Multimodal Transportation Systems Analysis to Characterize Petroleum-Related Freight Flows

By

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ABSTRACT

The purpose of this research is to inform planning, engineering, and management decisions concerning transportation systems that serve the petroleum exploration and production industry in North America. The research applies the transportation systems analysis approach to characterize the petroleum activity system and transportation system in southwest Manitoba and to develop freight flows. The research develops a framework to estimate and assign petroleum-related truck traffic to the regional highway network taking into account the variability of the industry. This is done by integrating components of freight demand modeling and truck traffic monitoring processes to improve understanding of truck traffic flow characteristics related to the industry. The results of the research are presented in an interactive mapping data dissemination tool. The approach and methodologies of this research are transferable to other jurisdictions and can be used to address the needs of other industry-specific developments.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 THE RESEARCH

The purpose of this research is to inform planning, engineering, and management decisions concerning transportation systems that serve the petroleum exploration and production (E&P) industry in North America. The research: (1) characterizes the activity generated by the petroleum industry; (2) characterizes the multimodal transportation system and operations; (3) gathers, analyzes, synthesizes, and interprets industry activity and traffic data to understand truck traffic flow patterns within a region; and (4) provides a transportation planning tool to assist jurisdictions that must plan and design for transportation facilities to support petroleum E&P. Currently, transportation agencies are aware of the transportation network impacts resulting from petroleum industry activity but lack the tools to reliably estimate the activity and traffic generated by this industry. The research benefits transportation engineering and planning for dynamic industries such as the petroleum industry by providing a framework for analysis and interpretation of the magnitude of industry needs and impacts on transportation networks. The framework is developed for the petroleum-producing region in southwest Manitoba that is part of a larger system that includes the neighboring jurisdictions in Saskatchewan and North Dakota.

1.2 BACKGROUND AND NEED

The petroleum sector in North America is a rapidly growing and changing industry that is placing significant demand on local transportation infrastructure. The current industry growth is important to regional and national economic development and is predicted to continue notwithstanding the current drop in oil prices. Industry growth has been stimulated by high oil prices and as a direct result of technological changes in the petroleum extraction process – primarily, advances in multi-stage hydraulic fracturing and directional drilling.

The current impacts of this growth can be seen throughout the transportation system in North America as companies plan the construction of new pipelines and expand existing lines, railroads and the petroleum industry invest significant capital funds towards routes and facilities that handle petroleum products, and highway traffic volumes and truck activity increase. The highway network, a public asset serving both public users and a myriad of industries, experiences unique challenges in transportation engineering and planning due to petroleum E&P. Present growth in the petroleum industry is typically occurring in rural regions with road infrastructure that has primarily served farm-to-market related trips with historically lower truck and total traffic volumes. While some of these roads may be designed to accommodate year-round heavy truck loads, many are not intended to handle the increased volumes and weights or temporal variations of the truck traffic that accompanies petroleum development. Regardless of transportation mode, an improved understanding of the petroleum industry, associated transportation network impacts, and planning strategies is required to maintain and enhance infrastructure.

Regional transportation planning can experience direct challenges from competitive and confidential industries such as the petroleum industry due to uncertain production yields and complex development cycles. Developing effective transportation plans requires a combination of qualitative and quantitative information to create short and long-term outlooks. The main challenge caused by the petroleum industry is the pace of development, influence of exogenous (and often unpredictable) factors, and the ability for regional and local planning to respond accordingly (Northern Tier Regional Planning and Development Commission, 2011; Tidd, 2013; Wilke and Harrel, 2011; Upper Great Plains Transportation Institute, 2013). In most studies, short-term and long-term plans are distinctly discussed because they have unique challenges.

Short-term planning (three to five years) can be successful in reasonably predicting impacts from quantitative data for well development and production levels (Upper Great Plains Transportation Institute, 2013). However, more recent studies suggest that an even shorter time frame (every two years) is necessary to stay up to date on industry development patterns (Upper Great Plains Transportation Institute, 2014). The highest density of truck traffic occurs during the drilling (development phase) of new wells and therefore short-term demands can be estimated from the number of permitted wells and active drilling rigs operating within a region. To assist in short-term and long-term planning, it is important to keep an up to date geodatabase of relevant energy and transportation-related datasets.

In comparison to short-term planning, long-term plans require more in-depth analysis and rely more heavily on qualitative data and active dialog with industry members. To develop long-term plans, the extent and geographic locations of development must be understood and are typically based on industry projections of economically viable reservoirs (Wilke and Harrel, 2011). However, these types of plans are best-guess scenarios and are highly susceptible to exogenous factors such as environmental regulations, the global economy, oil prices, actual versus projected oil productions rates, and discovery of new petroleum reserves. Recent studies show that traffic levels will increase in the long-term but are predicted to level off after most development has been completed (Upper Great Plains Transportation Institute, 2014). Two main challenges exist in long-term planning: (1) traffic patterns and volumes can shift within a region and (2) any major investments may lead to overdesigned roads when the development period subsides. To meet the demands of the petroleum industry, departments of transportation need to be agile and adapt to shifting industry patterns and infrastructure maintenance needs.

In addition to transportation planning, emerging infrastructure design practices, which incorporate mechanistic and probabilistic procedures, require increasingly detailed representations of traffic and loading characteristics. This research provides a benchmark of the current magnitude and characteristics of petroleum-related freight flows and develops an approach to understand current and near-term impacts of the petroleum industry on transportation networks. This research also assists transportation analysts, planners, and engineers in evaluation, maintenance, and infrastructure investment decisions for dynamic industry demands by developing an interactive data dissemination tool. Furthermore, the sectoral approach to freight movement applied in this research can be expanded to include other industries such as forestry and agriculture. Expansion of this research would help to develop a larger body of knowledge that supports multimodal freight transportation networks that contribute to regional economic development.

1.3 OBJECTIVES AND SCOPE

The objectives of the research are to:

1. Understand the current freight transport activity specific to the petroleum industry in southwest Manitoba along with other existing regional industry activity.
2. Develop a detailed inventory of the multimodal networks, vehicles, and regulations relevant to the transportation needs of petroleum E&P.

3. Characterize petroleum-related transportation flows for well development and market delivery in terms of commodity, origin, destination, mode and vehicle type, route, and temporal variations with a focus on truck traffic characteristics.
4. Design and develop a data dissemination tool for use by engineering, planning and operations professionals in a geographic information system (GIS) environment.

The scope of this research is limited to the provincial highway network, railroads, and pipelines within southwest Manitoba but the truck traffic flow analysis considers the influence the municipal road network has on the transportation network. Furthermore, this research is limited by the geology and operating policies present in Manitoba.

1.4 RESEARCH METHODOLOGY

The methodology used provides a broad understanding of the petroleum industry and transportation system serving the industry through extensive research into current levels of exploration and production, policies and regulations, and existing transportation networks. This research applies the transportation systems analysis approach which comprises the following components: transportation system (T); activity system (A); and flow system (F) (Manheim, 1979). The petroleum industry creates varying temporal and spatial demand on regional transportation networks and can be influenced by a fourth component, exogenous indicators (E) (Reimer and Regehr, 2014b). Figure 1 illustrates how these components are related to each other, with T, A, and F all operating within the exogenous indicators. Understanding and reviewing exogenous indicators that influence dynamic industries is important due to their ability to create large, and potentially sudden, changes in activity levels.

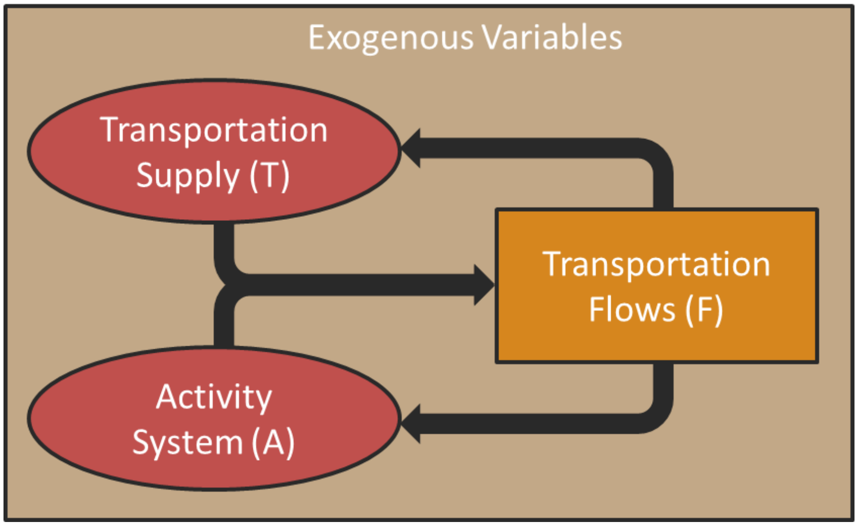


Figure 1: Transportation Systems Analysis Flow Diagram

Expanding on Figure 1, the transportation supply (T) represents the physical infrastructure that enables the movement of freight. Specific to the petroleum industry, this includes the road, rail, and pipeline networks as well as their various characteristics such as load rating and restrictions. The activity system (A) represents commodity and/or trip origins and destinations but includes data pertaining to commodity/trip generation, distribution (routing), and mode choice. Specific to the petroleum industry, this includes the facilities and locations related to well development, oil production, and equipment and material supply. The activity system places demand on the transportation supply which leads to transportation (freight) flows through the network. Changes in T and A will result in subsequent changes to F. Alternatively, changes in F can result in decisions being made that alter A or T. These three components all work within the influence of numerous exogenous socioeconomic factors that can influence industry activity and the resulting commodity and vehicle movements.

Due to the complexity of the petroleum industry and the dynamic demand it places on transportation networks this research developed and adopted a framework for integrating the four elements of the transportation systems analysis approach. The framework, shown in Figure 2, characterizes freight flows (predominantly truck traffic) using standard methodologies (Reimer and Regehr, 2014b) for monitoring truck traffic and modeling freight (multimodal) demand. Both of these methods rely on similar data sources for transportation and activity systems along with exogenous indicators to characterize either current or future traffic flow.

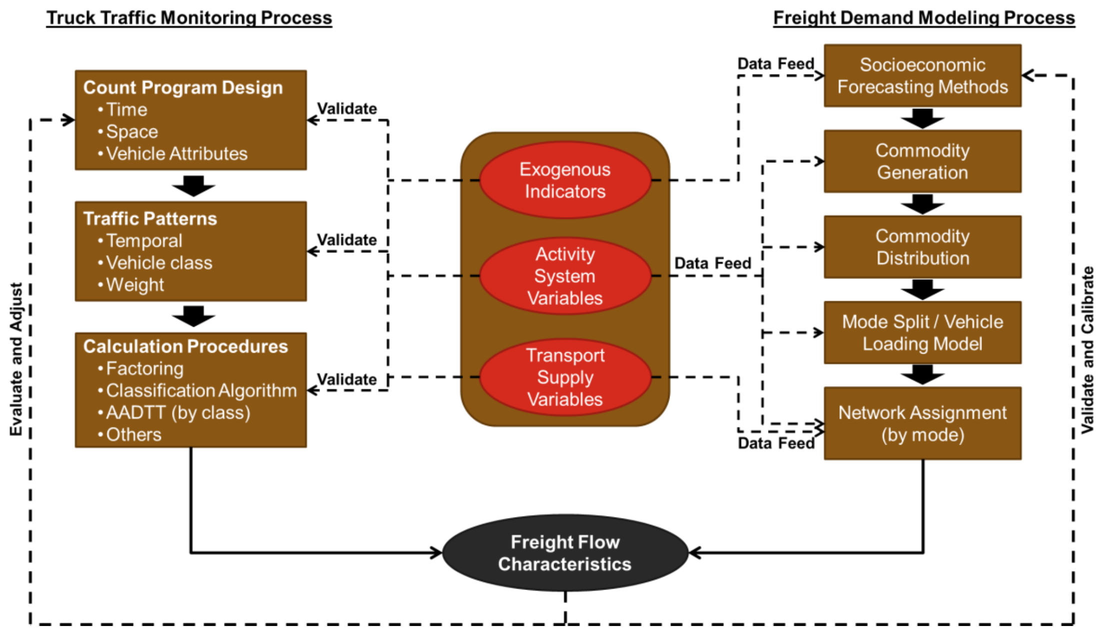


Figure 2: Integrated Framework for Estimating Freight Flow Characteristics
Source: Reproduced with permission of the Transportation Research Board from Reimer and Regehr (2014b)

The traffic monitoring process, shown on the left side of Figure 2, is a step-by-step process set forth by the *Traffic Monitoring Guide* (Federal Highway Administration, 2013) for continuous monitoring programs that collect highway traffic data on volume, vehicle class, and weight. There is an established traffic monitoring program across rural Manitoba that provides valuable data to this research. Furthermore, this research included short-term classification counts to provide further data on truck traffic characteristics within the study region. The freight demand modeling process, shown on the right side of Figure 2, is an adaptation of the typical "four-step" modeling approach and is classified as a commodity-based economic activity model (National Cooperative Highway Research Program, 2008). While this research does not directly apply a demand model, elements of the process are used to improve understanding of the industry, economics and freight characteristics experienced throughout the study region. The center of the schematic in Figure 2 shows data sources typical of freight demand modeling but these sources are not explicitly emphasized in standard traffic monitoring programs. The research links these two processes to achieve the common goal of characterizing regional freight flow and uses elements of each to help provide improved information on truck traffic characteristics.

The research was conducted using the following methodology:

1. Characterization of the activity system, *A*, present in regions affected by petroleum exploration and production. This component of the research was conducted through interviews with industry experts and analysis of public and private datasets. The activity generated by the petroleum industry can be influenced by regional and global economic and environment conditions and therefore exogenous factors, *E*, were used to enhance the activity system. The main components characterized are:
    - *Well development origins and destinations*
    - *Oil production origins and destinations*
    - *Modal choice*
    - *Freight and trip generation*
    - *Industry activity indicators*
2. Characterization of the transportation system, *T*, that serves the petroleum industry. Information and data relevant to the transportation system were collected through: (1) available public literature and reports; (2) interviews and discussions with professionals; (3) public and semi-public data sources and GIS data sets; and (4) independent data collection, site visits, and industry tours. This

data is integrated into the GIS data dissemination tool. The main components characterized are:

- *Road network*
- *Railroads*
- *Pipelines and flowlines*
- *Vehicle (truck and rail) characteristics*
- *Government regulations*

3. Synthesis of information and data to understand petroleum-related freight flows through southwest Manitoba. This component of the research integrates data obtained by characterizing the activity and transportation systems and is supplemented by interviews with industry experts and independent data collection. As shown in the framework outlined in Figure 2, freight flows are determined and validated using standard processes and by integrating multiple data sources. The flow of freight is separated into two main perspectives: well-specific and regional. These two perspectives have varying spatial and temporal characteristics. The synthesis provides insights into the types of trips generated in terms of commodity, origin, destination, trip length and route, vehicle type and weights, and seasonality of the industry within Manitoba. Application of the framework assists in estimating truck traffic generated as a result of industry activity and assigning this traffic to routes within the study region. The knowledge gained through this component is used to develop a GIS data dissemination tool for use by practitioners.

1.5 THESIS ORGANIZATION

The thesis consists of six chapters. Chapter 2 provides an overview of current understanding of the petroleum industry and its demand on transportation systems. This chapter contains details about: (1) oil and gas exploration and production and (2) the activity system (petroleum industry) that generates freight flows.

Chapter 3 characterizes the transportation system within southwest Manitoba that serves petroleum-related freight movements. These characteristics are described in terms of: (1) the multimodal network comprising pipelines, railroads, and highways; (2) unique vehicles of the petroleum industry and their characteristics; and (3) government regulations influencing the transportation system.

Chapter 4 develops the methodologies used to characterize petroleum-related freight flows. This chapter describes: (1) the transportation systems analysis approach and integrated framework; (2) the disaggregation of petroleum-related freight generation for development and production at various spatial resolutions, and (3) describes data sources used in the methodology and examples of integrating this data.

Chapter 5 discusses the results and findings from this research, specifically the petroleum-related freight flows and the development of a data dissemination tool for transportation engineers and planners. This section provides details on: (1) data processing and analysis to develop petroleum average daily truck traffic; (2) research results; and (3) developing an interactive data dissemination tool.

Chapter 6 summarizes the research, highlights major findings and provides recommendations for future research.

1.6 TERMINOLOGY

The following is a list of definitions of terms used in this thesis:

Active Well: A horizontal or vertical well that has been drilled and is currently producing emulsion. Other wells referred to as being active include saltwater disposal and water injection wells.

Battery: A facility used to separate emulsion into crude oil and water. A battery may exist as a 'tank battery' at a single well or exist as a group of equipment to separate, measure and store fluid from many wells.

Directional Drilling: Drilling technique in which a well is drilled vertically down to the target geological formation where the drill turns horizontally and continues through the target formation for up to a mile or more. This technique is also referred to as horizontal drilling.

Exploration and Production (E&P): The activities of the petroleum industry in drilling for and extracting oil and gas.

Emulsion: Mixture of oil and water produced by a well.

Flowline: Small diameter pipe used to carry emulsion or water from wells to batteries.

Hydraulic Fracturing: Technique used to improve productivity of petroleum products in shale or tight rock formations with low permeability. Fluids are pumped into the formation at high pressures to create fractures and proppants, mixed into the fluid, hold fractures open to increase permeability and thus well productivity.

Petroleum Average Daily Truck Traffic (PADTT) – An estimated value of the average number of trucks per day passing a point on the roadway resulting from petroleum-related activity when oil fields are experiencing both the well development and production phases.

Pipeline: Large diameter pipe used to carry crude oil only between facilities or from transload facilities to refinery markets.

Production Phase: Industry activity related to the actual production of crude oil resulting in truck traffic carrying crude oil and water.

Proppants: Sand or ceramics used in hydraulic fracturing to keep fractures open.

Tight Oil: Oil located in geological formations that have a very low permeability.

Transload Facility: A facility that is served by two or more modes of transportation.

Well Development Phase: Industry activity related to drilling and bringing a new well into production.

Classification CCS: A 48-hour coverage count station (CCS) that uses two road tubes a set distance apart to measure axle spacing and speed and classify vehicles.

2. OVERVIEW OF THE PETROLEUM INDUSTRY

This chapter provides an overview of current understanding of the petroleum industry and its demand on transportation systems. This chapter contains details about: (1) oil and gas exploration and production and (2) the activity system (petroleum industry) that generates freight flows.

