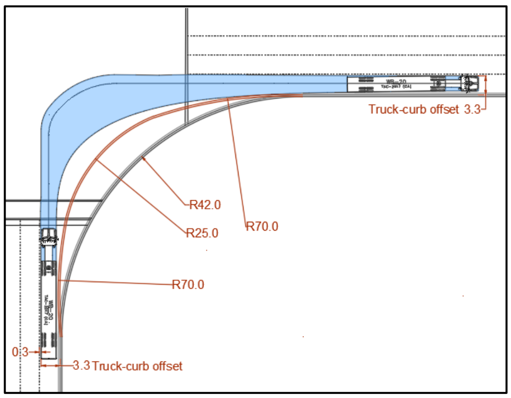
Note: All measurements are in metres
Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

	Design Vehicle			Accommodated Vehicle		
Context Zone	**Type**	**Turning Configuration**	**Maneuver Type**	**Type**	**Turning Configuration**	**Maneuver Type**
7	WB20	Approach leg: Curb lane Receiving leg: Curb lane	No Oversteer	N.A.	N.A.	N.A.

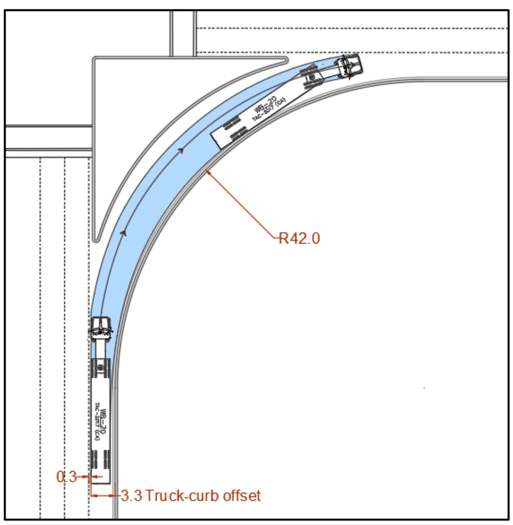
Freight Activity: Truck Preferential

Walkability: No Pedestrian Inclusion

Standard Intersection
(single curve or compound curve)



Standard Intersection
(with pedestrian refuge)



Intersection with Curb Bulbouts

N.A. (low walkability)

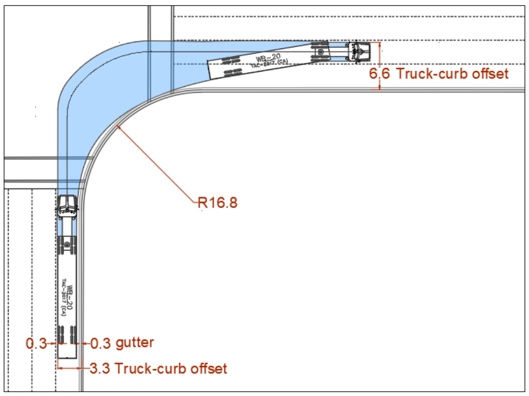
Note: All measurements are in metres
Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

	Design Vehicle			Accommodated Vehicle		
Context Zone	**Type**	**Turning Configuration**	**Maneuver Type**	**Type**	**Turning Configuration**	**Maneuver Type**
8	WB20	Approach leg: Curb lane Receiving leg: Up to 2 lanes	No Oversteer	N.A.	N.A.	N.A.

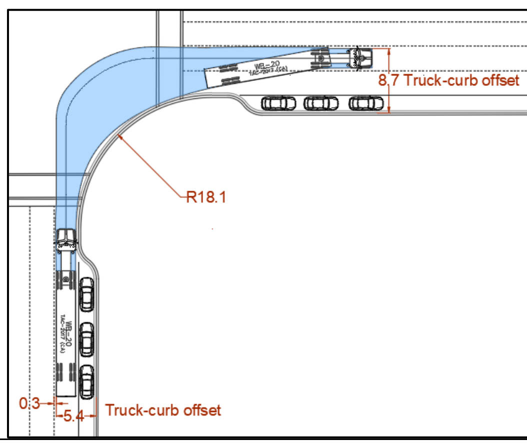
Freight Activity: Truck Preferential

Walkability: Pedestrian Friendly

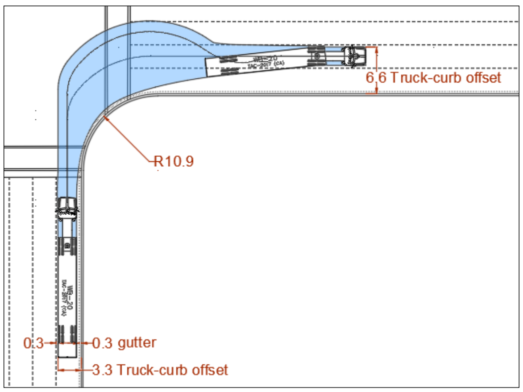
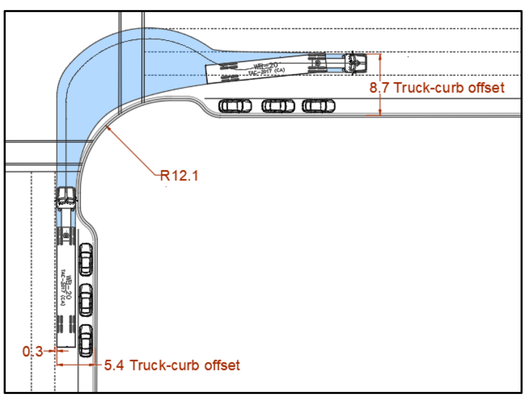
Standard Intersection
(Smart Channel is possible)



