Analysis of Transit Bus Weight Characteristics in the Canadian Prairie Region

by

TYLER ROSS GEORGE

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Department of Civil Engineering
University of Manitoba
Winnipeg, Manitoba

ABSTRACT

Within the transit industry it is well known that transit buses have the potential to operate at weights that exceed vehicle weight limits [1]. However, few attempts have been made to date to determine how often this occurs and to what degree. Stakeholders with a vested interest in transit bus weights include infrastructure providers, policy makers, bus manufacturers, enforcement agencies, and transit agencies.

This research begins by characterizing the current transit industry with respect to the regulatory environment, factors that have affected the weight of modern day transit buses, and methods for accommodating transit buses in pavement design. This research then develops and applies a methodology for calculating the in-service weights of standard 40-ft. transit buses using a combination of passenger characteristic data, transit bus curb weight data, and transit ridership data.

The findings of this research suggest that the transit bus industry is in a state of competing interests. Weight estimates developed in this research identify that current transit bus models are unable to comply with vehicle weight limits in most jurisdictions even with no passengers on board. Further, these estimates indicate that transit buses have a significant impact on pavements – comparable to those of fully-loaded, five-axle semi-trucks on a per vehicle basis. To date this issue has been addressed in the Canadian Prairie Region by indefinitely granting transit buses overweight permits. However, based on the current state of the transit industry there is little incentive for transit agencies to operate lightweight transit buses and little incentive for transit bus manufacturers to produce lightweight transit buses in order to address pavement and regulatory concerns. Consequently, transit bus axle weight issues in the Canadian Prairie Region are expected to continue in the foreseeable future.

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1 INTRODUCTION

1.1 PURPOSE

This research develops and applies a methodology for calculating the in-service weight of a standard 40-ft. transit bus using a combination of passenger characteristic data, transit bus curb weight data, and transit ridership data. Further, this research identifies the limitations of data sources commonly used for estimating in-service transit bus weights and describes a method to estimate the proportion of transit bus operations, in terms of vehicle-kilometres travelled (VKT), that occur at and above various weights. The results of this thesis are presented and discussed in terms of gross vehicle weight, steer axle weight, drive axle weight, and equivalent single axle loads (ESALs).

1.2 BACKGROUND AND NEED

In the transit industry it is well known that transit buses have the potential to operate at weights that exceed vehicle weight limits [1]. To date, few attempts have been made to determine how often this occurs and to what degree. In lieu of directly measuring the weight of in-service transit buses, researchers looking to address this issue must develop estimates based on available data from sources such as bus manufacturers, transit agencies, manual studies, and previous research. However, even with access to data from these sources, estimating the weight of an in-service transit bus can be a difficult task due to the numerous elements that influence transit bus weights. The weights of in-service transit buses are affected by factors such as bus type, modifications to transit bus design, fluctuations in passenger loading, and trends in the characteristics of transit passengers [2]. As such, estimates of in-service transit bus weights are often reliant on many assumptions, which, over time, become out-dated and no longer accurately reflect the current state of the transit industry.

The weight of in-service transit buses is a complex, multidisciplinary issue. Stakeholders with a vested interest in transit bus weights include infrastructure providers, policy makers, bus manufacturers, enforcement agencies, and transit agencies. These organizations operate on separate budgets, have different goals, and are subject to different sets of constraints. Further, each of these stakeholders has the ability to influence in-service transit bus weights and have different needs for transit bus weight data.

1.2.1 Infrastructure Providers

Transit buses are a major component of many cities' mass transportation systems and play an integral role in reducing congestion, reducing vehicle emissions, and providing affordable and accessible transportation to the public. Conversely, there are also many costs associated with providing transit service, including operating expenses, capital costs for new vehicles and infrastructure, and pavement lifecycle costs. Although transit buses are known to be a significant source of pavement damage based on equivalent single axle loads (ESALs), the pavement impacts of transit buses are not well quantified [3]. Qualitative evidence, such as shown in Figure 1, supports this claim.

Figure 1: Examples of Transit Bus-Related Pavement Damage

With sound pavement design and maintenance practices the pavement impacts of heavy vehicles, such as transit buses, can be managed [4]. Developing these practices is reliant on accurate estimates of expected traffic volumes and weights. Therefore, from the perspective of an infrastructure provider the primary benefit of researching in-service transit bus weights is the potential to improve pavement design and maintenance practices, which can reduce delays related to road rehabilitation and decrease pavement lifecycle costs.

1.2.2 Policy Makers

Agencies responsible for constructing and maintaining urban infrastructure rely on vehicle weight limits to protect road networks. Such limits are established by policy makers. Establishing vehicle weight limits can be a complicated task – limits that are set too low can disadvantage private industries and stifle economic activity, whereas limits set too high can lead to excessive pavement damage. Subsequently, knowledge of in-service transit bus weights can be used to help establish vehicle weight limits for transit buses that are reasonable to infrastructure providers, transit agencies, and the bus manufacturing industry [4]. Transit bus weight data can also be used by policy makers to resolve legal issues in jurisdictions where transit buses are known to exceed vehicle weight limits by helping to answer questions such as:

- Which vehicle weight limits pose compliance issues for transit buses?
- If transit buses are found to regularly operate overweight, what should be done to resolve this issue?
- Should publicly-operated transit buses have the same weight limits as other vehicles, such as privately owned buses, RVs, or trucks?

1.2.3 Transit Bus Manufacturers

The weight of in-service transit buses is largely dependent on transit bus design. Transit bus design is influenced by many factors, including material costs, requests from transit agencies, vehicle weight limits, and non-weight-related regulations, such as emissions restrictions and accessibility requirements [5]. Over the past few decades this has led to a situation in which transit bus weights have increased due to the addition of components that are needed to meet industry demands, without any increase to vehicle weight limits. As such, many transit bus manufacturers have difficulty designing buses that satisfy the needs of the transit industry, are affordable, and can comply with vehicle weight limits when loaded to capacity [5]. Knowledge of in-service transit bus weights can be a useful tool for transit bus manufacturers to make a case for the need to reform transit bus vehicle weight limits.

Another benefit of in-service transit bus weight data for transit bus manufacturers is the potential to improve transit bus design. As will be discussed in Chapter 3, some of the current design standards in the bus industry are outdated, in particular the assumptions surrounding the characteristics of an average passenger. Therefore, transit bus design could be improved by correcting these assumptions and designing buses based on more accurate in-service weight estimates. In particular, in-service transit bus weight data has the potential to help identify parts that are overdesigned or identify parts that need to be more robust. Therefore, a possible application for this data would be for determining appropriate tire capacities or gross axle weight ratings.

1.2.4 Enforcement Agencies

Enforcement of vehicle weight limits plays a large role in protecting road networks from excessive pavement damage. Enforcement is important because, “without effective enforcement, including certainty of penalties and sanctions sufficient to deter violation, weight limit laws become meaningless” [6]. Within urban areas, enforcement of vehicle weight limits is typically the responsibility of the police. Currently, transit buses are rarely subject to vehicle weight enforcement. In the majority of circumstances this is because transit buses are either operating within the legal range of weights or because they are permitted to operate overweight. However, in instances where this is not the case, the absence of enforcement can be attributed to the lack of awareness regarding in-service transit bus weights and the spatial characteristics of transit operations relative to common points of enforcement [4]. Therefore, from the perspective of an enforcement agency, transit bus weight data can be valuable to assess the need for enforcement and help identify locations where noncompliance is an issue.

1.2.5 Transit Agencies

Although transit agencies have a significant influence on the weight of in-service transit buses, they are, for the most part, unaffected by changes in transit bus weights. Under the current regulatory environment in which transit buses operate and the organizational structure of municipal governments [2]:

- transit agencies are not responsible for maintaining the majority of pavements on which transit operations take place;
- transit buses are often exempt from vehicle weight limits or permitted to operate overweight; and
- transit agencies often have to work within constrained budgets and, in many circumstances, cannot recoup their operating expenses from service revenue.

Based on these factors, there is currently little incentive for transit agencies to purchase and operate lightweight buses (which can be significantly more expensive), monitor the weight of the buses they operate, or ensure that the buses they operate comply with vehicle weight limits. In fact, under these circumstances transit agencies are incentivized to operate heavier transit buses that provide opportunities to improve service, reduce operational costs, and/or reduce vehicular emissions. Consequently, transit agencies have little need for in-service transit bus weight data, other than to identify when, or if, there is a need to apply for overweight permits in cases when transit operations cross jurisdictional boundaries.

1.2.6 General Need

In ideal situations, in-service vehicle weight estimates are based on direct measurements of vehicles in operation. Such is the case for the trucking industry. In the Canadian Prairie Region trucks are routinely weighed by weigh-in-motion (WIM) devices and at static scales. These data can be used to create distributions of axle weights disaggregated by truck type which can be utilized in pavement design and aid in vehicle weight enforcement. No such data exists for transit buses. Further, collecting in-service weight data using WIM devices or at static scales is not as practical for transit buses as it is for trucks. Challenges of collecting in-service transit bus weight data with WIMs or at static scales include [4]:

(1) Transit bus weights vary with passenger load and can change significantly over the course of one trip. WIM devices and static scales are only able to capture the weight of the bus at one point; therefore, WIM-collected weight data would have to be analyzed in conjunction with ridership data to portray an accurate picture of network-wide in-service weights; and

(2) Weigh scales capable of collecting transit bus weight data are typically located on interprovincial or international routes, while transit operations primarily take place in urban areas. Subsequently, transit buses seldom operate in the vicinity of weigh scales and have limited opportunity to be weighed while in service.

(3) Weighing devices often require vehicles to slow down or come to a complete stop to obtain accurate readings. This would be an inconvenience for transit bus scheduling and for transit riders.

Since in-service transit bus weight data are not readily available, weight estimates for transit buses are typically derived by combining passenger weight estimates with known curb weights [3] [7] [8]. As will be described in this research, there are several limitations of these estimates, namely, obtaining accurate in-service curb weights of transit buses, determining a representative value for the weight of an average passenger (including clothes and carry-on items), and appropriately distributing the total passenger weight between the steer axle and drive axle of the bus. The methodology described in Chapter 3 attempts to address these limitations.

1.3 OBJECTIVES AND SCOPE

Specific objectives of this research are to:

- understand the regulatory environment in which transit buses operate across the Canadian Prairie Region;
- develop a methodology for estimating the gross vehicle weight and axle weights of in-service transit buses along an entire transit route;
- apply the developed methodology to estimate the weight of in-service transit buses, using Winnipeg Transit Route 160 in Winnipeg as a case study;
- compare in-service weight estimates of transit buses to gross vehicle weight limits and axle weight limits in the Canadian Prairie Region; and
- discuss the lessons learned from the case study and the implications of the research findings.

Ultimately, the goal of this research is to increase understanding about transit bus weights in relation to their regulatory environment and the impact they have on urban infrastructure. To achieve this goal this research develops and applies a methodology to estimate the in-service weight of 2-axle 40-ft. transit buses (i.e., standard transit buses).

Over-the-road coaches, trolley buses, shuttle/cutaway buses, and school buses, such as those shown in Table 1, are not addressed in this research.

Table 1: Types of Buses

Bus Type	Photo	Included?	Source
2-axle 40-ft. Transit Bus (Standard Transit Bus)		✓	[9]
Over-the-road Coach		✗	[10]
Trolley Bus		✗	[11]
Shuttle / Cutaway Bus		✗	[12]
School Bus		✗	[13]

Additionally, this research focusses on 2-axle 40-ft. transit buses, which make up the majority of most transit bus fleets [14] [15]. It does not address 2-axle 35-ft. transit buses, 2-axle 45-ft. transit buses, 3-axle 45-ft. transit buses, 3-axle 45-ft. double-deck transit buses, and 3-axle 60-ft. articulated transit buses. Table 2 displays an example of each these types of transit buses.

Table 2: Types of Transit Buses

Transit Bus Type	Photo	Included?	Source
2-axle 35-ft. Transit Bus		✗	[16]
2-axle 40-ft. Transit Bus (Standard Transit Bus)		✓	[17]
2-axle 45-ft. Transit Bus		✗	[17]
3-axle 45-ft. Transit Bus		✗	[18]
3-axle 45-ft. Double-deck Transit Bus		✗	[19]
3-axle 60-ft. Articulated Transit Bus		✗	[20]

One of the assumptions of this research is that transit buses behave as a static system. This research acknowledges that dynamic effects, such as wheel/road interactions, aerodynamics, load transfer effects from acceleration/deceleration, and suspension characteristics, can have a significant effect on vehicle-pavement interactions [21]; however, they are outside the scope of this study.

1.4 THESIS ORGANIZATION

This thesis is organized into five chapters. Chapter 2 describes the methodology used for the environmental scan component of this research and provides a summary of its findings. Specifically, this Chapter discusses the current regulatory environment for transit buses in the Canadian Prairie Region, factors that influence transit bus weights with respect to transit bus design, and pavement issues associated with transit buses. Information presented in Chapter 2 is intended to provide context for the subsequent chapters of this thesis.

Chapter 3 describes a methodology to estimate the in-service weight of transit buses and applies this methodology to estimate the weight of in-service transit buses operating along Winnipeg Transit Route 160 in Winnipeg, Manitoba. Further, this chapter identifies the limitations of current data sources commonly used for estimating the weight of in-service transit buses and attempts to address these limitations.

Chapter 4 describes the results of the in-service weight estimates for Route 160 transit buses operating in Winnipeg. The findings of this research are organized into five sections: (1) gross vehicle weight analysis; (2) steer axle weight analysis; (3) drive axle weight analysis; and (4) ESAL analysis; and (5) discussion of findings.

Chapter 5 provides concluding remarks, describes the key findings of this research, and proposes opportunities for future research.

1.5 TERMINOLOGY

The following terms are used throughout the thesis:

Axle weight: The total weight carried by a specific axle group. The axle weight includes the weight of the axle itself and the weight of the bus that the axle supports [4].

Axle split: The proportion of the gross vehicle weight that is carried by each axle, expressed as a ratio (% steer axle / % drive axle) [4].

Base passenger weight*: The weight of a passenger excluding the weight of clothes and carry-on items.

Basic weight limit*: A weight limit that applies year-round unless otherwise specified.

Canadian Prairie Region: A region of Canada comprising the provinces of Alberta, Saskatchewan, and Manitoba [22].

Carry-on item*: Any personal item that is brought onto the bus by a passenger and contributes to the gross vehicle weight of the bus.

Curb weight (CW): The gross vehicle weight of a bus with no passengers. It includes the weight of the driver and a full tank of fuel [4].

Drive axle*: A single axle that is used for propulsion. In the case of a standard transit bus the drive axle is equipped with four tires and is situated towards the rear of the bus.

Equivalent single axle load (ESAL): The pavement damage caused by one pass of an axle relative to the damage caused by one pass of a single 18,000 pound axle (i.e., an axle that has an ESAL of 3.0 causes three times the amount of pavement damage as an 18,000 pound axle) [23].

Fourth Power Rule: According to the fourth power rule in pavement design the ESAL of an axle with dual tires can be estimated with the following formula [24]:

$$ESAL \approx \left(\frac{Axle\ Weight\ in\ Pounds}{18{,}000}\right)^4.$$

Fully-loaded weight (FLW)*: The gross vehicle weight of a bus when loaded to its passenger capacity. The FLW of a bus is not a constant value because the weight of a full complement of passengers is not constant.

Gross axle weight rating (GAWR): The maximum weight that can be safely carried on an axle, as stated by the manufacturer [4].

Gross vehicle weight (GVW)*: The operating weight of a bus. The gross vehicle weight of a bus is variable because it includes the weight of passengers, the driver, fuel, and the bus itself. This definition of GVW was created for use in this thesis and differs from the way it is defined by some of the sources used in this research. For example, the Altoona Bus Research and Testing Center uses the term GVW to represent a theoretical maximum bus weight, which is calculated by adding 150 pounds per seat and per 1.5 $ft.^2$ of floor space to the curb weight of the bus [4]. The latter definition of gross vehicle weight is not used in this thesis.

Gross vehicle weight rating (GVWR): The sum of the gross axle weight ratings for all axles on a vehicle [4].

Laden passenger weight*: The weight of a passenger including the weight of his or her clothes and carry-on items.

Overweight bus*: A bus that exceeds any applicable weight limit in its jurisdiction, including gross vehicle weight limits, axle weight limits, tire restrictions, and gross axle weight ratings.

Passenger Capacity*: The passenger load at which a bus driver will stop accepting new passengers onto the bus because the bus is deemed to be full (at the discretion of the driver). This definition of passenger capacity was created for use in this thesis and differs from the way it is defined by some of the sources used in this research. For example, the Altoona Bus Research and Testing Center (Altoona) calculates the passenger capacity of each bus model by assuming one passenger per seat and one passenger per 1.5 ft.^{2} of floor space. The Altoona definition of passenger capacity is not used in this report because observations made during data collection and analysis of ridership data provided by Winnipeg Transit showed that bus drivers stop accepting new passengers onto the bus before reaching the passenger capacities stated in Altoona bus reports.

Passenger car equivalent (PCE): A measure of pavement damage relative to the estimated pavement damage caused by typical passenger car [4].

Passenger load: The total number of passengers on board a bus at a given point in time [2]. The passenger load does not include the driver. The passenger load does not to refer to the weight of the passengers.

Passenger weight scenario (PWS)*: An assumed laden passenger weight that is used in this thesis to observe the effect that passenger weight has on transit bus gross vehicle weights.

Passenger seating model*: A model developed in this research that is used to estimate where passengers sit or stand on a bus at specific passenger loads.

Seated load weight (SLW)*: The weight of a bus with a passenger load equal to one passenger per seat. The seated load weight of a bus includes the weight of passengers, the driver, fuel, and the bus itself. This definition of seated load weight was created for use in this thesis and differs from the way it is defined in some of the sources used in this research. For example, the Altoona Bus Research and Testing Center (Altoona) calculates SLW assuming each passenger weighs 150 pounds. The Altoona definition of SLW is not used in this report because findings of this research suggest that 150 pounds is not representative of the weight of an average transit passenger.

Standard transit bus*:	A bus that is approximately 40 feet long and is equipped with one steer axle and one drive axle. Standard transit buses have two sets of doors – one at the front of the bus and one near the middle of the bus.
Steer axle*:	A single axle that is used for steering. Steer axles typically have two tires and are situated at the front of the bus.
Temporary Weight Limit*:	A weight limit that is in effect for a specified period of time shorter than one year. Temporary weight limits include spring weight restrictions, seasonal load bans, and winter premiums.
Weigh-in-motion (WIM) device:	A scale used for weighing vehicles in motion. Unlike static scales, WIM devices do not require vehicles to come to a complete stop to obtain weight measurements [23].
Weight limit:	The maximum weight that can legally be carried by a tire, axle, or all axles as stated by the governing jurisdiction [4]. A weight limit is not necessarily the same as a weight rating.
Weight rating:	The maximum recommended weight that should be carried by a tire, axle, or all axles as stated by the manufacturer [4]. Vehicles operating at weights that exceed their weight rating are at risk of mechanical failure. A weight rating is not necessarily the same as a weight limit.

Note: Terms and accompanying definitions denoted with an asterisk (*) were developed for this research to provide a mutual understanding between the reader and author and simplify any discussions involving said term.

2 ENVIRONMENTAL SCAN

This chapter describes the methodology used for the environmental scan component of this research and provides a summary of its findings. Information presented in this chapter is intended to provide context for the subsequent chapters of this thesis. The three topics covered in this chapter are: (1) transit bus weight regulations and enforcement; (2) transit bus manufacturing and design; and (3) the accommodation of transit buses in pavement design.

2.1 METHODOLOGY FOR ENVIRONMENTAL SCAN

The environmental scan component of this research consists of three parts: a literature review, a regulatory review, and a jurisdictional survey. Findings of the environmental scan are organized and discussed with respect to three topics: transit bus weight regulations and enforcement, transit bus manufacturing and design, and pavement issues associated with transit buses.

The first component of the environmental scan was an extensive literature review, which was conducted to identify factors that influence the weight of transit buses in Canada and establish how transit buses are addressed in current pavement design practices. Two primary sources for the literature review were *An Analysis of Transit Bus Axle Weight Issues* (2014) and *Study & Report to Congress: Applicability of Maximum Axle Weight Limitations to Over-the-Road and Public Transit Buses* (2003); however, the literature review encompassed more than 50 different sources, including:

- scholarly articles;
- test reports from the Altoona Bus Research and Testing Center bus database;
- information from transit bus manufacturer websites; and

- transit bus design specifications.

The second component of the environmental scan was a review of relevant vehicle weight laws and regulations, which was conducted in order to develop an understanding of the regulatory environment in which transit buses operate and establish points of reference for the weight analysis in Chapter 4. The primary sources for the regulatory review were: (1) provincial laws, acts, and regulations; (2) municipal by-laws; and (3) information found on municipal government websites.

Federal regulations were not included in the regulatory review because municipal and provincial jurisdictions are responsible for establishing and enforcing vehicle weight limits in Canada [25]. However, some federal regulations, such as emissions regulations and accessibility regulations, have the potential to indirectly influence transit bus weights. These regulations are briefly discussed in Section 2.3.1.

A jurisdictional survey was the third and final component of the environmental scan. The purpose of the jurisdictional survey was to address knowledge gaps identified in the literature and regulatory reviews, assess the "industry awareness" of transit bus weights, identify how/if jurisdictions enforce vehicle weight limits for transit buses, and determine how transit buses are accommodated in current pavement design practices. The jurisdictional survey included interviews with transit agencies, municipal and provincial governments, and enforcement agencies across the Canadian Prairie Region. Interviews were conducted in-person, over the phone, and via email.

2.2 TRANSIT BUS WEIGHT REGULATIONS AND ENFORCEMENT

This section outlines the regulatory environment in which transit buses operate in the Canadian Prairie Region. Specifically, it describes the basic weight limits that apply to transit buses, temporary weight limits imposed by several cities in the Canadian Prairie Region, and how transit bus weight limits are enforced within these jurisdictions.

2.2.1 Basic Weight Limits

In Canada transit buses are classified as commercial vehicles and are subsequently subject to commercial vehicle weight limits. Attempts to harmonize commercial vehicle weight limits across Canada have resulted in many provinces having similar weight limits for buses. With respect to municipal jurisdictions, some have adopted their respective provincial vehicle weight limits and others have instituted their own limits. In general, provincial and municipal vehicle weight limits address:

(1) Tire restrictions:
   a. Maximum tire pressure limits (pounds per inch of tire section width).
   b. Maximum tire weight (pounds).

(2) Axle weight restrictions:
   a. Maximum steer axle weight (pounds).
   b. Maximum single axle weight (pounds).
   c. Gross axle weight ratings (pounds).

(3) Gross vehicle weight restrictions.

Table 3 summarizes the basic vehicle weight limits for transit buses disaggregated by city and Table 4 summarizes the basic vehicle weight limits for transit buses by province. These tables were developed based on the author's interpretation of municipal and provincial laws and are not intended to act as legal references. Gross axle weight ratings are not listed in these tables because they differ based on vehicle model. Tire pressure limits listed in these tables are based on the section width of a tire.

Table 3: Municipal Transit Bus Basic Weight Limits in the Canadian Prairie Region

City	Vehicle Type	Tire Restrictions			Axle Weight Restrictions		Gross Vehicle Weight Limits (pounds)
		Tire Pressure		Tire Load (pounds)	Steer Axle (pounds)	Drive Axle (pounds)	
		Steer Axle (pounds/inch)	Drive Axle (pounds/inch)				
Calgary	Bus	560	560	8,050	16,090	20,060	36,150
Edmonton	Bus	560	560	8,050	16,090	20,060	36,150
Regina*	Straight Truck	560	560	6,610	12,130	20,060	36,000
Saskatoon	Transit Bus	Exempt	Exempt	Exempt	Exempt	Exempt	Exempt
Winnipeg	Bus	560	560	6,610**	16,090	20,060	36,150

*Vehicle weight limits for buses in Regina could not be found. The weight limits for two-axle straight trucks are listed instead.
**This limit does not apply to tires on steer axles
Sources: Based on provincial and municipal commercial vehicle size and weight regulations

Table 4: Provincial Transit Bus Basic Weight Limits

Province	Vehicle Type	Tire Restrictions			Axle Weight Restrictions		Gross Vehicle Weight Limits (pounds)
		Tire Pressure		Tire Load (pounds)	Steer Axle (pounds)	Drive Axle (pounds)	
		Steer Axle (pounds/inch)	Drive Axle (pounds/inch)				
Alberta	Bus	560	560	8,050	16,090	20,060	36,150
BC	Bus	560	560	6,610*	15,980	20,060	36,040
Manitoba	Bus	560	560	6,610*	16,090	20,060	36,150
New Brunswick	Intercity Bus	560	560	6,610*	15,980	20,060	36,040
Newfoundland	Intercity Bus	560	560	6,610*	15,980	20,060	36,040
Nova Scotia	Intercity Bus	560	560	6,610*	15,980	20,060	36,040
Ontario	Urban Transit Bus	616	560	-	19,840	25,130	44,970
PEI	Intercity Bus	560	560	-	15,980	20,060	36,040
Quebec	Bus	NS	560	-	15,980	22,050	38,030
Saskatchewan	Intercity Bus	560	560	6,610*	16,090	20,060	36,150

*This limit does not apply to tires on steer axles
Sources: Based on provincial commercial vehicle size and weight regulations

It should be noted that the Regina traffic by-law does not mention limits for bus weights. Multiple representatives from the City of Regina and Regina Transit were contacted regarding this issue. Neither organization was aware of the vehicle weight limits for transit buses in Regina.