2.1 OIL AND GAS EXPLORATION AND PRODUCTION

The southwest region of Manitoba has seen rapid development in petroleum production since the Sinclair Field was identified in 2004. This region is in the eastern extension of the Western Canada Sedimentary Basin (WCSB) and contains the northeastern extent of the Williston Basin and southeastern extent of the Elk Point Basin. These basins created the depositional environments that led to the generation of petroleum products. Production through the Williston Basin, which extends across North Dakota (where its depositional centre is located), Saskatchewan, Montana, and Manitoba, is expected to continue growing into the foreseeable future. Understanding why and where petroleum products occur in this region and the technology used to extract products is important for transportation networks and infrastructure planning. This section provides a summary of regional geology and geography (further details available in Appendix A), applied extraction techniques, and market trends.

2.1.1 Geological Setting

Within the Williston Basin are geological structural elements which trap hydrocarbons (the organic compound that make up petroleum products) and create reservoirs (Li and Morozov, 2007). The basin itself, along with major geological structures can be seen in Figure 3. Geological formations (layers of sediments) within the basin contain carbonate and evaporitic (water soluble minerals) sedimentary sequences that are indicative of the late Devonian era (375 million years ago) to the middle Cenozoic era (65 million years ago) (Nicolas and Barchyn, 2008). The Bakken formation is one sequence within this region and it acts as an oil source rock, reservoir, and trap.

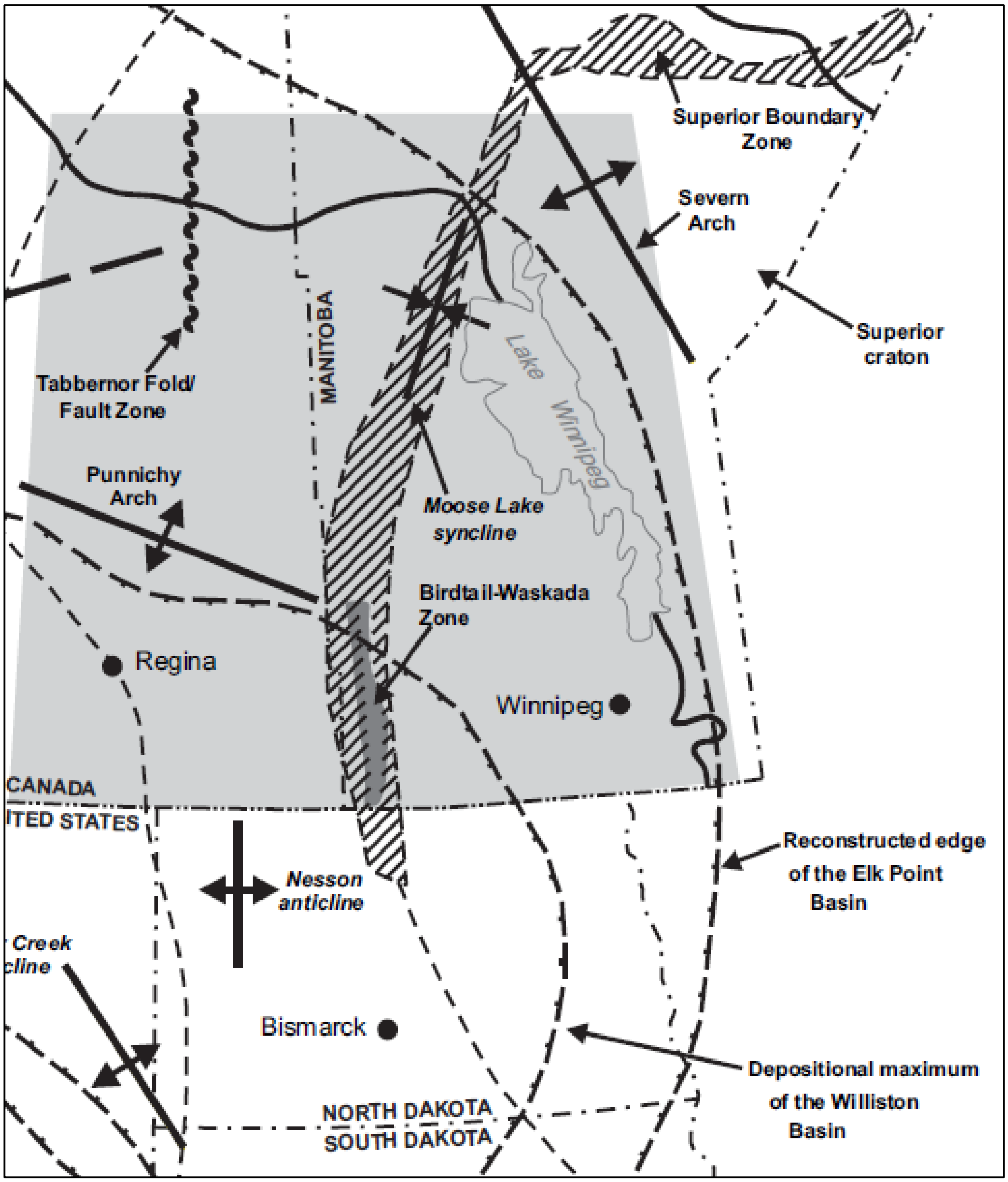


Figure 3: Williston Basin Location Map with Key Geological Structures
Source: Reproduced from Government of Manitoba with permission from Manitoba Mineral Resources from Nicolas and Barchyn (2008)

The geological sequences in the Basin that produce petroleum reach a maximum depth of 2.3km in the southwestern most corner of the province; this dip creates a geological wedge through the region. Geological features, such as the Precambrian Superior Boundary Zone and Birdtail-Waskada Axis (shown in Figure 3) create the traps and reservoirs that assist the movement of hydrocarbons (Li and Morozov, 2007). These two features locally control oil saturation, migration, and reservoirs (Nicolas, 2006). Within the geological sequences, the Mississippian layer is the most productive in Manitoba but recent developments in extraction techniques and an improved understanding of the geology in the region have moved exploration into deeper Devonian and Cambrian sequences (older sequences generally refer to deeper formations). There are four formations that are the primary targets for petroleum exploration and production. These formations include, from oldest to youngest geologically, the Three Forks, Bakken, Lodgepole, and Lower Amaranth. Details on the characteristics of these petroleum producing formations are provided in Appendix A.

2.1.2 Geographic Setting

Manitoba is home to 13 designated oil fields and has over 200 oil pools, all located in the southwest corner of the province. Typical depths of hydrocarbon reservoirs are up to 2300 metres, but most production occurs no deeper than 1200 metres. The oil fields and producing wells (there are over 4000 producing wells in Manitoba) are shown in Figure 4. Since the first well was drilled in 1951, Manitoba has produced over 300 million barrels of oil and recent development has increased rapidly with improved technology; production values are illustrated in Figure 4 (production was steady until about 2005 with previous “oil booms” occurring in the 1950s and 1960s). Further details on each oil field, including production and geological characteristics, are provided in Appendix A.

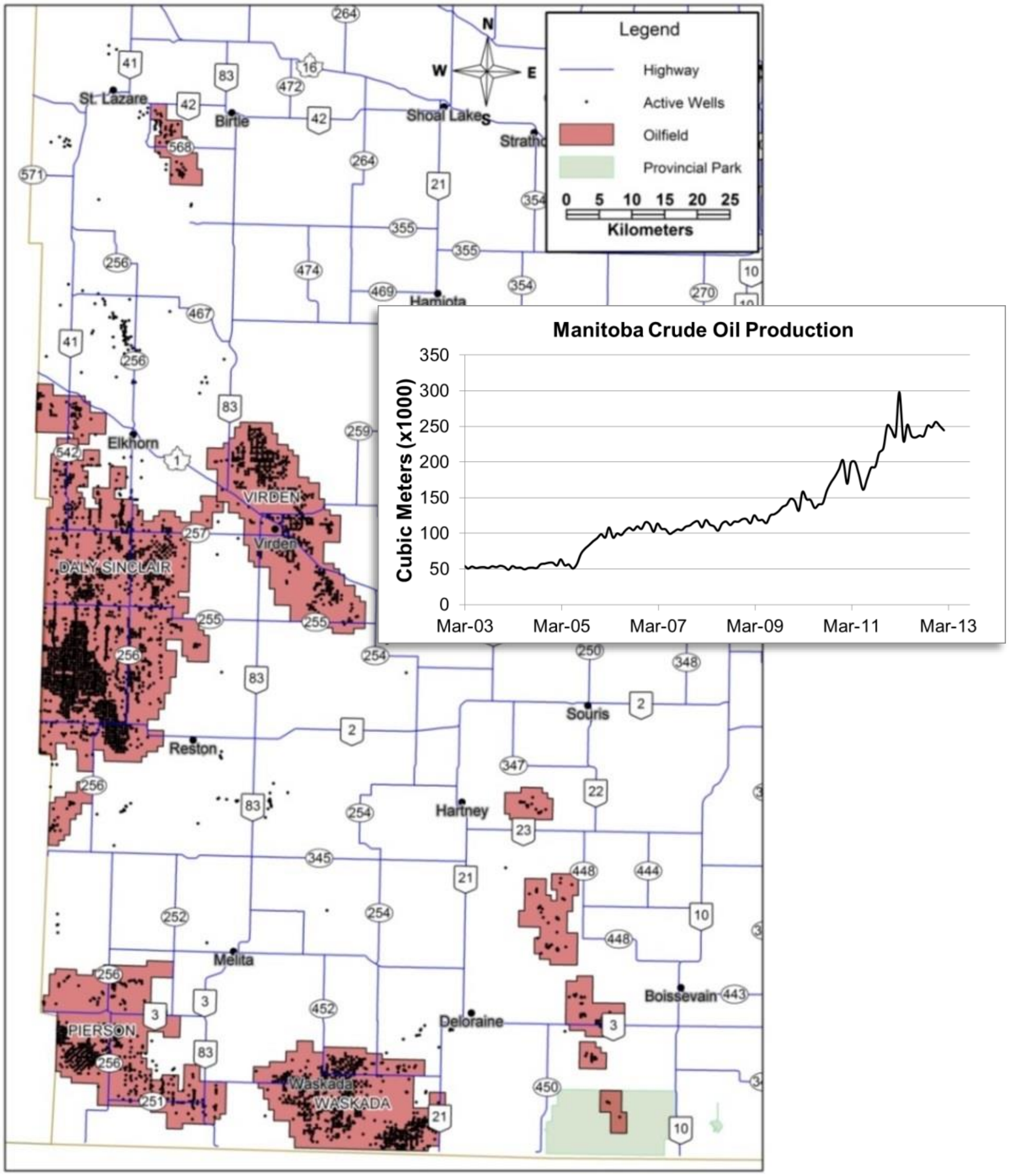


Figure 4: Manitoba oil Fields, Active Wells, and Productions Statistics

2.1.3 Extraction Techniques

Basins in North America are seeing increased levels of production because new technologies, including directional drilling, hydraulic fracturing, and earth imaging, have made E&P more economically feasible. When directional drilling and hydraulic fracturing are used in combination, the two technologies increase the ability of producers to profitably extract oil and gas from low-permeability geological plays like shale plays or tight sedimentary layers (United States of America, 2010). In Manitoba, hydraulic fracturing has been performed since the 1950s and some directional drilling was performed as early as 1991. Around 2005, horizontal wells began taking a larger share of the total wells drilled in Manitoba and by 2009 accounted for at least 90 percent of all new wells drilled in the region.

The hydrocarbon bearing formations of Manitoba can, for the most part, be considered 'tight' oil formations. This classification is a result of late-stage diagenesis activity and the occurrence of anhydrite cementation, which reduces porosity and permeability. The cementation has reduced pore space and size and the amount of interconnected pores. These tight formations are spread over a wide region where oil is not typically pooled and therefore may be considered as continuous resources. Tight oil comes in two forms:

1.) oil located in the original shale source rock with very low permeability; and

2.) oil that has migrated and is trapped in tight formations.

The second condition is present in Manitoba and can benefit from directional drilling and hydraulic fracturing while requiring less input resources (such as frack sand and water) than the first condition, as drillers are dealing with dolostone and sandstone rather than shale. The combination of directional drilling and hydraulic fracturing in this type of geological setting greatly increases a well's exposure to the producing formation and increases production rates (Canada, 2012).

Hydraulic fracturing, or fracking for short, is a method of oil and gas extraction that creates fractures in geological formations to enable hydrocarbons to flow more easily out of otherwise impermeable shale layers or other low permeability rock formations (tight formations). Fracking requires a mixture of water, sand or other proppants, and carefully engineered chemical additives to prop open fractures, protect the boreholes, and improve extraction rates. The use of each component of the fracking mixture is as follows:

- *Water*: large volumes are required to carry chemicals and proppants through the borehole and fractures;
- *Chemicals*: additives help prevent bacterial growth, reduce friction, and improve effectiveness of oil extraction;
- *Proppants*: material such as sand or ceramic beads are pushed into cracks and fissures at high pressure to keep fractures open as pressure dissipates

The process increases the hydraulic conductivity in the formation and creates higher flow rates of hydrocarbons. The process is not new and has been applied beyond hydrocarbon extraction to improve drinking water wells, dispose of waste, and enhance geothermal energy sources (ALL Consulting, 2012). It is a standard process for extraction from unconventional sources but only recently has it been applied to conventional sources to help improve productivity. The process is the same for both types of hydrocarbon sources, but when applied to a conventional source requires significantly fewer inputs.

The drilling stage of a well is only one of many stages to well development, as is the hydraulic fracturing process. Figure 5 shows the stages and duration of stage for a typical well in Manitoba before production begins, further details on each stage are provided in section 2.2 of this thesis (Abel, 2013). The use of hydraulic fracturing with directional drilling has helped decrease the total number of wells required by increasing each wells exposure to the formation and therefore decreasing total development costs, despite each well being more expensive. The technology applied in each geographic location is dependent on the underlying geology in terms of the target formation and the interaction of stresses, pressures, and temperatures within the formation; essentially subsurface conditions play the greatest role in determining how the process is applied (ALL Consulting, 2012). One major advantage of horizontal drilling is its ability to follow the geological formation for the well's entire length, regardless of how the formation may change over a distance.

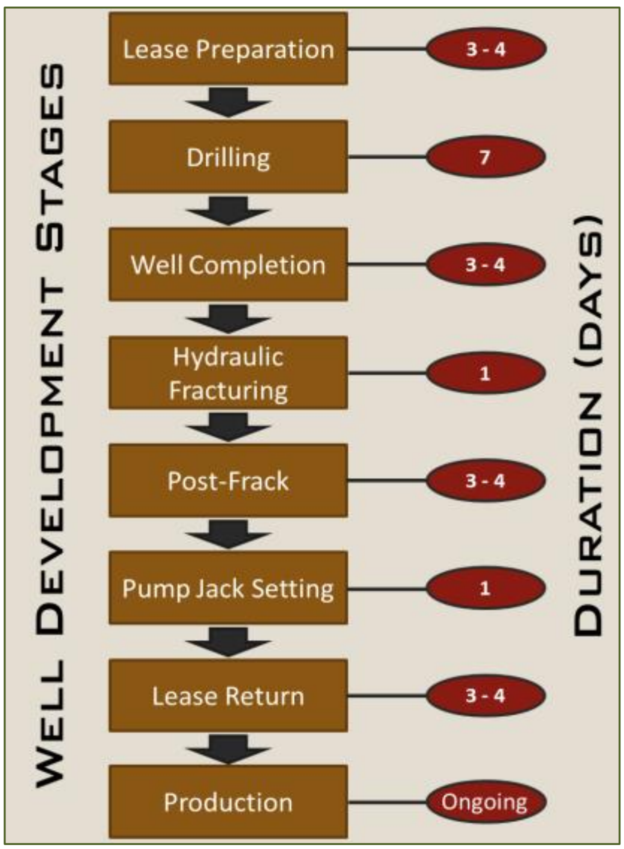


Figure 5: Development Stages for a Hydraulically Fractured Well

Additional information is provided in Appendix A on the application of hydraulic fracturing and directional drilling and the challenges associated with these techniques, such as the rapid decline in production rates.

2.1.4 Market Trends

Canadian crude oil production is primarily sourced from the oil sands of Alberta. However, conventional crude oil production has recently had the largest year-over-year changes due to extraction from tight oil rock formations. This growth is creating changes in the flow of crude oil resources throughout North America and impacting transportation networks as pipelines are at or near capacity and railroads supply the additional needed capacity (Canadian Association of Petroleum Producers, 2013). This growth in conventional light crude oil is replacing North American imports for light oil refineries in Canada and the U.S. while markets are emerging due to growth in demand in Asia. The largest demand for Western Canadian crude oil is the U.S. refineries located in the Midwest Petroleum Administration for Defense District II (PADD II), with demand also growing for heavy crude oil (tar sands) within PADD III (Gulf Coast) refineries that traditionally import from Venezuela and Mexico. The export terminals located near Cromer, Manitoba have direct access through pipelines to PADD II and III and refineries in Eastern Canada. Additional capacity and market access is provided by railway terminals that connect to PADD I on the U.S. east coast.

Current projects either proposed or under construction indicate the industry's desire to exploit new markets. Pipelines are being expanded or converted through new projects to help diversify market access – with railroads likely to continue to provide additional capacity and market diversification. With Canadian production expected to continue to increase until at least 2030, infrastructure will need to be provided to move this product to market. Canada has the third largest proven crude oil reserve and is the sixth largest crude oil producing country. Manitoba accounts for only a small proportion (less than 10%) of Western Canada production but production has tripled since 2004. Forecasts show that production will remain steady or slightly decline over the next decade.

However, due to the declining rates of horizontal hydraulically fractured wells, petroleum E&P activity will likely remain high in order to maintain production rates. Technological advances, such as EOR, may also lead to increase in production and revitalization of existing fields. Annual forecasts predict higher production rates each year as new information is gained and technology changes. Most forecasts are conservative and subsequent years show higher total production for the long-term future.

Domestic refineries are expected to increase their demand for Canadian light crude oil over the next decade through refinery expansions and developing transportation infrastructure. Two proposed projects, the Enbridge line reversal and TransCanada conversion project, will help meet demand at Eastern Canada refineries. While these projects are under development, a combination of pipeline, rail, and truck could fulfill the demand at these refineries. The largest market gains for Western Canada crude oil will be in PADD III with steady growth expected for PADD II. Railroads are currently moving crude oil from the Bakken region to PADD I refineries. U.S. growth in light oil production may limit the demand for Western Canada crude oil and thus diversifying market access for Canadian crude may be beneficial to long-term growth (Canadian Association of Petroleum Producers, 2013). West Coast refineries, primarily in Washington State, are expanding their rail access to receive crude oil from the Bakken region. Railroads also help the industry connect with smaller markets, like those on the East Coast and West Coast, and remove bottlenecks in the transportation network between producers and refineries.