Intersection with Curb Bulbouts



Note: All measurements are in metres
Note: The diagrams show intersection design examples with 3.3 metre travel lanes and 2.4 metre curb bulbout/extension widths

	Design Vehicle			Accommodated Vehicle		
Context Zone	**Type**	**Turning Configuration**	**Maneuver Type**	**Type**	**Turning Configuration**	**Maneuver Type**
9	WB20	Approach leg: Curb lane Receiving leg: Up to 2 lanes	With Oversteer	N.A.	N.A.	N.A.
Freight Activity: Truck Preferential Walkability: Pedestrian Preferential	*Standard Intersection*  *Intersection with Curb Bulbouts* 					

Note: All measurements are in metres
Note: The diagrams show intersection design examples with 3.3 metre travel lane and 2.4 metre curb bulbout/extension widths

Figure 40 shows examples of the minimum single curb radius in different Freight-Walkability context zones required by the decision support tool. The figure illustrates minimum radii for standard intersections (with 3.3m lanes) and intersections with a buffered bike lane on both the approach and receiving lanes (with 3.3.m lanes).

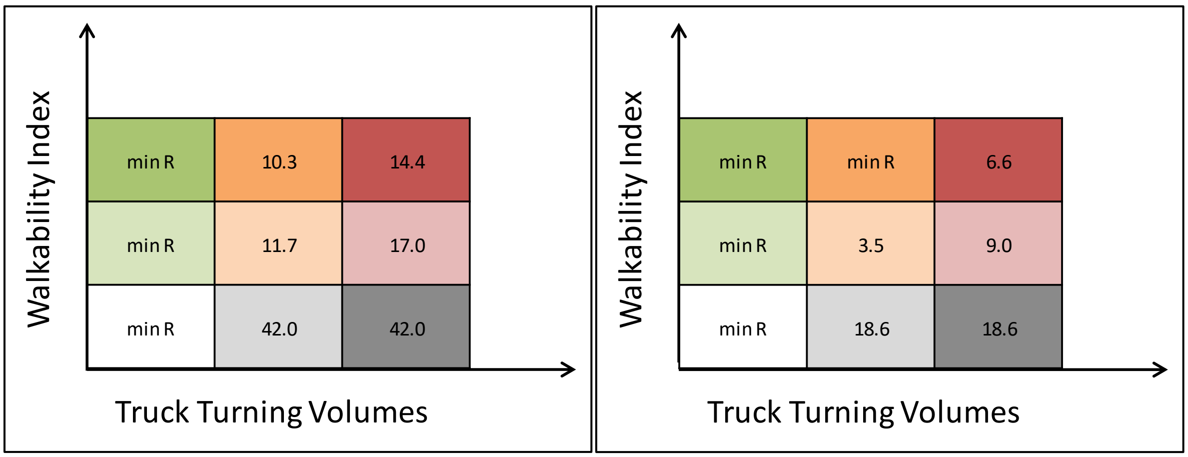


Figure 40: Minimum Curb Radius Required at a Standard Intersection (left) and an Intersection with Bike Lanes (right)

The TAC Geometric Design Guide (2017) recommends using a compound curve in cases where a tractor-semitrailer is required to make a right turn into the receiving curb lane as this would result in a large circular curb radius of 42 metres. A compound curve (two centred or three centred) follows the inside sweep of the tractor-semitrailer, thus reducing the amount of unused roadway space provided for vehicles at the intersection. The analysis in this research allowed the curb-to-curb lane right turn of a tractor-semitrailer in context zones 4 and 7, where there is moderate to high freight activity and low walkability. The City of Toronto Curb Radii Guideline (2017) recommends using a compound curve when a curb radius greater than 15m is required. Table 21 shows compound curve schematics for context zones 4 and 7 to emphasize these curves as an option for these context zones.

Right-turn channelization can be implemented where there is high vehicular right-turn activity and pedestrian refuge islands are used to reduce crossing distances. Channelization with pedestrian refuge islands can be considered in context zones 4 and 7 if pedestrian crossings are permitted, as shown in Table 21. However, channelization with traditional compound curves (e.g., 50m-25m-50m compound curb radii) is not recommended in areas with high pedestrian activity as it allows vehicles to maneuver a right-turn at higher speeds, which may pose safety hazards for crossing pedestrians (Suderman & Redmond, 2015).

Smart channel configurations are an emerging design strategy used in urban areas where there are both high vehicular and pedestrian activity. Smart channels create a discontinuous turning geometry that increases the angle of departure into the receiving roadway in order to force the turning vehicle to slow down to a yield or a full stop, while reducing the angle of entry into the smart channel to provide a better view of pedestrians. A typical smart channel geometry used in Winnipeg is a 60 m to 15 m radius compound curve joined by a tangent curb. This requires a tractor-semitrailer to occupy the entire receiving roadway space (Suderman & Redmond, 2015).