As shown in Figure 2, the section width of a tire is measured from one sidewall of a tire to the opposite sidewall and is not the width of the tire that makes contact with the pavement.

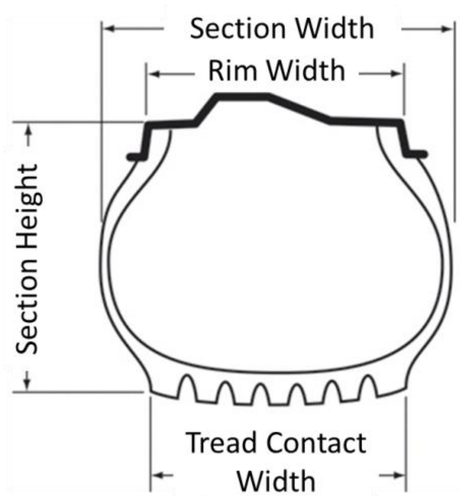


Figure 2: Tire Diagram [26]

Because of the way that vehicle weight limits are written, they often overlap with each other. In such cases the most restrictive limit governs. An example of how to calculate governing vehicle weight limits is shown in Table 5. The limits shown in Table 5 were derived using the vehicle weight limits for standard transit buses in Winnipeg. All tires were assumed to be B305/70R22.5 tires, which have a section width of 12 inches (305 mm) [27].

Table 5: Winnipeg Transit Bus Weight Limits Summary

Restriction	Weight Limit		
	Steer Axle (pounds)	Drive Axle (pounds)	Gross Vehicle Weight (pounds)
Tire Pressure	13,450	26,900	40,350
Tire Load	-	26,440	-
Axle Weight	16,090	20,060	36,150
Gross Axle Weight Rating*	14,780	27,760	42,540
Gross Vehicle Weight	-	-	124,650
Governing Limits	**13,450**	**20,060**	**33,510**

*The listed gross axle weight ratings are for the New Flyer D40 LF transit bus

From Table 5, it can be seen that in Winnipeg steer axle weights are governed by tire pressure limits, drive axle weights are governed by single axle weight limits, and gross vehicle weight is governed by the sum of the governing steer and drive axle weight limits. Other implications of this regulatory analysis are:

- The gross axle weight ratings (GAWR) for and New Flyer D40LF, which are set by the bus manufacturer, are higher than the maximum allowable weights for each axle. The steer axle GAWR is approximately 1,300 pounds more than the maximum allowable steer axle weight and the drive axle GAWR is approximately 7,500 pounds heavier than the maximum allowable drive axle weight. This indicates that transit buses are designed to accommodate higher loads than are currently allowed by law.
- It is possible for Winnipeg transit buses to exceed an axle weight limit without exceed the gross vehicle weight limit. However, Winnipeg transit buses cannot exceed the GVW limit without also exceeding an axle weight limit. Therefore, increasing the GVW limit for transit buses would have no effect on compliance and increasing axle weight limits would increase compliance.

2.2.2 Temporary Weight Limits

In addition to basic weight limits, roads can be subject to temporary weight limits. Depending on the province, temporary weight limits can be referred to as spring weight restrictions, road bans, or winter premiums. Spring weight restrictions and road bans are put in place to protect roads during periods when pavement strengths are known to temporarily decrease, such as during spring thaw conditions [28]. Conversely, winter premiums are put in place during colder months to promote economic activity in times when pavements are known to have increased strength [29]. Temporary weight limits vary by region and some jurisdictions opt not to have temporary weight limits at all. The following are summaries of the temporary weight limits in several cities in the Canadian Prairie Region:

2.2.2.1 Calgary

The City of Calgary currently adopts the vehicle weight limits set by the *Alberta Regulation 315/2002 – Traffic Safety Act – Commercial Vehicle Dimension and Weight Regulation,* which states that when road bans are in effect, transit buses are limited to 90% of the maximum allowable weight on each axle group. No mention is made within this provincial regulation or within the City of Calgary bylaws as to what conditions warrant a road ban or when road bans are in effect; however the City of Calgary website states that spring restrictions are in effect from March 15th – May 15th and restrict vehicles to 75% of their maximum allowable weight on specific roads [30].

2.2.2.2 Edmonton

The City of Edmonton restricts heavy vehicles using two types of road bans: (1) spring road bans; and (2) seasonal road bans [31]. The City of Edmonton's Traffic Bylaw 5590 states that spring road bans are in effect from March 1st to June 1st and seasonal road bans are in effect from March 1st to December 17th each year unless otherwise stated. This bylaw doesn't specify a particular axle weight reduction for each type of road ban, but states that road bans are "subject to any provincial legislation exempting certain vehicles from road bans or permitting an increased specified percentage of axle weight", which means that transit buses are at the most restricted to 90% of the maximum allowable weight [32]. Further, according to the City of Edmonton's 2015 road bans, spring road restrictions and seasonal road restrictions for trucks are 75% of the maximum allowable weight on specific roads and permanent road bans for trucks are either 50% or 75 % of the maximum allowable weight on specific roads [33]. It is unclear whether these bans also apply to buses.

2.2.2.3 Regina

Regina's Traffic Bylaw No. 9900 does not mention weight limits for buses; however, 2-axle straight trucks are granted a winter premium from December 1 to February 29, which allows them to operate with a gross vehicle weight of 38,000 pounds (the maximum allowable GVW is 36,000 pounds when winter premiums are not in effect). The bylaw does not state if there are any increases to axle weight limits during this period.

2.2.2.4 Winnipeg

As stated in Winnipeg's Traffic By-Law 1573/77, "the Director [of Public Works] may restrict the maximum weight of vehicles operated on those streets that do not have concrete pavement to the extent and for such period of time as is reasonably required to protect the streets from damage and deterioration during spring thaw conditions". According to this bylaw, transit buses are subject to Level 1 spring weight restrictions when operating on asphalt roads and granular roads (12,130 pounds on steer axles and 90% of the maximum allowable axle weights on all other axles). These restrictions are usually in place from mid-March until the end of May.

2.2.3 Enforcement and Compliance with Vehicle Weight Limits

Enforcement of vehicle weight limits in the Canadian Prairie Region is primarily the responsibility of police services, highway transport patrols, motor carrier enforcement agencies, and commercial vehicle enforcement agencies. Vehicles found to be noncompliant with vehicle weight limits can be subject to fines. According to the

Winnipeg Police Service Vehicle Inspection Unit, which is responsible for enforcing vehicle weight limits in Winnipeg, vehicle weight enforcement is primarily conducted at weigh scales located along major gateways into the City. Vehicles that solely operate within the city limits are subject to enforcement upon a visual assessment of weight by on-duty police officers. Upon visual assessment, vehicles suspected of being overweight are escorted to the nearest weigh scale for measurement. However, none of the interviewed enforcement agencies could recall requesting a transit bus to report to a weigh scale to be checked for compliance, nor could any enforcement agency recall issuing a fine to a transit agency for operating an overweight bus. The primary reason for this is because most transit agencies in the Canadian Prairie Region are issued annual fleet permits that allow them to operate transit buses at weights that exceed transit bus weight limits.

According to municipal bylaws and provincial laws, overweight permits can be issued by the Director of Public Works in municipal regions or by a representative of the Minister of Transport in provincial jurisdictions. Table 6 provides a summary of the overweight permits for several cities in the Canadian Prairie Region. This table includes all cities identified by the regulatory review and jurisdictional survey to operate with an overweight permit; however, it does not necessarily include all cities in the Canadian Prairie Region that have been issued overweight permits.

Table 6: Summary of Overweight Permits for Transit Buses in the Canadian Prairie Region

Province	City/Transit Agency	Summary of Overweight Permit
Alberta	Airdrie	Transit buses are permitted by Alberta Transportation to operate above the maximum allowable axle weights and gross vehicle weight, but are restricted to 560 pounds per inch on all tires. Based on 12 inch (305 mm) tires, this equates to 13,450 pounds on steer axles, 26,900 pounds on drive axles, and 40,350 pounds GVW.
	Bow Valley Regional Transit	
	Calgary	
	Edmonton	
	Leduc	
	Lethbridge	
	Medicine Hat	
	Red Deer	
	St. Albert	
	Strathcona County	
Manitoba	Winnipeg	Within the City of Winnipeg, single-chassis buses are permitted to operate above the maximum allowable axle weight and gross vehicle weight as long as they do not operate on a structure that has a posted gross vehicle weight limit of less than 44,100 pounds.
Saskatchewan	Saskatoon	Transit buses are not issued overweight permits because they are exempted from vehicle weight limits by municipal law.
	Regina	Transit buses are not issued overweight permits.

*This table does not include all cities in the Canadian Prairie Region that have been issued overweight permits

Sources: Based on municipal and provincial commercial vehicle size and weight regulations

Over the past 10 years, both the Province of Alberta and the City of Winnipeg have taken steps to increase the compliance of in-service transit buses through a regulatory means. In 2009, Alberta Transportation conducted a review of regional public transit service which included a review of the weights and dimensions of local, regional, and provincial transit buses. Although this review did not include the direct measurement of any in-service transit buses, the findings of this review led Alberta Transportation to introduce the Bus Modernization initiative in 2011. This initiative states that "regional public transit service providers will be required to use vehicles that are compliant with the Province's Commercial Vehicle Dimension and Weight Regulation by October 1, 2016" [34]. An interview with Alberta Transportation revealed that this deadline will likely not be met and that this initiative has had no significant effects on bus weights to date.

Consequently, Alberta Transportation will continue to grant overweight permits to transit agencies in the foreseeable future.

The City of Winnipeg has taken a similar approach to addressing transit bus weights as Alberta Transportation and has experienced similar results. An interview with the City of Winnipeg revealed that a requirement of their annual fleet permits is to maintain a "dialogue with bus manufacturers, with the intent of, in the future, having articulated buses as well as single-chassis buses manufactured such that they are in compliance [with applicable vehicle weight limits]"; however, to date this requirement has not had a noticeable effect on the weight of transit buses operating in Winnipeg.

2.3 TRANSIT BUS MANUFACTURING AND DESIGN

This section provides an overview of the manufacturing/design factors that influenced the weight of transit buses over the past few decades and provides a brief summary of the weight characteristics of the current transit bus fleet in the Canadian Prairie Region.

2.3.1 Trends in Transit Bus Design

Transit bus design is constantly adapting to meet market needs and to comply with regulatory changes. Each year transit agencies across Canada purchase new transit buses to replace ones that have reached the end of their lifespan. As such, the weight characteristics of transit fleets across Canada incrementally change to reflect the evolution of transit bus design. According to Winnipeg Transit, the desired lifespan of a transit bus in Winnipeg is 18 years. In comparison, the "minimum life" stated in the U.S. Federal Transit Administration's service life policy is 12 years [35]. This has been adopted by many transit agencies in the U.S. as the age of retirement for a transit bus. Consequently, the Canadian transit bus market is less sensitive to changes in transit bus design than the U.S. market.

The literature review and jurisdictional survey identified three major manufacturing/design influences on the weight of transit buses in the Canadian Prairie Region over the past few decades:

- **Regulatory Changes in the U.S. –** Some of the most significant contributions to changes in transit bus design over the past few decades have been the direct result of U.S. regulatory changes. These regulations have the ability to influence Canadian transit buses because of: (1) attempts to harmonize vehicle standards in North America; and (2) international transit bus manufacturers.

  Since the 1980's, Canada has continually attempted to harmonize its vehicular emissions regulations with the U.S. [36]. This means that when regulations are passed in the U.S., such the amendments to the Clean Air Act (CAA) in 1990, Canadian policy makers attempt to follow suit. This translates into design changes for transit buses as additional components are required to pass the new emissions regulations.

  Further, changes to emissions regulations in the U.S. have led to the development of alternatively fueled (non-diesel) buses, which have the potential to penetrate the Canadian market. Hybrid electric, compressed natural gas, and liquefied natural gas fueled buses are approximately 2,500 pounds heavier on average than equivalent diesel-fueled models [5].

  U.S. regulations also have the ability to influence transit buses operating in Canada because some of the major transit bus manufacturers in the U.S. also serve the Canadian market. In 1990, the U.S. passed the American's with Disabilities Act (ADA). This regulation requires transit bus manufacturers to incorporate additional components into bus design, such as wheelchair lifts or wheelchair ramps. Although Canada is transitioning towards providing accessible transit, Canada does not have a regulatory equivalent to the ADA [37]. Therefore, buses that are sold to Canadian markets can sometimes have additional components that are required to meet U.S. regulations.

- **Auxiliary Components –** Over the past decade transit agencies have attempted to improve the experiences of transit users through the addition of auxiliary features to their transit buses. Features such as air conditioning systems, exterior bike racks, next stop display systems, and security systems help promote transit ridership, but also contribute to increased transit bus weights [2].
- **Development of Lightweight Technologies –** Past attempts to develop lightweight bus models, such as the Advanced Technology Transit Bus (ATTB), CompoBus, and LCO-140H have produced promising results; however, the weight savings achieved through revolutionary design changes were often offset by increased passenger capacity [4]. Although these bus models are not commercially available, technologies and manufacturing methods developed during these projects have contributed to reductions in the weight of transit buses operating today [5].

2.3.2 Weight Characteristics of Standard Transit Buses

In North America the three most prominent transit bus manufacturers are Gillig, New Flyer, and Nova Bus; however, the transit market share in the Canadian Prairie Region is dominated by New Flyer. According to the Canadian Public Transit Discussion Board fleet rosters for Manitoba, Saskatchewan, and Alberta, the New Flyer D40 LF/R series is the most common transit bus model in the Canadian Prairie Region, representing approximately 66% of all transit buses and 78% of all 2-axle 40-ft. transit buses [38] [15]. Figure 3 shows an example of a New Flyer D40 LFR.

Figure 3: New Flyer D40 LFR

As of 2014 the D40 LF/R series is no longer being manufactured by New Flyer due to the introduction of its new line of buses – the Xcelsior series. Consequently, it is likely that the weight characteristics of transit buses in the Canadian Prairie Region will change as the New Flyer D40 LF/R series buses are phased out of service. Based on the makeup of current bus fleets, the two bus models most likely to replace the New Flyer D40 LF/R are the NovaBus LFS series and the New Flyer Xcelsior series. Table 7 shows the curb weights of the diesel versions of the NovaBus LFS series, New Flyer Xcelsior series, and the New Flyer D40 LF/R series, as reported by the Altoona Bus Research and Testing Center and the Canadian Urban Transit Association (CUTA). Due to the disparity in curb weights reported by Altoona and CUTA it is uncertain how the replacement of New Flyer D40 LF/R transit buses will affect the weight characteristics of the Canadian Prairie Region transit bus fleet.

Table 7: Curb Weight Estimates for Common Standard Transit Buses in Canada

		Altoona Reported			CUTA Reported		
Manufacturer	Model	Steer Axle (pounds)	Drive Axle (pounds)	GVW (pounds)	Steer Axle (pounds)	Drive Axle (pounds)	GVW (pounds)
New Flyer	D40 LF/R	8,070	19,050	27,120	8,700	20,500	29,200
	XD40*	8,750	18,890	27,640	8,100	19,700	27,800
NovaBus	LFS	7,800	20,820	28,620	7,790	20,210	28,000

*The XD40 is the diesel version of the New Flyer Xcelsior series transit bus
Sources: [27] [39]

In comparison to the weights displayed in Table 7, the American Public Transportation Association (APTA) Recommended Practice – *Designing Bus Rapid Transit Running Ways* states that a typical 40-ft. diesel BRT bus weighs 27,500 pounds at curb weight and weighs 39,600 pounds when fully-loaded [40]. The APTA report also states that the rear axle of BRT buses typically carry 70-75% of the GVW when fully-loaded. Based on these assumptions, fully-loaded BRT buses typically have steer axles weights ranging from 9,900 to 11,880 pounds and drive axle weights ranging from 27,720 to 29,700 pounds.

2.4 ACCOMMODATION OF TRANSIT BUSES IN PAVEMENT DESIGN

Pavement damage is a concern surrounding all heavy vehicle types; however, with sound pavement design and maintenance practices the impacts that these vehicles have on urban infrastructure can be minimized. The key findings of the literature review and jurisdictional survey regarding pavement design are organized into two topics: (1) current pavement design values; and (2) current pavement design practices.

2.4.1 Current Pavement Design Values

Pavement design can be categorized into two broad categories: (1) empirical approaches; and (2) mechanistic-empirical approaches. Empirical approaches use experimental results, such as the American Association of State Highway Officials (AASHO) Road Test, to relate vehicle weight characteristics to pavement damage. These types of approaches often rely on the calculation of equivalent single axle loads (ESALs), which can be used to relate the pavement impacts of various axle weights to a standard 18,000 pound axle.

A common shortcut or "rule of thumb" for calculating ESALs is the fourth power rule. The fourth power rule in pavement design states that this vehicle would have an approximate pavement impact, or equivalent single axle load (ESAL), equal to:

$$ESAL \approx \left(\frac{W_i}{18{,}000}\right)^4 + \left(\frac{W_{i+1}}{18{,}000}\right)^4 + \cdots + \left(\frac{W_{i+n}}{18{,}000}\right)^4$$

Where:

ESAL = Equivalent single axle load;

$\mathbf{W_i}$ = weight of axle "i" in pounds; and

n = number of axles.

One limitation of the fourth power rule is that it is intended to be used to calculate the ESAL for axles equipped with dual tires [41]. Consequently, it underestimates the pavement impacts of axles equipped with single tires, such as steer axles. In fact, evidence suggests that axles equipped with two tires can have greater impacts on flexible pavements than heavier axles equipped with dual tires [42]. Regardless of these facts some researchers use this rule to estimate the ESAL of steer axles [24] [43] [44]. To produce ESAL estimates this research assumes that the fourth power rule can be applied to steer axles, but acknowledges that this type of ESAL analysis underestimates the pavement impacts of steer axles.

Currently, there are no standard empirical pavement design values for transit buses, such as a design equivalent single axle load (ESAL). Estimates of a typical transit bus ESALs made by previous research are shown Table 8 along with an estimate of a typical passenger car for comparison. As it can be seen in this table, past attempts to quantify the impacts of transit buses on pavements have produced a wide range of results.

Table 8: Existing Bus and Passenger Car ESAL Estimates

Vehicle Description	ESAL Estimate	Passenger Car Equivalents	Source
Passenger Car	0.0004	1	[45]
FHWA vehicle class 4 – buses	0.57	1,425	[46]
"Prototypical transit bus"	1.40 – 1.60	3,500 – 4,000	[1]
Non-interstate urban buses	1.60	4,000	[47]
"Typical bus load"	2.47 – 2.73	6,175 – 6,825	[3]
Transit buses	3.00	7,500	[48]
City buses at seating capacity	6.00	15,000	[49]

In 2008, the American Association of State Highway and Transportation Officials (AASHTO) released the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice* as an update to the traditional empirical pavement design methods. Instead of ESALs, this method utilizes distributions of axle weights for various axle types (i.e., single, tandem, tridem) called axle load spectra (ALS). Currently, there no standard axle load spectra for mechanistic-empirical pavement design approaches. This can largely be attributed to the lack of available data for in-service transit buses.

It should be noted that although there has been a shift towards the use of mechanistic-empirical approaches in pavement design, many jurisdictions still opt to use empirical approaches. Consequently, this research presents estimates for both axle load spectra and ESALs.

2.4.2 Pavement Design Practices

Pavement design in urban areas is typically based on road class, as opposed to rural highways which are based on ESAL estimates or axle load spectra. Common urban road classifications are: local, collector, arterial, and expressway/freeway. Transit bus operations are typically restricted from operating on local roads, which are less capable of accommodating them in terms of geometric design and pavement strength. The environmental scan revealed three commonly used pavement design practices that are used to accommodate transit buses:

- **Spot Treatments** – Many jurisdictions install concrete pads at locations, such as bus stops, which are subject to frequent stopping and starting to prevent extensive rutting often associated with asphalt pavements [4]. Figure 4 shows a concrete bus pad at a bus stop in Winnipeg.

Figure 4: Concrete Pad at Bus Stop

- **Roadway Rehabilitation –** Concrete overlays have been successfully implemented in Canada and the U.S. for rehabilitating or resurfacing pavements on roadways that experience high volumes of trucks or buses. The primary advantage of concrete overlays is their ability to resist rutting and shoving, which can increase pavement life and reduce pavement lifecycle costs on roadways subject to high volumes of heavy vehicles [50].
- **Design of New Facilities** – Table 9 summarizes the recommended pavement design for BRT runningways according to the APTA Recommended Practice – *Designing Bus Rapid Transit Running Ways*. The planned pavement structure for the runningways of Phase 2 of the City of Winnipeg Southwest Transitway is

shown in Table 10. This design meets the minimum recommendations of the APTA Recommended Practice.

Table 9: APTA Recommended Practice for BRT Runningways

Pavement Component	Thickness (mm)	Pavement Design Life
Rigid Pavements		40 years
Portland Cement Concrete: Crushed Granular Base Course:	175-250 150	
Flexible Pavements		20 years
Asphaltic Concrete: Crushed Granular Base Course:	125-175 300-375	

Source: [40]

Table 10: Southwest Transitway Phase 2 Pavement Structure

Pavement Component	Thickness (mm)
Plain Dowelled Concrete:	230
Base Course:	75
Sub-Base Course (50 mm diameter):	150
Sub-Base Course (150 mm diameter):	450
Sub-Drains:	N/A
Non-Woven Geotextile Fabric:	N/A
Geogrid:	N/A
Total Structural Depth	905

Source: [51]

3 ESTIMATING THE WEIGHT OF IN-SERVICE TRANSIT BUSES

This chapter describes a methodology to estimate the in-service weight of transit buses and applies this methodology to estimate the weight of in-service transit buses operating on Winnipeg Transit Route 160 in Winnipeg, Manitoba. Further, this chapter identifies the limitations of current data sources commonly used for estimating the weight of in-service transit buses and attempts to address these limitations. The primary advantage of the methodology proposed in this chapter is the ability to leverage data that are typically already collected by transit agencies or provided to transit agencies by bus manufacturers.

3.1 METHODOLOGY

A description of the methodology proposed by this research is shown in Figure 5. Steps 1-4 (data collection) shown in Figure 5 are explained in further detail in the subsequent sections of this Chapter. Steps 5-9 (data analysis) are explained in further detail in Appendix A.

Data Collection	Estimate Curb Weight	1. Estimate the curb weight of transit buses operating within the desired jurisdiction.
	Estimate Passenger Weight	2. Develop laden passenger weight estimates for male and female transit passengers based on available base passenger weight data, demographic data, and estimates for carry-on items.
	Estimate Passenger Load	3. Determine the typical number of male and female riders (disaggregated by bus stop) on buses operating within the study area.
	Estimate Axle Split	4. Estimate the proportion of the gross vehicle weight that is carried on the steer axle and drive axle of the bus based on the amount of passengers on board.
Data Analysis	Calculate Total Passenger Weight	5. Calculate the total weight of all passengers on a specific bus at a specific bus stop by multiplying the laden passenger weight estimates developed in Step 2 by the typical passenger loads determined in Step 3.
	Calculate Gross Vehicle Weight	6. Calculate the gross vehicle weight of each bus at each bus stop by adding the total passenger weight determined in Step 5 to the curb weight of the bus determined in Step 1.
	Calculate Axle Weights	7. Calculate the steer axle weight and drive axle weight by multiplying the gross vehicle weight determined in Step 6 by the axle split determined in Step 4.
	Assign Weights to Road Network	8. Assign the weight calculated at each bus stop a distance value based on the length of the road segment between the current stop and the next stop on the route.
	Calculate Exposure	9. Create a distribution of gross vehicle weights or axle weights by calculating the proportion of vehicle-kilometres travelled (VKT) that is conducted above or below various weights.

Figure 5: Methodology for Estimating In-service Transit Bus Weights

3.1.1 Estimating Curb Weight

The first step in developing in-service weight estimates of transit buses is to determine how much a bus weighs with no passengers on board (i.e., its curb weight). This can be a complex task because the curb weight of transit buses within a given fleet can vary based make/model, production year, seating layout, stanchion layout, and other factors [2]. Further, as mentioned in Chapter 2, the curb weight of transit buses is gradually changing over time as new technologies are incorporated into bus design and new bus models are introduced into service. To address these issues and simplify subsequent analyses, researchers can select one or several bus models to represent the entire fleet. Two sources for determining representative bus models for a specific region are the Canadian Public Transit Discussion Board (online bus fleet rosters) and local transit agencies.

However, this still leaves an essential question unanswered – what is the best or most appropriate source of curb weight data? Arguably the most comprehensive source of publically available transit bus weight data in North America is the Altoona Bus Research and Testing Center at the Thomas D. Larson Pennsylvania Transportation Institute (LTI), hereafter referred to as Altoona. As a part of U.S. federal requirements, all bus models must undergo testing at Altoona before they can become commercially available in the U.S. [52]. As mentioned in Chapter 2, the transit bus manufacturers in Canada also serve the U.S. market; therefore, all bus models that are commercially available in Canada have undergone testing at Altoona. This testing process includes a “test bus check-in”, during which each bus model is weighed at its curb weight (no passengers on board), seated load weight (one passenger per seat), and fully-loaded weight (one passenger per seat and one passenger per 1.5 ft.^{2} of floor space). Table 11 shows a sample Altoona bus report weight summary.