Western Canada crude oil transportation capacity is currently limited, which results in discount prices on the world market. Pipeline proposals currently being developed, increased rail capacity, and diversified market access can help alleviate these price discounts. The primary export markets for Western Canada are refineries in eastern

Canada, major and minor markets in the U.S., and Asia. Current pipeline infrastructure enables crude oil from Manitoba to reach markets in the U.S. Midwest, eastern Canada (but not Atlantic Canada), and the Gulf Coast, with most going to the Midwest.

Crude oil production techniques continue to improve and are increasing domestic supply, particularly in the U.S., reducing the demand for Canadian crude oil (U.S. Energy Information Administration, 2013). Shale and tight formations are the source of this increase and production is in its early stages, resulting in highly uncertain forecasts.

One of the major factors for market access is the spot prices for Brent crude oil and the West Texas Intermediate (WTI). The price difference between the two has grown in recent years due to an influx of domestic (North American) crude oil. WTI is quoted in Cushing, Oklahoma, where infrastructure bottlenecks are occurring as transportation networks that link Cushing with the Gulf Coast exceed capacity. Extra pipeline capacity would reduce the price discount of WTI versus Brent as access to Cushing increases.

Long-term supply and demand is a function of non-OPEC and OPEC economics and world demand for petroleum products (U.S. Energy Information Administration, 2013). Transportation system constraints influence the price of crude oil and as solutions are found to these constraints, it is likely that the spread between WTI and Brent spot prices will close. As the spread between these two indices closes, shipping crude by rail is less lucrative and without increased access to pipeline capacity may limit Manitoba production. Projections are difficult due to market volatility and assumptions regarding the future of the world economy; regardless, basic logic suggests that oil prices would rise in the long term, but concerns about carbon emissions on climate change and the rapid rise of alternative energy add uncertainty to the future of oil prices.

Currently Manitoba has no refineries or plans to construct a refinery. The nearest refinery is a Co-Op refinery located in Moose Jaw, Saskatchewan. Most Manitoba crude oil is shipped to markets in the U.S. and Canada through the Enbridge Pipeline. However, since 2011 some crude oil has left by rail through the terminal at Woodnorth, Manitoba and as of 2013 through the terminal located near Cromer, Manitoba. The Enbridge pipeline brings products to markets at Flanagan and Patoka in the state of Illinois, and Sarnia, Ontario.

A cost-effective transportation system is essential to the petroleum industry in Canada (Canadian Association of Petroleum Producers, 2013). The lack of additional pipeline capacity has led to high price discounts for Canadian crude oil and creates price uncertainties. High production of light tight oil in the U.S., and whether these production rates can be maintained, creates uncertainty for the Canadian crude oil industry. These production rates have led to downward trending oil prices that are expected to stay weak until 2015. On the other hand, global geopolitical stability, cost of oil production, and OPEC target prices will help maintain higher prices. The rising light crude oil production from inland U.S. competes with the Canadian markets and producers will need to look for ways to access higher international prices (Brent prices rather than WTI). Rising inland production, higher transportation costs and an overabundance of oil are expected to maintain the discounted WTI price at Cushing for the next decade (Canadian Association of Petroleum Producers, 2013).

Production from tight formations is highly dependent on market prices because maintaining production levels requires continuous well development due to rapid production drop rates. This feature allows producers to annually re-evaluate their drilling programs to determine if it is worth maintaining or increasing production. Unconventional and tight formation oil is sensitive to changes in prices and production costs go up as the most productive zones are drilled first. Increasing rail capacity is expected to reduce some of the larger price differentials for Canadian crude oil resulting from over-supply.

2.1.5 Government Regulations

In Manitoba, the petroleum industry is governed by the Oil and Gas Act. The Act includes, but is not limited to, regulations on the following items related to drilling and production activity (Manitoba, 2014a):

- Well licenses, including surface lease information;
- Spacing units (for wells) and target areas within geological formations;
- Equipment registration for drill rigs, service rigs, and saltwater trucks;
- Drilling, completion, servicing, and abandoning of wells which includes details on site cleanup and rehabilitation;
- Production operations that includes saltwater disposal, enhanced oil recovery, and battery operating permits;
- Environmental protection; and
- Fluid measurement, well data, and reporting.

In addition to The Oil and Gas Act, the Petroleum Branch issues informational notices that update industry members on amendments, reporting requirements, or other updates that may affect the petroleum industry in Manitoba. Royalties and taxes resulting from oil and gas production are regulated by The Oil and Gas Production Tax Act.

Starting in 1992, oil E&P companies operating in Manitoba have benefited from the Manitoba Drilling Incentive Program (MDIP). The MDIP was put in place to create a competitive investment climate to develop oil and gas reserves in Manitoba. This program led Manitoba to be ranked as the best place in Canada for oil and gas investment in 2012 (according to Fraser Institute's Global Petroleum Survey). The key attribute of the MDIP is the holiday oil volume (HOV) given to each newly drilled well. Producers are not required to pay any Crown royalty or freehold production tax until a well has reached its HOV. The HOV is determined as a function of oil price (at time of drilling) and location of the well in relation to other producing wells. Currently, the MDIP is trying to encourage further development in Manitoba's deeper formations (below the Three Forks and Bakken). Incentives vary between vertical and horizontal wells, but each well type was capable of earning up to 10,000 m^3 of HOV under the previous MDIP. Due to the rapidly declining production rates of horizontal wells, the Petroleum Branch reassessed the HOV to a maximum of 8,000 m^3 under the new fiscal regime effective after December 31, 2013 to December 31, 2018. Details on HOV, Crown royalties, freehold production tax and all drilling and production incentives are available from the *Manitoba Petroleum Fiscal Regime* (Manitoba, 2014b).

2.2 ACTIVITY SYSTEM

Petroleum well development requires large quantities of material input for oil drilling and production. An oil well serves as a destination for inputs, as shown in Figure 6, and as an origin for produced water and crude oil destined for transload facilities. These inputs and outputs are moved through truck, rail, pipeline/flowline, or various combinations of these three modes. As highlighted in section 2.1 of this thesis, exogenous factors related to production, prices, and demand play a role in industry activity levels. Much of the rail industry growth caused by the oil and gas industry is a result of pipelines being at capacity. Railroads have stepped in to move the excess crude and have marketed themselves as being capable to deliver to any market or oil processing facility. There has been additional railroad growth in handling supplies such as sand used in the hydraulic fracturing process, which is typically sourced from the U.S. Midwest (Upper Great Plains Transportation Institute, 2010; 2013). Railroads also handle pipe, cements, hydrochloric acid, brine water, and other materials and supplies. This section discusses the transportation demand generated by the petroleum industry in North America and specifically southwest Manitoba.

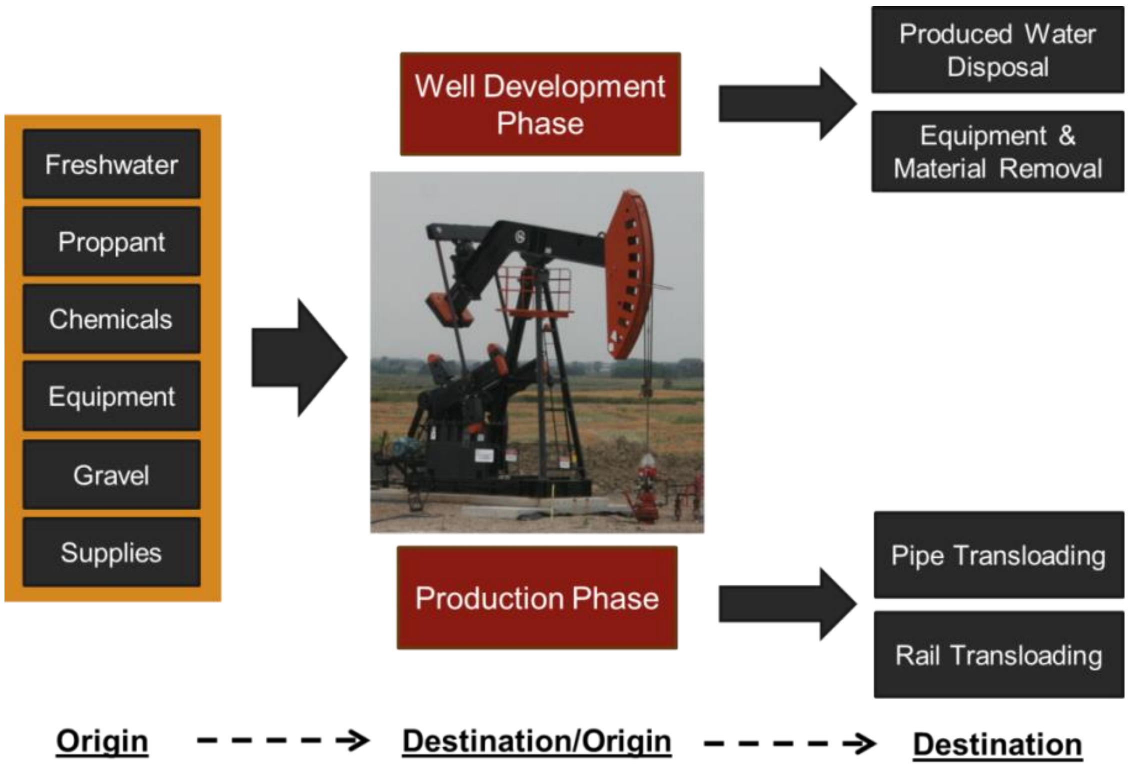


Figure 6: Material Flow Diagram for a Typical Oil Well
Source: Reproduced with permission of the Transportation Research Board from Reimer and Regehr (2014b)

2.2.1 Origins and Destinations

Shale play and tight oil development has, and continues, to impact the transportation system through increased heavy truck traffic, increased freight rail movement, and increased vehicle traffic generated by employment growth. As such, it is necessary to acquire data on the locations of origins and destinations that generate freight movements. Origins include:

- Freshwater sources such as wells or surface water;
- Locations outside the region that source sand or proppant, pipelines, and casings which are brought to the region by rail and trucked to site;

- Completed drilling sites for drill rig and associated equipment; and
- Gravel pits for pad preparation.

Destinations include:

- Saltwater treatment or disposal sites;
- New well sites for drill rig and associated equipment; and
- Rail or pipeline transload facilities.

2.2.2 Trucking

To determine the demand the petroleum industry puts on highway networks there are two key stages in the industry lifecycle to understand: development and production. There are three main stages to drilling a directional hydraulically fractured well: (1) lease preparation and return; (2) drilling; and (3) hydraulic fracturing. In addition to these main stages, equipment such as casing and pump jacks must be brought to site and installed to bring a well into production. Research from across North America indicate that up to 2000 loaded truck trips can be required to bring one well into production (Wilke and Harrel, 2011; Tidd, 2013). The total number of trips is a function of the extraction process, geological conditions, and well depth and length.

As discussed in section 2.1 and Appendix A, Manitoba has tight oil formations at a relatively shallow depth and therefore does not have the same level of inputs required for drilling as regions with shale at great depths. Figure 7 illustrates the number of truck trips and duration of each activity required to develop a single well in southwest Manitoba (Abel, 2013; Day, 2014). The truck trips in these stages include single unit, single trailer, and multi-trailer combinations as well as configurations unique to the petroleum industry (Appendix C provides sample vehicle types). Variations in drilling activity are a result of water requirements, depth and length of well, and location of water inputs. In some instances, water may be located at or near the site and greatly reduce the number of truck trips required. Wells drilled in Manitoba do not typically have high water requirements. This leads to lower total truck trips than experienced in other petroleum producing regions, particularly where target drilling formations are shale.

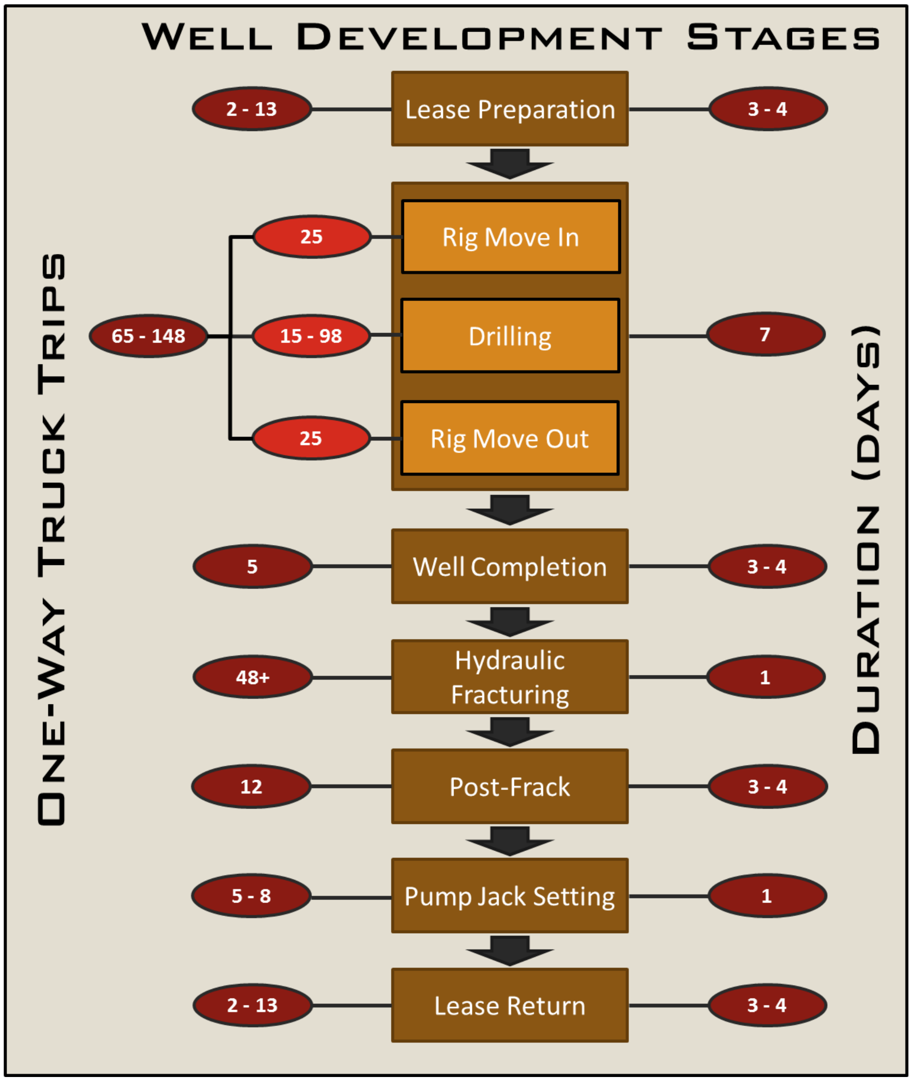


Figure 7: One-Way Truck Trips and Duration by Stage for Developing a Well
Source: Reproduced with permission of the Transportation Research Board from Reimer and Regehr (2014b)

Details for each stage in developing a well, as shown in Figure 7, are as follows:

1. *Lease Preparation/Return:* Heavy equipment is brought to the site to excavate an area of three acres to clay base. In some instances wooden mats may be placed at the site when soil conditions are poor to create a stable driving surface,

resulting in a higher number of truck trips. Lease site is returned to green field with an access road once well is completed.

2. *Rig Move:* Approximately 25 truckloads are used to bring equipment to site including the derrick, pumps, pipe tube, and matting. The total number of trips can vary based on equipment required and rig configuration.

3. *Drilling*: Movement of materials and equipment are brought to site, including water, fuel, cement trucks, and casing. Mud cuttings from drilling may be disposed of on site or hauled away. Variations in total truck trips required is primarily a function of water sourcing on-site versus off-site, depth of well, and the geological formation being drilled through.

4. *Well Completion*: Service rig is moved to site to complete the well, install tubing, and cased hole loggers.

5. *Hydraulic Fracturing*: This stage involves a high intensity of truck traffic over a short activity duration. Fracturing may be performed by a service rig or a coil rig unit (becoming more common as it is a much faster technique). Wells in Manitoba may receive a three or five ton frack (amount of sand used) with a larger frack requiring higher volumes of water. The fracturing process is done in stages and each well will have approximately 18 fracture zones that receive a three or five ton frack.

6. *Post-Frack:* Service rig is brought to site to run tubing and rods into the well. Flowback water from the drilling process is removed from site.

7. *Pump Jack Setting:* Gravel, concrete pads, pump jack, and test tanks are brought to well. The number of tanks and size of the pump jack will vary based on well characteristics (flow, depth, horizontal length, etc.).

In total, the development of a typical well in Manitoba could generate between 140 and 250 one-way truck trips, depending on material sourcing and well characteristics. Typically, these trips are three axle tractors with tridem axle trailers (moving water, sand, and equipment) and trucks specific to the petroleum industry with unique axle configurations. The one-way truck trips by stage, as shown in Figure 7, are estimated from discussions with industry and average material volumes required for each stage. The length of each trip is difficult to assess and is dependent on the location of the well, inputs, and transload facilities. Typical trip lengths can vary between 50 and 250 or more kilometres and can change rapidly with drilling programs. Water is an example of a dynamic origin-destination pair, and producers attempt to minimize the total distance required to travel. However, regional limits on water withdrawal or saltwater injection wells may be reached and result in longer travel distances.

Well development in a region leads to increased traffic volumes and specifically increased truck volumes. Research show that in Pennsylvania, where hydraulic fracturing and directional drilling are being employed for natural gas extraction, annual average daily traffic (AADT) increased by 12 percent on state highways while annual average daily truck traffic (AADTT) increased by 22 percent between 2007 and 2010 (Northern Tier Regional Planning and Development Commission, 2011; Tidd, 2013). The impacts to major U.S. highways in the region were extensive, with truck traffic volume increasing by over 100 percent (Upper Great Plains Transportation Institute, 2014).