Context zones 1, 2, and 3 have low freight activity with varying walkability levels. Since these context zones do not require the accommodation of freight vehicles, the minimum curb radius can be selected. For example, the minimum curb radius set by the City of Toronto (2017) is four metres, whereas Complete Streets guidelines commonly recommend a minimum curb radius of three metres. Table 21 shows intersection design options when designing for a light single unit truck (which is a van-type delivery vehicle). It is evident that a minimum curb radius of 5.5m is required for a standard intersection and 9.2m for a curb bulbout, thus the minimum curb radius of four metres can be restrictive for an LSU. However, an LSU can be accommodated at both intersection types with the minimum radius of four metres with slight encroachment on an additional lane and/or possible encroachment into the 0.3m curb buffer.

Jurisdictions provide different guidelines on maximum allowable curb radii, thus the curb radii graphs and schematics presented in this research provide an initial step for designers to determine the curb radius required to accommodate a truck-turn in a certain context zone. If the curb radius required to accommodate a truck movement is larger than their jurisdiction's limit, the designer can choose to modify the street design elements or truck maneuver configuration.

5.4. Application of the Freight-Walkability Decision Support Tool for Curb Radii Design to Winnipeg

This research applies the decision support tool in Winnipeg, Manitoba. The application of the tool is context-sensitive, meaning that users may define different maximum values, minimum values, and break points for the two axes of the Freight-Walkability relationship (i.e., truck-turning volume and Walkability Index when using the relationship to select a curb radius).

For the purpose of selecting an appropriate curb radius, the amount of freight activity was measured by the peak hour truck right-turning volumes at an intersection. The City of Winnipeg provided all intersection traffic counts available for the most recent five year period from 2014 to 2018. Peak hour right-turning heavy-vehicle volumes (i.e., combination vehicles) were obtained for each leg at 640 intersections. Peak hour turning volumes were estimated from the maximum volumes obtained from four consecutive 15-minute count intervals. Of the three or four intersection legs, the maximum peak hour truck turning volume was selected as representative of truck turning volumes at that intersection.

Figure 41 shows the distribution of the right-turn peak hour volumes for the heavy vehicle classification, which represents combination vehicles, most commonly the tractor-semitrailer. The peak hour truck turning volumes are shown in five natural break categories, obtained from ArcGIS. The natural break categories provide the best representation of the data distribution as they are obtained from a cluster analysis to provide categories with the most variance between data groups and the least variance within each data group. Categorizing the data through a cluster analysis (i.e., natural breaks) allows jurisdictions to replicate this process to their freight context and data; thus the freight activity scale can vary between jurisdictions. However, since natural breaks are data-specific, the results cannot be compared between jurisdictions.

Figure 41 shows that the majority (69 percent) of the analyzed intersections have low peak hour truck turning volumes of zero to two trucks, followed by 21 percent of intersections seeing three to eight trucks completing a right-turn during the peak hour. Approximately 10 percent of intersections have peak hour truck turning volumes of nine trucks or greater. Freight activity in the Freight-Walkability matrix is categorized into the three aforementioned categories.

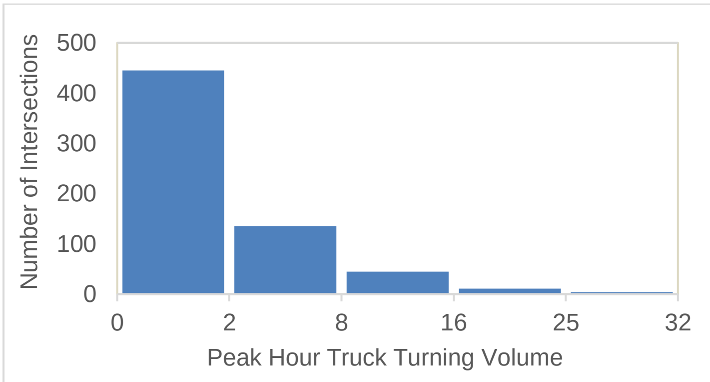


Figure 41: Peak-Hour Heavy-Vehicle (i.e., Truck) Turning Volumes for Winnipeg Intersections (2014-2018)

Similar to the freight activity scale, the Walkability Indices for Winnipeg Census Tracts were categorized into three natural break categories. Figure 42 shows the Walkability Index distribution, with 22 percent of Census Tracts measuring walkability levels well-below the average of zero (between -4.18 and -1.37), 44 percent measuring around average (between -1.37 and 0.8), and 34 percent measuring well-above average (between 0.8 and 5.69).

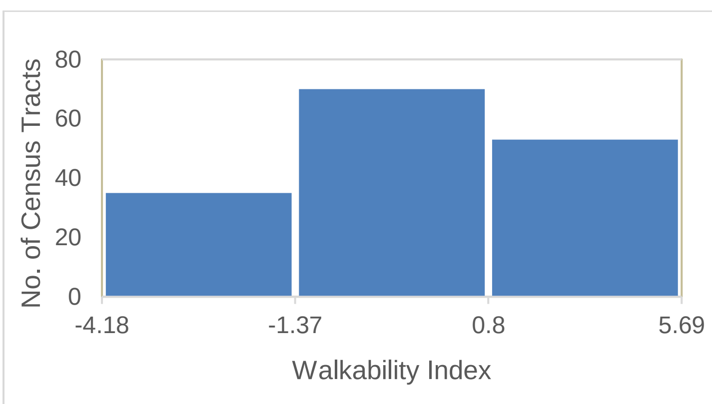


Figure 42: The Winnipeg Census Tract Walkability Indices

Figure 43 shows the overlap of the Census Tract Walkability Indices and intersection peak hour truck turning volumes for Winnipeg. The combination of the two data sets with natural break categories determines an intersection's context zone.