Table 11: New Flyer D40 LF Altoona Bus Report Check-in Weight Summary [8]

Axle	Curb Weight (pounds)	Seated Load Weight (pounds)	Fully-Loaded Weight (pounds)	Gross Axle Weight Rating (pounds)
Front Axle	8,070	10,160	12,970	14,780
Rear Axle	19,050	22,480	24,650	27,760
GVW	27,120	32,640	37,620	42,540

Although the bus weights measured during the "check-in" phase are sufficient for meeting U.S. federal requirements, there are several factors that limit their applicability for use in estimating in-service transit bus weights. Buses that undergo testing at Altoona are stock models and do not include any auxiliary features that may be desired by a transit agency, such as fare boxes, next stop display systems, bike racks, and various forms of advertisements [53]. Further, transit agencies can request modifications to the stock models which can have a significant effect on the overall weight. Common modification requests include seating and stanchion layout, window type, and flooring material [2]. Subsequently, the curb weights reported by Altoona are biased to underestimate the weight of in-service transit buses.

Curb weight data can also be sourced directly from bus manufacturers. Bus manufacturers commonly collect their own weight data for use in design [53]; however, obtaining this data from bus manufacturers can be a challenge for private researchers due to privacy concerns. Some bus manufacturers have specification sheets available online, but this data typically only includes weight details for stock transit bus models.

Alternatively, curb weight data can sometimes be obtained from transit agencies. Although transit agencies often rely on weight data provided by bus manufacturers, in some cases they collect their own weight data. For example, Winnipeg Transit weighs newly purchased buses at local weigh scales to ensure that the buses won't exceed the capacity of lifting devices used for bus maintenance. If available, locally-weighed curb weight data are desirable because it most closely reflects the actual curb weight of in-service transit buses. Selection between the other sources of curb weight data should be done on a case-by-case basis if locally-weighed curb weight data are unavailable.

3.1.2 Estimating Laden Passenger Weight

The second step in developing in-service weight estimates of transit buses is to determine the weight of an average passenger including their clothes and carry-on items (i.e, laden passenger weight). Laden passenger weight is a much debated topic in the transit industry and has undergone scrutiny over the past decade [54]. The current industry standard for laden passenger weight in bus design is 150 pounds. In comparison, the U.S. Federal Aviation Administration (FAA) currently uses 190 pounds as the laden passenger weight for airplanes, which includes 16 pounds for carry-on items [55]. In 2011 the U.S. Federal Transit Administration (FTA) proposed increasing the average passenger design weight for buses to 175 pounds; however, this notice of proposed rulemaking was later withdrawn [56]. The U.S. is currently in the process of determining a more representative average passenger weight design value in accordance with the requirements of *Moving Ahead for Progress in the 21st Century* (MAP-21). In the meantime, 150 pounds per passenger remains the current transit industry design standard for laden passenger weight and is often adopted by researchers attempting to estimate in-service transit bus weights even though it is widely accepted to be unrepresentative of the typical transit passenger.

That being said, determining a more representative value for the laden weight of an average transit passenger is not an easy task. Issues that must be addressed include:

- What are good sources of base passenger weight data?
- Is the average weight of the general population representative of the average transit passenger's base weight?

- How much weight should be added to the base passenger weight to account for clothing and carry-on items?

In Canada, public surveys are the primary sources of base passenger weight data. In some cases it may be possible to obtain data disaggregated by province, which can increase the accuracy of a base passenger weight estimate for a particular jurisdiction. However, one of the biggest challenges of obtaining base passenger weight data is that most publically available health surveys report average body mass index (BMI) instead of average weight because BMI is viewed as a better indicator of obesity and overall health. Another issue is that these surveys are voluntary and can contain self-reported results, which can introduce bias.

Further, some researchers argue that the average transit passenger is significantly different from the average member of the general population. In particular, some claim that transit users are, on average, lighter than the general populous [57]. It can also be argued that the average transit rider is different than the average member of the general populous because public transit is an attractive transportation mode choice for certain demographics. For example, senior citizens may opt to use public transit in lieu of driving. Therefore, certain demographics of the general population may be overrepresented within the population of transit users. This issue is further complicated by the fact that the average transit bus passenger can change based on location and bus route. For example, a transit route through a business district would likely serve a higher proportion of middle-aged commuters, whereas a university-destined route may serve a higher proportion of people in their early twenties.

In addition to the challenges of determining an appropriate base passenger weight, there are many challenges associated with estimating the average weight of clothing and carry-on that should be assigned to each transit passenger. Items commonly seen on transit buses include backpacks, grocery bags, and handbags. Weight estimates of carry-on items are dependent on estimates of how much these items weigh and how often transit users bring them onto the bus. An estimate of average carry-on item weight is provided in Section 3.2.3; however, this estimate is based on Winnipeg Transit Route 160 users. Similar to Step 1, the selection of a laden passenger weight should be done on per case basis and take into account time, resource, and data availability.

3.1.3 Estimate Passenger Load

The third step in developing in-service weight estimates of transit buses is to determine the number of passengers on each bus (i.e., the passenger load). Passenger loads can be included in transit bus weight estimates in two ways: (1) using ridership data provided by a local transit agency; or (2) estimating the weight of a transit bus for selected passenger loads. Both of these methods are similar; however, ridership data has the added benefit of including information on ridership frequency and spatial characteristics. Therefore, ridership data can be used to determine how often transit buses operate above selected weight limits, pinpoint where transit buses are most likely non-compliant with weight limits, and identify what road segments are experiencing the heaviest loads.

One limitation of ridership data is that it does not include any information on the gender of transit riders. According to Statistics Canada, the difference between the base weight of male and females in Canada is approximately 25 pounds [58]. Assuming that the capacity of a bus is 65 passengers, a bus fully-loaded with only male passengers would be estimated to weigh approximately 1,600 pounds more than a bus with all female passengers. Gender data can be collected several ways, including surveys, manual observation, and on-board security footage. Similar to previous steps, addressing passenger gender when developing in-service transit bus weight estimates should be done on per case basis and take into account time, resource, and data availability.

3.1.4 Estimating Axle Split

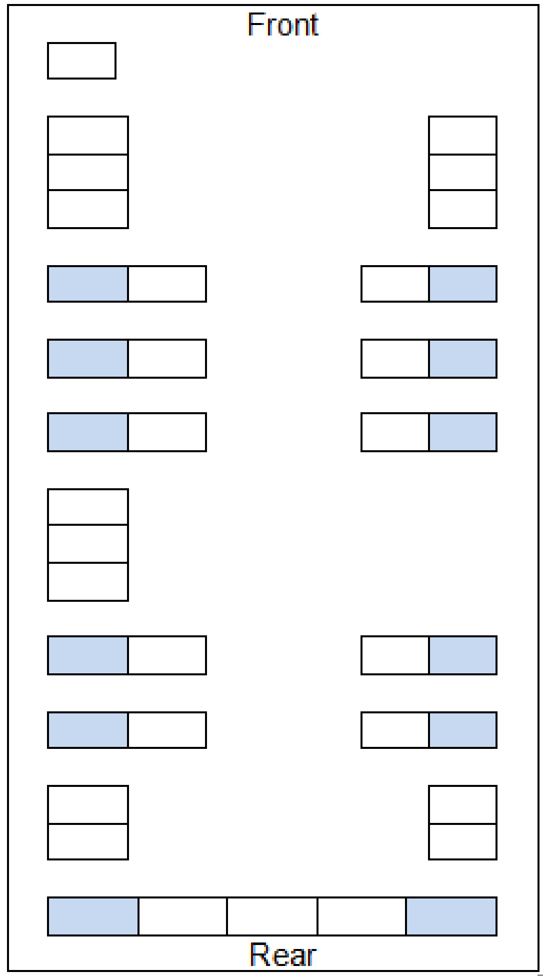
The fourth step in developing in-service weight estimates of transit buses is to estimate the proportion of the total weight of a bus that is carrier by each axle (i.e., the axle split). Estimating the axle split for a transit bus is difficult because transit bus passenger loads are variable – both in terms of the total number of passengers on board and the location of those passengers on the bus. To simplify this process many researchers assume a constant axle split of between 30-35% of the weight on the steer axle and 65-70% of the weight on the drive axle. Consequently, the selection of an axle split can have significant impacts on axle weight estimates.

Another way to determine axle splits is to load buses with passengers and weigh the axles of the bus at a static scale, such as is done by Altoona. During the bus test check-in, transit buses are weighed by axle at curb weight, seated load weight, and fully-loaded weight (shown in Table 12). Passengers are simulated in these weight measurements by placing a 150 pound weight in the bus for each passenger. Since all buses in the U.S. must undergo testing at Altoona, this database is capable of providing approximate axle splits for most bus models; however, these axle splits are subject to the limitations stated in Section 3.1.1 and Section 3.1.2.

Table 12: Axle Splits for the New Flyer D40 LF [27]

Axle	Curb Weight		Seated Load Weight		Fully-loaded Weight	
	Pounds	%	Pounds	%	Pounds	%
Steer Axle	8,070	29.8	10,160	31.1	12,970	34.5
Drive Axle	19,050	70.2	22,480	68.9	24,650	65.5
GVW	27,120		32,640		37,620	

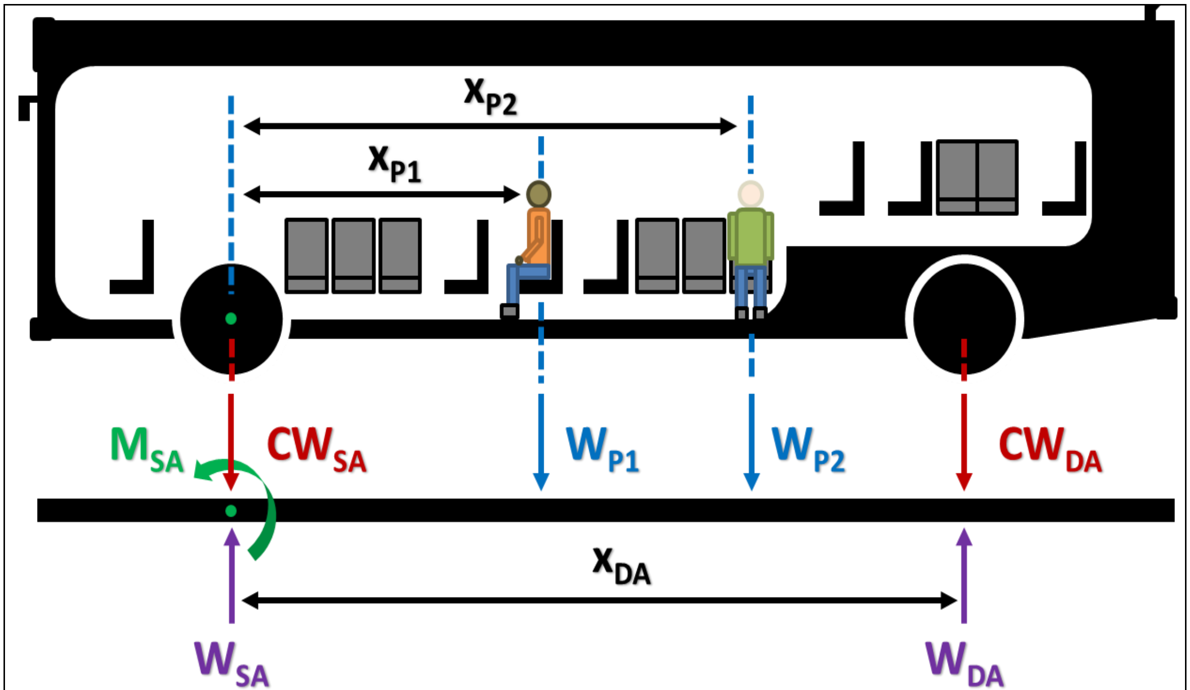
Alternatively, this research proposes that axle splits can be calculated based on passenger seating models (PSMs). PSMs were developed as a part of this research to estimate where passengers sit or stand on a bus at a specific passenger load. A sample passenger seating model is shown in Figure 6.



*An estimate for the occupied seats with 12 passengers on the bus are shown in light blue

Figure 6: Sample Passenger Seating Model for a Transit Bus with 12 Passengers

These models can be used in conjunction with bus specifications to develop moment diagrams, which can be used to calculated axle reactions at various passenger loads. A sample moment diagram and the equations required to calculate axle weights are shown in Figure 7 (see Section 3.2.5 and/or Appendix A for further explanation). It is important to note that this type of analysis assumes that a transit bus behaves statically. Dynamic effects, such as wheel/road interactions, aerodynamics, load transfer effects from acceleration/deceleration, and suspension characteristics, are outside the scope of this study and are not taken into account.



Equation 1: $\Sigma M_{SA} = 0 = \Sigma(W_P * x_P) + CW_{DA} * x_{DA} + W_{DA} * x_{DA}$

Equation 2: $\Sigma W_P + CW_{SA} + CW_{DA} = W_{SA} + W_{DA}$

Where:

- M_{SA} = moment about the steer axle
- W_{SA} = steer axle reaction
- W_{DA} = drive axle reaction
- W_{Pi} = weight of passenger "i"
- CW_{SA} = steer axle weight at curb weight
- CW_{DA} = drive axle curb weight at curb weight
- x_i = distance from load "i" to the steer axle

*the steer axle and drive axle reactions (W_{SA} & W_{DA}) are equal to the weight transferred to the ground through the steer axle and drive axle

Figure 7: Sample Moment Diagram and Moment Equations

Similar to the previous steps, the selection of an appropriate axle split when developing in-service transit bus weight estimates should be done on per case basis and take into account time, resource, and data availability.

3.2 CASE STUDY – WINNIPEG TRANSIT ROUTE 160

This section applies the methodology described in Section 3.1 to estimate the weight of transit buses along Winnipeg Transit Route 160 in Winnipeg, Manitoba.

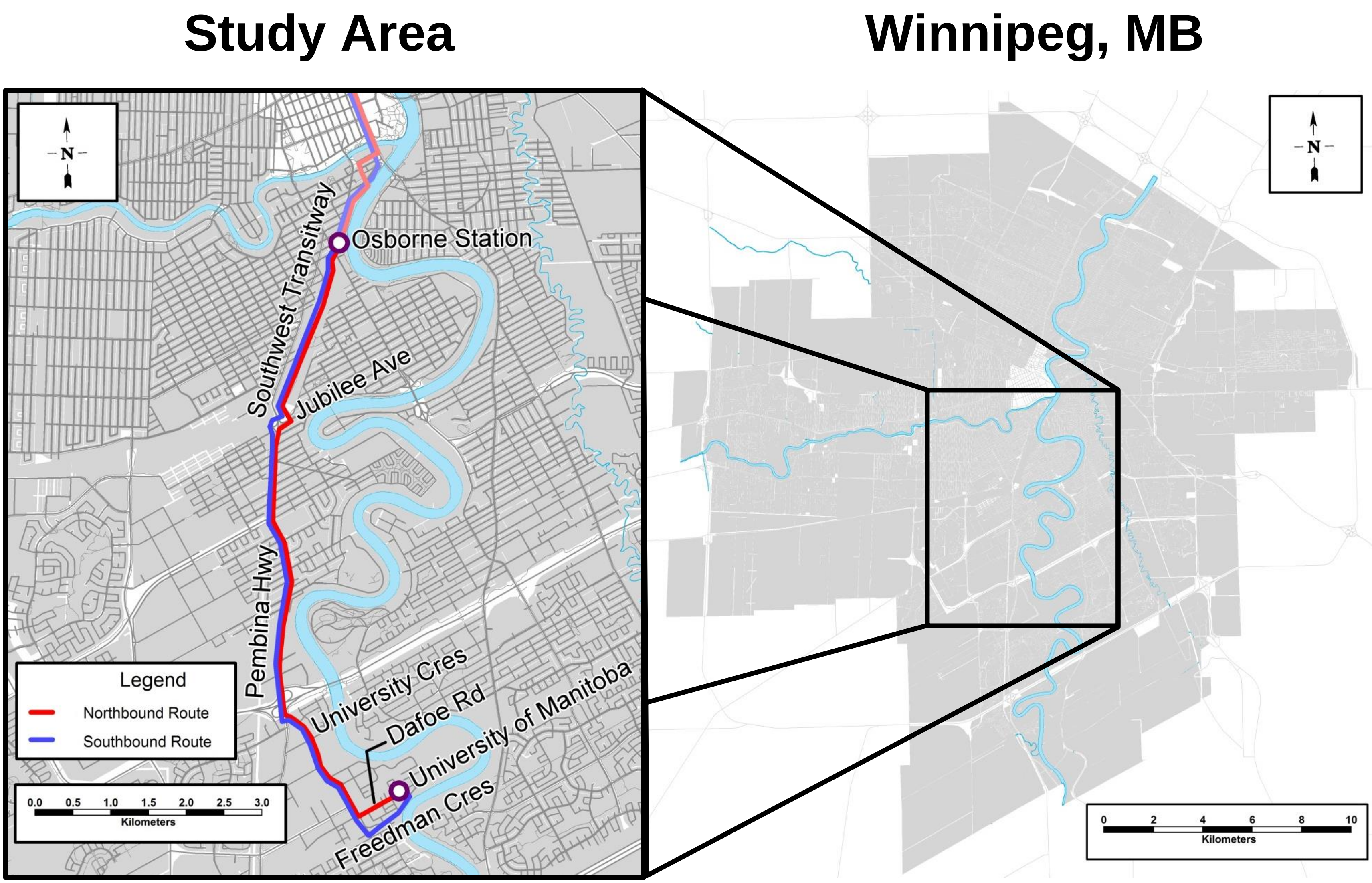
3.2.1 Study Area

The study area for this research was Winnipeg Transit Route 160 between Osborne Station (Central Winnipeg) and University of Manitoba Station (South Winnipeg), as shown in Figure 8. Route 160 continues north beyond Osborne Station to downtown Winnipeg, but this portion of the route was excluded from the study to simplify the data collection process.

The primary purpose of Route 160 is to serve as a “commuter” bus for University of Manitoba students. For this reason, the typical Route 160 bus riders are students aged 18 to 24. However, because the bus has a number of stops along Pembina Highway it also serves as a commuter bus for businesses in downtown Winnipeg and as a commuter/retail bus for businesses along Pembina Highway. Route 160 was chosen for this study because it is a high volume route (in terms of buses and passengers) with many stops within the study area compared to other routes. Table 13 shows information about the northbound and southbound Route 160 schedules based on the Winnipeg Transit schedule for August 31 – December 21, 2014. Table 14 lists all of the Route 160 bus stops that are within the study area along with the distance to that stop relative to the first stop on the route within the study area (i.e., SB Southwest Transitway –Osborne Station for the southbound route and WB Dafoe – U of M for the northbound route.)

Table 13: Route 160 Schedule Information

Scheduled Buses Per Day	Weekday	Saturday	Sunday
Southbound	81	57	29
Northbound	78	57	29



*The sections of Route 160 north of Osborne Station are shown as faded because they are outside the study area

Figure 8: Map of Study Area

Table 14: Northbound and Southbound Route 160 Bus Stops*

Northbound Route Stop Name	Distance (m) **
WB Dafoe - U of M	0
WB Dafoe - U of M (School of Music)	494
NB University - Chancellor Matheson	830
NB University - Dysart	1,146
NB University - Markham	1,535
NB University - Thatcher	1,894
NB University - Wedgewood	2,204
NB University - Pembina	2,373
NB Pembina - Plaza	2,916
NB Pembina - Adamar	3,064
NB Pembina - Adamar North	3,259
NB Pembina - Manahan South	3,535
NB Pembina - Manahan	3,665
NB Pembina - Crescent	3,946
NB Pembina - Nesbitt	4,050
NB Pembina - Crane	4,334
NB Pembina - Fletcher	4,516
NB Pembina - Dowker	4,765
NB Pembina - Waller	4,885
NB Pembina - Oakenwald	5,042
NB Pembina - Riverwood	5,187
NB Pembina - North Drive	5,479
NB Pembina - Point Road	5,791
NB Pembina - Calrossie	5,960
NB Pembina - Merriam	6,097
NB Southwest Transitway - Jubilee	6,551
NB Southwest Transitway - Fort Rouge Station	7,681
NB Southwest Transitway - Osborne Station	8,920

Southbound Route Stop Name	Distance (m)**
SB Southwest Transitway - Osborne Station	0
SB Southwest Transitway - Fort Rouge Station	1,279
SB Southwest Transitway - Jubilee	2,333
SB Pembina – Calrossie	2,817
SB Pembina – Byng	2,953
SB Pembina – Windermere	3,129
SB Pembina - North Drive	3,378
SB Pembina – Southwood	3,678
SB Pembina – McGillivray	3,922
SB Pembina – Radisson	4,129
SB Pembina – Kelsey	4,280
SB Pembina – Clarence	4,412
SB Pembina – Royse	4,651
SB Pembina – Chevrier	4,883
SB Pembina – Manahan	5,308
SB Pembina - Manahan South	5,479
SB Pembina - Adamar North	5,679
SB Pembina – Adamar	5,809
SB Pembina – Plaza	6,052
SB Pembina - University Crescent	6,539
SB University – Pembina	6,648
SB University – Wedgewood	6,835
SB University – Thatcher	7,073
SB University – Markham	7,497
SB University – Dysart	7,916
SB University – Dafoe	8,287
SB University – Freedman	8,514
EB Freedman - King's Drive	8,858
EB Freedman – Maclean	9,098
WB Dafoe - U of M	9,458

* Data obtained from Winnipeg Transit
** Distance is measured relative to the first stop on the route within the study area

The study area can be separated into three sections based on geographical, operational, and physical characteristics: (1) the Southwest Transitway; (2) Pembina Highway; and (3) University Crescent.

Southwest Transitway

The Southwest Transitway is a two-lane, transit exclusive facility. It was constructed as part of Winnipeg's rapid transit program and is completely separated from public travel lanes. High access control allows the Transitway to operate similar to a freeway between bus stations with a speed limit of 80 km/h. Osborne Station, shown in Figure 9, is the northern boundary of the study area and one of the three current rapid transit stations along the Southwest Transitway. Within the study area, the Southwest Transitway is bordered by rail lines to the west and residential housing to east. The entirety of the Southwest Transitway is paved with Portland cement concrete pavement.

Figure 9: Osborne Station

Pembina Highway

Pembina Highway is six-lane, divided, arterial roadway. Transit operations primarily take place in the curb lane; however, on-street parking during off-peak periods can cause transit buses to spend a significant time in the middle lane of traffic. Pembina Highway is fronted by many commercial businesses and is a major corridor for transit operations in Winnipeg. Most of Pembina Highway is paved with an asphalt overlay on top of Portland cement concrete; however, concrete pads have been installed at several bus stops to address pavement rutting issues and prevent premature pavement failure, as shown in Figure 10.

Figure 10: Portland Cement Concrete Pad at a Bus Stop on Pembina Highway

University Crescent

University Crescent is a four-lane, divided collector which acts as one of the two main gateways to the University of Manitoba Fort Garry campus. Transit operations primarily take place in the curb lane along University Crescent and operate on both asphalt overlays and Portland cement concrete pavements. Near the university, transit operations transfer to Freedman Crescent and Dafoe Road, both of which are two-lane, local roadways. Freedman Crescent and Dafoe Road are paved with asphalt overlays on top of Portland cement concrete pavement, as shown in Figure 11.

Figure 11: Asphalt Overlay on Dafoe Road

3.2.2 Estimating Curb Weight

Winnipeg Transit provided two sources of weight data that could be used to estimate the curb weight of Route 160 buses: (1) a detailed bus fleet roster; and (2) local weigh scale data. Table 15 is a modified version of Winnipeg Transit's bus fleet roster and only includes buses that operate on Route 160. Winnipeg Transit's bus fleet roster is a mixture of data provided by the bus manufacturer and collected by Winnipeg Transit.

Table 15: Winnipeg Transit Route 160 Bus Fleet Roster

Bus Series*	Model	Year	Active Buses	Seating	Length (feet)	Curb Weight (pounds)
101-135	D40LFR	2009	35	38	40	29,211
140-169	D40LFR	2010	30	38	41	28,952
201-230	D40LF	2004	29	38	40	27,000
231-260	D40LF	2005	30	38	40	27,000
270-281	D40-LF	2007	12	39	40	27,100
401-443	D40-LF	1998	43	39	40	26,220
444-504	D40-LF	1999	60	39	40	26,220
510-561	D40-LF	2002	52	38	40	26,220
570-599	D40-LF	2003	30	38	40	26,220
601-640	D40-LFR	2011	40	38	41	29,387
701-733	D40LFR	2008	33	38	40	27,820
735-767	D40LFR	2009	33	38	40	27,820
770-799	D40LFR	2009	30	38	40	27,820
800-830	D40LFR	2012	31	38	41.8	28,600
901-910	INVERO	2002	10	44	40	29,040
991-993	D40-LF	1994	3	39	40	26,220
					Average Curb Weight**	27,470

*Data obtained from Winnipeg Transit
**The average curb weight is weighted by the number of active buses

Table 16 displays weight data collected by Winnipeg Transit at a local weigh scale for two New Flyer D40 LFR buses. This data was collected by Winnipeg Transit to ensure that their hoisting system had sufficient capacity and not for weight compliance purposes. Unlike the bus fleet roster, the weigh scale data includes axle weights in addition to gross vehicle weights. The axle split of these bus models is approximately 30/70 at curb weight.