In comparison, some highways in southwest Manitoba have seen doubling and even tripling of annual average daily traffic (AADT) between the start of the current industry growth in 2005 and 2013. The growth in traffic is most evident on key corridors into major oil fields and those highways that serve the transload facilities near Cromer. For example, PR 452, which provides access for development in the Waskada field, has had a 125 percent increase in AADT since 2005. Another important highway link, PR 256, which provides access to the Enbridge and Tundra transload facilities north of Cromer as well as accommodates well development trips for the Daly-Sinclair field has seen growths on some sections of over 200 percent. It is important to note that these values are calculated by expanding 48-hour traffic counts to an AADT using traffic pattern groups and truck percent values that may not have accurately reflected actual traffic. However, both years used the same expansion method and therefore are relative to each other. The percent changes are also a result of the timing of data collection as counts may have been performed during peak development periods. The intent of these examples is to highlight the impact a dynamic and rapidly growing industry such as petroleum E&P can have in a short time frame on the transportation network.

In petroleum development and production, water is a major generator of truck trips and creates variability in total trips for developing a well. Fresh water may be located near and even adjacent to a well, within the field of development, or obtained from outside the field. The availability of fresh water and its location can increase or decrease the total number of trips and total vehicle kilometers travelled. In addition, wastewater from well development and production creates variability in truck traffic characteristics. This by-product of drilling and crude oil production is transported and disposed of at treatment facilities or disposal and injection well sites. In both situations, there is a maximum volume any one site can accommodate (Quiroga, et al. 2012). Operators will generally attempt to minimize costs by routing to the nearest facility but this may not always be possible due to ownership and capacity constraints. In some cases, flowlines may be used to move wastewater from wells to disposal sites. Removal and disposal of wastewater is estimated at between 10 and 20 percent of the water transported to a site during development (Northern Tier Regional Planning and Development Commission, 2012). After a well has been developed, one well can require up to 300 trucks or more to haul water away throughout its lifespan. These trips are usually considered local as saltwater injection wells are scattered throughout the region (i.e., they may not utilize provincial highway infrastructure).

Understanding the truck traffic generated by developing a single well is challenging but in Manitoba can currently be assumed to be between 140 and 250 one-way truck trips (as shown in Figure 7). The difficulty lies in determining when and where this development will place demand on the transportation network. Origins and destinations are dynamic and can change rapidly, but high truck volumes can be expected in regions with ongoing well development. To determine the demand on the transportation system, it is necessary to estimate the number of wells and the associated vehicle fleet for the industry (Wilke and Harrel, 2011; Northern Tier Regional Planning and Development Commission, 2011). Truck traffic is expected to grow over the next ten years within the Williston Basin. As the oil and gas region matures, some research indicate that truck traffic volumes will decline to pre-development levels (Upper Great Plains Transportation Institute, 2010; 2013). Mature oil producing regions often develop pipelines to move crude oil between fields to transload facilities and establish extensive flowline networks to collect emulsion from wells to a central point such as a battery. This infrastructure reduces regional and local truck traffic (Northern Tier Regional Planning and Development Commission, 2011; Upper Great Plains Transportation Institute, 2013). Daily truck traffic is influenced by the number of operating drill rigs, an indicator of well development activity, but the number of service trucks will increase with the number of active wells as each well is required to be inspected daily.

2.2.3 Railroads

Railroads have experienced considerable growth in carloadings due to increases in oil and gas production over the last two to three years with this trend expected to continue into the near future. Currently, railroads are constructing multi-use transload facilities in many of the major shale and tight oil formations in North America to ship in supplies and materials and move crude oil to refineries and export terminals. In regions that require large fracks, a single well may require up to 25 rail cars of proppant which subsequently requires four or five trucks per rail car to move the material to a well (Northern Tier Regional Planning and Development Commission, 2011). In Manitoba, where the fracturing process occurs at a smaller scale due to geological conditions, it is closer to one rail car of sand per well. Sand is typically brought into multi-use rail terminals in

Saskatchewan and trucked to the region. The existing petroleum rail terminals in Manitoba are used to export crude oil. These terminals are located near the communities of Cromer and Woodnorth. The Cromer terminal has a capacity of 30,000 bopd (one train every two days) with expected expansion to 60,000 bopd (one train per day). The Woodnorth terminal handles less than 3,000 bopd (approximately five rail cars). Recently, crude oil carloadings have been doubling annually in western Canada, as shown in Figure 8, and are projected to continue growing into the foreseeable future (Tolliver, 2013; Upper Great Plains Transportation Institute, 2013).

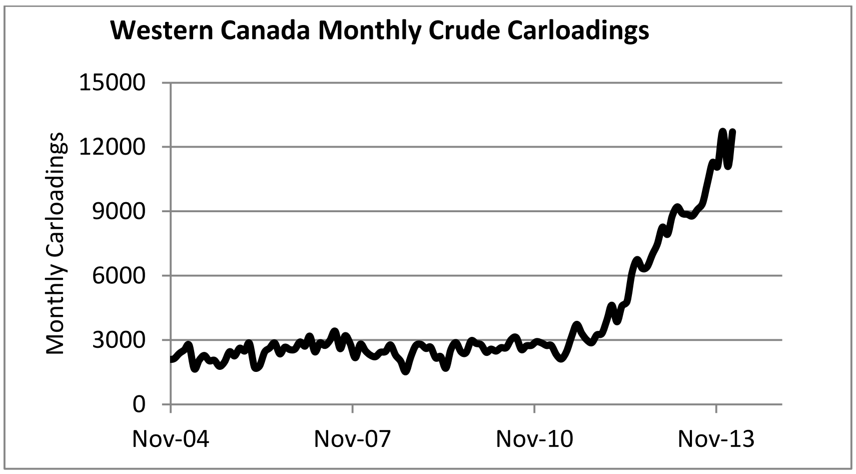


Figure 8: Growth in Railroad Shipments of Crude Oil Since 2004
Source: Statistics Canada (2014)

2.2.4 Pipelines and Flowlines

Pipelines are located at major facilities such as large batteries or transload facilities. Typically a pipeline is used to move oil or gas from a producing region to a refinery or end market location. In addition, a pipeline is used to collect crude oil from batteries within oil fields of a region and transport the product to a facility capable of exporting to market. In Manitoba such pipelines connect the Pierson, Waskada, and Virden fields with the export facilities at Cromer and connect batteries within the Daly-Sinclair field to the Cromer facilities. The location of pipelines and the facilities connected to them are examples of trip attractors as these are typically final destinations for oil and gas within a region. Connecting fields within a region using pipelines helps reduce total truck traffic as crude oil is moved by pipeline rather than truck. Pipelines are not accessible to all companies operating within a field because they are owned by one or two operators and therefore do not eliminate all truck trips between a single field and transload facility.

Flowlines are used to collect emulsion directly from wells and move the mixture of water and oil to a battery to be separated prior to being sent to market through pipelines. Flowlines reduce truck traffic by moving product that would otherwise have to be transported by truck. Often flowlines are only installed in mature fields and materials generated at new wells, when production rates are higher, must be trucked until the well is added to the network. New wells may require one or more truckloads (Federal Highway Administration (FHWA) Class 10 or 13 tanker truck) per day (See Appendix B for FHWA vehicle class definitions).

3. CHARACTERISTICS OF THE TRANSPORTATION SYSTEM IN SOUTHWEST MANITOBA

This chapter characterizes the transportation system within southwest Manitoba that serves petroleum-related freight movements. These characteristics are described in terms of: (1) the multimodal network comprising pipelines, railroads, and highways; (2) unique vehicles of the petroleum industry and their characteristics; and (3) government regulations influencing the transportation system.

3.1 TRANSPORTATION NETWORK

This section outlines the transportation infrastructure in southwest Manitoba used to support the petroleum industry in developing new wells and enabling continued petroleum production. Characteristics of each component of the transportation system are provided along with details on how it serves the larger regional freight system used in petroleum-related activities.

3.1.1 Highways, Roads, and Structures

The highway network in southwest Manitoba falls under one of two categories: (1) Provincial Trunk Highways (PTH); and (2) Provincial Roads (PR). These highways are classified in terms of their load rating, namely: RTAC, A1, and B1. Details on weight limitations for each highway class are provided in Table 1 in terms of GVW and axle groups. In some instances, a highway may be classified as a seasonal RTAC route that allows higher GVWs and axle loads during the winter months when road bases are frozen and capable of accommodating heavier loads. Many highways within the study region are also susceptible to spring road restrictions (SRRs). These restrictions fall under three categories: Level 1, Level 2, and no restrictions. A highway with a Level 1 restriction allows vehicles to operate at 90 percent of normal axle loading while a Level 2 restriction allows 65 percent of normal axle loading.

Table 1: Gross Vehicle and Axle Weight Limits by Highway Classification

Hwy Class	GVW (kg)	Steer (kg)	Single (kg)	Tandem (kg)	Tridem (kg)
RTAC	62,500	5500	9100	17,000	24,000
A1	56,500	5500	9100	16,000	23,000
B1	47,630	5500	8200	14,500	20,000

Table 2 shows sample gross vehicle weights of the truck trips generated to a drill a well (Upper Great Plains Transportation Institute, 2010). Most of these trips exceed the RTAC GVW limit of 62,500. The high weights and intense truck volumes can be more problematic on municipal or county roads that provide access to materials and wells. These roads may be paved all-season, paved seasonal, gravel, or graded. Seasonal restrictions when soil strength is low are also common for the highway networks that serve the petroleum industry; however, enforcing these restrictions is challenging as it reduces regional productivity, is unpopular, and is limited by jurisdictional financial constraints [Wilke and Harrel, 2011; Miller and Sassin, 2013). In many regions, enforcement is lagging behind the rate of development and estimates are that approximately 25 percent of trucks operating in oil producing regions are overloaded and unpermitted (Tolliver, 2013; Upper Great Plains Transportation Institute, 2014).

Table 2: Typical Gross Vehicle Weights to Move Drilling Equipment

Equipment Moved	GVW (kg)
Generator House	72,700
Shaker Tank/Pit	64,700
Derrick	72,100
Mud Pump	75,300
Substructure	72,800
Mud Tank	63,000
Workover Rigs	47,600

The complete highway network for southwest Manitoba, along with the geographic locations of designated oil fields, is shown by highway load rating class in Figure 9. As this map shows, much of the network in southwest Manitoba is classified as B1 which allows a GVW of 47,630kg. These weight limits throughout the highway network can create operational challenges for the truck fleet that serves the well development stage of the petroleum industry.

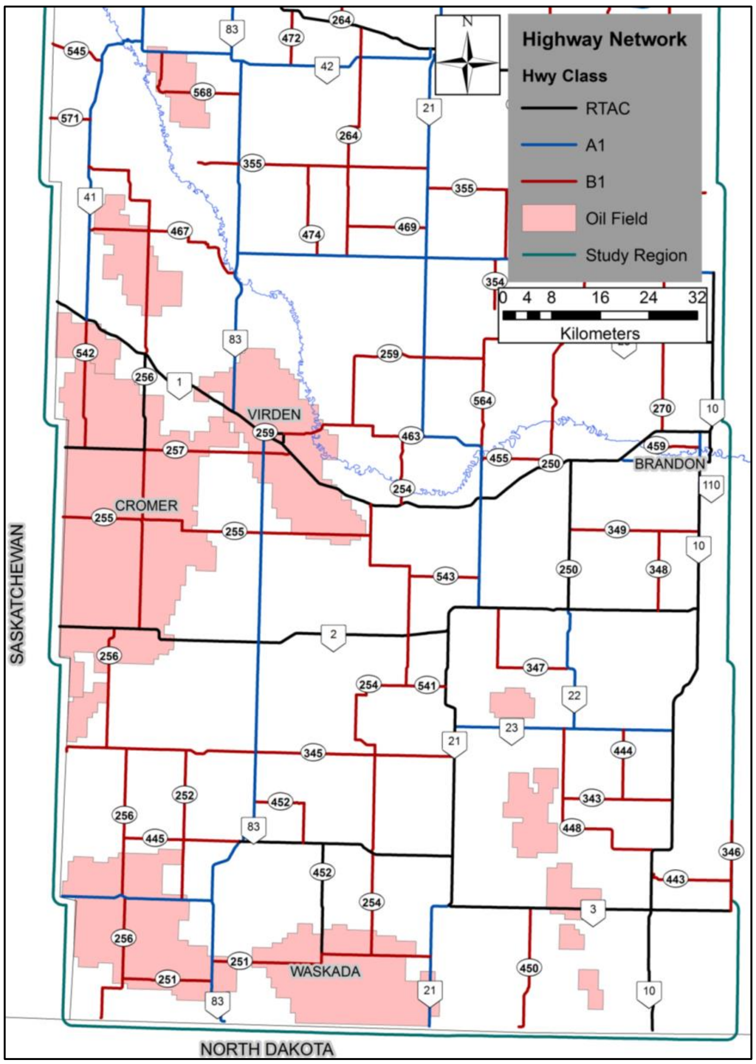


Figure 9: Highway Network by Classification

The same highway network is illustrated in Figure 10 by spring road restriction level. The two categories of restrictions are Level 2, which permits 65 percent of normal allowable weights and Level 1, which permits 90 percent of normal allowable weights. Through much of the oil fields Level 2 restrictions are common in the region along primary routes. During the spring this means that important segments of the highway network serving the petroleum industry operate at a GVW of approximately 31,000kg. Under these operating conditions, many of the trucks required for drilling new wells cannot operate normally or under OS/OW permits which prevents new wells from being drilled. Furthermore, these restrictions reduce the carrying capacity of tanker trucks hauling crude oil to transload facilities or result in trucks taking less desirable routes. In both scenarios this results in additional vehicle miles travelled, more trucks on the road, increased use of the municipal road network, or operational non-compliance.

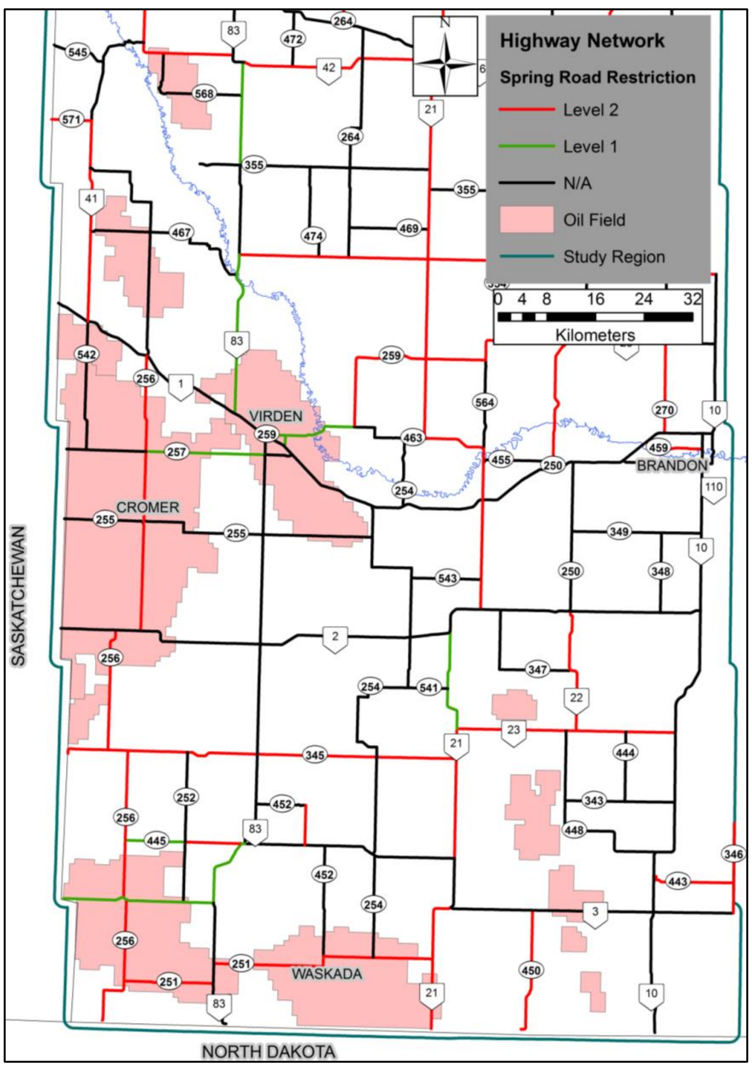


Figure 10: Highway Network by Spring Road Restriction Level

A variety of bridge structures are used throughout the highway network to cross rivers, creeks, and ditches. These structures are critical components of the transportation infrastructure that can cause major disruption to regional connectivity if taken out of service. Furthermore, the condition of these structures and original design characteristics can create limitations on the effective road network serving the petroleum industry. Bridges can limit network capacity when either the width or strength of a bridge is inadequate to accommodate the modern truck fleet (Upper Great Plains Transportation Institute, 2014). Both of these characteristics can lead to increases in travel distance and use of less desirable routes which leads cost and time overruns for carriers. Two examples in recent years provide insights into the impact of structures on connectivity:

- In 2011, flooding of the Souris River damaged a bridge on PR 251 that provided a connection between the Waskada and Pierson oil fields. Trucks were rerouted through 18km of municipal gravel roads to the nearest RTAC rated bridge.
- In 2014, above average rainfall damaged approximately 30 structures in the region. This resulted in bridge restrictions with reduced speeds and weight limits. The industry experienced below-average rig activity as most of the OS/OW equipment was unable to find a suitable route through the network. Figure 11 shows the disrupted network for the study region as of July 30th, 2014.