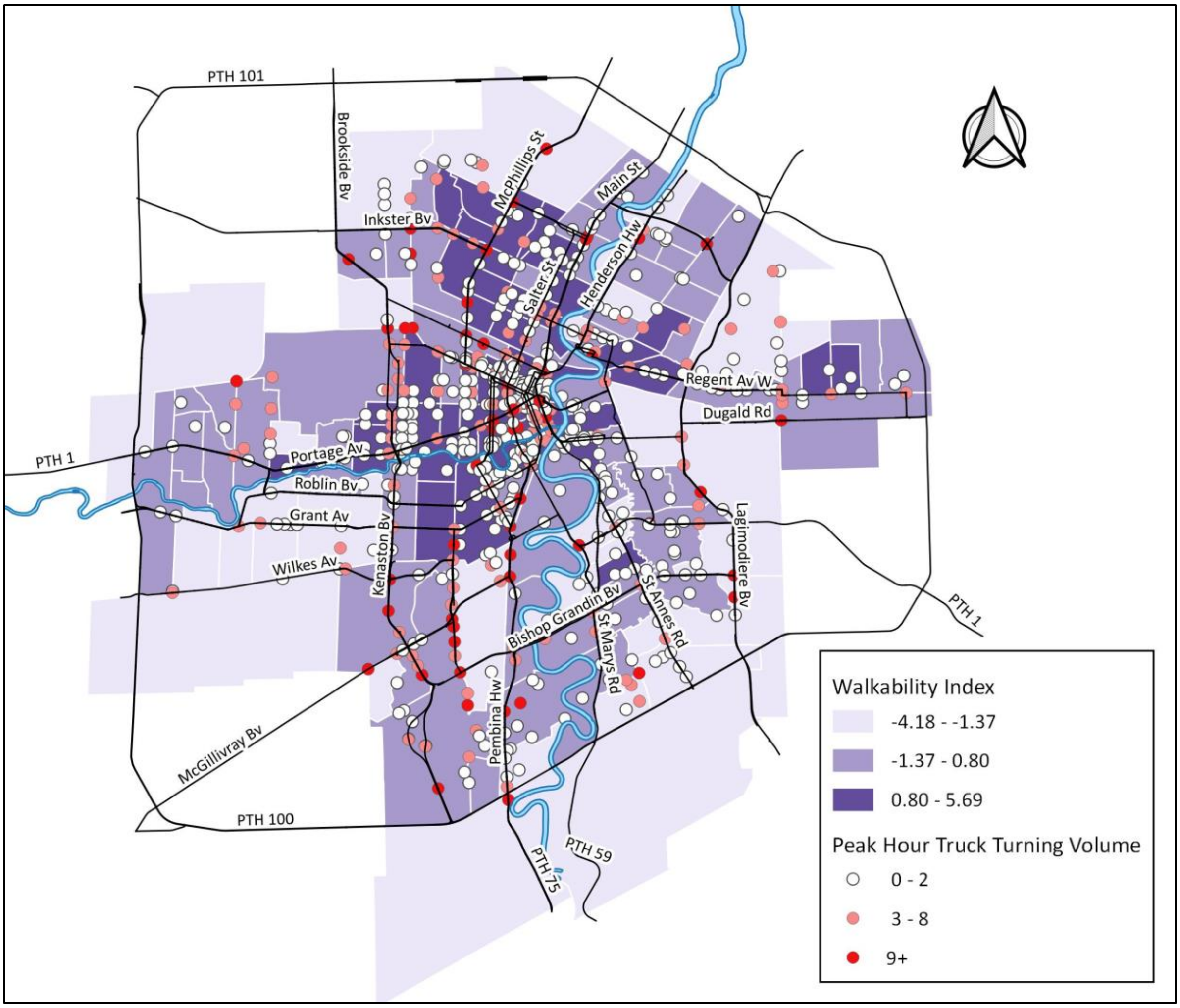


Figure 43: The Census Tract Walkability Indices and Intersection Peak Hour Truck Turning Volumes for Winnipeg

Figure 44 shows the Freight-Walkability relationship with the freight activity and walkability scales conforming to the Winnipeg land use, transportation system and truck activity contexts. Complying with this relationship, each of the 640 analyzed intersections were categorized into one Freight-Walkability context zone, shown in Figure 45. Intersection points that were on Census Tract boundaries were manually adjusted to be associated with the Census Tract with the higher Walkability Index.