Table 16: Winnipeg Transit Weigh Scale Data

Bus Series	Model	Year	Front Axle Weight (pounds)	Rear Axle Weight (pounds)	Curb Weight (pounds)
101 to 135	D40LFR	2009	8,531	20,767	29,298
601 to 640	D40LFR	2011	8,708	20,370	29,078
Average (n=2)			**8,620**	**20,568**	**29,188**

*Data obtained from Winnipeg Transit

The curb weight estimate used in this research is taken from the average of the two bus models shown in Table 16. Based on this information, the baseline weights for buses in this study are 8,620 pounds for the steer axle, 20,568 pounds for the drive axle, and 29,188 pounds for the curb weight. The primary reason the curb weight estimate used in this research was derived from the weigh scale data instead of data from the bus fleet roster is because the weigh scale data includes a measured axle load distribution for the buses at curb weight. Additionally, the bus fleet roster data are an amalgamation of data from several sources; therefore, some of the weights included in Table 15 may correspond to stock bus models and some may include the weight of auxiliary components.

3.2.3 Estimating Laden Passenger Weight

Laden passenger weight estimates for this research were calculated using the following three steps: (1) establish the base male and female weights in Manitoba; (2) estimate the additional amount of weight that should be added to the average male and female base weights to account for clothing and carry-on items; and (3) develop passenger weight scenarios to represent a range of plausible laden passenger weights.

Estimating Base Passenger Weight

Statistics Canada, Health Canada, the Canadian Health Information Management Association (CHIMA), the Canadian Institute for Health Information (CIHI), and Manitoba Health were solicited for weight data in order to establish a representative transit passenger base weight. Statistics Canada was the only source able to provide weight data, as the other organizations are primarily concerned with body mass index (BMI).

The most recent, applicable source of weight data for Manitobans is the *2011 Canadian Community Health Survey* conducted by Statistics Canada. This survey includes self-reported weights disaggregated by age group, gender, and province/territory. No direct-measured (measured by professionals) weight data was available for Manitoba. It should be noted that self-reported weights gathered by the *Canadian Community Health Survey* are on average lower than direct-measured weights [59]. Analysis of the *2008 Canadian Community Health Survey* revealed that men underreported their weights on average by approximately five pounds and women underreported their weights on average by approximately 6 pounds. However, no adjustments were made to the self-reported weights used in this study because the magnitude of underreporting in the *Canadian Community Health Survey* was found to vary significantly based on survey year and no information was available regarding the bias of the *2011 Canadian Community Health Survey*.

Table 17 displays the average base weights for males and females in Manitoba, as presented in the *2011 Canadian Community Health Survey*. The two age groups of interest for this study were ages 18-24 and "all ages". These two groups were included in this study in order to provide an envelope of plausible passenger weights. People aged 18-24 were specifically included in this study because Route 160 is a University route, which primarily serves people of this age range.

Table 17: Average Manitoban Weights by Gender

Age Group	Weight (pounds)	
	Male	Female
Age 18-24	178	141
All Ages	191	153

Source: [60]

Estimating Carry-on Item and Clothing Weight

Laden passenger weight is equal to a passenger's base weight plus the weight of his/her clothing and carry-on items. Therefore, an accurate estimate of a transit rider's laden weight is dependent on the type of items that are common to transit riders, how much these items weigh, and what proportion of riders bring these items onto the bus. The following section of this thesis explains how clothing and carry-on item weights were calculated in this research. Carry-on items were grouped into the six categories shown in Table 18.

Table 18: Assigned Weight of Carry-on Items

Carry-on Item	Description	Assigned Weight (pounds)	Source
Clothes	Fall/spring clothing, such as jeans, sweaters, and casual shoes.	2	[61]
Backpack	A two-strapped bag meant to be worn on the back.	10	[62]
Purse/Handbag	A two handled bag meant to be held in one hand or over one shoulder.	6	[63]
Laptop Bag	A one-strapped bag meant for carrying laptop computers, typically worn over one shoulder.	7	[64]
Other	Miscellaneous items such as musical instruments, skateboards, and other personal items not carried in bags.	5	N/A
No Carry-on		0	N/A

The next step in estimating the weight of carry-on items was to determine the proportion of transit riders that bring each item type onto the bus. This was accomplished with manual counts. Two types of manual carry-on item counts were performed: (1) bus stop counts; and (2) in-service counts.

Bus stop counts involved recording the carry-on items of all passengers boarding and alighting transit buses at a specific bus stop. Two bus stop count locations were selected for this study: (1) Osborne Station; and (2) University of Manitoba Station. Counts were conducted at random times of the day and only passengers boarding and alighting route 160 buses were recorded at these stops. Over 400 transit riders were recorded during these counts (132 counted at Osborne Station and 303 counted at University of Manitoba Station). Approximately the same amount of time was spent conducting manual counts at each site, but more riders were counted at University of Manitoba Station due to the larger volume of riders boarding and alighting at this stop.

In-service counts involved riding Route 160 buses and recording the carry-on items of passengers boarding and alighting the bus and were conducted concurrently with gender split counts. During in-service counts the data recorder sat on the right side of the bus behind the rear door in order to have good vision of both sets of doors, as shown in Figure 12. In-service counts were not conducted when more than 30 passengers were on a bus because the counter's vision of carry-on items could be blocked by other passengers.

Figure 12: View During an In-service Carry-on Item Count

The results of the carry-on item bus stop counts and in-service counts are shown in Table 19. All counts (i.e., bus stop counts and in-service counts) produced similar results. Time limitations were the primary factor in determining sample size for all count types; however, the agreement of the results of each count type suggest that the sample size is sufficiently large for the needs of this study.

Table 19: Carry-on Item Count Results

Carry-on Item	Count			Total	Proportion of Riders (%)
	Osborne Station	U of M Station	In Service		
Backpack	90	198	151	439	65.3
Purse/Handbag	20	56	44	120	17.9
Laptop Bag	14	25	22	61	9.1
No Carry-on	6	18	19	43	6.4
Other	2	6	1	9	1.3
Total	132	303	237	672	100.0

The average carry-on item weight was calculated based on the assigned item weights and cumulative results of the carry-on item counts. The assigned weight of each carry-on item was multiplied by its corresponding proportion of transit riders to obtain a contribution to the average carry-on item weight. The average carry-on item weight was calculated by taking the sum of the contributions of each item type and was found to be approximately 10 pounds. Table 20 shows a summary of how the average carry-on item weight was calculated.

Table 20: Total Weight of Clothing and Carry on Items per Passenger

Carry-on Item	Assigned Weight (pounds)	Proportion of Riders (%)	Contribution (pounds)
Clothing	2	100.0	2.0
Backpack	10	65.3	6.5
Purse/Handbag	6	17.9	1.1
Laptop Bag	7	9.1	0.6
No Carry-on	5	6.4	0.0
Other	0	1.3	0.1
Total			**10.3**

Calculating Laden Passenger Weight

The laden passenger weights for male and female transit riders were calculated by adding the average carry-on item weight (10 pounds) to the base Manitoban weights for each gender (shown in Table 17). Three passenger weight scenarios (PWS) were used in this research to provide an envelope of possible weights for in-service transit buses and to demonstrate the effect of passenger weight estimates on bus weight estimates. Table 21 shows the results of these calculations and summarizes the three PWSs that were used in the axle weight and gross vehicle weight calculations.

Table 21: Passenger Weight Scenarios (PWS)

PWS	Base Passenger Weight Used	Carry-on Weight Added?	Purpose	Laden Passenger Weight (pounds)		
				Male	Female	Avg.
1	Design Standard (150 pounds)	No	To compare the current design standard for average passenger weight to more realistic estimates.	150	150	150
2	Avg. Weight for Manitobans Ages 18 - 24	Yes	To serve as a lower boundary for the weight estimate envelopes.	188	151	169
3	Avg. Weight of Manitobans	Yes	To serve as an upper boundary for the weight estimate envelopes.	201	163	182

3.2.4 Estimate Passenger Load

Winnipeg Transit regularly collects ridership data as a way to improve transit service in Winnipeg and plan future developments. The primary sources of Winnipeg Transit's ridership data are electro-optical sensors located at the front and rear doors of each bus. According to Winnipeg Transit, these sensors are capable of recording the number of passengers boarding and alighting the bus with 98% accuracy. Boarding and alighting data are time stamped and combined with GPS data to determine the passenger loads at each bus stop.

In order to obtain an accurate estimate of typical ridership patterns for Route 160 buses, Winnipeg Transit was solicited for its ridership data for Route 160 trips conducted in 2013. This data included over 70,000 data records containing information on 22 fields. The data was then filtered to exclude all stops outside the study area and to remove extraneous fields. The remaining 50,000 bus stop records represent 791 northbound trips and 961 southbound trips. The four fields required for weight analysis were:

- **Stop ID**: a unique identification number given all Winnipeg Transit stops.
- **Direction:** a binary field that is 0 for southbound trips and 1 for northbound trips.
- **Distance:** the distance in metres between the current stop and the previous stop along the route. This value is equal to 0 for the first stop on each route.

- **Load:** the number of passengers on board the bus as the bus departs the current stop.

The fifth field required for weight analysis was the proportions of the passenger load for each gender. Two sources of gender split data were reviewed as a part of this research: (1) the 2006 Winnipeg Transit Public Attitude Survey; and (2) manually-collected gender split counts.

3.2.4.1 Winnipeg Transit Public Attitude Survey

Public surveys are Winnipeg Transit's only source of gender data. The most recent Winnipeg Transit survey containing gender metrics is the *2006 Public Attitude Survey*. This survey identified several trends about the gender of Winnipeg Transit users that are pertinent to this research (shown in Figure 13):

- Approximately 56% of women use transit compared to 53% of men.
- A higher proportion of women reported using Winnipeg transit than men in each age group except ages 55-64.

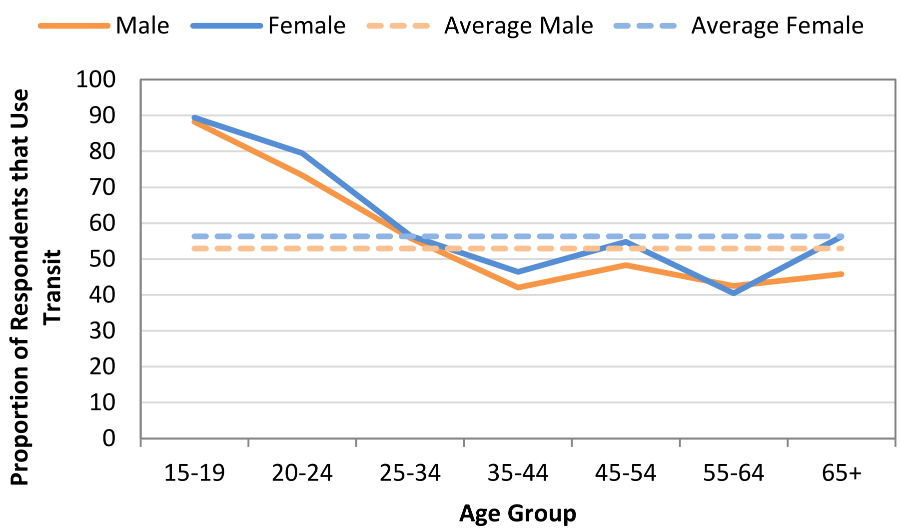


Figure 13: Gender and Age Characteristics of Winnipeg Transit Users

Although the *2006 Public Attitude Survey* identifies that a higher proportion of women in Winnipeg use public transit than men, it does not address the average length of trip made by each gender. Therefore, the findings of this study cannot be used to calculate the probability of a bus passenger being male or female.

3.2.4.2 Gender Split Counts

Instead of using the data provided in the 2006 Public Attitude Survey, manual counts were performed to approximate the gender split of Winnipeg Transit riders on Route 160 at each bus stop. Thirty-six gender split manual counts were conducted (18 northbound and 18 southbound), resulting in more than 300 passengers being counted at each stop (male and female combined). The gender split counts were conducted on weekdays over a three week period from October 14th to November 3rd, 2014. In order to get a more representative sample, researchers attempted to collect at least one count from each hour between 7:00AM – 6:00PM in each direction. Counts were only conducted on weekdays and between 7:00AM – 6:00PM because Route 160 has high passenger volumes and bus frequency during these times. Consequently, the results are biased towards the gender split of Winnipeg Transit users at peak times.

The gender split counts were performed as follows:

1. Record the date and time the bus arrives at the first stop on the route (i.e., Osborne Station for the southbound route or the University of Manitoba Station for the northbound route).
2. Record the bus identification number and gender of the bus driver while boarding the bus.
3. Sit (or stand) in a position on the bus with unobstructed sightlines of both doors, preferably towards the rear of the bus.
4. Take an initial count of the male and female passengers.

5. Record any changes to the number of male and female passengers at each bus stop in the study area. (Note: if one passenger exited the bus and a passenger of the same gender boarded the bus at the same stop then no change was recorded).
6. Periodically recount the passengers on board to ensure accuracy of the count. Recounts were not always feasible due to the work load they imposed on the counter and/or obstructed views caused by high passenger loads. Subsequently, recounts were done at the discretion of the counter.

The three main challenges of the Winnipeg Transit passenger gender split counts were (1) conducting initial counts when there were more than 45 passengers on board, (2) maintaining an accurate count when there were more than 45 passengers on board, and (3) maintaining an accurate count when multiple people board and exit the bus simultaneously. In several circumstances the manual counts had to be discarded due to these issues.

The results of the gender split manual counts are shown in Figure 14, Figure 15, and Table 22. The total male and female passenger counts displayed in Figure 14 and Figure 15 were used to calculate the proportion of male and female riders at each bus stop, as shown in Table 22.

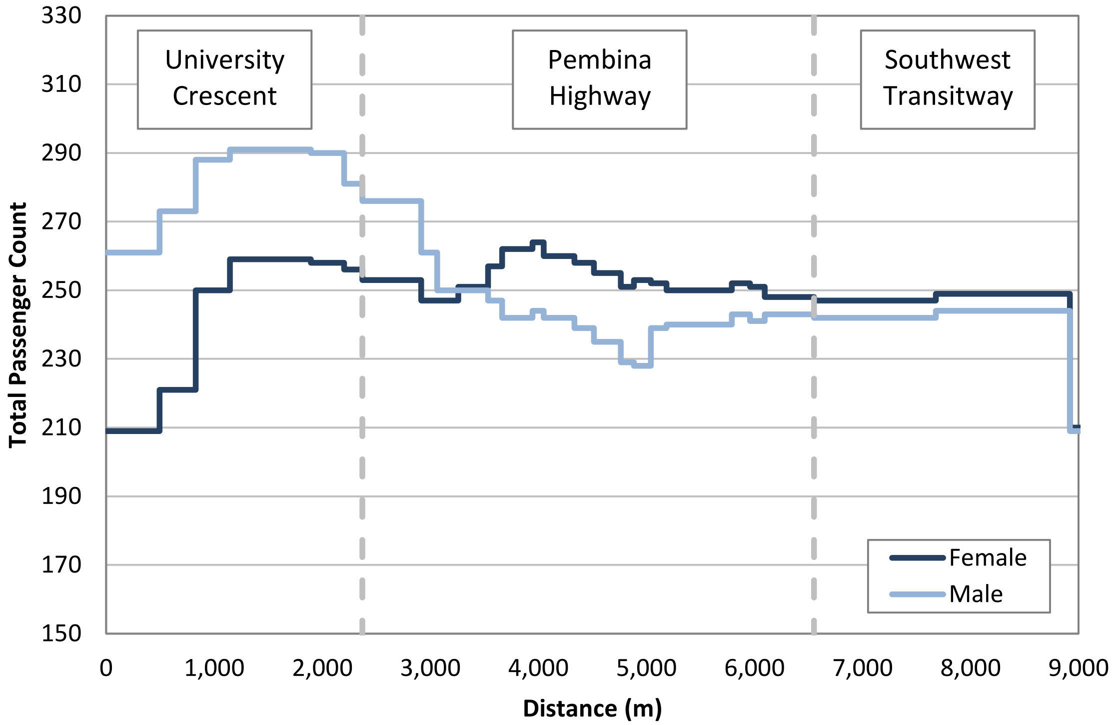


Figure 14: Northbound Gender Split – U of M Station to Osborne Station

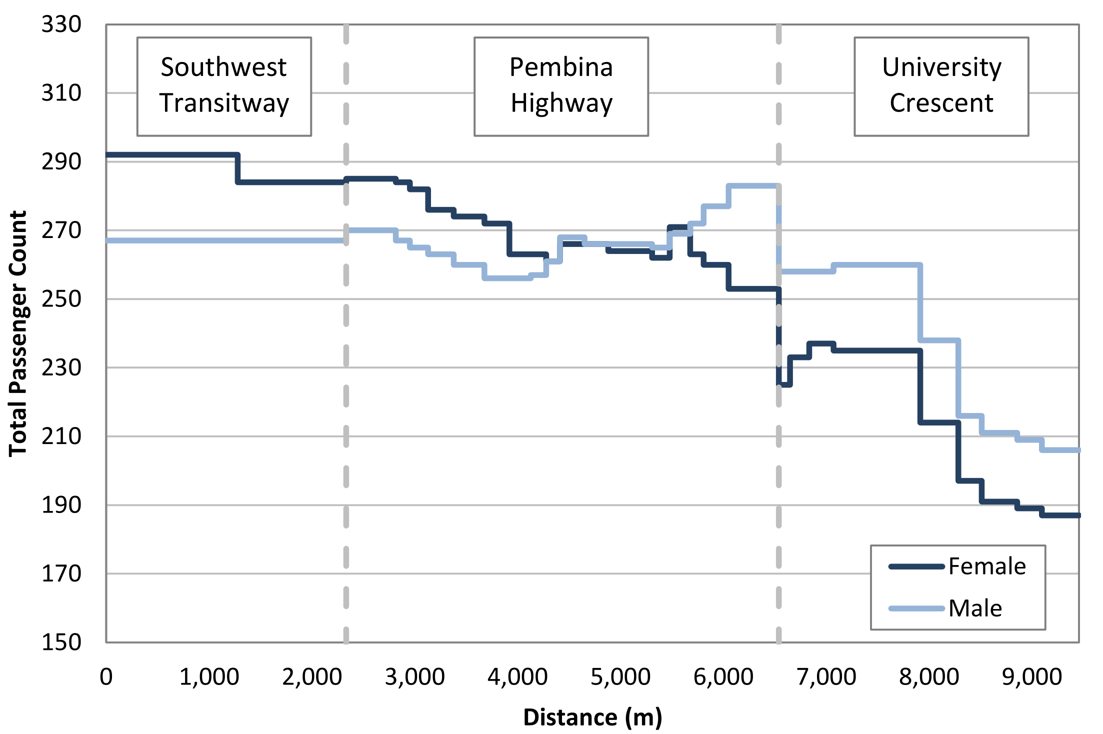


Figure 15: Southbound Gender Split – Osborne Station to U of M Station

Table 22: Gender Splits by Bus Stop

Northbound Route Stop Name	Male (%)	Female (%)
WB Dafoe - U of M	55.5	44.5
WB Dafoe - U of M (School of Music)	55.3	44.7
NB University - Chancellor Matheson	53.5	46.5
NB University - Dysart	52.9	47.1
NB University - Markham	52.9	47.1
NB University - Thatcher	52.9	47.1
NB University - Wedgewood	52.3	47.7
NB University - Pembina	52.2	47.8
NB Pembina - Plaza	51.38	48.62
NB Pembina - Adamar	50.3	49.7
NB Pembina - Adamar North	49.9	50.1
NB Pembina - Manahan South	49.0	51.0
NB Pembina - Manahan	48.0	52.0
NB Pembina - Crescent	48.0	52.0
NB Pembina - Nesbitt	48.2	51.8
NB Pembina - Crane	48.1	51.9
NB Pembina - Fletcher	48.0	52.0
NB Pembina - Dowker	47.7	52.3
NB Pembina - Waller	47.4	52.6
NB Pembina - Oakenwald	48.7	51.3
NB Pembina - Riverwood	49.0	51.0
NB Pembina - North Drive	49.0	51.0
NB Pembina - Point Road	49.1	50.9
NB Pembina - Calrossie	49.0	51.0
NB Pembina - Merriam	49.5	50.5
NB Southwest Transitway - Jubilee	49.5	50.5
NB Southwest Transitway - Fort Rouge Station	49.5	50.5
NB Southwest Transitway - Osborne Station	49.9	50.1

Southbound Route Stop Name	Male (%)	Female (%)
SB Southwest Transitway - Osborne Station	47.8	52.2
SB Southwest Transitway - Fort Rouge Station	48.5	51.5
SB Southwest Transitway - Jubilee	48.7	51.3
SB Pembina - Calrossie	48.5	51.5
SB Pembina - Byng	48.5	51.5
SB Pembina - Windermere	48.8	51.2
SB Pembina - North Drive	48.7	51.3
SB Pembina - Southwood	48.5	51.5
SB Pembina - McGillivray	49.3	50.7
SB Pembina - Radisson	49.4	50.6
SB Pembina - Kelsey	50.0	50.0
SB Pembina - Clarence	50.2	49.8
SB Pembina - Royse	50.0	50.0
SB Pembina - Chevrier	50.2	49.8
SB Pembina - Manahan	50.3	49.7
SB Pembina - Manahan South	49.8	50.2
SB Pembina - Adamar North	50.8	49.2
SB Pembina - Adamar	51.6	48.4
SB Pembina - Plaza	52.8	47.2
SB Pembina – University Crescent	53.4	46.6
SB University - Pembina	52.6	47.4
SB University - Wedgewood	52.1	47.9
SB University - Thatcher	52.5	47.5
SB University - Markham	52.5	47.5
SB University - Dysart	52.6	47.4
SB University - Dafoe	52.3	47.7
SB University - Freedman	52.5	47.5
EB Freedman - King's Drive	52.5	47.5
EB Freedman - Maclean	52.4	47.6
WB Dafoe - U of M	N/A	N/A

Although the results of the 2006 Public Attitude Survey suggest that women are more likely to use Winnipeg Transit, the gender split manual counts conducted in this research can be used to illustrate that overall both genders have an equal amount of exposure (in terms of VKT) on Route 160 buses. Therefore, without knowing the location of a Route 160 bus the probability that a passenger on that bus is female (or male) is approximately 50%. Table 23 shows the level of exposure for men and women determined during the gender split manual counts.

Table 23: Male and Female Transit Exposure

Direction	Exposure (VKT)		
	Male	Female	Total
Northbound	2,474	2,421	4,895
Southbound	2,438	2,427	4,865
Total	4,912	4,848	9,760
Proportion	50.3%	49.7%	

The levels of exposure shown in Table 23 were calculated using the following formula:

$$Exposure_g = \sum_{Bus\ Stop\ i=1}^{n} Passengers_g \times Distance_i$$

Where:

Exposure$_g$ = the total vehicle-kilometres travelled by all passengers of gender 'g'

Bus Stop$_i$ = one of the bus stops listed in Table 14, with i = 1 referring to the first stop on the route and i = n referring to the last stop on the route.

Passengers$_g$ = the total number of passengers of gender 'g' counted at bus stop 'i' as the bus departs the stop

Distance$_i$ = the distance between bus stop 'i' and bus stop 'i+1'

3.2.5 Estimating Axle Split

The axle split for each bus was calculated using: (1) passenger seating models (PSMs) to estimate where passengers sit at various passenger loads; and (2) moment diagrams to calculate the axle split based on the passenger seating models.

3.2.5.1 Passenger Seating Models

The axle split of a transit bus can be difficult to estimate because it is dependent on the total number of passengers on the bus and where each passenger sits (or stands) on the bus. Observations made during the gender split manual counts were used to develop estimates of where passengers sit based on the total number of passengers on board, hereafter referred to as passenger seating models (PSMs). In these models, buses were assumed to have the seating layout shown in Figure 16 (a common seating layout for Winnipeg Transit buses). Additionally, all passengers were assumed to be travelling as individuals.