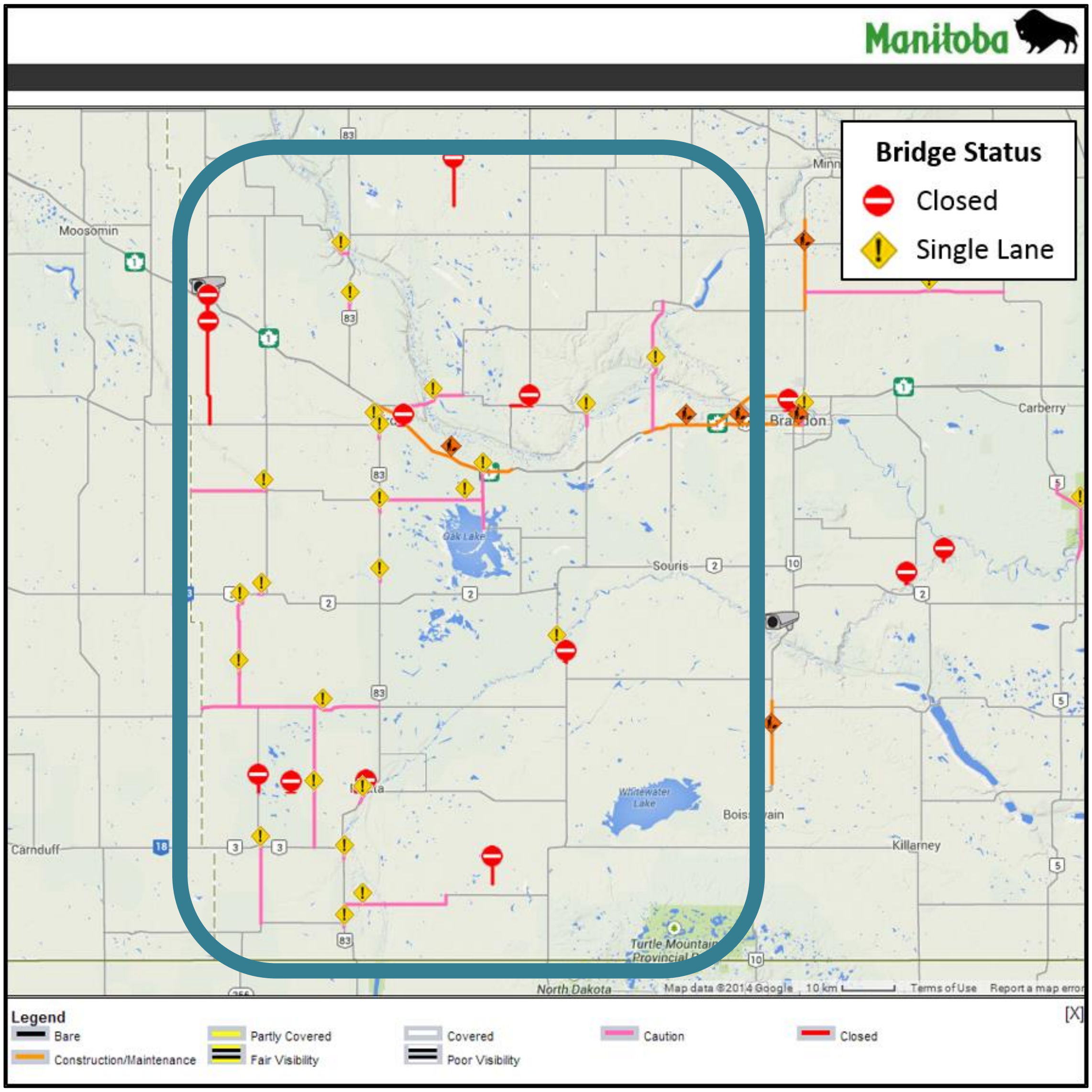


Figure 11: Disrupted Highway Network in Southwest Manitoba
Source: Used with permission from Manitoba 511, image captured July 30th, 2014.

In addition, the drilling stage for new wells requires OS/OW trucks to move equipment between drill sites. Maintaining and using an up to date inventory of structures can help plan safe and efficient routes that accommodate both infrastructure and industry.

The first and last mile to most wells in the region is provided by the municipal road network. Typically, this is a mile grid system of gravel and dirt roads through most of the petroleum producing region in southwest Manitoba. These roads are essential for providing access to wells, batteries, and other materials such as gravel. As shown in

Figure 12, the municipal road network is dense and interconnected with the provincial road network. Knowledge of where and how industry uses this component of the transportation system is improved by understanding the location of petroleum-related origins and destinations. Typically, the petroleum truck fleet takes the shortest path between wells and facilities and the provincial highway and road network. This information can be used to inform analysts and planners on where trucks typically access the provincial network from municipal roads.

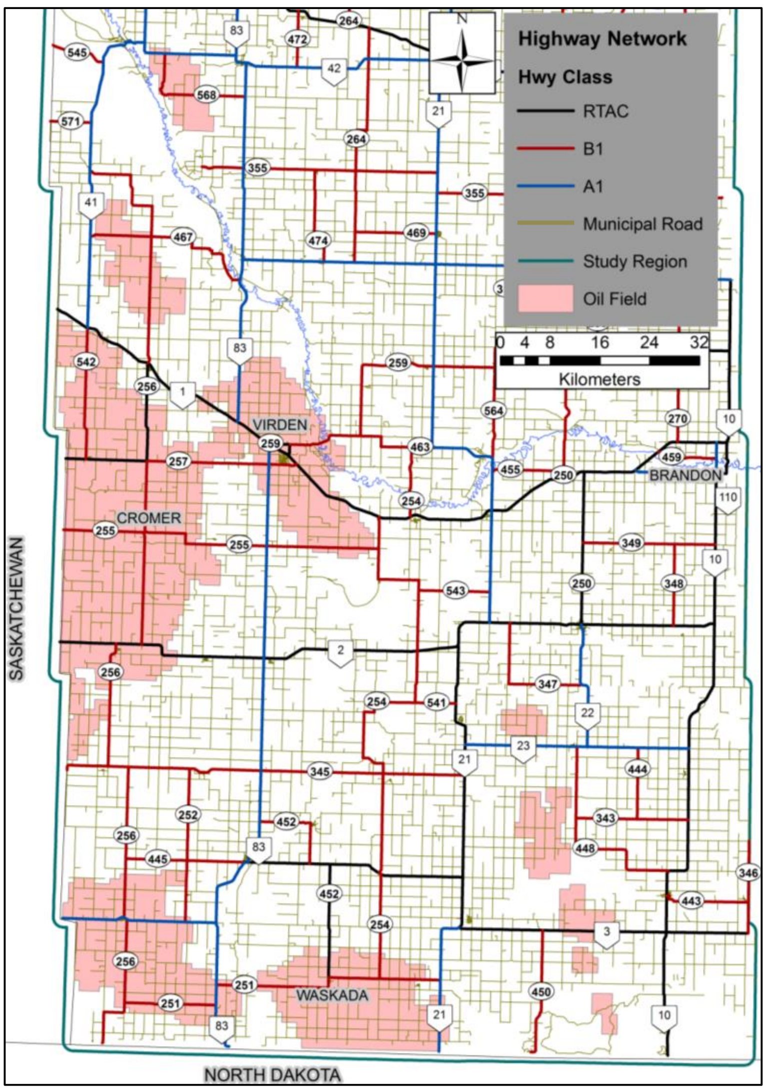


Figure 12: Southwest Manitoba Municipal Road Network

3.1.2 Railroads

Railroads have been investing in their infrastructure to increase their market share of oil shipments. Primarily, railroads have been building crude-by-rail facilities and other transload facilities that can handle frack sand, equipment, and other materials. New crude-by-rail facilities in North Dakota are capable of handling 70,000 to 90,000 barrels per day, or more than a unit train per day (Upper Great Plains Transportation Institute, 2013). In addition, railroads are increasing their ability to handle frack sand through unit trains sourced from Wisconsin and Illinois and ceramic proppants sourced from China (Hart, et al., 2013). This leads to increases in train volumes on sections of track that previously did not experience these volumes or weights, requiring extensive upgrade investment to maintain operating speeds and reliability (Smith, 2013). The growth in rail is evident as regions such as North Dakota have gone from 20,000 barrels per day in 2008 to over 800,000 barrels per day in 2013 (Tolliver, 2013). This is nearly 13 unit trains per day from only one unit train every three days.

Southwest Manitoba is served by Canada's two largest railroads: Canadian Pacific and Canadian National. Currently, Canadian Pacific does not have a transload facility within Manitoba that serves the petroleum industry. However, across the border in Saskatchewan, CP has a major facility in Bienfait that handles crude oil, frack sand, and other supplies. Typically, crude oil from Manitoba is not trucked to Saskatchewan for export but frack sand and other supplies are moved into Manitoba from these facilities. Canadian National currently has two crude oil transload facilities located on their Cromer Subdivision (locations, along with the rail network, are shown in Figure 13). One facility, operated by Tundra Energy Marketing Limited (TEML), is located outside the village of Cromer and capable of handling approximately 50 rail cars per day (30,000 bopd). A second facility in the village of Woodnorth, operated by Watco Terminal and Port

Services, handles less than 3000 bopd (or about 5 rail cars per day). The facility near Cromer acts as an alternative to pipeline for export to market and generates truck trips to the TEML Cromer transload facilities regardless of train operations. The Woodnorth facility, which is much smaller, generates approximately 10 truck trips per day. As the industry grows and market demand changes, capacity constraints in pipelines may result in a growth in rail shipments. Alternatively, a larger spread between WTI and Brent crude oil prices may encourage further growth in rail shipments to refineries on the USA east coast.

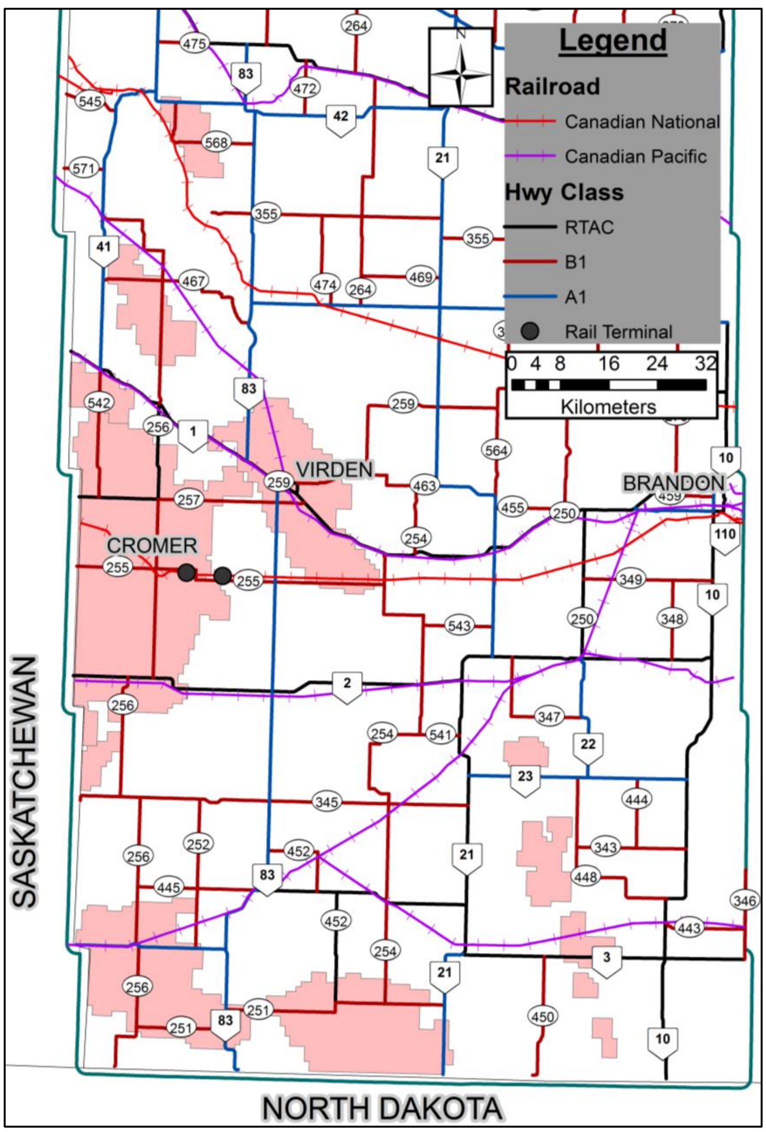


Figure 13: Railroads Operating in Southwest Manitoba

3.1.3 Pipelines and Flowlines

Pipelines are used both for exporting crude oil to refineries and as gathering networks from wells to storage and transload facilities. Most crude oil is exported from regions by pipelines, but capacity challenges have enabled railroads to capture more market share. Figure 14 shows the main pipeline network in eastern North America and direction of oil movement from Manitoba; PADD II and III refineries are a main destination for oil produced in Manitoba. Pipelines may exist within a region, such as southwest Manitoba, to move crude oil between producing oil fields and export facilities. Within petroleum producing regions there is also a pipeline gathering network made up of flowlines (small diameter pipes) that move emulsion from wells to centralized locations and alleviate local road traffic. In mature oil producing regions, up to two-thirds or more of oil may be gathered by flowlines. Currently, in North Dakota (a young oil producing region), it is estimated that approximately 27 percent of crude is moved via flowlines from wells to storage facilities with the remaining 73 percent moved by trucks (Tolliver, 2013). These values are expected to reverse as the region becomes more mature within the next decade (Upper Great Plains Transportation Institute, 2014). In Manitoba, mature fields may have two thirds or more of their wells flowlined while younger producing regions could be as low as 25 percent.

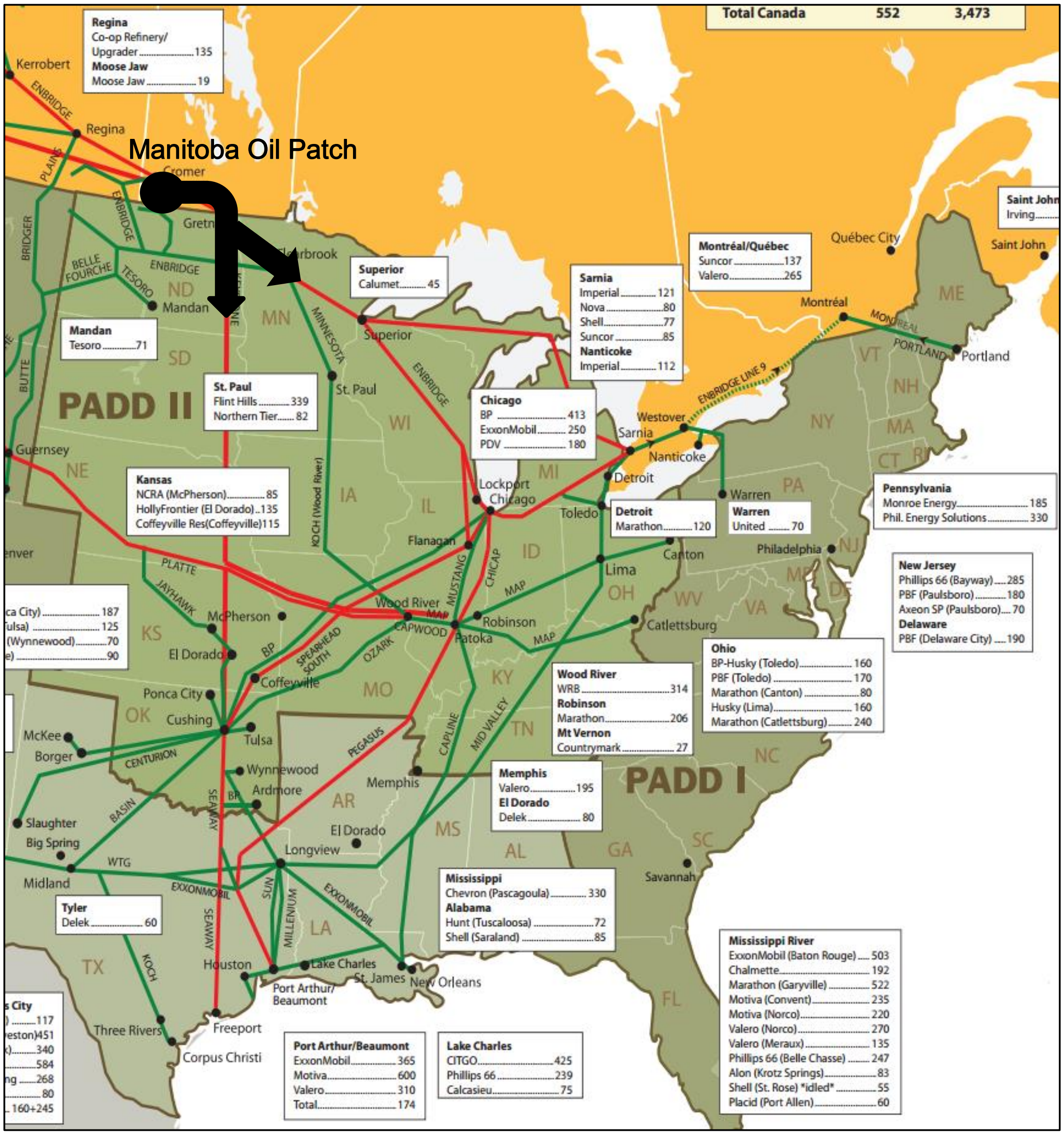


Figure 14: Eastern North America Pipeline Network with Flow Direction from Manitoba
Source: Canadian Association of Petroleum Producers (2013)

Crude oil pipelines in Manitoba serve two main purposes: export to market and regional collection. Currently, there are three main pipelines in Manitoba that export crude oil to market: Enbridge Alberta Clipper, Enbridge Mainline, and the Transcanada Keystone. Transcanada does not connect with the industry in Manitoba and therefore all product in Manitoba carried by pipeline is served by the Enbridge facility at Cromer. In addition to their export lines, Enbridge has a pipeline gathering network that connects at Cromer from North Dakota and Saskatchewan capable of carrying about 210,000 bopd. Within Manitoba, there are a number of gathering pipelines that move crude oil from batteries located in the various oil fields to the Enbridge and TEML facilities. These pipelines connect the southeast section of the Pierson Field to the western section of the Waskada Field and Waskada to the Cromer facilities. Within the Daly-Sinclair Field, several batteries are connected by pipeline to the Cromer facilities. The Virden Field is connected to the Enbridge facility through the Enbridge Virden pipeline network. Pipelines help reduce the number of year-round truck traffic by providing an alternative mode of transportation to move crude oil.

In addition to pipelines there exists an extensive network of flowlines. Flowlines are smaller diameter pipes that connect wells to each other and to facilities such as batteries. This dense network operates much like the municipal road network and accommodates the “first mile” of product movement. Flowlines primarily move emulsion (the mixture of water, fluids, and oil that come directly out of a well) to batteries. They are also used to move wastewater to injection wells. These lines help reduce the number of internal truck trips within an oil field by gathering product to centralized locations where crude oil and wastewater can then be moved by pipeline or truck to their final destination. When wells are not connected by flowline, storage tanks must be installed at a well to store product until a truck can collect it. Some wells may require one or two trucks per day to carry crude oil to a battery or the Cromer facilities. As an oil field matures the density of the flowline network increases. Table 3 lists the percentage of wells flowlined for the highest producing fields in Manitoba; the most mature field, Virden, has the highest density of flowlined wells. A higher flowline density indicates a reduced number of local truck trips and provides higher confidence that trucks carrying crude oil from a field originate at batteries not connected by a pipeline.