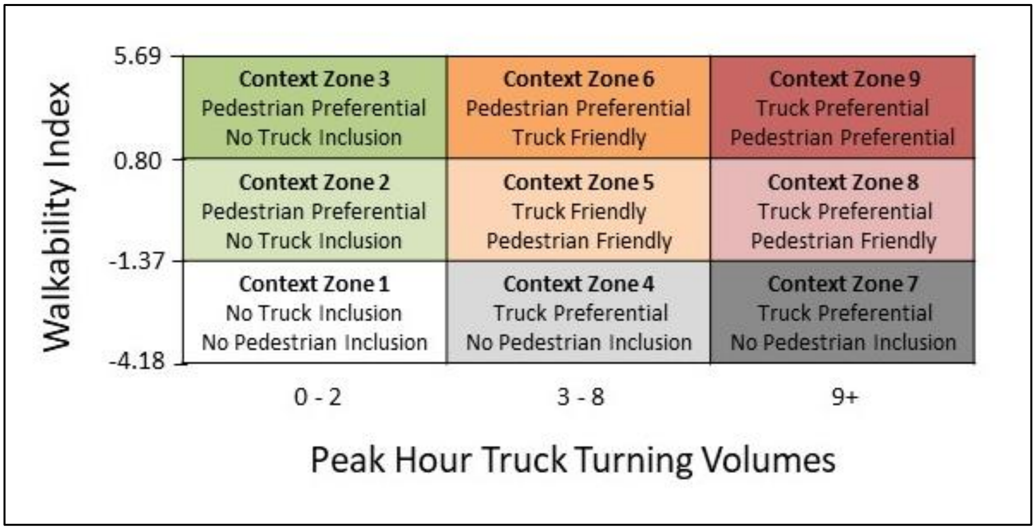


Figure 44: Freight-Walkability Matrix for Winnipeg

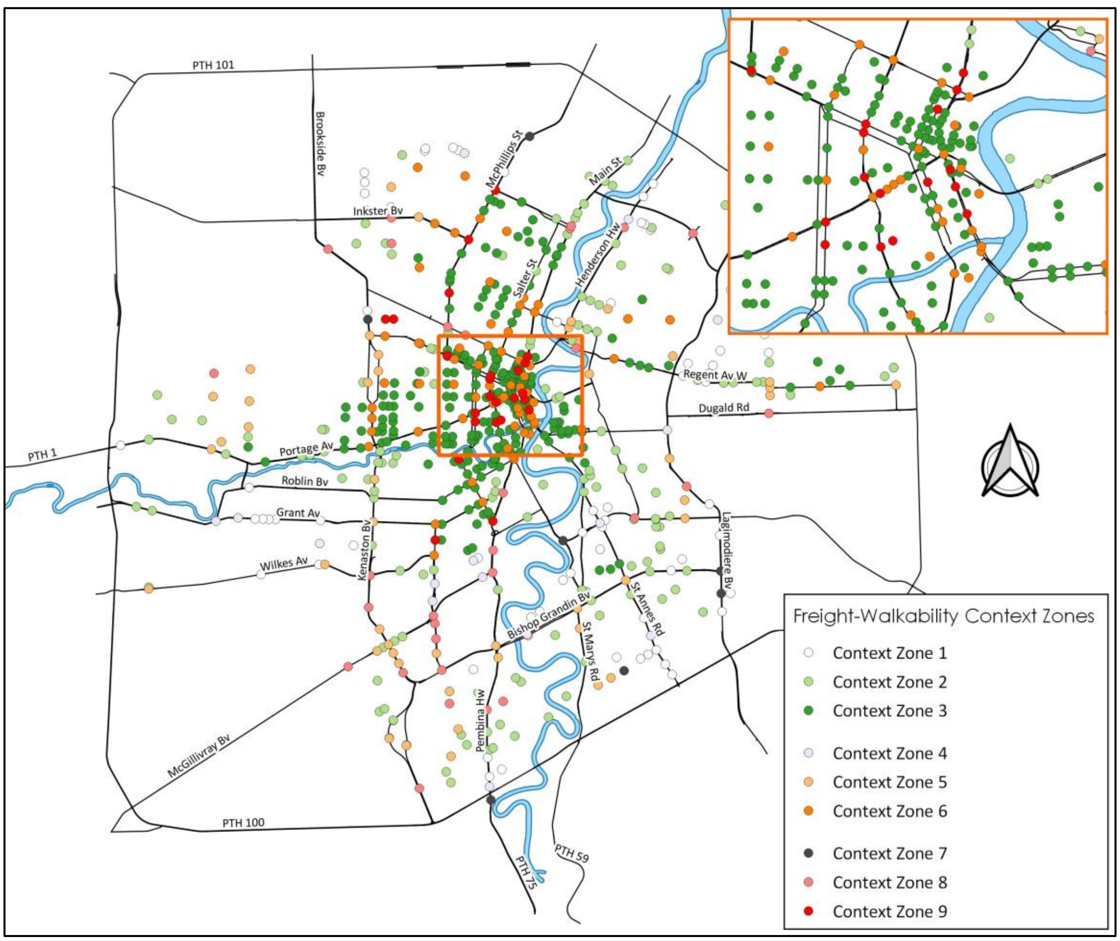


Figure 45: Freight-Walkability Context Zones for Winnipeg Intersections

Table 22 shows the number of Winnipeg intersections within each Freight-Walkability context zone.

Table 22: Number of Winnipeg Intersections in Each Context Zone

Context Zones	Number of Intersections	% of Total
1	66	10.3
2	141	22.0
3	238	37.2
4	23	3.6
5	48	7.5
6	64	10.0
7	7	1.1
8	29	4.5
9	24	3.8
Total	**640**	**100**

The results of applying the Freight-Walkability relationship to Winnipeg intersections are summarized:

- The greatest number of intersections (238 out of 640 intersections) fall within context zone three, which is identified as having high walkability and low truck turning movement, followed by context zones one and two at 10.3 and 22.0 percent respectively.
- It is evident by the location of the intersection counts that most of them were conducted in more central areas of the city and few counts were conducted in the outskirts where there are lower walkability and higher freight activity. This may influence the distribution of intersections by context zone.
- Intersections in context zone one that have low truck turning activity and low walkability comprise 10.3 percent of the intersections. These intersections are typically in highly residential areas with no land use diversity that see minimal large truck activity, or areas

with higher truck activity where truck-turning operations are limited to a main intersection in the area.