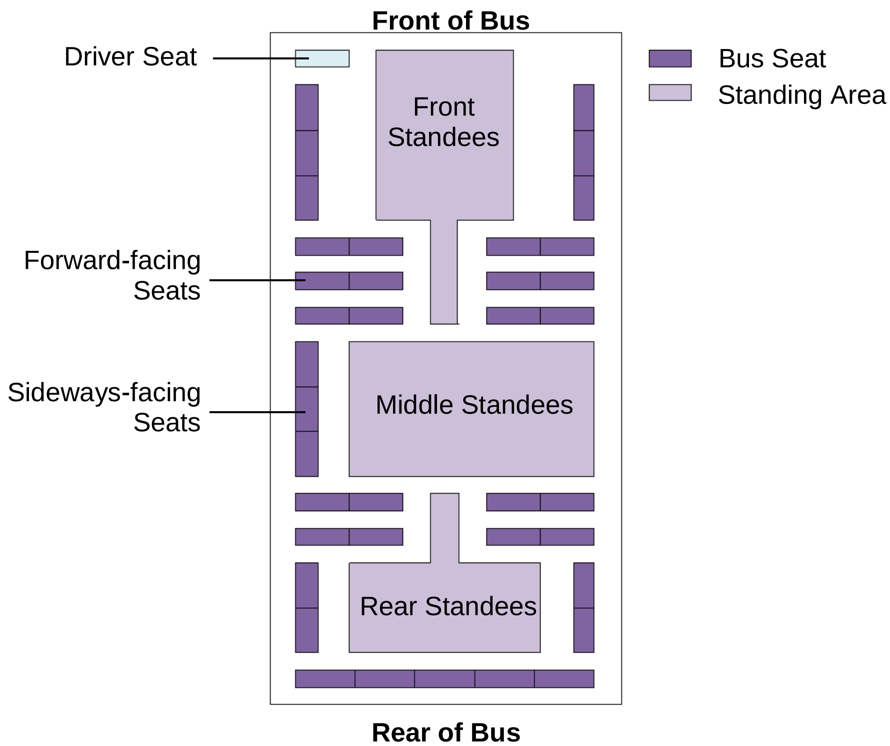


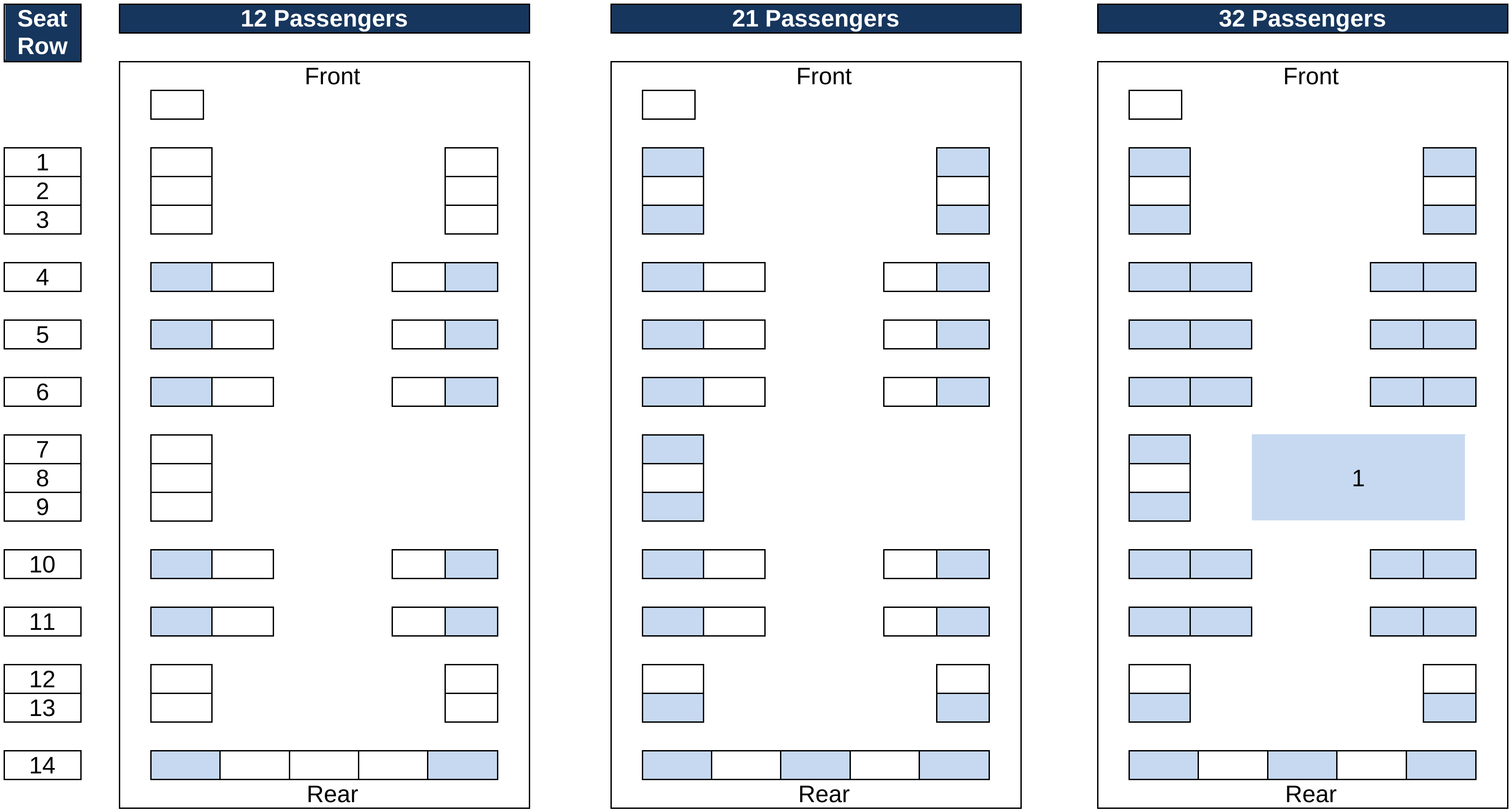
Figure 16: Bus Seating Layout

The following observations were made during manual counts regarding how passengers select where to sit on the bus:

- Passengers prefer to sit in seats that have no adjacent passengers.
- On average, passengers have no preference for sitting near the front or rear of the bus. Their highest priority is sitting in a row with no other passengers.

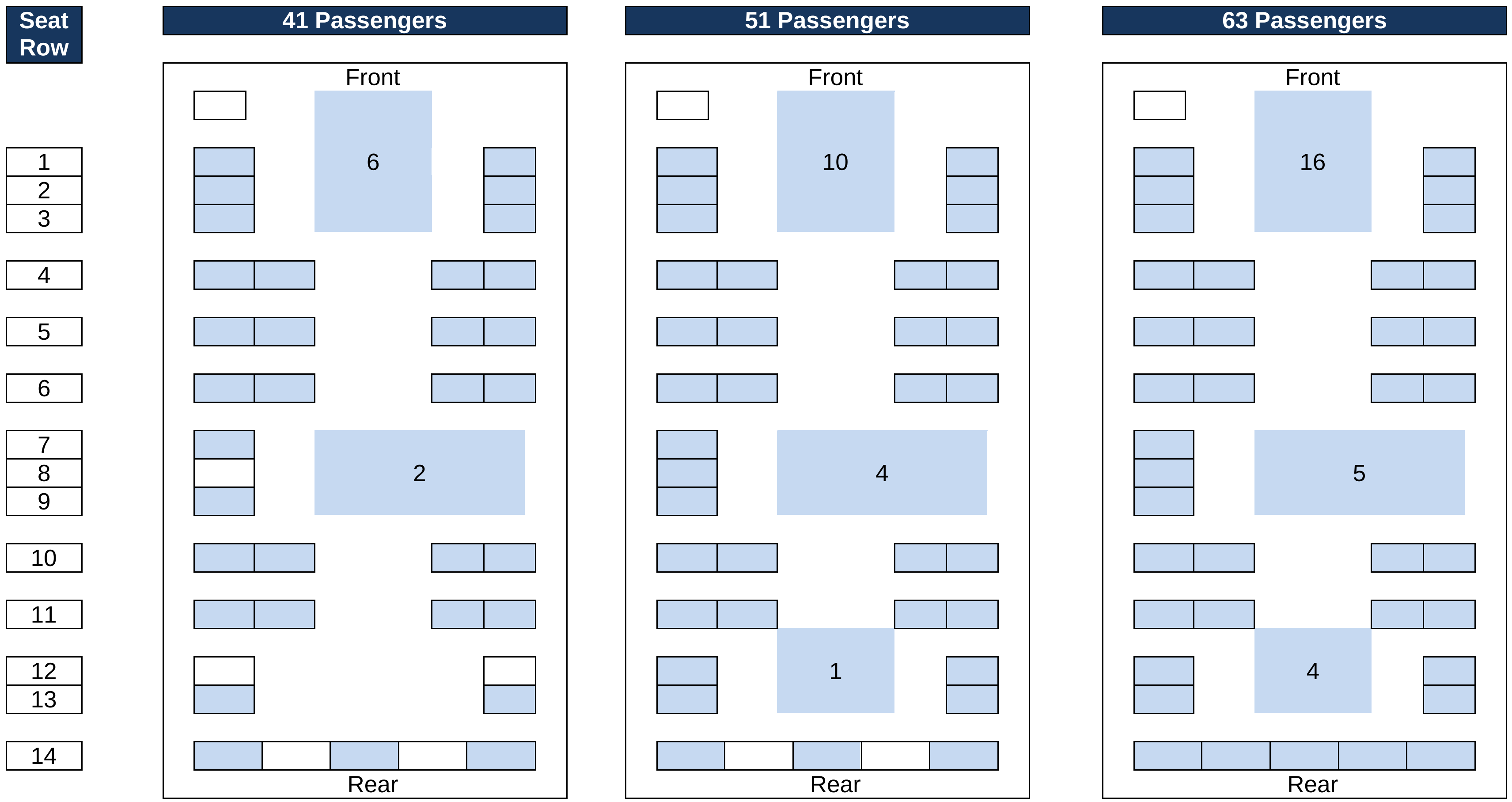
- In general, passengers prefer to sit in the forward-facing seats. However, passengers will sit in sideways-facing seats rather than sit beside another passenger.
- Once there are no more spots where passengers can sit without another person beside them, passengers will begin to stand or sit beside other passengers in the forward-facing rows.
- The first person to stand will generally stand by the rear door.
- Passengers strongly avoid sitting between two other passengers.
- Passengers will often opt to stand rather than sit between two other passengers, even when the bus is crowded.
- Passengers attempting to avoid sitting between two other passengers often block other passengers from accessing these seats.
- Passengers strongly avoid standing at the rear of the bus.
- Passengers attempting to avoid standing at the rear of the bus often block other passengers from standing at the rear of the bus and force many people to stand near the front of the bus.

Six PSMs were developed based on these observations and are shown in Figures 17 to 22. Occupied seats are designated by blue shading and the number of standees in the standing areas is displayed with numerical values. No PSMs were developed with more than 63 passengers because 63 passengers was the highest passenger load for Route 160 buses in 2013, according to the Winnipeg Transit ridership data.



*Blue shaded areas represent occupied seats/standing areas. The number of standees in standing areas is designated by a numerical value.

Figure 17: PSM A – 12 Passengers **Figure 18: PSM B – 21 Passengers** **Figure 19: PSM C – 32 Passengers**



*Blue shaded areas represent occupied seats/standing areas. The number of standees in standing areas is designated by a numerical value.

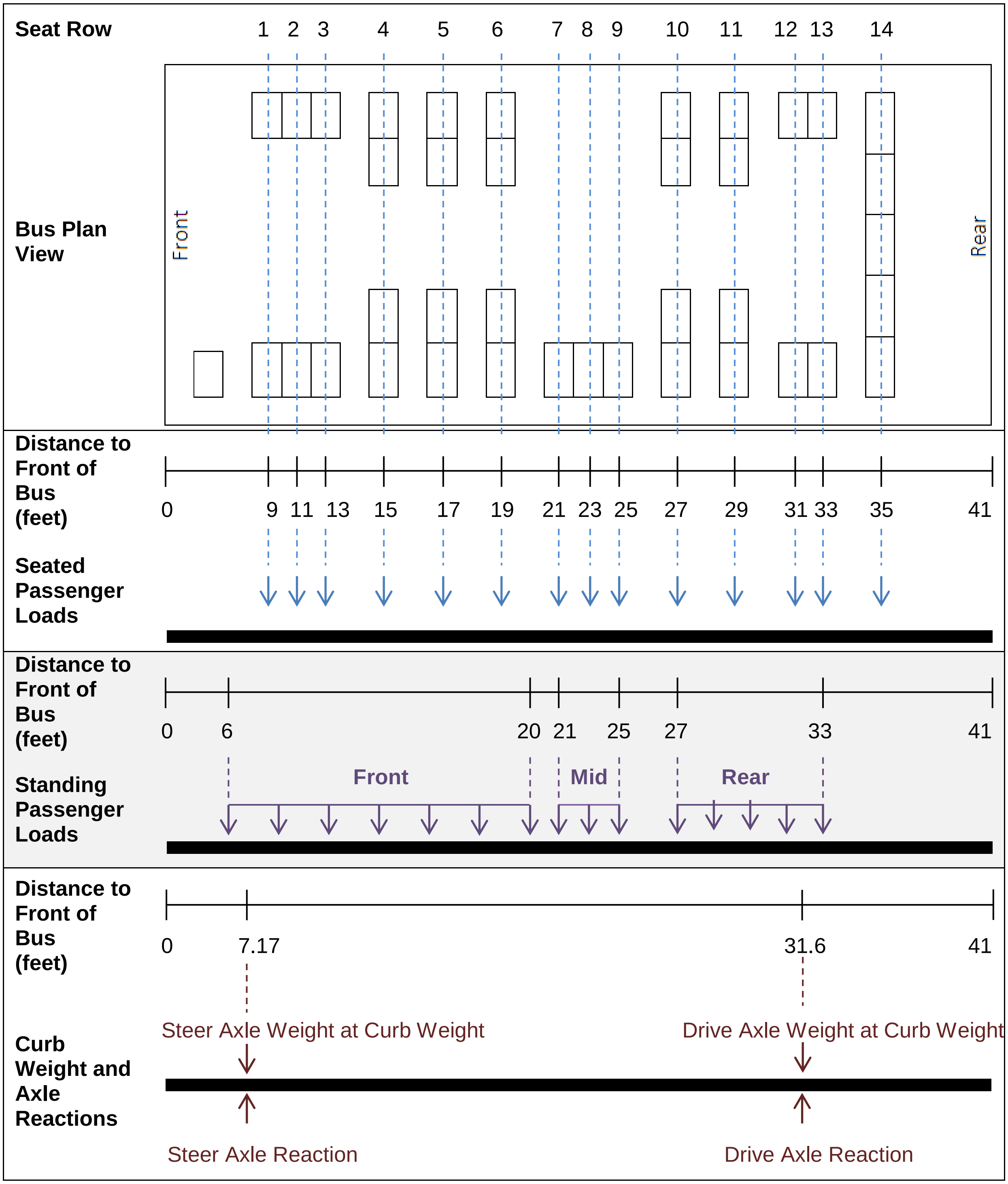
Figure 20: PSM D – 41 Passengers **Figure 21: PSM E – 51 Passengers** **Figure 22: PSM F – 63 Passengers**

3.2.5.2 Moment Diagrams

Once the passenger seating models (PSMs) were established, moment diagrams were used to calculate the axle weight split for each PSM. When calculating moments the gender split was assumed to be 50% male – 50% female because of the exposure results determined in Section 3.2.4.2. Based on a 50/50 gender split, each passenger was assumed to weigh 169 pounds, which is the average laden weight of Passenger Weight Scenario 2 (Manitobans aged 18-24 with carry-on items). As mentioned in Section 3.2.2, the curb weight axle loads used in this study were 8,620 pounds on the steer axle and 20,568 pounds on the drive axle.

Collectively, the seated passenger load moment diagram, standing passenger load moment diagram, and the curb weight and reactions moment diagram (shown in Figure 23) form the total moment diagram that was used when calculating axle split. Six axle splits were calculated using the total moment diagram – one for each PSM (see Table 24). The axle splits for all other passenger loads were calculated by linearly interpolating from the PSMs' axle splits. As shown in Table 24, this research estimates that the steer axle of a standard transit bus carries a higher percentage of the gross vehicle weight as passenger load increases.

The steer axle location and drive axle location shown in the moment diagrams are based on the dimensions reported by Altoona for the New Flyer D40LF model tested in 2007 [8]. However, no specifications were available regarding the exact locations of seats and standing areas. Instead, the seat locations and standing locations were estimated in the moment diagrams using approximate measurements taken during data collection in conjunction with the known New Flyer D40LF axle locations.



*Diagrams are not to scale

**The passenger seating model moment diagrams were developed assuming that seating passengers were point loads and standing passengers were uniformly distributed loads.

Figure 23: Passenger Seating Model Moment Diagram

Table 24: PSM Derived Axle splits

PSM	Passengers	GVW (pounds)	Steer Axle Weight (pounds)	Drive Axle Weight (pounds)	Steer Axle (%)	Drive Axle (%)
Curb Weight	**0**	29,188	8,620	20,568	29.5	70.5
A	**12**	31,217	9,278	21,939	29.7	70.3
B	**21**	32,739	9,924	22,815	30.3	69.7
C	**32**	34,599	10,688	23,911	30.9	69.1
D	**41**	36,121	11,805	24,316	32.7	67.3
E	**51**	37,812	12,517	25,295	33.1	66.9
F	**63**	39,841	13,334	26,507	33.5	66.5

4 ANALYSIS AND DISCUSSION

This Chapter describes the results of the in-service weight estimates for Route 160 transit buses operating in Winnipeg. The findings of this research are organized into five sections: (1) gross vehicle weight analysis; (2) steer axle weight analysis; (3) drive axle weight analysis; (4) ESAL analysis; and (5) discussion of findings. Four weight estimates are analyzed and discussed in each analysis section – one estimate from Altoona's bus testing program and one estimate for each passenger weight scenario (PWS) described in Table 21.

4.1 GROSS VEHICLE WEIGHT ANALYSIS

The gross vehicle weight analysis consists of three components:

(1) **General Analysis –** a comparison of the weight estimates for a transit bus under various loading conditions.

(2) **Exposure analysis** – an estimation of the percent of travel (in terms of VKT) that Route 160 transit buses operate below specific gross vehicle weights.

(3) **Spatial analysis –** identification of spatial trends of transit bus weights.

4.1.1 General Analysis

Figure 24 shows the curb weight (CW), seated load weight (SLW), and fully-loaded weight (FLW) estimates for:

- PWS 1: all passengers are assumed to weigh 150 pounds;
- PWS 2: male passengers are assumed to weigh 188 pounds and female passengers are assumed to weigh 151 pounds;
- PWS 3: male passengers are assumed to weigh 201 pounds and female passengers are assumed to weigh 163 pounds; and

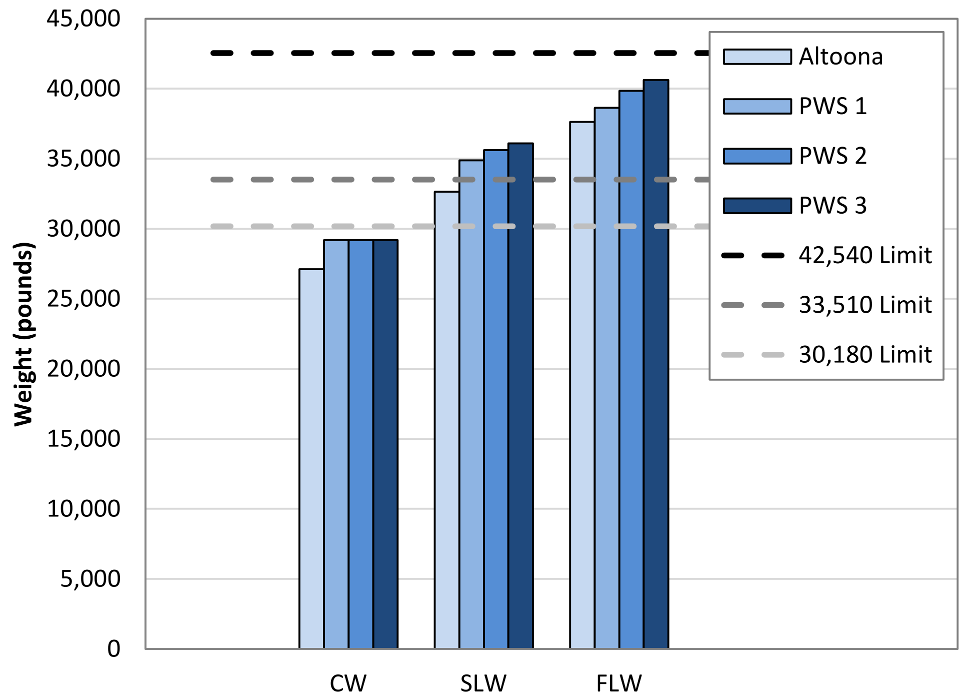
- The New Flyer D40 LF as reported in its Altoona bus test report weight check-in summary (see Table 11).

The SLW estimates shown in Figure 24 were calculated assuming a passenger load of 38 passengers. The FLW estimates shown in Figure 24 were calculated assuming a passenger capacity of 63 passengers for the estimates produced by this research and a passenger capacity of 73 passengers for the Altoona estimate (Altoona assumes the passenger capacity of a transit bus is one passenger per seat and one passenger per 1.5 ft^2 of floor space). The following GVW limits are shown in Figure 24 to act as a reference:

(1) Winnipeg's spring weight restriction GVW limit– 30,180 pounds

(2) Winnipeg's maximum allowable GVW – 33,510 pounds

(3) Gross vehicle weight rating (GVWR) for a New Flyer D40 LF – 42,540 pounds



* The Altoona weight estimates presented in this figure are derived from Table 11

Figure 24: GVW Estimate Comparison at Curb Weight (CW), Seated Load Weight (SLW), and Fully-Loaded Weight (FLW)

Key Findings of the General Analysis

This research estimates that:

- Transit buses exceed the governing GVW limit in Winnipeg (33,510 pounds) when at seated load and fully-loaded, regardless of the assumed passenger weight.
- The maximum GVW estimate is 40,630 pounds (PWS 3 at fully-loaded weight).
- Fully-loaded Route 160 transit buses exceed the GVW limit in Winnipeg during spring weight restrictions by approximately 8,500-10,400 pounds.
- The FLW estimate for PWS 1 (Design Standard) is approximately 1,200 pounds lighter than the FLW estimate for PWS 2 (Ages 18-24) and 2,000 pounds lighter than the FLW estimate for PWS 3 (All Ages).
- The Altoona FLW estimate is approximately 1,000 pounds less than the lowest estimate calculated in this research even though the Altoona estimate assumes that there are 10 more passengers on board a New Flyer D40 LF when fully-loaded.

4.1.2 Exposure Analysis

Figure 25 shows the estimated cumulative distribution of gross vehicle weights by VKT for 1,752 Route 160 trips for each of the three Passenger Weight Scenarios (PWS). Gross vehicle weights analyzed in this section are plotted against cumulative distribution of vehicle-kilometres travelled (VKT) in order to reflect the loading experienced by the pavements in the study area. An analysis by VKT is possible because transit bus weights remain constant between bus stops; therefore, the weight estimate at each bus stop can be assigned to the road segment between the current stop and the next stop on the route. These trips represent a total VKT of 16,145 kilometres.