Table 3: Percent of Wells Flowlined in Select Oil Fields

Oil Field	% of Wells Flowlined
Waskada	65%
Pierson	45%
Daly-Sinclair	65%
Virden	90%
Manson	25%

3.2 CHARACTERISTICS OF PETROLEUM-RELATED VEHICLES

This section discusses the various vehicles being used by the petroleum industry to move product and equipment by truck and rail.

3.2.1 Petroleum Industry Truck Fleet

The truck fleet associated with the petroleum industry includes single unit trucks, single trailer units, and multiple trailer units. The vehicle class distributions (VCDs) in the study region are dominated by FHWA Class 6, 10, and 13, as shown from a sample site in Figure 15. Definitions of the FHWA vehicle classes can be found in Appendix B.

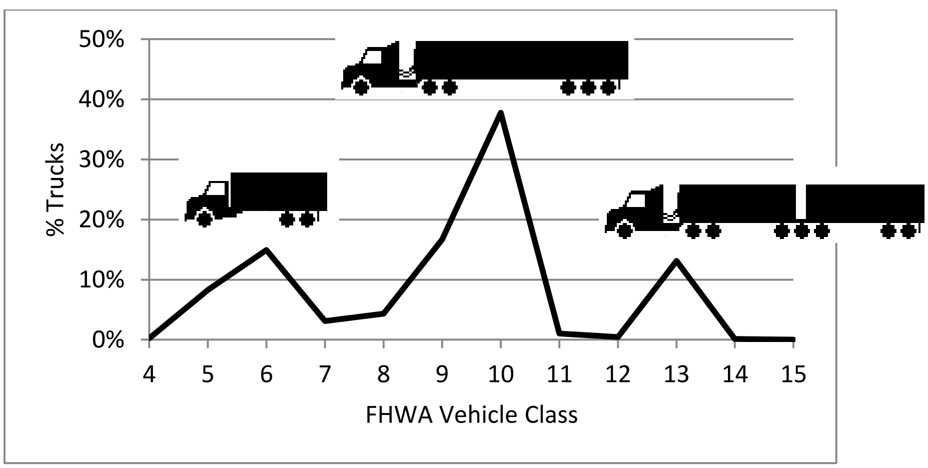


Figure 15: Example Vehicle Class Distribution in Southwest Manitoba

Single unit trucks, primarily tanker trucks classified as FHWA Class 6, also include unique vehicles such as service rigs (2-axle, 4-tire tandem steer with 2-axle, 8-tire tandem drive) and crane trucks (single or tandem axle steer with tandem or tridem drive). These unique single unit trucks may be classified as FHWA Class 7, 8, or 11 depending on configuration and axle spacing. Most of the single unit trucks have permanently mounted apparatus (PMA), such as a crane or service rig. Body types of non-PMA vehicles are typically tanker units moving crude oil, water, or other liquids. Figure 16 provides examples of single unit trucks operating in southwest Manitoba.

Figure 16: Example Single Unit Trucks Serving the Petroleum Industry (Clockwise: Winch Truck, Crane Truck, Service Rig)
Source: Photos taken by J.McKee and reproduced with permission from J.McKee

Single trailer trucks include tractors with a tandem or tridem axle trailer. These vehicles are used to move a variety of products and equipment including wooden mats, pipe, frack sand, crude oil, water, and drilling equipment. Near transload facilities or large batteries, most single trailer trucks will be FHWA Class 10 trucks with tanker bodies. Tanker body types are common throughout the region due to the large amount of liquid (water, crude oil, and produced water) that must be moved. Other body types include flat decks (for equipment and material) and hoppers (for frack sand). Some configurations that are less common but representative of the industry includes tri-drive tractors and 7-axle Class 10 trucks (tandem steer, tandem drive, tridem trailer). Figure 17 provides examples of single trailer trucks operating in southwest Manitoba.

Figure 17: Example Single Trailer Trucks Serving the Petroleum Industry (Clockwise: Coil Rig Unit, Crude Oil Tanker, Frack Sand Hopper)
Source: Photos taken by M.Reimer

Multiple trailer trucks that serve the petroleum industry include common configurations such as 8-axle B-trains but are predominantly single unit trucks with trailers. FHWA Class 13, which includes 8-axle B-trains, also includes single unit tanker trucks with 4-axle tanker trailer and other tractor-trailer combinations used to move OS/OW equipment associated with oilfield activities. These OS/OW vehicles are configured with boosters and jeeps to distribute the weight of heavy equipment across more axles and wheels. Figure 18 provides examples of multiple trailer trucks operating in southwest Manitoba.

Figure 18: Example Multi-Trailer Trucks Serving the Petroleum Industry (Top Photo: Crude Oil Tanker; Bottom Photo: Drilling Derrick)
Source: Top Photo Taken by M.Reimer, Bottom Photo Taken by J.McKee and reproduced with permission from J.McKee

Characterization sheets for sample vehicles, including axle configuration, spacing, and weights, are included in Appendix C.

3.2.2 Railroad Cars

Railroads are used to move equipment, material, and supplies to petroleum producing regions and move petroleum products (crude oil) out to refineries and export markets. Commonly used rail cars include tankers (for crude oil), hoppers (for frack sand), and flat decks. Figure 19 provides examples of two rail cars used by the petroleum industry. These cars may operate in blocks (sets of similar cars) or unit trains (100+ car train of the same product). The transload facilities in Manitoba handle only crude oil tank cars.

Crude oil tank cars can handle up to about 700 barrels of oil (110 cubic metres) but in Manitoba the car capacity is constrained by the track load restriction (263,000 pound gross weight on the Cromer Subdivision).

Figure 19: Example Rail Cars Serving the Petroleum Industry (From Left to Right: Sand Hopper, Tanker)
Source: Photos Taken by M.Reimer

3.3 GOVERNMENT REGULATIONS

This section outlines the government regulations that influence petroleum exploration and production activity. These regulations include those that apply to the transportation system and to the petroleum industry directly that can influence the level and type of activity occurring in Manitoba.

3.3.1 Manitoba Truck Size and Weight Regulations

Manitoba signed the Memorandum of Understanding Respecting A Federal-Provincial-Territorial Agreement on Vehicle Weights and Dimensions (referred to as RTAC MoU) in 1988 along with all Canadian provinces and territories. The document is a result of technical research that reviewed the impacts of trucks on pavement and structures. Furthermore, this document provides the relationship between truck configurations and dynamic stability and control. The MoU had goals of improving regulatory uniformity between jurisdictions, enabling economic opportunity through improved truck productivity, and making sure trucks met specific safety-related dynamic performance criteria (Woodrooffe et al. 2010; Regehr, Montufar, and Clayton, 2009).

The RTAC regulations created increased productivity for both weight and cubic capacity for payloads. In Manitoba, these productivity gains are available along primary highways defined as RTAC routes. In addition to RTAC highways, Manitoba has classified, in decreased weight allowances, A1 and B1 highways. The axle weight limits and maximum GVW for each highway load class are shown previously in Table 1.

In addition to weight restrictions by highway load rating, standard vehicle configurations are given maximum size and weight dimensions. The allowable width and height of vehicles throughout the network is 2.6 m and 4.15 m, respectively. Lengths vary based on configuration with single unit trucks at 12.5 m, single trailer at 23 m, and double trailers at 25 m. Gross vehicle weights are subject to axle configuration, including axle groups and axle group spreads. The GVW for the following FHWA vehicle classes on RTAC highways are: Class 6 at 24,300 kg; Class 9 at 39,500 kg; Class 10 at 46,500 kg (a function of tridem axle spread); and Class 13 at 62,500 kg. At lower highway weight classes (A1 and B1 highways) these weights are reduced as allowable GVW for these highways are lower.

3.3.2 Permitting of Oversize and Overweight Vehicles

The weight and length limits outlined in the previous section are known as “basic” truck size and weight regulations. However, many vehicles in the petroleum producing region of Manitoba fall outside of the truck size and weight “envelopes” that outline vehicle specifications on weight, axle configuration, and length limits. In Manitoba, trucks that fall outside the basic envelopes can be given one of two types of permits: (1) annual “blanket” permits; or (2) single-trip permits (Reimer, Regehr, and McKee, 2014). Single-trip permits are issued for vehicles that exceed basic truck size and weight regulations for a given route. In some instances when the same vehicle will travel the same route a single-move permit may be valid for several months. Manitoba has put significant effort into accommodating unique vehicles that are standard to the petroleum industry to reduce administrative burdens and facilitate industry needs.

Annual permits, or blanket permits, are issued to carriers for specific OS/OW truck configurations that are routinely used. The permit may restrict these vehicles to a limited highway network based on engineering assessment of the requested route and structures along the corridor. However, these vehicles may take multiple trips under this type of permit. The Government of Manitoba has made efforts to improve the permitting process by creating and issuing annual permits for OS/OW vehicles routinely used by the petroleum industry (Reimer, Regehr, and McKee, 2014). Vehicles that have been moved from one-move to annual permits in recent years include service rigs, winch-bed trucks, concrete trucks, and pumper trucks. All these vehicles are non-articulated straight trucks with permanently mounted apparatus. Sample vehicles and maximum permitted weights for these vehicles are shown in Figure 20 and Table 4.

Figure 20: Divisible Load Single Unit Trucks (From Top to Bottom: Single Steer Tridem Drive, Tandem Steer Tandem Drive)
Source: Photos taken by J.McKee and reproduced with permission from J.McKee

Table 4: Legal and Permitted Axle Loads for PMA Divisible Load Straight Trucks
Source: Reproduced with permission from ASCE from Reimer, Regehr, and McKee (2014)

	Legal Limit (kg)	Maximum Limit by Annual Permit (kg)
PMA divisible load straight truck with single steer and tridem drive		
Single steer axle	7300	9100
Tridem axle	17,000	22,000
PMA divisible load straight truck with tandem steer and tandem drive		
Tandem steer axle	7300	16,000
Tandem drive axle	17,000	21,960

For both annual and single-trip permits, carriers must submit information related to the vehicle's dimensions, GVW, axle spacing, and axle weights. The approval process from Manitoba Infrastructure and Transportation for OS/OW vehicles includes an assessment of public safety impacts, current infrastructure condition (roadway and bridges), vehicle characteristics, and proposed route of travel. Based on the assessment, carriers may be granted a permit with restrictions on scheduling, speed limits, travel lanes, and require escorts or inspections. Permits requested where the vehicle meets the axle and GVW listed below may be issued without requiring a bridge assessment.

- 21,960 kg (48,310 lb) for an eight-wheel tandem axle group (the maximum legal limit on RTAC roads is 17,000 kg);
- 27,500 kg (60,500 lb) for a 16-wheel tandem axle group, 12-wheel tridem axle group, and 24-wheel tridem axle group (the maximum legal limit for tridems on RTAC roads is 24,000 kg);
- 16,000 kg (35,200 lb) for a tandem steer axle group;
- 22,000 kg (48,400 lb) for a tridem drive axle group;
- 38,000 kg (83,600 lb) for the GVW of a non-articulated straight truck; and
- 60,000 kg (132,000 lb) for the GVW of articulated trucks.

When a vehicle exceeds these limits, a full bridge assessment is required which may involve a detailed load rating for each bridge along the carrier's requested route.

3.3.3 Railroads

Railroads that cross provincial boundaries are federally regulated by Transport Canada. Regional or short line railroads are regulated by the province in which they operate. Furthermore, as railroads maintain and operate their own infrastructure, the railroad itself will have its own rules and regulations for operation throughout its network and specific Subdivisions. In Manitoba, the Subdivision connected to crude oil transload facilities is posted at a maximum carloading weight of 263,000 lbs and has operational restrictions that are a function of track and bridge condition.

Recently, railroads have been the target of public safety reviews with crude oil train derailments in Lac-Mégantic and North Dakota, among other smaller incidents. With the growth in crude-by-rail due to pipeline capacity restraints, North American agencies have been amending and updating crude-by-rail regulations. Transport Canada has recently published the *Regulations Amending the Transportation of Dangerous Goods Regulations (Update of Standard)* which came into effect on July 15th, 2014 (Canada Gazette, 2014). The new amendment requires crude oil to be tested and classified to ensure shipping documents are accurate and introduces the new design and construction standards for DOT-111 rail tank cars. The new tank car standard introduces features for increased safety when transporting dangerous goods with a focus on structural integrity and protection.

In 2013, approximately 30 percent (about 12,000 cars) of the DOT-111 crude oil tank car fleet met the higher safety standards voluntarily adopted by railroads in 2011. The higher safety standards have created an influx of new tank car orders. Many older tank cars, including the AAR-211 tank car, cannot be used to transport crude oil across the U.S./Canada border (subject to a fine up to $175,000). In Canada, both CN and CP have introduced their own policies to improve safety on their network. This improved safety (starting March 2014) includes charging higher transport rates for moving crude oil with older DOT-111 cars and phasing out or retrofitting older cars (Canadian Association of Petroleum Producers, 2014).

3.3.4 Pipelines and Flowlines

Pipelines are regulated both provincially and federally. Any pipeline that crosses a provincial or international boundary is regulated by the National Energy Board (NEB) and other agencies depending on land type and ownership (such as Fisheries or Natural Resources Canada). Pipelines operating solely within a province or territory are regulated by an agency within the operating province; in Manitoba this is the Manitoba Public Utilities Board (for gas lines) or The Oil and Gas Act (for pipelines and flowlines). In general, regulations for pipelines ensure safety for communities and the environment and govern transportation rates. Regulating agencies must ensure pipelines are operated safely, responsibly and in the interest of the public. Standards for Canadian pipelines are developed by the Canadian Standards Association that cover design, construction, operation, and maintenance (Canadian Energy Pipeline Association, 2014).

In Manitoba, pipelines operating wholly within the province are regulated under The Oil and Gas Act (Manitoba, 2014a). The purpose of this Act in regards to pipelines is to provide for the safe and efficient construction and operation of pipelines. Information regarding flowlines and pipelines is contained within Part 12 of The Oil and Gas Act. Flowlines must have approval of an inspector, a flow line license, and surface rights prior to construction and operation. Effective August 1, 2014, producers must also submit spatial data for all flowline submissions to assist the Petroleum Branch in providing fast and efficient service (Manitoba Mineral Resources, 2014). Pipelines are more strictly regulated, requiring application for construction to be sent to and approved by the minister (member of the Executive Council charged by the Lieutenant Governor in Council) along with obtaining the necessary surface rights. In addition, this Act governs pipeline operation, carrier rights, abandonment, public safety, and right-of-way conflicts with other modes of transportation.

4. METHODOLOGY TO CHARACTERIZE PETROLEUM-RELATED FREIGHT FLOWS

This chapter develops the methodologies used to characterize petroleum-related freight flows. This chapter describes: (1) the transportation systems analysis approach and integrated framework; (2) the disaggregation of petroleum-related freight generation for development and production at various spatial resolutions, and (3) describes data sources used in the methodology and examples of integrating this data.

4.1 CHARACTERIZING PETROLEUM-RELATED TRUCK TRAFFIC

The petroleum industry relies on various modes of transportation to meet its freight needs through the development and production phase of each well. This thesis highlights the freight impacts on railroads, pipelines, and highways. The primary difference between the three modes is the variety of users operating on a highway and the public nature of highway transportation infrastructure. There is a need for industry-specific data and knowledge on how the petroleum industry affects highway networks. This section provides details on the approach taken to understand, interpret, and estimate petroleum-related truck traffic to provide data and information for transportation engineering, planning, and maintenance.

4.1.1 Transportation Systems Analysis

The methodology applied in this research is based on the transportation systems analysis approach that comprises the following components: transportation system (T); activity system (A); and flow system (F) (Manheim, 1979). The petroleum industry creates varying temporal and spatial demand on regional transportation networks and can be influenced by a fourth component, exogenous indicators (E) (Reimer and Regehr, 2014b). Understanding and reviewing exogenous indicators that influence dynamic industries is important due to their ability to create large, and potentially sudden, changes in activity levels. Characterization of the transportation system and activity system, and the impacts of exogenous indicators, is necessary prior to developing the flow system. To assist in developing and applying the integrated framework, this research used the following methodology:

1. Characterization of the activity system, *A*, present in regions affected by petroleum exploration and production (Chapter 2 of this thesis). This component of the research was conducted through interviews with industry experts and analysis of public and private datasets. The activity generated by the petroleum industry can be influenced by regional and global economic and environment conditions and therefore exogenous factors, *E*, were used to enhance the activity system. The main components characterized are:
    - *Well development origins and destinations*
    - *Oil production origins and destinations*
    - *Modal choice*
    - *Freight and trip generation*
    - *Industry activity indicators*
2. Characterization of the transportation system, *T*, that serves the petroleum industry (Chapter 3 of this thesis). Information and data relevant to the transportation system were collected through: (1) available public literature and reports; (2) interviews and discussions with professionals; (3) public and semi-public data sources and GIS data sets; and (4) independent data collection, site visits, and industry tours. This data is integrated into the GIS data dissemination tool. The main components characterized are:
    - *Road network*

- *Railroads*
- *Pipelines and flowlines*
- *Vehicle (truck and rail) characteristics*
- *Government regulations*

Characterization of the activity and transportation systems is supplemented by interviews with industry experts and independent data collection to develop an understanding of petroleum-related freight flows through southwest Manitoba.

4.1.2 Integrated Framework

The need for an integrated framework is due to the complexity of the petroleum industry, its freight transportation demand, and the impacts these demands place on transportation infrastructure. The characteristics of the petroleum industry challenge traditional traffic monitoring approaches in two ways. First, truck traffic monitoring programs are not capable of capturing the multimodal nature of the industry, particularly the effects that mode shift has on truck traffic characteristics. Second, it is difficult to design a truck traffic monitoring program that adequately reflects the temporal and spatial dynamics of the industry; there is a need to change the way we do counts for specific industries (Quiroga, 2014). Despite these challenges, there is a need for truck traffic data such as volume, classification, and weight to support highway engineering functions such as pavement maintenance and rehabilitation, bridge evaluation, capacity analyses, and road safety reviews. Less urgent, but perhaps equally important, is the need to forecast near- and long-term truck traffic demand to support highway planning functions; this is typically the function of freight demand modeling.

To address the unique challenges of the petroleum industry, an integrated framework, illustrated schematically in Figure 21, has been developed to help characterize truck traffic. The framework draws from standard methodologies used for monitoring truck traffic (the left side of the schematic) and modeling freight transport demand (the right side of the schematic) and illustrates how these methodologies interrelate through their reliance on common data sources and their mutual goal of characterizing truck traffic.