- Context zone nine, which is the most diverse area with high truck turning volumes and walkability, accounts for approximately four percent of the analyzed intersections. These intersections are mainly in the city centre, which comprises the most multimodal network and mixed-use area.
- The diverse intersections with high walkability and moderate to high truck turning activity (i.e., context zones 6 and 9) mainly occur along Portage Ave, Notre Dame Ave and Main Street.
- In the city centre, a diverse intersection (context zone nine) can be found next to a highly walkable intersection with no truck activity (context zone three), as trucks are routed through specific intersections or only able to turn at certain one-way streets. Similarly, intersections on the opposite spectrum of the truck activity context zone scales can be found next to one another elsewhere in the city. A context zone seven intersection could be found next to a context zone one intersection due the truck routes guiding the truck activity through specific major routes.

The results of the identified intersection Freight-Walkability context zones can be used to guide the selection or check the compliance of the curb radius designs of intersections, following the developed decision support tool. The resulting context zones could also guide operational restrictions or modifications in the truck route network dependent on the desired Freight-Walkability relationship of an intersection.

5.5. Limitations of the Decision Support Tool

The limitations of the decision support tool developed in this research follow:

- To limit the scope of the research, the decision support tool provides guidance on curb radius design based on the interaction between trucks and pedestrians, not considering other modes such as transit and bicycles. Although standard intercity buses are accommodated at intersections that accommodate heavy single unit trucks (HSU), transit vehicles operate in different contexts than freight vehicles, thus in order to apply the decision support tool to transit vehicles, the characterization and quantification of the Freight-Walkability context zones should be modified to accommodate transit activity and operational contexts. This is specifically the case in context zone three, where high walkability and low freight activity suggest providing the minimum curb radius. However, in this context, the designer should ensure that transit maneuverability is accommodated in a high walkability area. The addition of bicycle lanes can benefit both truck and pedestrian curb radius needs, where the added truck-curb offset can both reduce the curb radius and provide more roadway space for a truck turning maneuver. However, the designer must ensure the possible encroachment of the truck on the bicycle lane in the receiving leg safely accommodates bicyclists.
- The walkability levels are measured based on infrastructure and land use; thus the tool can result in the prioritization of trucks in areas with poor pedestrian infrastructure, regardless of the level of pedestrian activity. Consequently, judgment should be used in selecting the appropriate context zone based on existing conditions or desired conditions. Curb radius design is not conducted in isolation of other intersection and street design elements. For example, an area with a low Walkability Index that is observed to have higher pedestrian activity or demand, would require improvements to its pedestrian infrastructure to reach a desired context zone prior to selecting a curb radius.

- The truck turning volumes for Winnipeg intersections were determined by the maximum truck turning volumes from the intersection legs. In reality, each intersection leg could be designed for its truck turning activity so each curb at an intersection could incorporate a different design and curb radius.

6. CONCLUSIONS

This chapter summarizes the key findings from this research and provides recommendations for future research.

6.1. Key Findings and Contributions

The results from this research contributes new knowledge concerning the challenges of simultaneously accommodating trucks and pedestrians at urban intersections. As urban areas progress towards context-sensitive consideration of the needs of all users, the research offers a timely addition to existing guidance available to urban designers. This section summarizes key findings and contributions regarding: (1) truck-pedestrian collisions in Canada; (2) the design and development of a new Walkability Index; and (3) the development and application of a decision support tool to facilitate the design of intersection curb radii.

6.1.1. Truck-Pedestrian Collision Analysis

The collision analysis conducted in this research provides an overall depiction of truck-pedestrian collision characteristics in Canadian urban centres to understand the safety implications of the interaction of the two modes and the need to plan and design the urban form to accommodate both modes. The collision analysis revealed that an average of 337 collisions occur per year between trucks and pedestrians in Canadian urban centres and these collisions are more likely to result in a pedestrian fatality than collisions that do not involve trucks. The majority of trucks involved in pedestrian collisions were single unit trucks (84 percent), followed by truck tractors (i.e., tractor-semitrailers combinations). Although truck tractors accounted for a lower number of trucks in collisions with pedestrians relative to single unit trucks, they accounted for a higher proportion of fatal collisions, with 14 percent of collisions resulting in a fatality compared to five percent.

The analysis found that the majority of collisions between trucks and pedestrians occur at urban intersections. Left and right turns are the most common truck maneuver at intersection collisions with pedestrians, with right turns accounting for 30 percent and left turns accounting for 28 percent of collisions. The majority of pedestrians were involved in collisions with trucks while the pedestrian was crossing an intersection, while approximately 12 percent of all urban truck-pedestrian collisions and eight percent of collisions at urban intersections occurred while the pedestrian was on the sidewalk, median or safety zone, the result of a truck mounting the curb onto the sidewalk/median.

The findings from the collision analysis emphasize the safety risks associated with truck and pedestrian interactions at urban intersections, specifically involving right-turning trucks. Thus, the geometric design of intersections to adequately accommodate right-turning trucks and pedestrian crossings is essential.