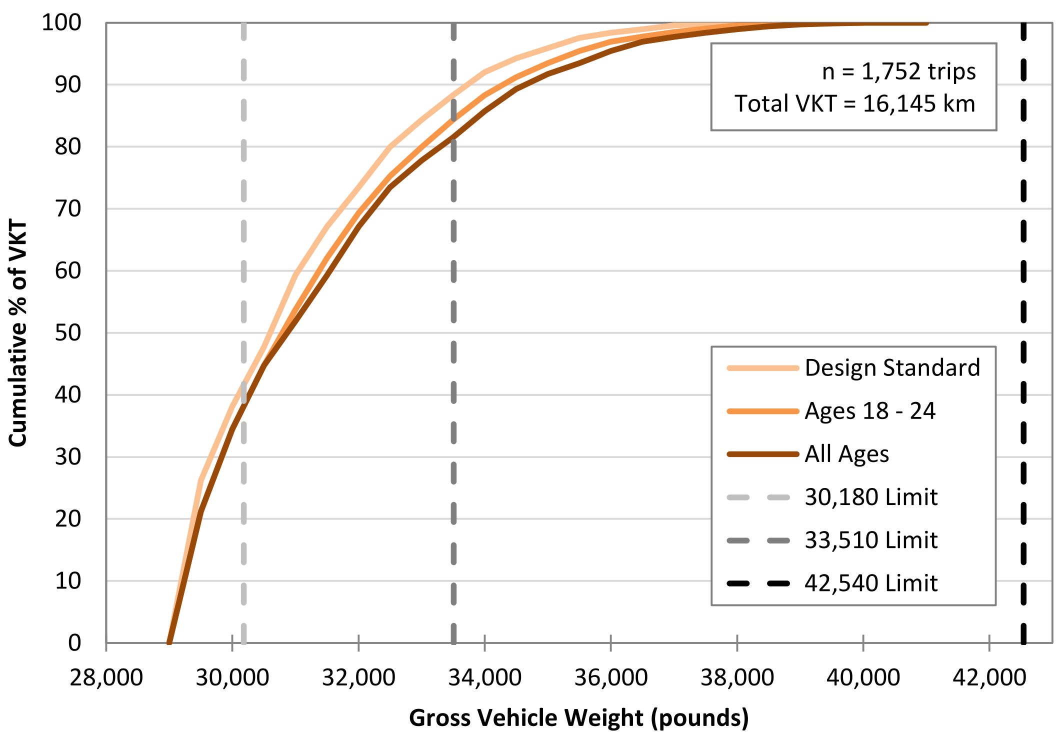
Figure 26 shows the estimated cumulative distribution of gross vehicle weights by VKT for the 1,752 Route 160 trips separated by the direction of travel (791 northbound and

961 southbound). These trips resulted in 7,056 northbound VKT and 9,089 southbound VKT. Only the results for Passenger Weigh Scenario 2 (Ages 18-24) are shown Figure 26. It should be noted that cumulative distribution weight curves typically take the form of an “S-curve”; however, this trend in is not present in Figure 25 and Figure 26 because all Route 160 transit buses are assumed to have a curb weight of 29,188 pounds in this analysis. The following gross vehicle weight limits are shown on Figures 25 and 26 to act as a reference:

(1) Winnipeg’s spring weight restrictions gross vehicle weight limit – 30,180 pounds

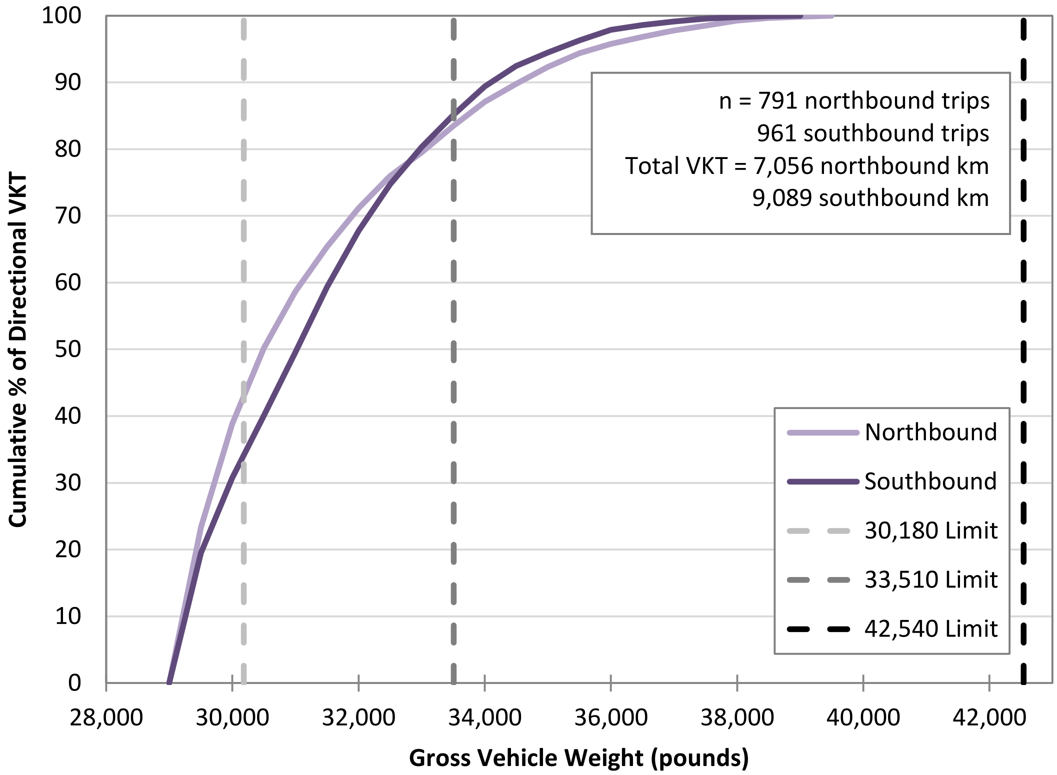
(2) Winnipeg’s maximum allowable GVW – 33,510 pounds

(3) Gross vehicle weight rating (GVWR) for the New Flyer D40 LF – 42,540 pounds



Assumed Weight (pounds)	PWS 1 (Design Standard)	PWS 2 (Ages 18-24)	PWS 3 (All Ages)
Male Passengers	150	188	201
Female Passengers	150	151	163

Figure 25: Route 160 Transit Bus GVW Distribution by VKT



Assumed Weight (pounds)	Male Passengers	Female Passengers
PWS 2 (Ages 18-24)	188	151

Figure 26: GVW Distribution by Direction for Passenger Weight Scenario 2

Key Findings of the Exposure Analysis

This research estimates that:

- 38% of Route 160 transit bus VKT is in compliance with the GVW limit on roads subject to spring weight restrictions (30,180 pounds)
- 81-84% of Route 160 transit bus VKT is in compliance with the Winnipeg's maximum allowable GVW (33,510 pounds)
- 100% of Route 160 transit bus VKT is in compliance with the GVWR for the New Flyer D40 LF (42,540 pounds)
- Route 160 transit buses operate at weights below the GVWR for New Flyer D40 LF buses at all times.
- Route 160 transit buses are rarely fully-loaded (less than 1% of the total VKT).

- From a practical standpoint there is no significant difference between the distributions of GVW for northbound and southbound Route 160 transit buses. However, Figure 26 shows that a greater percent of VKT for northbound buses is conducted at weights close to the curb weight (29,188 pounds) and close to the fully-loaded weight (~40,000 pounds) than for southbound buses.

4.1.3 Spatial Analysis

Figures 27 and 28 show the mean, 85th percentile, and maximum GVW estimate for each bus stop along Route 160's northbound and southbound routes. In Figures 27 and 28, distance is measured relative to the first stop on the route and is based on the bus stop information presented in Table 14. The sections of each route that are conducted on University Crescent, Pembina Highway, and the Southwest Transitway are identified in each figure.

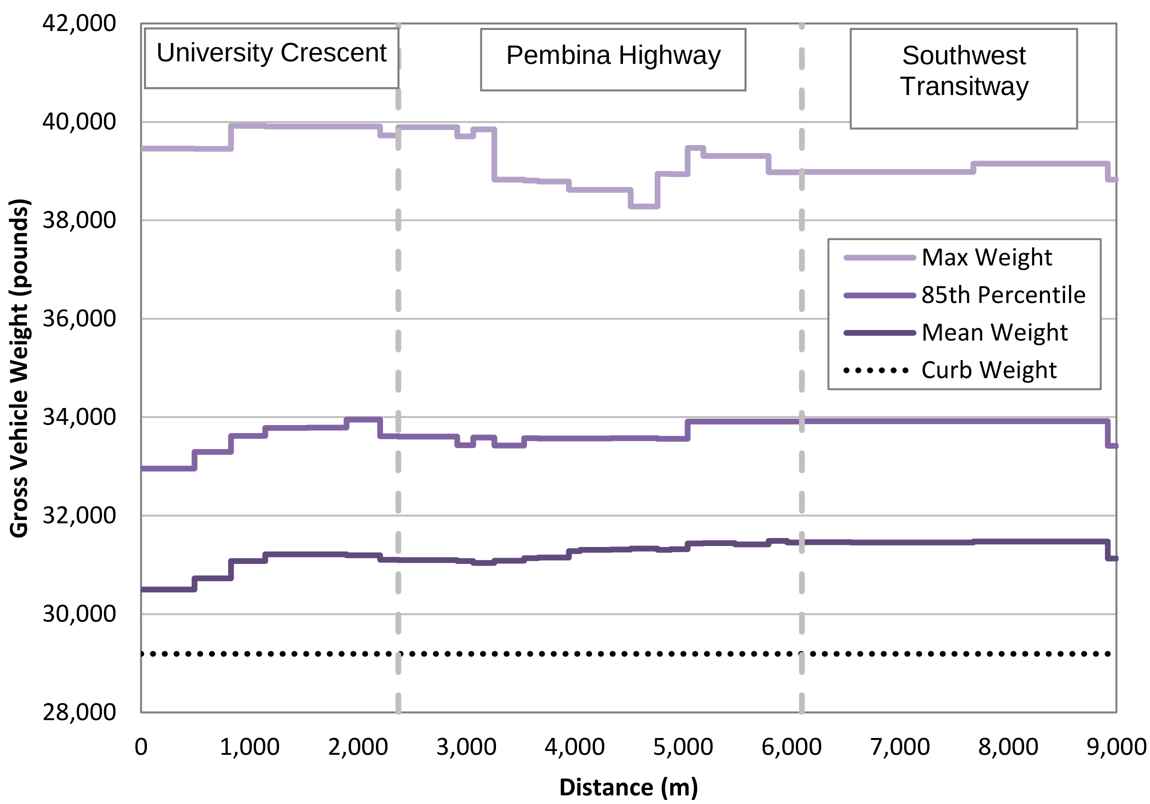


Figure 27: Northbound Gross Vehicle Weights by Location

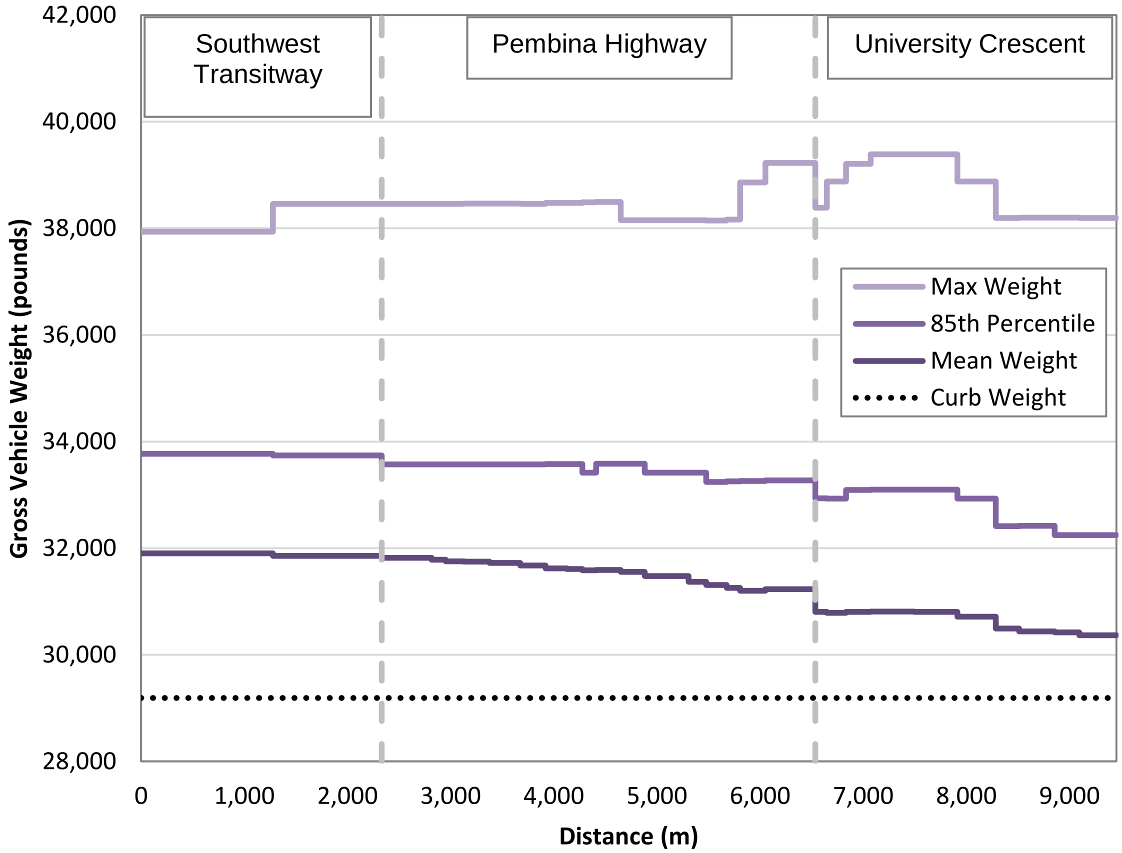


Figure 28: Southbound Gross Vehicle Weights by Location

Key Findings of the Spatial Analysis

This research estimates that:

- Route 160 transit buses have the highest average weights when operating on, or in close proximity to, the Southwest Transitway. This trend is present for both northbound and southbound buses.
- In the northbound direction Route 160 transit buses are the heaviest on University Crescent between Chancellor Matheson Road and Wedgewood Drive.
- In the southbound direction Route 160 transit buses are the heaviest on University Crescent between Thatcher Drive and Dysart Road.

4.2 STEER AXLE WEIGHT ANALYSIS

The steer axle weight analysis consists of two components:

(1) **General Analysis** – a comparison of the weight estimates for the steer axle of a transit bus under various loading conditions.

(2) **Exposure analysis** – an estimation of the percent of travel (in terms of VKT) that Route 160 transit buses operate with steer axles below specific weights.

Since steer axle weights in this research are calculated based on GVW, a spatial analysis of the steer axle weight estimates would be redundant. That is, the spatial trends in transit bus steer axle weights are the same as the spatial trends in GVW. The spatial trends in transit bus GVW are shown in Figures 27 and 28.

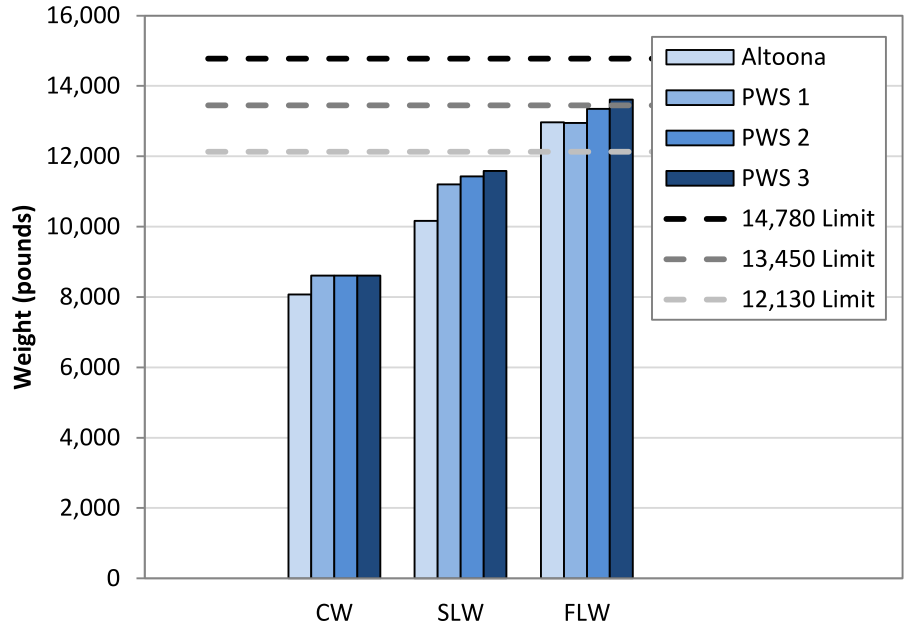
4.2.1 General Analysis

Figure 29 presents a comparison of steer axle weights for transit buses at curb weight (CW), seated load weight (SLW), and fully-loaded weight (FLW). The weight estimates in Figure 29 correspond to each of the passenger weight scenarios (PWS) in this research and the steer axle weight estimates published by Altoona for the New Flyer D40 LF. The SLW estimates shown in Figure 29 were calculated assuming a passenger load of 38 passengers. The FLW estimates shown in Figure 29 were calculated assuming a passenger capacity of 63 passengers for the estimates produced by this research and a passenger capacity of 73 passengers for the Altoona estimate. Three steer axle weight limits are shown in Figure 29 to act as a reference:

(1) Winnipeg's spring weight restrictions steer axle weight limit – 12,130 pounds

(2) Winnipeg's maximum allowable steer axle weight – 13,450 pounds

(3) GAWR for the steer axle of a New Flyer D40 LF bus – 14,780 pounds



* The Altoona weight estimates presented in this figure are derived from Table 11

Figure 29: Steer Axle Weight Estimate Comparison at Curb Weight (CW), Seated Load Weight (SLW), and Fully-Loaded Weight (FLW)

Key Findings of the General Analysis

This research estimates that:

- The steer axle weight of a fully-loaded Route 160 transit bus is below the governing steer axle weight limit in Winnipeg (13,450 pounds) for all assumed passenger weights except for PWS 3 (All ages).
- The FLW estimate for PWS 3 is 13,610 pounds, which equates to a tire pressure of approximately 567 pounds per inch. This exceeds the governing steer axle weight limit by a total weight of 160 pounds or 7 pounds per inch of tire width.
- The FLW steer axle weight estimates for PWS 1, 2, and 3 exceed the spring weight restriction limit in Winnipeg (12,130 pounds) by 800 pounds, 1,200 pounds, and 1,500 pounds, respectively.
- The steer axle weight estimate for a fully-loaded transit bus for PWS 1 (Design Standard) is approximately 400 pounds lighter than the estimate for PWS 2 (Ages 18-24) and 700 pounds lighter than the estimate for PWS 3 (All Ages).

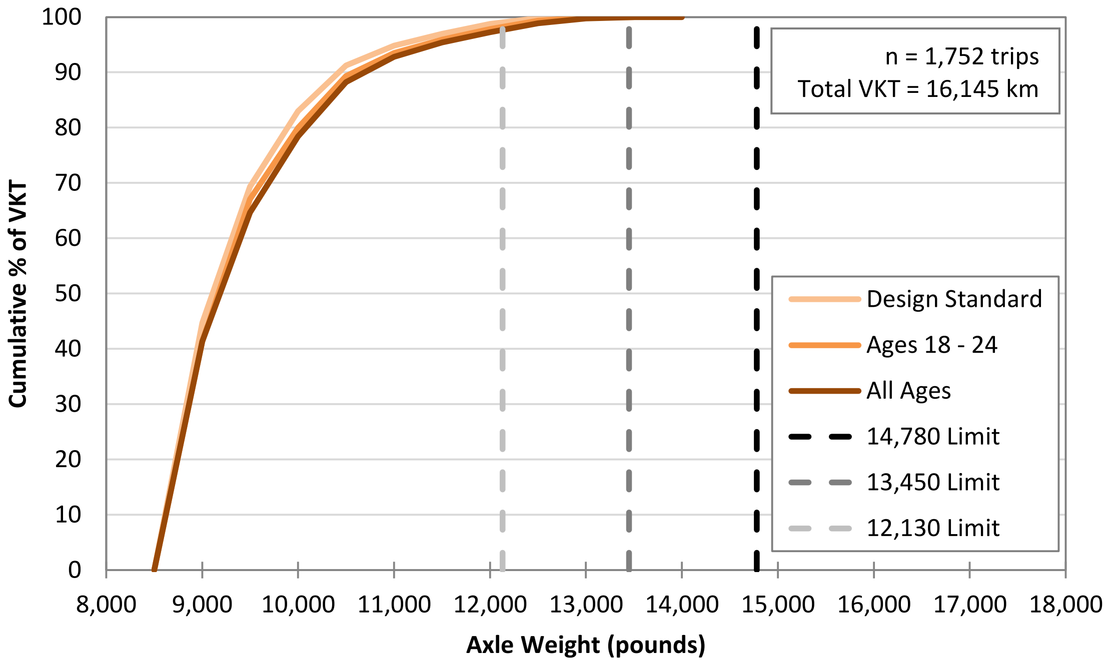
4.2.2 Exposure Analysis

Figure 30 shows the cumulative distribution of steer axle weights by VKT. Similar to the GVW analysis, steer axle weights displayed in this section are plotted against cumulative distribution of VKT in order to assess how often pavements are exposed to various transit bus steer axle weights. Three steer axle weight limits are shown on Figure 30 to act as a reference:

(1) Winnipeg's spring weight restrictions steer axle weight limit – 12,130 pounds

(2) Winnipeg's maximum allowable steer axle weight – 13,450 pounds

(3) GAWR for the steer axle of a New Flyer D40 LF – 14,780 pounds



Assumed Weight (pounds)	PWS 1 (Design Standard)	PWS 2 (Ages 18-24)	PWS 3 (All Ages)
Male Passengers	150	188	201
Female Passengers	150	151	163

Figure 30: Steer Axle Split by VKT

Key Findings of the Exposure Analysis

This research estimates that:

- 98-99% of Route 160 transit bus VKT is conducted in compliance with the steer axle weight limit on roads subject to spring weight restrictions (12,130 pounds)

- >99.9% of Route 160 transit bus VKT is conducted in compliance with Winnipeg's maximum allowable steer axle weight (13,450 pounds)
- 100% of Route 160 transit bus VKT is conducted in compliance with the steer axle GAWR for the New Flyer D40 LF (14,780 pounds)

4.3 DRIVE AXLE WEIGHT ANALYSIS

The drive axle weight analysis consists of two components:

(1) **General Analysis** – a comparison of the weight estimates for the drive axle of a transit bus under various loading conditions.

(2) **Exposure analysis** – an estimation of the percent of travel (in terms of VKT) that Route 160 transit buses operate with drive axles below specific weights.

Similar to the analysis of steer axle weights, a spatial analysis of drive axle weights would be redundant since drive axle weights in this research are calculated based on GVW.

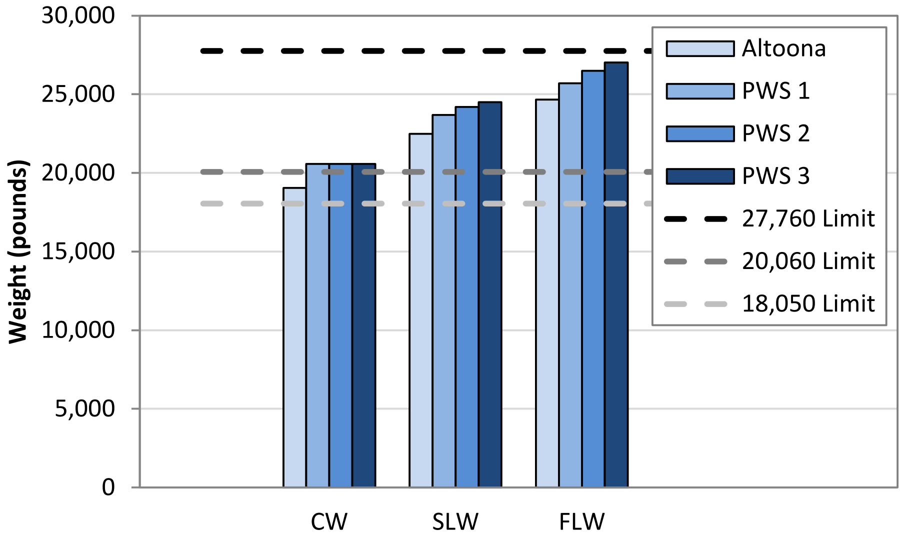
4.3.1 General Analysis

Figure 31 presents a comparison of drive axle weights for transit buses at curb weight (CW), seated load weight (SLW), and fully-loaded weight (FLW). The weight estimates in Figure 29 correspond to each of the passenger weight scenarios (PWS) in this research and the estimates published by Altoona for the New Flyer D40 LF. The SLW estimates shown in Figure 31 were calculated assuming a passenger load of 38 passengers. The FLW estimates shown in Figure 31 were calculated assuming a passenger capacity of 63 for the estimates produced by this research and 73 for the Altoona estimate. Three drive axle weight limits are shown on Figure 31 to act as a reference:

(1) Winnipeg's spring weight restrictions drive axle limit – 18,050 pounds

(2) Winnipeg's maximum allowable drive axle weight – 20,060 pounds

(3) GAWR for the drive axle of a New Flyer D40 LF bus – 27,760 pounds



* The Altoona weight estimates presented in this figure are derived from Table 11

Figure 31: Drive Axle Weight Estimate Comparison at Curb Weight (CW), Seated Load Weight (SLW), and Fully-Loaded Weight (FLW)

Key Findings of the General Analysis

This research estimates that:

- The drive axle of a fully-loaded Route 160 transit bus weighs 6,600-9,000 pounds more than the single axle weight limit on roads subject to spring weight restriction in Winnipeg (18,050 pounds).
- The drive axle of a fully-loaded Route 160 transit bus weighs 4,600-7,000 pounds more than the governing single axle weight limit in Winnipeg (20,060 pounds).
- The drive axle of an empty Route 160 transit bus weighs approximately 500 pounds more than the governing single axle weight limit in Winnipeg (20,060 pounds).
- The FLW estimate for PWS 3 is 27,020 pounds, which equates to a tire pressure of approximately 563 pounds per inch of tire width. This exceeds the governing driver axle weight limit by 6,960 pounds and exceeds the tire pressure limit by approximately 3 pounds per inch of tire width (the tire pressure limit is not the governing limit for drive axles and is not shown in Figure 31).

- The drive axle weight estimate for a fully-loaded transit bus for PWS 1 (Design Standard) is approximately 800 pounds lighter than the estimate for PWS 2 (Ages 18-24) and 1,300 pounds lighter than the estimate for PWS 3 (All Ages).