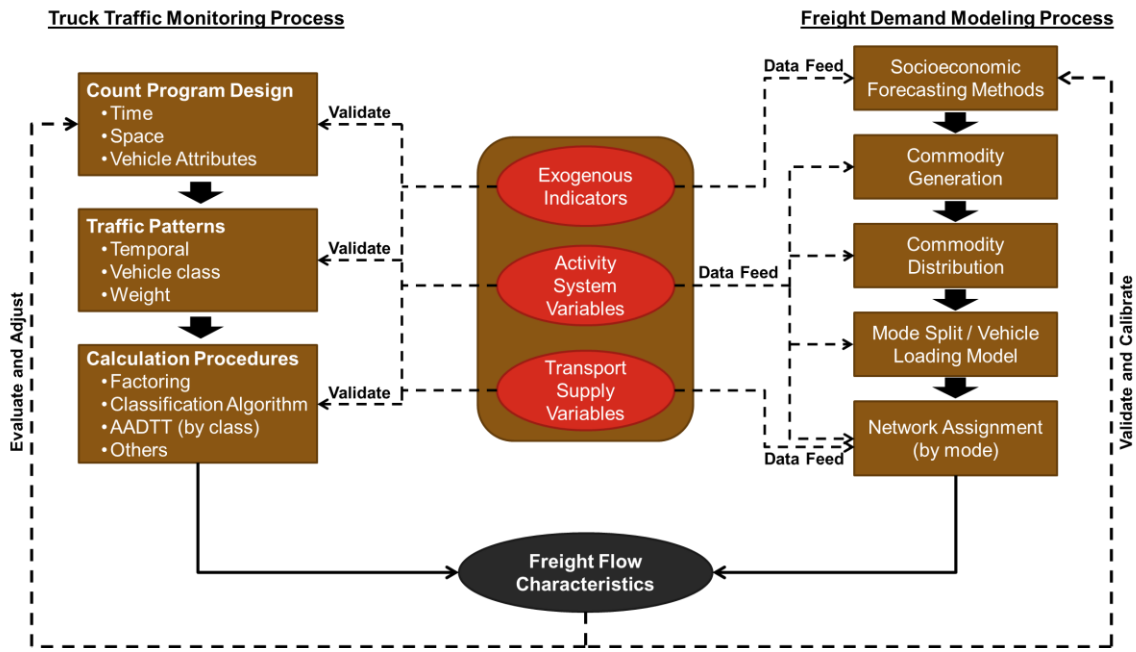


Figure 21: Integrated Framework for Estimating Freight Flow Characteristics
Source: Reproduced with permission from TRB from Reimer and Regehr (2014b)

The central components of Figure 21 are the broad data categories that are important to both processes used to develop truck traffic flow characteristics. Exogenous indicators are those socioeconomic factors that affect industry development and production, such as the market price of oil, price spread between markets, and ability to export product to markets. The activity system variables are related to origins, destinations, and commodity/trip generation characteristics. Lastly, the transport supply variables reflect the physical transportation infrastructure being used by the petroleum industry and associated attributes of that infrastructure, such as load classification and capacity. As highlighted in Chapter 2 and 3 of this thesis, these are the three components required to link together to understand the petroleum industry and its impacts. The common reliance of both traffic monitoring and freight demand modeling on these components allows them to be integrated together in their mutual goals.

4.1.2.1 Truck Traffic Monitoring Process

The *Traffic Monitoring Guide* outlines a step-by-step process for creating and maintaining a continuous data program for volume, vehicle classification, and weight. In essence, this process involves the following elements, which are portrayed on the left side of Figure 21 (Federal Highway Administration, 2013).

- *Count program design and review*: This element involves a review of the existing program used to monitor truck traffic volume, vehicle classification, and weight; development of an inventory of available datasets; and design of the count program (consisting of automatic vehicle classifiers and weigh-in-motion devices) to ensure adequate temporal and spatial coverage and sufficient capability to produce data attributes required by end users.
- *Design and development of pattern groups*: A fundamental role of a continuous count program is to enable factoring of short-term classification counts. To enable this functionality, truck traffic pattern groups are needed that describe temporal patterns (e.g., monthly, day-of-week, hourly), vehicle classification distributions, and truck weight distributions. The *Guide* recommends integration of industry-specific information in the development of pattern groups, though details of how to do this are not provided.
- *Calculation of standard metrics*: Data collected at both continuous and short-term sites are processed into standard metrics such as annual average daily truck traffic (AADTT) by vehicle class, vehicle-distance travelled, axle load spectra, and others.

- *Evaluation and adjustment*: The *Guide* recommends a formal evaluation of the process every five years. As indicated by the feedback loop in the figure, results from the evaluation process support adjustments to the program design so that it is better able to meet evolving user needs.

The outcome of this process is a database capable of characterizing *current* (or recent past) truck traffic on a relatively dense highway network in terms of volume, vehicle classification, and weight, in addition to details on temporal and directional variations. These provide fundamental inputs for a host of engineering functions.

This thesis relied on data available from the Manitoba Infrastructure and Transportation department specific to automatic vehicle classifiers (AVCs) that provided traffic and truck volumes, vehicle classification, and axle spacing information. Additional data were acquired from existing short term coverage count stations (CCSs) and new classification CCSs. The classification CCSs were employed as part of this research to provide better data on truck traffic where traditional CCSs only count axles (not truck traffic data). Weight data specific to the petroleum industry were not available because no traffic counting equipment in the study region is equipped with the ability to weigh vehicles in motion. Static weight was collected through the roadside survey conducted as part of this research and from reported weights available through the permitting database.

4.1.2.2 Freight Demand Modeling Process

Various processes are used to model freight demand; these are generally classified as applying either a trip-based or commodity-based modeling platform (Holquin-Veras and Thorson, 2000). Most of these processes adopt some form of the “four-step” modeling approach. The right side of Figure 21 depicts one such process, namely the commodity-based economic activity model (National Cooperative Highway Research Program, 2008). As shown in the figure, the demand modeling process involves:

- *socioeconomic forecasting methods* for relevant industry sectors;
- *commodity generation* based on generation rates by commodity group;
- *commodity distribution* between origin and destination zones, normally using a gravity model;
- *mode split and vehicle loading models* to distribute tonnage to various modes and convert tonnage to vehicles;
- *network assignment* based on zone-to-zone impedances;
- *validation*, which normally relies on truck traffic monitoring data; and
- *calibration*, which may involve an adjustment to the socioeconomic forecasts based on predicted network performance.

Similar to the outcome of the truck traffic monitoring process, the freight demand modeling process produces a database capable of characterizing various aspects of truck traffic, including truck volume by class and truck weight (though aspects of these characteristics are presumed as part of the modeling process rather than a result of direct on-road measurements). The logic built into the demand modeling process enables it to forecast *future* truck traffic characteristics based on information about origins, destinations, and routing, though typically this occurs at a relatively high level of spatial aggregation (e.g., county or state level).

4.1.3 Framework Data Sources

The middle portion of Figure 21 shows three general categories of data that are relevant for both the truck traffic monitoring process and the freight demand modeling process: exogenous indicators, activity system variables, and transport supply variables. From a freight demand modeling perspective, inclusion of these data sources is not novel because they provide the fundamental inputs for the components of the modeling process. However, from a truck traffic monitoring perspective, explicit integration of these non-traditional datasets has not been emphasized, despite general recognition that better information about industry-related patterns and trends supports more robust monitoring practices and better data interpretation (Reimer and Regehr, 2014b). Therefore, the framework offers a structured way of relating the two processes that ultimately have a common objective.

The following list describes examples of how specific datasets within these three categories would be relevant for the petroleum industry. Table 5 summarizes these datasets, along with traditional datasets normally developed within a truck traffic monitoring program.

- *Exogenous indicators*: Numerous exogenous socioeconomic factors influence industry activity and the resulting commodity and vehicle movements. Within the petroleum industry, for example, the crude price spread between WTI and Brent may alter the market destination of crude, particularly for Bakken crude which currently has limited pipeline capacity. This resulted in a growth in the transport of crude by rail in North Dakota, which reached a peak in May 2013 when 84 per cent of crude from the area moved by rail (this share was back down to 70 per cent by June) (Smith, 2013). A related example is pipeline capacity, which may also impact the level of production in a region.
- *Activity system variables*: Industry activity datasets principally comprise commodity and/or trip origins and destinations, but could include any data related to commodity/trip generation, distribution (routing), and mode choice. As discussed earlier, development of a well site requires inputs from numerous

origins, and is itself an originator of produced water and oil products destined for disposal sites and transload facilities, respectively. Rig movements and permit information (e.g., oversize/overweight permits, permits for raising overhead power lines to accommodate drill rigs) are two additional examples of activity data.

- *Transport supply variables:* These datasets represent the properties of the physical infrastructure that enables freight transportation. For the petroleum industry, these datasets include: (*a*) the road network, including features such as capacity, functional classification, load classification, bridge load restrictions, height and width restrictions (some of these features would also traditionally be used within a traffic monitoring program); (*b*) the rail network, including class, capacity, load rating, and bridge restrictions; and (*c*) pipelines, including capacity constraints and the presence and staging of flowlines used to gather emulsion.

Table 5: Example Data Sources for Characterizing Petroleum-Related Truck Traffic
Source: Reimer and Regehr (2014b)

Dataset	Domain	Source
Truck Traffic Monitoring		
Automated Vehicle Classifiers	Public	Department of Transportation
Weigh-in-Motion	Public	Department of Transportation
Coverage Count Classification Station	Public	Department of Transportation
Exogenous Indicators		
Crude Oil Pricing	Public	Market Reports
Crude Oil Exports by Region	Public	National Statistics Data
Pipeline Capacity	Public	Interregional Transmission Capacity Levels
Crude Oil Reserves	Public	National Statistics Data
Activity System		
Highway Permit Data	Semi-Public	Department of Transportation
Utility Moves Permit Data	Private	Utility Companies
Land Use (by Petroleum Industry)	Public	Open GIS Databases
Rig Activity	Public	Weekly Rig Counts
Oil Production Statistics	Public	National Statistics Data
Rail Car Loadings	Public	National Statistics Data
Transport Supply		
Rail Network	Semi-Public	Open GIS Databases
Road Network	Public	Open GIS Databases
Road Functiona/Load Classification	Semi-Private	Department of Transportation
Bridge Location and Weight Rating	Semi-Private	Department of Transportation
Pipelines	Private	Private Corporations
Flowlines	Private	Private Corporations

Estimating and analyzing petroleum-related truck traffic flow requires many data sources. As such, it is necessary to select data sources and identify components that can help estimate and assign truck traffic volumes to the region and validate these estimations. Included in this list is traffic monitoring datasets, general industry statistics, and commodity-based data. Furthermore, some of the components can assist decision makers in understanding future demand and identify potential for changes in the industry. Table 6 provides a summary of the data used in this research and where the data was obtained.

Table 6: Data Sources Used in this Research to Characterize Truck Traffic

Data	Domain	Data Source
Truck Traffic Monitoring		
Automated Vehicle Classifiers	Public	Manitoba Infrastructure and Transportation
Portable Weigh Scales	Semi-Public	Manitoba Infrastructure and Transportation
Classification Coverage Count	Public	Manitoba Infrastructure and Transportation
Roadside Survey	Semi-Public	Manitoba Infrastructure and Transportation
Freight Demand		
Manitoba Crude Oil Export	Public	Statistics Canada
Monthly Crude Oil Prices	Public	Imperial Oil Crude Oil Prices
Highway Permit Data	Semi-Public	Manitoba Infrastructure and Transportation
Utility Moves Permit Data	Private	Manitoba Hydro
Well Production Statistics	Public	Manitoba Petroleum Branch
Pipeline/Flowline Status	Semi-Public	Manitoba Petroleum Branch, Industry Interviews
Rig Activity	Public	Baker-Hughes Investor Reports
Western Canada Rail Car Loadings	Public	Statistics Canada
Truck Traffic Generated by Facilities	Private	Industry Interviews
Petroleum Industry Land Use	Public	Manitoba Petroleum Branch

Truck traffic monitoring data provides information on vehicle class distributions, GVW and axle group weights, temporal distributions, and routing. Vehicle class distributions are taken from 48-hour classification coverage count stations (CCSs) using pairs of road tubes to measure axle spacing and vehicle speed. The classification CCS data provides information on temporal (hourly) distribution which is supplemented with AVC data and exogenous indicators (active rigs and wells drilled) to understand industry seasonality. Weight data for total and axle weights were obtained through portable weigh scales deployed during a roadside survey and supplemented with permitted weight data from MITs permit database. The roadside survey identified vehicles by type, axle groupings, commodity carried/industry served, and route taken or intended by each driver. Exogenous indicators, primarily price indices and export volumes, give insights into production and movement patterns based on global economic trends. The data from exogenous indicators are most useful when compared with development and production levels in Manitoba as higher global prices and demand provide incentives for companies to develop unconventional oil sources.

The traffic monitoring and freight demand model elements and the information they supply on truck traffic characteristics, as highlighted in Table 6, are as follows:

- Highway Permit Data: unique vehicle configurations, permitted weights, and routing
- Utility Moves Permit: insights into routing and regional operator
- Well Production Statistics: regional and localized production levels for crude oil
- Pipeline/Flowline Status: regional and localized truck traffic characteristics
- Western Canada Rail Car Loading: rail transload facility annual growth
- Truck Traffic by Facility: vehicle configurations, OD characteristics, and truck traffic volumes
- Petroleum Industry Land Use: location of key infrastructure and well development levels

Using the logic provided by the framework shown in Figure 21, the various datasets can be integrated to estimate and understand truck traffic flow characteristics specific to the petroleum industry. Specifically, the quantitative data from truck traffic monitoring can be understood using the supplemental knowledge from how the petroleum industry operates in development and crude oil production and makes use of regional infrastructure.

4.1.3.1 Roadside Survey

In September, 2013, a three day roadside survey was conducted to determine origins and destinations, routing, and weights of petroleum and non-petroleum related truck traffic in the area. The survey was a valuable data source and assisted in validating truck traffic distribution through the region. The location of the roadside survey was in a central location in relation to the oil fields and origins and destinations that serve the industry. A safe location was selected that could accommodate larger vehicles and enable easy access near the intersection of PTH 2 and PTH 83. PTH 2 is a major east-west corridor in the region and PTH 83 is a major north-south corridor that provides connectivity for the petroleum industry, agriculture industry, and other freight movement. The questionnaire from the roadside survey can be found in Appendix D.

4.2 ESTIMATING PETROLEUM-RELATED FREIGHT FLOW

The petroleum industry has two primary phases: well development and oil production. Both phases can generate freight movements for railroads, trucks, and pipelines/flowlines. The location of origins and destinations influence modes of transportation used, level of traffic generated, and intensity of traffic. The phases are distinguished from one another due to their different temporal and spatial characteristics. Furthermore, each phase is influenced by the various modes of transportation to varying degrees. For example, the flowline network and oil field maturity influences truck trips generated during the production phase. In comparison, the spring road restrictions affect the well development phase by limiting overweight moves, which results in no new wells being drilled during this season. Spatially, the industry operates within individual oil fields and across the petroleum producing region as a whole. The operational characteristics of the industry at these resolutions influences petroleum-related freight flow but can be disaggregated to assist in transportation systems analyses.

4.2.1 Spatial Resolution of Petroleum-Related Freight Flow

There are two geographic perspectives to consider in an analysis of the petroleum industry: regional and well-specific. The well-specific perspective is localized and looks at the finer network around a specific well and its nearby supporting infrastructure. The second perspective, regional, looks at the transportation and activity from a higher level and how general locations, such as oil fields, are connected to each other and to sources of materials and equipment.

4.2.1.1 Well-Specific Perspective

The well-specific perspective is localized and assesses each well individually in how it is connected to the larger network. This perspective includes provincial roads and highways as well as the denser municipal road network. This research uses knowledge of the well-specific perspective but does not perform a full analysis at this spatial resolution. Figure 22 shows the well-specific perspective within the Waskada oil field in southwest Manitoba. This map highlights surrounding wells, direction of drilling, well spacing, and support infrastructure such as water supply wells, water injection wells and batteries.

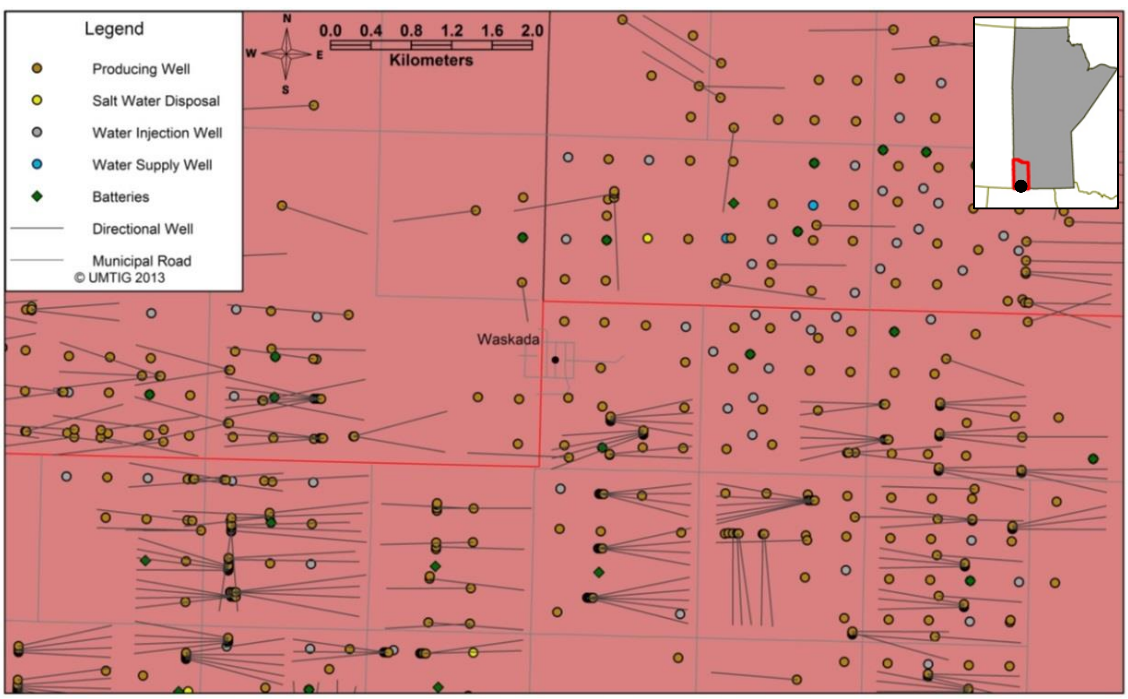


Figure 22: Well-Specific Perspective in the Waskada Oil Field

In any given oil field, there would be many localized trips or flowline connections between wells and the support infrastructure. The challenge is routing these trips as in-depth knowledge would be required of municipal roads, support infrastructure ownership, production rates of wells, and limits on disposal wells. Many of these trips are not taken on provincial highways and roads and the effort required to perform comprehensive traffic counts on municipal routes makes these counts infeasible. Rather, knowledge of this perspective helps feed into the broader objective of understanding how the industry uses infrastructure.