6.1.2. Design and Development of a Walkability Index

This research describes the design and development of a novel Walkability Index based on both demand-based (i.e., planning-oriented) and supply-based (i.e., engineering-oriented) indicator variables. Studies show that both land use patterns and the physical design of the transportation system influence walkability. However, existing walkability indices in the literature and in practice principally depend on demand-related variables rather than infrastructure-related variables because of the planning orientation. By incorporating supply-based variables in the analysis, the Walkability Index developed in this research provides a more engineering-oriented perspective by relating the safety and connectivity of pedestrian infrastructure design to the level of walkability, in addition to the demand-related variable of accessibility.

The Walkability Index introduces a safety indicator to assess the adequacy of existing pedestrian crossing control treatments. This indicator has never been measured nor used as an indicator in a Walkability Index. To overcome this knowledge gap, this analysis developed a new metric to assess the adequacy of pedestrian crossing infrastructure by determining the compliance rate of existing pedestrian crossing control treatments in a Census Tract, according to the Transportation Association of Canada's Pedestrian Crossing Control Guide (TAC, 2018). Approximately 26 percent of crossing control treatments in Winnipeg were non-compliant and required a more enhanced crossing control treatment. However, since the majority of crossing control treatments were compliant, this metric mainly resulted in a reduction of the Walkability Index in areas with non-compliant crossings, while not significantly affecting areas with few or no pedestrian crossings or with many fully compliant pedestrian crossings.

Connectivity of the sidewalk network is the second engineering-related indicator used in the Walkability Index. Although connectivity is used as an indicator in a few existing Walkability Indices, it is typically measured by intersection density, which can overestimate the number of walkable intersections. This research measures connectivity by the amount of adequate sidewalk coverage relative to the roadway network, thus determining the percentage of roads with adequate sidewalks on one or both sides of the roadway. More than half (56 percent) of Winnipeg's roads have adequate sidewalks on at least one side of the road, while the other 44 percent have no sidewalks or have sidewalks with substandard widths. The central city areas have higher sidewalk coverage than the surrounding areas. These surrounding areas are mainly industrial zones or residential neighborhoods, which do not have sidewalk infrastructure.

Accessibility to daily services and destinations was the demand-based indicator of walkability included in the Walkability Index, measured by the residential density, proximity of residential areas to daily destinations, and proximity to transit stations within a reasonable walking distance. Although accessibility in terms of land use types is a commonly used indicator of walkability in existing walkability indices, this research provided different metrics to improve on the measure of accessibility performance measures. This research used a proximity to daily destinations metric to measure the level of land use diversity, instead of the commonly used Entropy Index, where the proximity measure is based on the presence of a variety of daily destination types within walking distance, while an Entropy Index is based on equal distribution of land use types, which can be misleading. In addition, although proximity to transit stops and adequate transit service has been identified as an influencer of walkability in the literature, it has not been incorporated into a walkability index. This research introduced a Transit Score into the Walkability Index, that provided a weighted score representing proximity of residents to transit stops with various bus headways (i.e., frequency of service).

By incorporating the two transportation system supply indicators into the analysis, the Walkability Index provides street-level variables that can be physically changed by engineers in the short-term to influence walkability levels. In contrast, planning-oriented measures such as land use, demographics, and economic activities provide planning-level inputs but do not necessarily lead to near-term actions. Finally, the quantification of walkability facilitates the subsequent development of one of the dimensions of the Freight-Walkability relationship, which underpins the curb radii decision support tool.

6.1.3. Development of a Freight-Walkability Decision Support Tool

Pedestrian-friendly design guidelines, specifically Complete Streets design guidelines, emphasize the integration of land use context within a street typology. The land use/street typology can guide the planning and design decisions to develop a street or area by considering the area's context and not solely the function of the roadway. However, few guidelines discuss truck accommodation other than in industrial areas, and the few that do, do not utilize their integrated land use/street typology to provide geometric street design guidance.

The few Complete Streets guides that consider trucks in curb radius design provide general ranges or prescriptive maximum curb radii values for areas with high truck activity, thus not considering the variations and diversity of land use and modal activity that can occur in various urban areas. To limit pedestrian crossing exposure, most Complete Street designs minimize the curb radius at an intersection, typically to a three-metre radius. Some guides additionally recommend a maximum radius of nine metres (30ft) or 12m (40ft) in locations with high large-truck activity or various ranges such as 4.6 to 12 metres (15-40ft).

In this research, a decision support tool is designed and developed to guide the design of urban intersection curb radii that facilitate the safe and efficient accommodation of trucks and pedestrians. The decision support tool applies the generic concept of the Freight-Walkability relationship introduced in this thesis. For the selection of intersection curb radius, the relationship is numerically characterized in terms of the Walkability Index and the truck turning volume at an intersection.

Conceptually, the decision support tool aligns with the analogous concepts of a design domain and performance-based geometric design by offering considerable flexibility for the designer. The designer can adjust the boundaries of the Freight-Walkability context zone to suit local conditions and can select values for four street design variables, namely: curb radius, approach leg offset, receiving leg offset or type of vehicle maneuver. Moreover, the designer may choose to adopt the methodology to select a curb radius suitable for the existing or desired Freight-Walkability context zone of an intersection, or may adjust the truck-curb offset in the approach or receiving legs (i.e., modify the intersection design elements) to allow the right-turn maneuver of a truck at a set curb radius. The designer can also verify the type of truck maneuver and turning configuration required at an existing intersection and determine whether it is suitable to the actual context of the area. In this case, the designer can choose to adjust the street design elements to allow a more suitable truck maneuver at the intersection or modify the area's context zone through changes in the urban form. An intersection's Freight-Walkability context zone can be modified by altering the level of walkability and/or freight activity at an intersection. The Freight-Walkability thresholds can also be refined to incorporate the jurisdiction's experienced freight and pedestrian activity. On a short-term basis, designers can make street-level changes such as the level of street connectivity or compliance of pedestrian crossing control treatments to improve the walkability levels of an area, or through regulatory restrictions on truck operations at an intersection (i.e., allowing or prohibiting the maneuver of a truck at an intersection) to alter amount of truck activity.