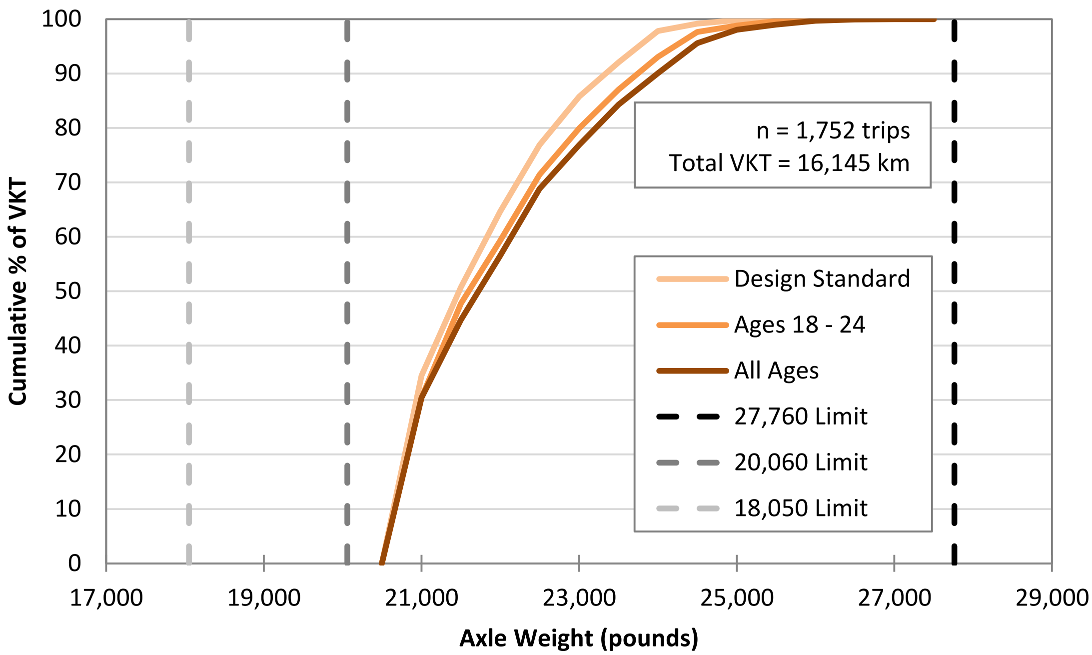
4.3.2 Exposure Analysis

Figure 32 shows the estimated cumulative distribution of drive axle weights by VKT. Similar to the GVW and steer axle weight analyses, the drive axle weights in this analysis are plotted against cumulative percent of VKT in order to assess how often pavements are exposed to various transit bus drive axle weights. Three drive axle weight limits are shown in Figure 32 to act as a reference:

(1) Winnipeg's spring weight restrictions drive axle limit – 18,050 pounds

(2) Winnipeg's maximum allowable drive axle weight – 20,060 pounds

(3) GAWR for the drive axle of a New Flyer D40 LF – 27,760 pounds



Assumed Weight (pounds)	PWS 1 (Design Standard)	PWS 2 (Ages 18-24)	PWS 3 (All Ages)
Male Passengers	150	188	201
Female Passengers	150	151	163

Figure 32: Drive Axle Split by VKT

Key Findings of the Exposure Analysis

This research estimates that:

- 0% of Route 160 transit bus VKT is conducted in compliance with the drive axle weight limit on roads subject to spring weight restrictions (18,050 pounds)
- 0% of Route 160 transit bus VKT is conducted in compliance with Winnipeg's maximum drive axle weight (20,060 pounds)
- 100% of Route 160 transit bus VKT is conducted in compliance with the drive axle GAWR for the New Flyer D40 LF (27,760 pounds)

4.4 ESAL ANALYSIS

The ESAL analysis consists of two components:

(1) **General Analysis** – a comparison of the ESAL estimates for a transit bus under various loading conditions.

(2) **Exposure analysis** – an estimation of the percent of travel (in terms of VKT) that Route 160 transit buses operate with specific ESAL values and an estimation of the relative proportion of pavement damage that results from Route 160 transit buses operating at various passenger loads.

4.4.1 General Analysis

Figure 33 presents a comparison of steer axle ESAL estimates, drive axle ESAL estimates, and total ESAL estimates for transit buses operating at curb weight (CW), seated load weight (SLW), and fully-loaded weight (FLW). The SLW estimates shown in Figure 33 were calculated assuming a passenger load of 38 passengers. The FLW estimates shown in Figure 33 were calculated assuming a passenger capacity of 63 passengers for the estimates produced by this research and a passenger capacity of 73 passengers for the Altoona estimate.

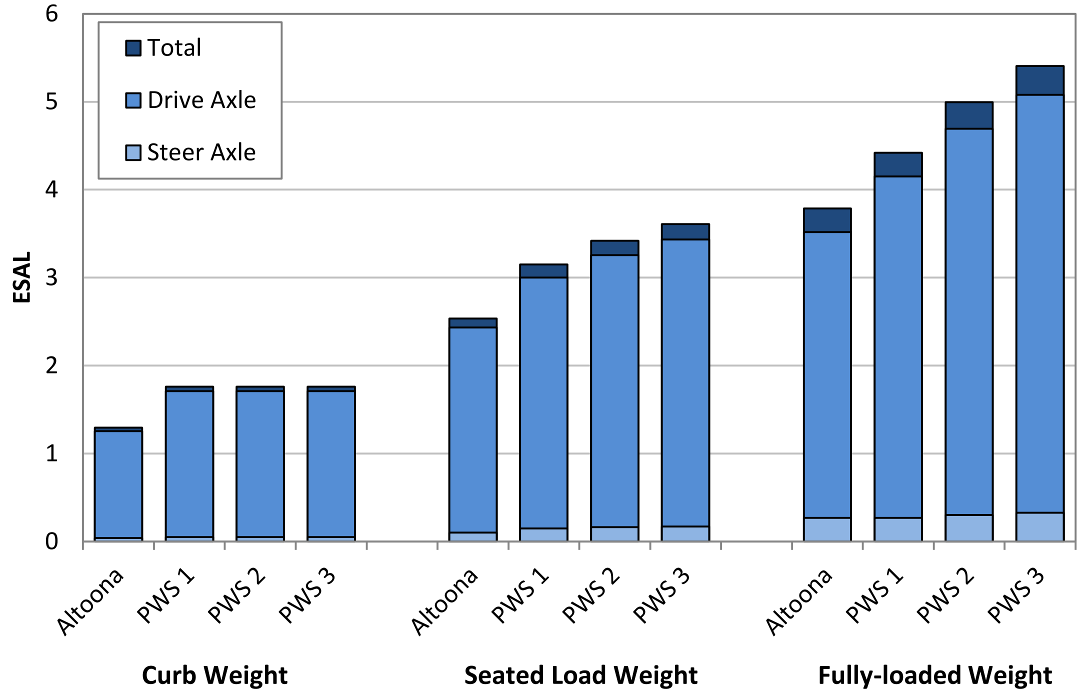


Figure 33: ESAL Estimate Comparison at Curb Weight (CW), Seated Load Weight (SLW), and Fully-Loaded Weight (FLW)

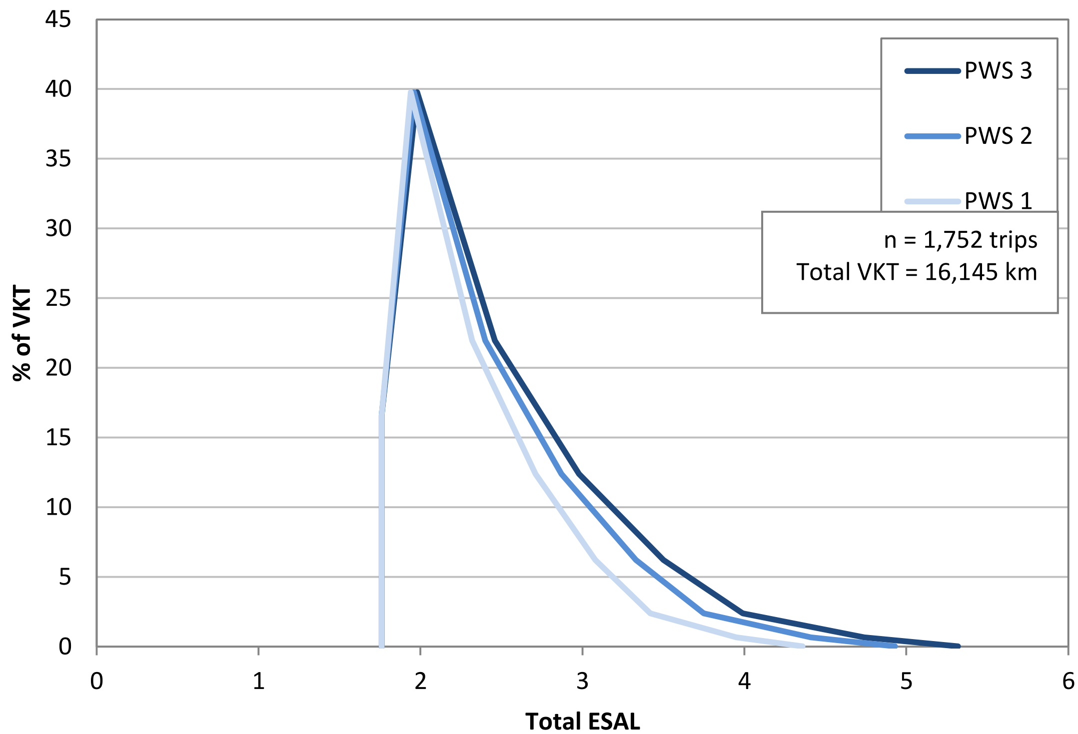
Key Findings of the General Analysis

This research estimates that:

- The ESAL estimates for a fully-loaded transit bus are 4.4-5.5 ESALs.
- Drive axles account for a significantly higher proportion of the total ESAL of a transit bus than steer axles, regardless of the passenger load and passenger weight scenario.

4.4.2 Exposure Analysis

Figure 34 shows the distribution of ESAL estimates for Route 160 transit buses as a function of vehicle-kilometres travelled (VKT). This figure also shows the average ESAL for a Route 160 transit bus, weighted by VKT, for each passenger weight scenario. It should be noted that the "sharp peak" in Figure 34 between 1.5 ESALs and 2.5 ESALs is a result of the assumption in this research that all Route 160 transit buses have the same curb weight (i.e., 29,188 pounds). In reality the ESAL distribution would likely be a more gradual curve. It should be noted that the results shown in Figure 34 are presented as a probabiltiy distribution function, whereas the exposure analyses for GVW, steer axle weight, and drive axle weight are presented as a cumulative probabilty distribution. These analyses are presented differently because the weight analyses make reference to vehicle weight limits and, therefore, require a cumulative probability distribution to demonstrate compliance.



	PWS 1	PWS 2	PWS 3
Weighted Average ESAL	2.21	2.28	2.33

Figure 34: ESAL Distribution by VKT and Weighted Average ESAL

Table 25 shows a comparison between the percent of Route 160 travel that is conducted at various passenger loads (in terms of VKT) and the estimated proportion of pavement impacts of those buses (in terms of ESAL-km). For example, the results in Table 25 show that empty Route 160 buses account for approximately 16.6% of all VKT and 12.5-13.2% of all pavement impacts.

Table 25: Pavement Impacts Relative to Passenger Loading and VKT

Passenger Load	% of VKT	% of ESAL-km		
		PWS 1	PWS 2	PWS 3
0	16.58	13.21	12.79	12.50
1 to 10	39.79	34.95	34.19	33.75
11 to 20	21.95	23.05	23.10	23.13
21 to 30	12.40	15.21	15.60	15.83
31 to 40	6.22	8.67	9.08	9.33
41 to 50	2.38	3.68	3.91	4.07
51 to 60	0.66	1.18	1.28	1.34
61 to 63	0.02	0.04	0.04	0.05

Key Findings of the Exposure Analysis

This research estimates that:

- Route 160 buses have the following ESAL distribution (using the 4^{th} power rule):
  - 16.6% VKT at 1.76 ESALs (0 passengers)
  - 39.8% VKT at 1.96-1.98 ESALs (1-10 passengers)
  - 22.0% VKT at 2.40-2.46 ESALs (11-20 passengers)
  - 12.4% VKT at 2.87-2.98 ESALs (21-30 passengers)
  - 6.2% VKT at 3.33-3.50 ESALs (31-40 passengers)
  - 2.4% VKT at 3.75-3.99 ESALs (41-50 passengers)
  - 0.6% VKT at 4.41-4.74 ESALs (51-60 passengers)
  - <0.1% VKT at 4.93-5.32 ESALs (61+ passengers)
- The average ESAL of a Route 160 transit bus weighted by VKT is approximately 2.21 for Passenger Weight Scenario 1 (Design Standard), 2.28 for Passenger Weight Scenario 2 (Ages 18-24), and 2.33 for Passenger Weight Scenario 3 (All Ages).
- Empty Route 160 transit buses are estimated to account for 16.6% of all VKT and 12.5-13.2% of the pavement impacts. This does not take into account the distance travelled to and from the route by buses that are not in service.

- Route 160 transit buses operating with fewer than 40 passengers (approximately seated load) account for 97% of all VKT and 95% of pavement impacts of all Route 160 transit buses.

4.5 DISCUSSION

This section discusses the implications of the findings of this research. It is organized into six subsections:

(1) Lessons Learned from the Case Study

(2) Implications for Infrastructure Designers

(3) Implications for Policy Makers

(4) Implications for Bus Manufacturers

(5) Implications for Enforcement Agencies

(6) Implications for Transit Agencies

4.5.1 Lessons Learned from the Case Study

This section summarizes the lessons learned from applying the methodology for estimating in-service transit bus weights outlined in Section 3.1 to the case study outlined in Section 3.2.

4.5.1.1 Estimating Curb Weight

As mentioned in Section 3.2.2, two sources of weight data were evaluated in the case study to estimate the curb weight of Route 160 buses. The average weight of the locally-weighed buses was found to be approximately 1,700 pounds heavier than the weighted average of the buses reported in Winnipeg Transit's bus fleet roster. This finding exemplifies the fact that curb weight data sources can have a significant impact on in-service transit bus weight estimates. Two possible reasons for this difference are:

1. The local weigh scale information only includes weights for New Flyer D40 LFR buses, whereas the fleet roster has weights for New Flyer D40 LF, D40 LFR, and Invero buses.
2. Because the fleet roster is an amalgamation of data from several sources, some of the reported weights in the roster may correspond to stock bus models, which don't include the weight of auxiliary components or alterations made to the buses after being delivered to Winnipeg Transit from the manufacturer.

Regardless of the difference in reported weights, this research recommends using locally-weighed curb weight data provided by a transit agency when developing in-service transit bus weight estimates (if available). The primary reason for this is because using data from locally-weighed buses eliminates any uncertainty surrounding what components are included in the reported weight.

4.5.1.2 Estimating Laden Passenger Weight

This research attempted to address the inherent uncertainties in estimating laden passenger weight by evaluating a range of plausible laden passenger weights when developing in-service transit bus weight estimates. The case study component of this research (Section 3.2) provides evidence that it is reasonable to assume average laden passenger weights between 169 pounds and 182 pounds; however, these values may not be representative of all jurisdictions because they are based on weight data for Manitobans and carry-on item data biased towards university students.

These results also suggest that the proposed change to the average passenger design weight for buses (i.e., from 150 pounds to 175 pounds) by the U.S. Federal Transit Administration (FTA) is well warranted. However, in the U.S. the average male adult (20 years and over) is estimated to weigh 195.5 pounds and the average female adult (20 years and over) is estimated to weigh 166.2 pounds [65]. This is approximately 5 pounds and 13 pounds heavier than the average weights of male and female Manitobans, respectively, that were used in this research. Consequently, the findings of this research suggest that the proposed average passenger weight of 175 pounds likely underestimates the weight of average transit rider in the U.S.

This research recommends assuming a laden passenger weight between 169 pounds and 182 pounds when developing in-service transit bus weight estimates. It should be noted that because of the bias towards university students in the case study the 169 pound estimate likely underestimates the base passenger weight and the 182 pound estimate likely overestimates the carry-on item weight of the average transit user. Further research is required to determine where the average laden passenger weight lies within this envelope.

4.5.1.3 Estimating Passenger Load

Passenger load data used in the case were obtained from Winnipeg Transit. This data was in a readily available and easy to use format since Winnipeg Transit currently uses this data for internal purposes. Based on the positive results of this case study, this research recommends obtaining passenger load data from local transit agencies to estimate passenger loads (if available) when developing in-service transit weight estimates.

The second component involved in estimating passenger load in the case study was the use of gender data to improve the weight estimates. As was discussed in Section 3.2.4, gender data used in the case study were obtained from manual observations. This method of obtaining gender data proved to be extremely intensive and time consuming and is not recommended in future studies. Further, the findings of the case study suggest that in lieu of manually collecting gender data a 50/50 gender split is reasonable to assume.

4.5.1.4 Estimating Axle Split

This research estimates that the axle split of a New Flyer D40 LFR bus is approximately 30/70 with no passengers on board and 34/66 when fully-loaded (this research assumes that the passenger capacity of a New Flyer D40LFR is 63 passengers based on the Winnipeg Transit ridership data). These estimates were developed using Passenger Seating Models (PSMs) in conjunction with moment diagrams. In comparison, the Altoona bus report weight check-in summary for the New Flyer D40LF estimates that D40 LF buses have an axle split of approximately 30/70 with no passengers on board and 34/66 when fully-loaded (Altoona assumes that the passenger capacity of the New Flyer D40LF is 73 passengers based on one passenger per seat and one passenger per 1.5ft^2 of floor space). Based on the approximate agreement of these results this research recommends assuming an axle split of 30/70 for buses at curb weight and 34/66 for fully-loaded buses. Further, axle splits for passenger loads between these values can be derived using linear interpolation.

4.5.2 Implications for Infrastructure Designers

In pavement design there are two common methods for calculating expected pavement life: (1) empirical; and (2) mechanistic-empirical. Although these methods are quite different, they both rely on vehicle weight estimates. In empirical analyses these weight estimates are expressed in terms of equivalent single axle loads (ESALs) to account for the effect of varying axle and tire configurations on the pavement impact of a given axle load. Conversely, mechanistic-empirical approaches utilize distribution of axle weights by axle type, referred to as axle load spectra (ALS).

As mentioned in Chapter 3, two limitations of developing weight estimates for transit buses are:

(1) Transit bus weights fluctuate with changes in passenger load and can vary significantly over the course of a single trip; and

(2) In the Canadian Prairie Region weight estimates for many vehicle types are developed using data collected at static weigh scales and with weigh-in-motion devices (WIMs). These weighing devices are typically located on major highways; therefore, vehicles operating solely within city limits, such as transit buses, have limited opportunity to be weighed.

To overcome these limitations this research developed transit bus weight estimates and ESAL estimates based on transit bus curb weight data, ridership data, and passenger characteristic data.

Based on the weight analysis conducted in this research, the ESAL of a fully-loaded transit bus is estimated to be approximately 4.4-5.5 ESALs. This is comparable to the ESAL of an 80,000 pound five-axle tractor trailer [1] and is equivalent to the same amount of pavement damage as is caused by 11,000-13,750 passenger cars (assuming that a passenger car has an average ESAL of 0.0004). It should be noted that the vast majority of the total ESAL value of a transit bus is estimated to be contributed by the drive axle due to the methodology used in this calculation; however, current research suggests that heavy steer axles can have a greater pavement impact on flexible pavements than a 20,000 pound dual-tired axle [42].

With that said, Route 160 transit buses were found to rarely operate at or near their passenger capacity. In fact, 95% of all pavement impacts caused by Route 160 transit buses can be attributed to buses that have approximately one passenger per seat or less and 13% of the pavement impacts can be attributed to empty buses. When weighted by VKT, Winnipeg Transit Route 160 transit buses are estimated to impose 2.3 ESALs, on average. This result is lower than, but comparable to, the typical bus load estimate of 2.47-2.73 ESALs identified in *Impacts of Buses on Highway Infrastructure: Case Study for New Jersey State* [3] and the design value for transit buses of 3.0 ESALs used by the City of Calgary. However, since the average ESAL of a transit bus is dependent on passenger volume, transit buses operating on routes with higher passenger volumes than Winnipeg Transit's Route 160 would be expected to have a higher average ESAL than 2.3. For example, 97% of all Route 160 VKT is conducted with less than 40 passengers and 16.6% of VKT is conducted with no passengers on board. Consequently, more research is required to determine if 2.3 ESALs is representative of the average ESAL of a standard transit bus in Winnipeg and across the Canadian Prairie Region.

As mentioned in Chapter 2, recent innovations in pavement design have led to the development of mechanistic-empirical approaches. Mechanistic-empirical methods are based on axle load spectra, unlike empirical pavement design approaches which are based on ESALs. This research presents axle load spectra estimates for transit bus steer axles and drive axles which are weighted by transit bus VKT.

In addition axle load spectra, it is important to take into account maximum vehicle weights in pavement design because rigid pavements can potentially fail from one extreme axle loading [1]. Based on the heaviest weight estimates produced in this research (Passenger Weight Scenario 3), pavements on facilities expected to have standard transit buses should be designed to withstand tire pressures of at least 567 pounds per inch of tire section width (on steer axles), single axle weights of at least 27,020 pounds (on drive axles), and GVWs of at least 40,630 pounds.

With respect to the pavement impacts of transit buses on Route 160 specifically, the spatial analysis identified two road segments of interest: (1) University Crescent between Chancellor Matheson Road and Wedgewood Drive; and (2) the Southwest Transitway.

University Crescent between Chancellor Matheson Road and Wedgewood Drive was identified as being exposed to the highest absolute weights and the Southwest Transitway was identified as being exposed to the highest average weights.

Even though the Southwest Transitway is estimated to be exposed to the highest average weights, rapid pavement deterioration is not expected because:

- The Southwest Transit was specifically designed for bus traffic and meets the APTA Recommended Practice for designing bus rapid transit running ways.
- The APTA Recommended Practice for designing bus rapid transit running ways estimates that fully-loaded transit buses have drive axle weights ranging from 27,720 to 29,700 pounds, which is 700-2,700 pounds heavier than the heaviest drive axle weight estimate produced in this research.

Conversely, rapid pavement deterioration may be an issue on University Crescent between Chancellor Matheson Road and Wedgewood Drive (in both directions) because:

- University Crescent was designed for general traffic and not specifically for high volumes of transit buses like the Southwest Transitway.
- Segments of University Crescent are paved with asphalt overlays. Asphalt pavements have been shown to be prone to rutting from heavy vehicles, such as transit buses [50].
- The highest passenger loads, and subsequently heaviest GVWs, for Route 160 buses were observed on University Crescent. These high passenger loads could be caused by events such as the spring examination period, during which many students attempt to get the university at the same time (normally passenger demand is spread out by staggered classes). Fully-loaded buses are estimated

to exceed the spring weight restriction weight limits by 800-1,500 pounds on the steer axle and 6,600-9,000 pounds on the drive axle.

4.5.3 Implications for Policy Makers

With respect to this research, policy makers are a major stakeholder because they establish vehicle weight limits, introduce legislation that has an influence on transit bus weights over time (such as emissions and accessibility requirements), and are responsible for developing strategies to address issues related to vehicle weights, should they arise.

The jurisdictional survey component of this research revealed that most jurisdictions in the Canadian Prairie Region are aware of transit bus weight issues and are seeking ways to increase transit bus compliance with vehicle weight limits so that in the future overweight permits will no longer be required. However, deciding which strategy (or strategies) to pursue to increase compliance can be a difficult task because of the numerous stakeholders that are affected by or have influence on transit bus weights. Nevertheless, knowledge about in-service transit bus weights can be used to identify which strategies are feasible. Examples of potential strategies include [4]:

- placing requirements on transit agencies which limit them from purchasing transit bus models that are known to exceed vehicle weight limits (i.e., models that require overweight permits);
- providing incentives to transit agencies for purchasing bus models with greater expected compliance (e.g., buses that utilize lightweight alternative materials or have a lower passenger capacity);
- providing incentives to bus manufacturers to develop bus models that have greater expected compliance with vehicle weight limits (e.g., buses that utilize lightweight alternative materials or have different axle/tire configurations); and

- adjusting axle weight regulations.

4.5.3.1 Requiring Transit Agencies to Purchase 100% Compliant Bus Models

As mentioned previously, this research estimates that the weight of the drive axle of a Route 160 transit bus would have to be reduced by approximately 4,600-7,000 pounds in order to operate without an overweight permit in Winnipeg. Although transit bus curb weights vary by model, none of the currently available standard (40-ft) transit bus models have a curb weight of at least 4,600-7,000 pounds less than the New Flyer D40 LF [66]. Therefore, it is unlikely that any currently available standard transit bus model would be able to operate without an overweight permit in Winnipeg when fully-loaded. Consequently, limiting transit agencies from purchasing bus models that require an overweight permit would mean limiting them from purchasing all standard bus models (which make up the majority of most modern transit bus fleets).

4.5.3.2 Providing Incentives to Transit Agencies to Increase Compliance

The findings of this research suggest that requiring transit agencies to purchase lightweight buses would likely only be a partial solution to compliance issues. In particular, the magnitude of weight reduction that is required to make the drive axle of a fully-loaded transit bus compliant with vehicle weight limits in Winnipeg (4,600-7,000 pounds) is unlikely to be achieved solely by incorporating alternative materials into transit bus design [1]. Therefore, even if lightweight, alternative-material buses were available, it is unlikely that they would be able to operating in Winnipeg without an overweight permit.

Similarly, lowering the number of passengers allowed on transit buses is a solution that would only partially address compliance issues with vehicle weight limits. Reducing passenger capacity can be accomplished by several means, such as restricting the number of passengers allowed on existing buses or requiring transit agencies to purchase smaller buses (e.g., 35-ft buses). Since transit buses drive axles were found to exceed 20,060 pounds even when at curb weight, restricting the number of passengers allowed existing buses would have no effect on compliance rates, but would only help reduce the magnitude of which vehicle weight limits are exceeded.

Conversely, using smaller buses, such as 35-ft buses, could potentially increase compliance; however, it could also increase operating costs for transit agencies if more buses are required to provide the same service.

4.5.3.3 Providing Incentives for Transit Bus Manufacturers to Help Increase Compliance

The findings of this research suggest that vehicle weight compliance issues for standard transit bus models are primarily the result of overweight drive axles. Therefore, a strategy that could potentially increase transit bus compliance with vehicle weight limits (in terms of the percent of VKT operated below the vehicle weight limits) is to redistribute weight from the drive axle of the bus to the steer axle of the bus. This research estimates that if steer axle weights were increased by 3,000, Route 160 transit buses would still be compliant with steer axle weight limits for more than 85% of all VKT. Conversely, if drive axle weights were reduced by 3,000 pounds they would be compliant with single axle weight limits approximately 80% of the time. Therefore, transit bus compliance with axle weight limits could increase from 0% compliance to 80% compliance (in jurisdictions with similar vehicle weight limits as Winnipeg) by shifting 3,000 pounds from the drive axle to the steer axle. With that said, this strategy would require transit buses to be equipped with more robust steer axles, as increasing the steer axle weight by 3,000 pounds could cause it to exceed its GAWR when loaded with passengers. Further, adding 3,000 pounds to the steer axle could cause its tires to be at risk of exceeding the tire pressure capacity specified by the manufacturer. This also has significant implications for pavement design as redistributing weight to the steer axle could increase the pavement impacts. Therefore, more research is required to determine if this solution is economically or physically feasible.

4.5.3.4 Adjusting Vehicle Weight Limits

Transit bus vehicle weight compliance issues can also be addressed by adjusting vehicle weight limits. This can be done in several ways, including (Note – the following "option names" are for reference purposes only and are not intended to be viewed as a ranking system) [4]:

Option A: Exempting transit buses from some or all vehicle weight limits.

Benefits

- 100% compliance rate
- Cost effective solution for transit agencies and bus manufacturers

Drawbacks

- Provides no incentive to transit agencies or bus manufacturers to reduce the impact of transit buses on pavements
- Potential increase to pavement lifecycle costs
- Could possibly be met with opposition from trucking companies and trucking lobbyists

*Option A is currently in practice in Saskatoon, SK

Option B: Raising vehicle weight limits for transit buses so that buses currently in operation would be considered compliant. Based on the findings of this research, transit buses would have approximately 90% compliance if the drive axle weight limit was increased to 24,000 pounds and 98% compliance if the drive axle weight limit was increased to 25,000 pounds, respectively.

Benefits

- Increased compliance rate
- Cost effective solution for transit agencies and bus manufacturers

Drawbacks

- Provides no incentive to transit agencies or bus manufacturers to reduce the current impact of transit buses on pavements

- Provides incentive for transit agencies and bus manufacturers to prevent transit bus weights from increasing

- Could possibly be met with opposition from trucking companies and trucking lobbyists
- Could require the adoption of new enforcement practices/technologies in urban areas

Option C: Raising vehicle weight limits for transit buses to levels that are agreed upon by all stakeholders, but might require current bus models to continue operating with overweight permits.

Benefits

- Increased compliance rate
- Provides incentive to transit agencies or bus manufacturers to reduce the impact of transit buses on pavements
- Potential decrease to pavement lifecycle costs
- Provides time for transit agencies and bus manufacturers to adjust to regulation changes

Drawbacks

- Potential increased costs for transit agencies and bus manufacturers
- Could possibly be met with opposition from trucking companies and trucking lobbyists
- Could require the adoption of new enforcement practices/technologies in urban areas

**Option C is currently in practice in Ontario*

Option D: Enforce current weight limits and continue to issue overweight permits to transit bus fleets (i.e., no change in regulation).

Benefits

- Cost effective solution for transit agencies and bus manufacturers
- Provides incentive for transit agencies to prevent bus weights from increasing to comply with overweight permit requirements
- Similar overweight permitting scheme as is standard in the trucking industry

Drawbacks

- No expected change to compliance
- Provides no incentive to transit agencies or bus manufacturers to reduce the impact of transit buses on pavements
- Potential increase to pavement lifecycle costs
- Could require the adoption of new enforcement practices/technologies in urban areas

4.5.4 Implications for Bus Manufacturers

With respect to transit bus manufacturers, this research provides insight on: (1) the adequacy of current gross axle weight ratings; and (2) improved estimates for average passenger weight and passenger load capacity.

The structural design capacity of a transit bus is defined by the gross axle weight rating (GAWR) of each axle, as stated by the vehicle manufacturer. For a New Flyer D40LF, the GAWR for the steer axle is 14,780 pounds for and the GAWR for the drive axle is 27,760 pounds. In comparison, the heaviest weight estimates produced in this study (Passenger Weight Scenario 3) indicate that the steer axle and drive axle of a fully-loaded Route 160 transit bus weigh approximately 13,612 and 27,020 pounds, respectively. Therefore, axles used on New Flyer D40 LF transit buses have sufficient design capacity to accommodate a full passenger load (i.e., 63 passengers).

As mentioned in Chapter 3, the current industry standard for average transit bus passenger weight is 150 pounds. This value is widely viewed to be unrepresentative of the actual average weight of a transit bus passenger and is currently under review by the U.S. Federal Government. This research provides strong evidence to support the need to change the average passenger weight used in design and testing. According to this research, the average transit passenger weight is approximately 169-182 pounds, including carry-on items. In comparison to estimates made using the average passenger weights developed in this research, estimates made using an average passenger weight of 150 pounds underestimate the steer axle weight, drive axle weight, and GVW of a fully-loaded transit bus by approximately 400-700 pounds, 800-1,300 pounds, and 1,200-2,000 pounds, respectively.

Another finding of this research is that the current standard for average passenger footprint is not representative of a typical transit passenger and its use can lead to overestimates of the transit bus passenger capacities. Using the current standard, passenger capacities of transit buses can be calculated by assuming one passenger per seat and one passenger per 1.5 ft^2 of floor space. This results in an estimated passenger capacity of 73 passengers for the New Flyer D40 LF. However, manual observations and the ridership data analyzed in this research indicate that the passenger capacity of a New Flyer D40 LF is approximately 63 passengers. If one assumes that the passenger capacity of a New Flyer D40 LF is 63 passengers (instead of 73 passengers) and that there are 38 seats, this equates to each standing passenger occupying approximately 2.1 ft^2 of floor space. This is important to note because if the average passenger weight used in bus testing was changed without also adjusting the passenger load capacity it could lead to inaccurate estimates of the GVW of a fully-loaded bus. For example, if a passenger capacity of 73 passengers was used in conjunction with PWS 3 (182 pounds per passenger), fully loaded transit buses would have a GVW of approximately 42,400 pounds, a steer axle weight of 14,200 pounds, and a drive axle weight of 28,200 pounds. This would suggest that a New Flyer D40 LF does not have a high enough gross axle weight rating on its drive axle and could result in unnecessary design alterations.

4.5.5 Implications for Enforcement Agencies

The findings of this research have limited implications for enforcement agencies in the Canadian Prairie Region because most transit agencies are routinely issued overweight fleet permits. However, the steer axle weight analysis revealed that transit buses operating in Alberta have the potential to exceed the tire pressure limits which are a requirement of the overweight permits issued by Alberta Transportation (560 pounds per inch of tire width). According to the axle weight estimates calculated using PWS 3, standard transit buses operating in Winnipeg have the potential to exceed 560 pounds per inch of tire width on both the steer axle and drive axle when fully-loaded. Since the weight estimates in this research are based on New Flyer D40 LF models and 78% of all standard transit buses operating in the Canadian Prairie Region are New Flyer D40 LF models [38], there is a high probability that fully-loaded transit buses operating in Alberta also have the potential to have tire pressures greater than 560 pounds per inch of tire width when fully-loaded.

4.5.6 Implications for Transit Agencies

Similar to enforcement agencies, the results of this research have limited implications for transit agencies because of the overweight permits routinely issued to transit bus fleets. Perhaps the most significant implication of this research is that transit agencies may have to be more conscientious of the weights of transit buses purchased in the future. As mentioned previously, a requirement of the overweight permits issued to transit agencies in Alberta is to not exceed a tire pressure of 560 pounds per inch of tire width and a requirement of the overweight permits issued to Winnipeg Transit is to work with transit bus manufacturers towards developing bus models that are compliant with the current vehicle weight limits. These requirements could limit transit agencies in the Canadian Prairie Region from purchasing specific types of buses. For example, these requirements could slow the rate of adoption of environmentally-friendly, alternatively-fuelled transit buses, which are on average heavier than their more common diesel counterparts [5].

5 CONCLUSIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

This chapter provides concluding remarks, outlines the key findings of this research, and proposes opportunities for future research.

5.1 CONCLUSIONS

Transit buses are commonplace in cities across the Canadian Prairie Region and play a vital role in providing an affordable and environmentally-friendly means of transportation to the public. Currently, the impact of transit buses on pavements is not well quantified because little data exists on in-service transit bus weights. This research attempts to make the first steps toward increasing understanding of in-service transit bus weights by estimating the proportion of VKT that transit buses operate above various weight thresholds, with the intent of leading to improved pavement design practices and aiding jurisdictions with determining feasible strategies for addressing transit bus axle weight issues. In order to accomplish this goal, this research developed a methodology to estimate in-service transit bus axle weights and then applied the methodology to estimate the in-service weights of Route 160 transit buses operated by Winnipeg Transit.

Key findings of this research are:

- The transit bus industry in is in a state of competing interests. Current transit bus models are unable to comply with vehicle weight limits in most jurisdictions. Weight limits are established by policy makers to protect road networks from excessive pavement damage. In most jurisdictions transit buses have been granted overweight permits which allow them to operate at weights above these limits, even during times when pavements are known to have decreased strength. Further, the organizational structure of municipal governments and regulatory environment for transit buses provide little incentive for transit agencies to purchase and operate lightweight buses. Consequently, transit bus axle weight issues in the Canadian Prairie Region are expected to continue in the foreseeable future.

- Transit bus curb weight data can be obtained from numerous sources, including the Altoona Bus Research and Testing Center, transit bus manufacturers, and transit agencies. This research recommends using locally-weighed curb weight data provided by a transit agency when developing in-service transit bus weight estimates (if available).
- The current transit design standard for average laden passenger weight (150 pounds), which is commonly used in in-service transit bus weight estimates, underestimates the weight of the average transit user. This research estimates that the average transit user in Winnipeg weighs approximately 169- 182 pounds, including clothing and carry-on items. Based on these findings, this research recommends that 169-182 pounds be used as the average laden passenger weight of transit riders in Canada.
- Passenger load data with temporal and spatial metadata were obtained from Winnipeg Transit to estimate passenger loads in this research. These data were used to assign passenger loads to specific routes and help estimate the proportion of transit bus VKT that is conducted at various weights. This research recommends that researchers developing in-service transit bus weigh estimates obtain passenger load data from transit agencies. Additionally, this research found that it is reasonable to assume a gender split of 50/50 when converting passenger loads into passenger weights.

- This research developed six Passenger Seating Models (PSMs) and used them in conjunction with moment diagrams to estimate the axle splits of Based on the approximate agreement of findings of this research with the values reported by Altoona, this research recommends assuming an axle split of 30/70 for buses at curb weight and 34/66 for fully-loaded buses. Further, this research recommends that axle splits for buses with passenger loads between these values be calculated using linear interpolation.
- Route 160 transit buses have the following compliance with vehicle weight limits in Winnipeg (note – transit buses are issued permits which allow them to legally operate above these limits):
    - 38% of VKT is in compliance with the GVW limit on roads subject to spring weight restrictions (30,180 pounds)
    - 81-84% of VKT is in compliance with Winnipeg's maximum allowable GVW (33,510 pounds)
    - 100% of VKT is in compliance with the GVWR for the New Flyer D40 LF (42,540 pounds)
    - 98-99% of VKT is in compliance with the steer axle weight limit on roads subject to spring weight restrictions (12,130 pounds)
    - >99.9% of VKT is in compliance with Winnipeg's maximum allowable steer axle weight (13,450 pounds)
    - 100% of VKT is in compliance with the steer axle GAWR for the New Flyer D40 LF (14,780 pounds)
    - 0% of VKT is in compliance with the drive axle weight limit on roads subject to spring weight restrictions (18,050 pounds)
    - 0% of VKT is in compliance with Winnipeg's maximum allowable drive axle weight (20,060 pounds)

    - 100% of VKT is in compliance with the drive axle GAWR for the New Flyer D40 LF (27,760 pounds)
- Based on the assumptions of this research, Route 160 transit buses have the following ESAL distribution (using the 4th power rule):
    - 16.6% VKT at 1.76 ESALs (0 passengers)
    - 39.8% VKT at 1.96-1.98 ESALs (1-10 passengers)
    - 22.0% VKT at 2.40-2.46 ESALs (11-20 passengers)
    - 12.4% VKT at 2.87-2.98 ESALs (21-30 passengers)
    - 6.2% VKT at 3.33-3.50 ESALs (31-40 passengers)
    - 2.4% VKT at 3.75-3.99 ESALs (41-50 passengers)
    - 0.6% VKT at 4.41-4.74 ESALs (51-60 passengers)
    - <0.1% VKT at 4.93-5.32 ESALs (61+ passengers)

  It should be noted that based on the methodology used in this research to calculate ESALs the impact of transit bus steer axles is underestimated.
- Currently, there are no standard pavement design values for transit buses, such as an average ESAL. This research estimates that Route 160 transit buses have an average ESAL (weighted by VKT) of approximately 2.3 and a maximum ESAL of 4.4-5.4. More research is needed to determine if these values are representative of transit buses operating on other routes in Winnipeg and in other Canadian jurisdictions.
- This research estimates that infrastructure expected to have standard transit buses should be designed to withstand tire pressures of at least 567 pounds per inch of tire section width, single axle weights of at least 27,020 pounds, and GVWs of at least 40,630 pounds.

- There are many ways that transit bus axle weight issues can be addressed and selecting a course of action can be difficult due to the numerous stakeholders involved. Potential strategies for policy makers to increase transit bus compliance with vehicle weight limits discussed in this research are:
    - providing incentives to transit agencies for purchasing bus models with greater expected compliance (e.g., buses that utilize lightweight alternative materials or have a lower passenger capacity);
    - providing incentives to bus manufacturers to develop bus models that have greater expected compliance with vehicle weight limits (e.g., buses that utilize lightweight alternative materials or have different axle/tire configurations);
    - placing requirements on transit agencies which limit them from purchasing transit bus models that are known to exceed vehicle weight limits; and
    - adjusting axle weight regulations.
- Of the aforementioned strategies, the only option that would have a significant effect on compliance in the short-term is adjusting axle weight regulations. This research estimates that transit buses would have approximately 90% compliance if the drive axle limit was increased to 24,000 pounds and 98% compliance if the drive axle limit was increased to 25,000 pounds.
- Even if transit bus manufacturers were to develop bus models that utilized lightweight alternative materials, it is unlikely that these buses would be able to operate without overweight permits in most of the Canadian Prairie Region (based on the current regulatory environment).

5.2 OPPORTUNITIES FOR FUTURE RESEARCH

Future research topics that extend from this thesis are:

1. **Application of the Developed Methodology to Other Bus Routes**

   The findings of this research are based on estimates of Winnipeg Transit Route 160 buses only. Winnipeg Transit operates 89 fixed service routes, some of which have higher passenger volumes than Route 160 [67]. The methodology for estimating in-service weights of transit buses developed by this research could be applied to other bus routes in Winnipeg (or routes in other jurisdictions) in order to obtain a more comprehensive analysis of in-service transit bus weights.

2. **Modification of the Developed Methodology to Estimate the Weights of Other Bus Types**

   Although the bulk of transit bus operations in the Canadian Prairie Region are performed by standard transit buses, many other bus types are commonly used by transit agencies. Other transit bus types include: 35-ft. 2 axle buses, 3-axle 60-ft. articulated buses, and 3-axle double-decker buses. The methodology developed in this research could be modified to estimate the weights of any or all of said bus types.

3. **Transit Bus Weight Analysis Using Portable WIMs**

   As mentioned in Chapter 3, transit buses are not typically weighed at weigh scales because they seldom operate in the vicinity of a scale. Portable weigh-in-motion (WIM) devices offer the opportunity to take direct measurements of the weight of in-service buses at various locations in an urban setting. An analysis of directly-measured in-service transit bus weights would provide a more definitive answer (than the estimates that have been made to date) as to how much transit buses weigh and how often transit buses exceed vehicle weight limits.

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7 APPENDIX A – SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

This section shows two sample calculations. The first sample calculation shows how the axle splits were calculated for each passenger seating model. The second sample calculation shows how the gross vehicle weight, steer axle weight, and drive axle weight were calculated at each bus stop for each bus trip. Values displayed in this section are rounded to simplify the explanation process and may not exactly match the values used in the analysis component of this research.

AXLE SPLIT SAMPLE CALCULATION

This research included six axle split calculations – one for each PSM. The following series of calculations show how the axle split was calculated for PSM D. The assumptions used in these calculations are:

- **Passenger Seating Model**: PSM D – 41 Passengers (Figure 20)
- **Average Passenger Weight:** 169 pounds (average of male and female weights from Passenger Weight Scenario 2 in Table 21)
- **Bus Dimensions:** As shown in Figure 23.
- **Static system:** All calculations neglect dynamic effects, such as wheel/road interactions, aerodynamics/drag, acceleration/deceleration, etc.

Step 4A: Calculate the moment contribution of the seated passengers about the steer axle.

The moment contribution of a passenger is equal to the product of the weight of the passenger and the distance from their seat to the steer axle. Therefore, the moment contribution of the sitting passengers about the steer axle can be calculated by summing the individual moment contributions for each passenger shown in PSM D (Figure 20). The distance from each seat to the steer axle can be calculated using the dimensions shown in Figure 23. Table 26 shows the results of these calculations.

Table 26: Moment Contribution of Seated Passengers

Seat Row	Distance to Front of Bus (feet)	Distance to Steer Axle (feet)	# of Passengers	Weight (pounds)	Contribution to Moment (feet*pounds)
1	9	1.83	2	338	620.
2	11	3.83	2	338	1,295
3	13	5.83	2	338	1,971
4	15	7.83	4	676	5,293
5	17	9.83	4	676	6,645
6	19	11.83	4	676	7,997
7	21	13.83	1	169	2,337
8	23	15.83	0	0	0
9	25	17.83	1	169	3,013
10	27	19.83	4	676	13,405
11	29	21.83	4	676	14,757
12	31	23.83	0	0	0
13	33	25.83	2	338	8,731
14	35	27.83	3	507	14,110
Total				**5,577**	**80,172**

Step 4B: Calculate the moment contribution of the standing passengers about the steer axle.

Although the standing passengers are shown as uniformly distributed loads in Figure 23, calculating their moment contribution can be simplified by replacing the uniformly distributed load with a single point load located at the midpoint of the uniformly distributed load. Table 27 shows the contribution of the standing passengers to the moment about the steer axle.

Table 27: Moment Contribution of Standing Passengers

Standing Area	Distance from Front of Bus (feet)	Distance from Steer Axle (feet)	# of Passengers	Weight (pounds)	Contribution to Moment (feet*pounds)
Front	13	5.83	6	1014	5,912
Middle	23	15.83	2	338	5,350
Rear	30	22.83	0	0	0.0
Total				**1,352**	**11,262**

Step 4C: Calculate the moment contribution of the drive axle at curb weight about the steer axle.

The moment contribution of the steer axle and drive axle at curb weights are shown in Table 28. Although it is included in this example, it is not necessary to calculate the moment contribution of the steer axle about the steer axle because it is equal to 0.

Table 28: Curb Weight Moment Contributions of the Axles

Axle	Distance from Front of Bus (feet)	Distance from Steer Axle (feet)	# of Passengers	Weight (pounds)	Contribution to Moment (feet*pounds)
Drive	31.6	24.42	0	20,568	502,202
Steer	7.16	0	0	8,620	0
Total				**29,188**	**502,202**

Step 4D: Calculate the weight of the drive axle (W_{DA}).

The weight of the drive axle can be calculated by substituting the moment contributions calculated in Steps 1-3 into Equation 1 (as stated in Figure 7), as follows:

Equation 1: $\sum M_{SA} = 0 = \sum(W_P * x_P) + CW_{DA} * x_{\ DA} + W_{DA} * x_{\ DA}$

$$\sum M_{SA} = 0 = (80{,}238 + 11{,}273) + 502{,}202 + W_{DA} * 24.42$$

$$W_{DA} = \frac{80{,}172 + 11{,}262 + 502{,}202}{24.42}$$

$$W_{DA} = 24{,}309\ pounds$$

Step 4E: Calculate the weight of the steer axle (W_{SA}).

The weight of the steer axle can be calculated by substituting the weights calculated in Steps 1-4 into Equation 2 (as stated in Figure 7), as follows:

Equation 2: $\sum W_P + CW_{DA} + CW_{SA} = W_{DA} + W_{SA}$

$$(5{,}577 + 1{,}352) + 8{,}620 + 20{,}568 = 24{,}309 + W_{SA}$$

$$W_{SA} = 11{,}808\ pounds$$

Step 4F: Calculate the axle split for each axle.

The axle split for each axle is equal to the proportion of the gross vehicle weight (GVW) and can be calculated as follows:

$$Steer\ Axle\ Proportion = \frac{W_{SA}}{W_{SA} + W_{DA}} * 100\%$$

$$Steer\ Axle\ Proportion = \frac{11{,}808}{11{,}808 + 24{,}309} * 100\%$$

$$Steer\ Axle\ Proportion = 32.7\%$$

$$Drive\ Axle\ Proportion = \frac{W_{DA}}{W_{SA} + W_{DA}} * 100\%$$

$$Drive\ Axle\ Proportion = \frac{24{,}309}{11{,}808 + 24{,}309} * 100\%$$

$$Drive\ Axle\ Proportion = 67.3\%$$

GVW AND AXLE WEIGHTS SAMPLE CALCULATION

The GVW, steer axle weight, and drive axle weight of Route 160 buses were calculated at each bus stop in the study area (28 northbound stops and 30 southbound stops) for each Route 160 bus trip (791 northbound trips and 961 southbound trips). This equates to more than 50,000 calculations of GVW, steer axle weights, and drive axle weights. The following series of calculations show how the GVW, steer axle weight, and drive axle weight were derived for a specific bus stop on a northbound bus trip. The assumptions used in these calculations are:

- **Passenger Load**: 43 passengers
- **Passenger Weight Scenario**: 2 (Ages 18-24)
- **Bus Stop**: NB University - Dysart

Step 3A: Determine the gender split for NB University – Dysart.

According to Table 22, NB University – Dysart bus stop has a gender split of 52.91% male and 47.09% female.

Step 3B: Calculate the number of male passengers (N_M) and female passengers (N_F) on the bus (since these estimates are averages there is no need to round to the nearest whole person).

$$N_M = Proportion\ Male * Passenger\ Load$$

$$N_M = 0.5291 * 43$$

$$N_M = 22.75 \text{ males}$$

$$N_F = Proportion\ Female * Passenger\ Load$$

$$N_F = 0.4709 * 43$$

$$N_F = 20.25\ females$$

Step 4: Determine the axle split.

Based on Table 24, the axle split for a bus with 43 passengers can be calculated by linearly interpolating between the axle splits for PSM D and PSM E.

$$Steer\ Axle\ Proportion = 32.7 + \frac{(43-41)}{(51-41)} * (33.1 - 32.7)$$

$$Steer\ Axle\ Proportion = 32.78\%$$

$$Drive\ Axle\ Proportion = 100 - Steer\ Axle\ Proportion$$

$$Drive\ Axle\ Proportion = 100 - 32.78$$

$$Drive\ Axle\ Proportion = 67.22\%$$

Step 5A: Determine the average weight of male passengers (W_M) and female passengers (W_F).

According Passenger Weight Scenario 2, the average male weight, W_M, is 188 pounds and the average female weight, W_F, is 151 pounds.

Step 5B: Calculate the total weight of all passengers (W_P).

$$W_P = (N_M * W_M) + (N_F * W_F)$$

$$W_P = 22.75 * 188 + 20.25 * 151$$

$$W_P = 7{,}334 \; pounds$$

Step 6: Calculate the GVW.

$$GVW = Curb\ Weight + W_P$$

$$GVW = 29{,}188 + 7{,}334$$

$$GVW = 36{,}523 \; pounds$$

Step 7: Calculate the axle weights.

$$Steer\ Axle\ Weight = Steer\ Axle\ Proportion * GVW$$

$$Steer\ Axle\ Weight = 0.3278 * 36{,}523$$

$$Steer\ Axle\ Weight = 11{,}972 \; pounds$$

$$Drive\ Axle\ Weight = Drive\ Axle\ Proportion * GVW$$

$$Drive\ Axle\ Weight = 0.6722 * 36{,}523$$

$$Drive\ Axle\ Weight = 24{,}551 \; pounds$$

Steps 8 and 9: Assign calculated weights to road segment for VKT analysis.

Since transit bus weights are constant between successive stops, the GVW, steer axle weight, and drive axle weight calculated in Steps 5-7 can be assigned to the road segment connecting these stops. According to Table 14, the distance between NB University – Dysart and NB University – Markham is 389 m (0.389 VKT).