It was found that the typically recommended Complete Streets curb radius of 12m (40ft) for areas with truck activity facilitates the right-turn maneuver of a tractor-semitrailer at a standard intersection from the curb lane if it is oversteering and occupying multiple receiving lanes. This turning configuration is suitable for areas with both high freight and pedestrian activity. However, areas where trucks are the modal priority but with some level of pedestrian activity require larger curb radii to allow the maneuver of a truck with fewer constraints (e.g., enabling the truck to turn from the approach curb lane to the second receiving lane). In contrast, at locations where pedestrians are the modal priority but which have moderate truck activity, a reduced curb radii would be more suitable to accommodate the truck turning maneuver while ensuring pedestrians have a reduced crossing distance. For example, the vehicle can complete the turn starting from the second approach lane and occupy multiple receiving lanes with oversteering. Adding bicycle lanes or parking lanes would reduce the required curb radius in both scenarios.

It was found that the recommended Complete Streets curb radius of three metres (10ft) is appropriate in areas with pedestrian priority and no large-truck activity. However, a three-metre curb radius still requires a light single unit vehicle (i.e., van type delivery vehicle) to maneuver with a slight oversteer when completing a curb to curb right-turn at a standard intersection, whereas a 5.5m radius is required to allow the delivery truck to make a right-turn with no constraints. Since transit operation is common in walkable neighborhoods, this radius would be too restrictive for a transit bus to maneuver the right-turn with no constraints. However, walkable areas typically have bicycle lanes and on-street parking which would increase the truck-curb offsets, thus allowing the curb radius to be reduced and facilitating right-turning trucks.

In this research, the decision support tool (and the underlying Freight-Walkability relationship) was applied to the Winnipeg, Manitoba context, using local data to quantify the two dimensions of the Freight-Walkability relationship. Specifically, the analysis estimated the Walkability Index for each Census Tract in Winnipeg and quantified peak hour right-turning truck volumes at 640 intersections in Winnipeg. Cluster analyses revealed natural breaks in the data, which effectively calibrated the Freight-Walkability relationship to the Winnipeg context. This approach demonstrates the transferability of the tool (and the underlying Freight-Walkability relationship) to other urban contexts. While transferability is desirable, cross-jurisdictional comparisons may require the definition of absolute thresholds for the two dimensions of the relationship. Regardless of the type of application, the curb radii design domains recommended in the research remain valid.

6.2. Limitations and Recommendations for Future Research

The decision support tool and the measurement of the Freight-Walkability relationship are subject to limitations that should be considered during implementation. Firstly, the Walkability Index used in the measurement of the Freight-Walkability relationship is a relative measure; thus, improvements in one area can reduce the walkability levels in another untouched area. Notably, the Index is used as a prioritization tool within a jurisdiction and not as an absolute measure of walkability. Therefore, the Walkability Indices cannot be compared between jurisdictions.

Secondly, selecting the appropriate context zone is a critical first step in making a performance-based design decision using the developed tool. The context zone can be selected based on existing conditions; however, judgement should be used in ensuring that the measured context zone is representative of the area. Since walkability is measured based on infrastructure and land use characteristics rather than pedestrian activity or demand, areas with poor infrastructure but high pedestrian demand may require an upgrade of the pedestrian infrastructure to improve walkability levels to achieve a more appropriate context zone prior to following the remaining steps in the decision support tool for curb radius selection. Alternatively, desired context zones can be selected based on an understanding of the area's pedestrian activity or community goals; thus measurement of the Freight-Walkability relationship is not required.

In this research, the following future research needs were identified:

- Future research should evaluate other engineering-related walkability indicators and their influence on walkability and a composite Walkability Index. This research introduced the pedestrian crossing control compliance metric as an initial step to providing a transportation supply-based variable into walkability measurements. A correlation analysis revealed a negative relationship between this metric and the percentage of walking and transit commuter trips in a Census Tract. This result may arise because crossing control compliance need not stimulate an increase in pedestrian activity, even if it reduces exposure risk. Future research should consider additional safety indicators or surrogates and integrate them into the Walkability Index, as appropriate.
- Future research should evaluate the impact of modifying vehicle dimensions and configurations to reduce the effective curb radii and the potential consequences on operations and vehicle dynamic performance (e.g., by increasing the kingpin setback or implementing cab-over tractors). Modified vehicle configurations can be incorporated into the decision support tool and the associated curb radii selection graphs.
- Future research should develop an index of freight activity (or "freightability"), analogous to the Walkability Index, to measure urban form characteristics that promote (or constrain) freight activity in an area. In this research, peak-hour truck turning volumes were used to

measure freight activity, which was suitable for curb radius selection. However, a "freightability" scale would allow the Freight-Walkability relationship to be applied to the planning and design of other urban form features.

- To better understand the results of this research, future work should involve a field-based audit of randomly selected Census Tracts to more fully characterize the physical and land use features commonly present in each of the nine context zones defined within the Freight-Walkability relationship.

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