Locally, much of the emulsion produced by wells will be transported to nearby batteries owned by the same E&P companies. Emulsion may be moved by either flowline or truck and well and battery ownership can be linked. Through industry knowledge and databases, production quantities, mode of transportation and local destination (battery) can be reasonably estimated and mapped. Truck traffic density can be assumed to increase with proximity to larger batteries and shortest path concepts applied to link facilities to the provincial highway and road network. In addition, statistics are maintained by the Manitoba Petroleum Branch on which batteries are connected through large diameter pipeline to move crude oil to the transload facilities near Cromer.

Knowledge of the well-specific perspective and information on a field's level of activity (annual wells drilled and production statistics) combined with the locations of origin-destination pairs that supply material and equipment can be used to understand freight flow throughout the region.

4.2.1.2 Regional Perspective

The regional perspective is used to understand freight flow and connectivity of the selected study area. Primarily, the purpose is to use this perspective to assign truck traffic to the provincial road and highway network. Assigning freight flow is done by applying knowledge of what occurs at the well-specific perspective and aggregating that knowledge for larger area units, such as oil fields. Figure 23 highlights the larger study region and provides an inset of the well-specific perspective (from Figure 22).

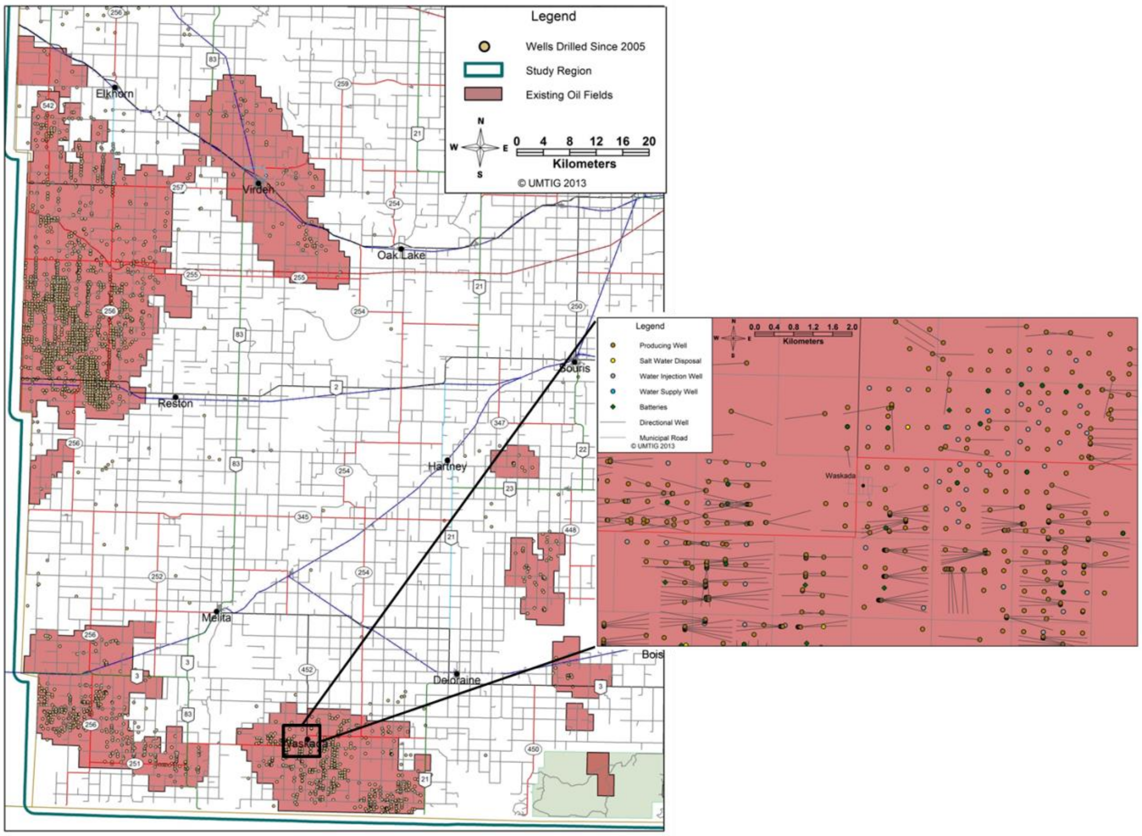


Figure 23: Petroleum Producing Study Region with Inset Map of Well-Specific Perspective

The regional perspective requires aggregating petroleum-related activity levels in each field and details on the transportation supply that serves each sub-region. An inventory of the transportation supply at this spatial resolution requires knowledge on highway and road classification data as well as intra-regional pipelines. Highway and road classification data include spring road restrictions and weight classification. Spring road restrictions influence regional connectivity during the spring thaw. Weight classification for a road or highway indicates the gross vehicle and axle weight limits which in turn affects truck routing into and out of fields. Intra-regional pipelines move crude oil between fields and from batteries to the transload facilities at Cromer. The presence of pipelines reduces the number of production-related truck trips generated by each field.

Aggregating the well-specific data within each field draws on industry activity related to the development and production phases. For the development phase, analysis for a given year requires mapping new wells drilled within each field to visualize this activity in relation to the provincial road and highway network. Mapping this data provides insights into the likely route taken into the field from development-related origins. For the production phase, all crude oil is assumed to be moved to the export transload facilities at Cromer. Total daily and cumulative production values can be calculated per well and summer for an entire oil field. Using battery and well ownership data, connectivity between sites can be used to estimate crude oil volumes moved to each battery (currently, the Manitoba Petroleum Branch has changed their reporting requirements and starting in 2014 all producers are required to provide data on battery crude oil volumes). When a battery is connected to the Cromer facilities via pipeline, all crude oil associated with that battery up to the pipelines capacity is assumed to be moved via pipeline. Crude oil not assigned to a battery with pipeline connectivity is assumed to move to the Cromer facilities via truck on the nearest provincial highway or road.

4.2.2 The Development Phase

The well development phase is when a new well is drilled and completed. This phase primarily generates truck traffic as most wells require equipment and resources to be trucked to remote sites using a combination of provincial and municipal roads. Materials and supplies may be brought into a region through rail, but the last leg of freight movements occur between transload facilities and well sites via truck. Noted earlier in Figure 7 in Chapter 2, well development has seven main phases that include the drilling of the well and hydraulic fracturing. These stages combine for a total of between 140 and 250 one-way loaded truck trips. Furthermore, this phase is dynamic in nature as origins and destinations (primarily the wells) change from week to week as each E&P company executes their drilling program.

Wells are considered both origins and destinations in the well development phase (as shown in Figure 6 in Chapter 2). Origins include freshwater, proppant, chemicals, equipment, gravel, and other supplies. These locations were identified for Manitoba through industry interviews and site visits. In many instances, locating origins can be difficult without the assistance of industry experts because they are not found along primary highway routes or may exist outside of the study region. Figure 24 shows a sample of static origins that serve the well development phase.

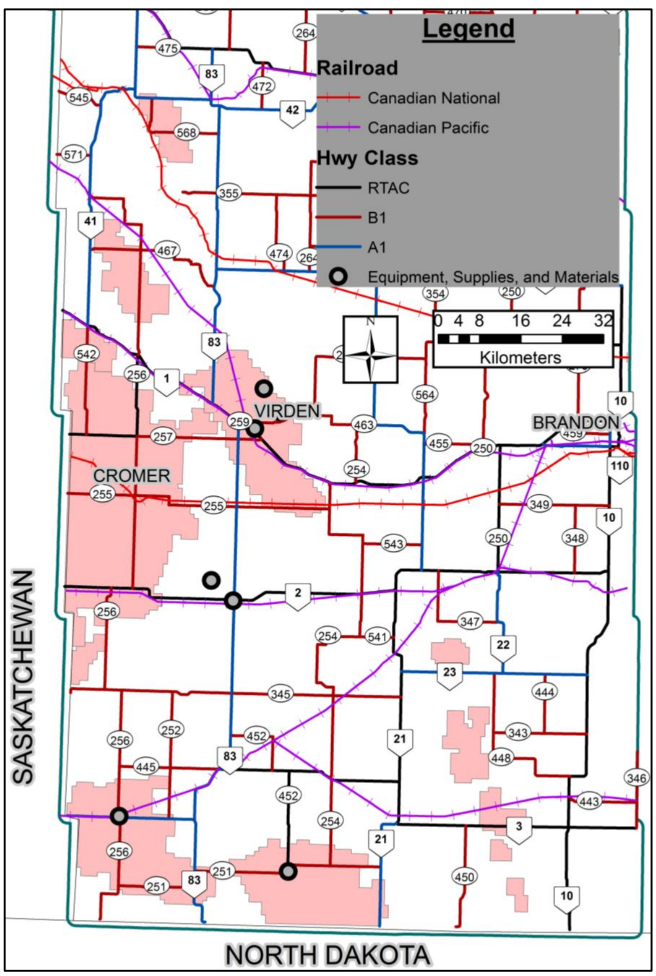


Figure 24: Locations of Equipment, Supplies, and Materials for the Petroleum Industry

The first major truck traffic generator is freshwater. This input is difficult to track and monitor for each well due to two characteristics: (1) water requirements for each well; and (2) locations for water withdrawal. Large quantities of freshwater are required for both the drilling and hydraulic fracturing stages. The final amount is dependent on local geological characteristics, depth of well, length of well, and number of fracture stages and is difficult to predict accurately. Estimates for the drilling phase can be between 10 and 40 truckloads and 20 or more for the hydraulic fracturing phase (assuming approximately 250 barrels per truck). When a slough is located near the well, water may be pumped directly to the well and reduce the need to transport water to site (Day, 2014). Municipalities and the province have some freshwater wells available to industry for water withdrawal, but aside from these known locations, it is difficult to map and determine water withdrawal sites.

Oil wells act as an origin for produced water (water that has mixed with drilling and fracturing fluids and water from the geological layer being drilled). Disposal wells are available and tracked by the Manitoba Petroleum Branch. These wells have often been converted from defunct producing wells and are owned by the company that drilled them. Typically, produced water will travel the shortest available distance but well ownership may dictate where the final destination is; drilling companies will transport produced water to disposal wells owned by the same company.

Equipment involved in the development of a new well may be transported to site from a variety of locations. Drill rigs will typically come from a well site where drilling has been completed. Again, this makes tracking the origin difficult as industry drilling plans are subject to rapid change. Other equipment, such as mobile cranes and service rigs, are sourced locally and may move from well site to well site. The primary source of equipment is in Saskatchewan or locally in Virden, Manitoba. For equipment, wells serve as both an origin and destination.

Other supplies and materials, such as proppant (frack sand), gravel, and wooden mats may be sourced from a variety of locations. Frack sand is primarily produced in the U.S. Midwest and brought to the region on train into Saskatchewan. The frack sand is hauled by truck to Manitoba directly to wells or stored at local depots (Abel, 2014). Gravel is sourced from local gravel pits that have been identified through industry interviews. Gravel may also be moved to storage depots within an oil field for use at a later time. Wooden mats, along with many other supplies like pipes and pump jacks, are stored in or near Virden, Manitoba. However, wooden mats may also be stored locally within each oil field as they are regularly moved between sites and in some instances may move directly between well sites. For supplies and materials, well sites primarily act as a destination but in some instances, such as for wooden mats, also serve as an origin.

4.2.2.1 Estimating Truck Traffic for the Development Phase

There are multiple activity stages with varying durations and truck traffic activity (seen in Figure 7 in Chapter 2) to develop a green field site. The estimated one-way loaded truck trips required per well is approximately 140 (discussed in section 2.2 of this thesis), distributed with varying intensity over a 25 day period. Due to the dynamic nature of the industry it is difficult to predict when these trips are generated but weekly well completions and rig activity provide a snapshot of industry development for the region and by field. Weekly development activity can change quickly and calculations for development truck trips should be representative only for periods of activity for the year of analysis. Due to the complexity and challenge of estimating petroleum-related truck traffic, this research develops a flow diagram for estimating regional and field specific truck traffic related to the well development phase (shown schematically in Figure 25).

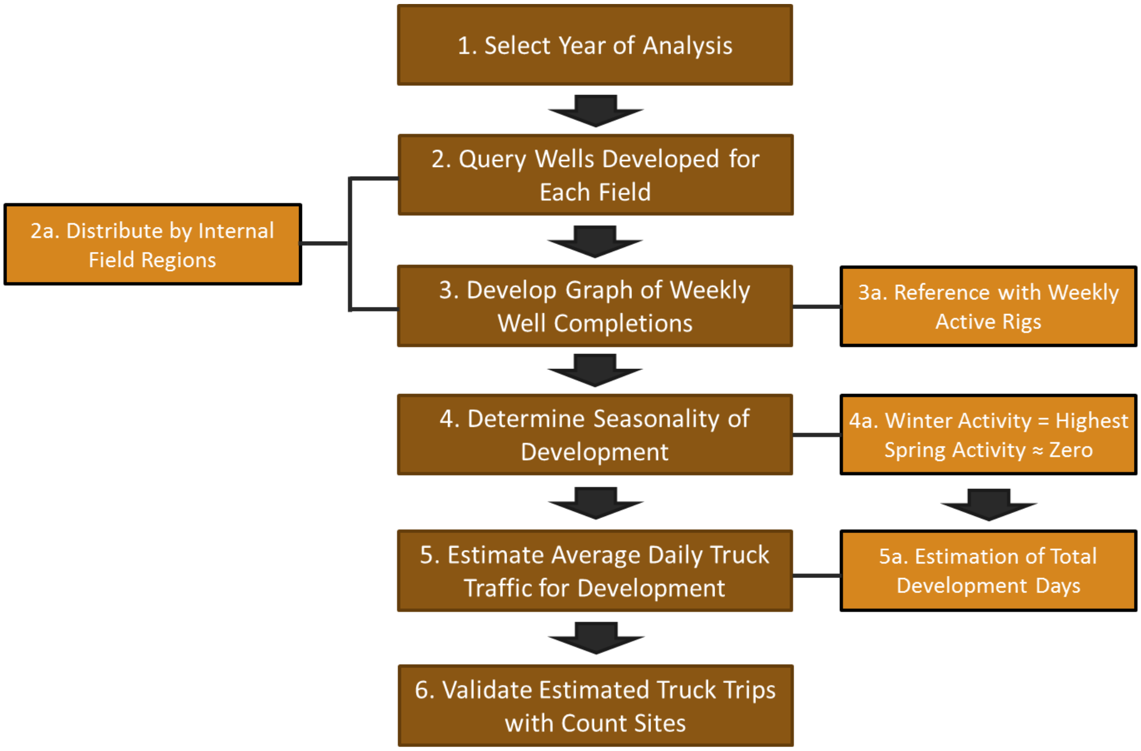


Figure 25: Decision Flow Diagram for Determining Well-Development Activity

Estimating truck traffic for a given year for the petroleum industry is dependent on several factors. First, truck traffic generated by a single well must be determined as discussed in Chapter 2 of this thesis. This knowledge is gained through interviews with industry involved in drilling wells and moving equipment and material. The number of truck trips generated can change as a function of current technology used, local geology, depth and length of well, and water usage. The value provided (140 loaded one-way truck trips) is a typical value used for this analysis but is subject to change under different regional conditions. Further details on the six steps used to estimate development truck trips follow:

1. *Select Year of Analysis:* Each year, total wells developed and the location of development can vary. Annually, and within a given year, the oil field with the highest development in the region can shift, leading to routing and truck traffic volume changes.

2. Query Wells Developed for Each Field: Select wells developed for current study year within each field to determine where, within each field, development is occurring. Step 2a provides knowledge of these locations to help determine which highways are likely carrying development truck trips and identifies industry trends within the field.

3. *Develop Graph of Weekly Well Completions*: Weekly well completions provide information on development intensity both within the entire study region and within each field (Step 2a). The duration leading up to a well completion is likely the period of peak truck traffic and this information can be linked with weekly rig activity (Step 3a). Drilling, which typically takes about seven days, is a truck intensive stage of well development. Data to develop weekly well completions was obtained from the Manitoba Petroleum Branch; similar data can typically be obtained from petroleum industry governing bodies in other jurisdictions.

4. *Determine Seasonality of Development*: Both weekly well completions and weekly rig activity highlight seasonal changes in development. In winter, when truck weight premiums on highways are in effect, well development increases. In contrast, during the spring road restrictions (approximately two months from mid-March to mid-May), development is essentially non-existent. Building off Step 3 and Step 4, the total number of development days (days when drilling is occurring within a field) can be estimated.

5. *Estimate Average Daily Truck Traffic for Development*: Estimating the total number of development truck trips is a multiplication of total wells developed in a field by the average number of trucks required to develop a well (two-way truck trips). This value is then distributed across the estimated number of development days to provide average daily truck trips when development was occurring in the field.

6. *Validate Estimated Truck Traffic with Count Sites*: Once truck traffic has been estimated, counts can be validated using coverage classification counts or permanent classification counts. In Manitoba, no permanent classification counts exist for routes directly into an oil field. For this study, 20 sites were selected for coverage classification counts based on petroleum industry land use. These sites provided 48-hour counts that were used to validate truck traffic estimates in and out of several oil fields. Further count validation can be done for materials and supplies through interviews with industry and knowledge of truck trips generated from material source sites.

These trips can then be assigned to routes that connect the oil field with key facilities, materials, and supplies. Routing is determined on the basis of highway load classification, bridge restrictions, and shortest path. Based on data obtained from the roadside survey and highway permit database, many trips taken followed the shortest path or took place on routes with higher road strength such as RTAC and A1 highways.

4.2.3 The Production Phase

The production phase for a well is the majority of its lifespan. In this phase, the well acts as an origin for emulsion. Emulsion, the mixture of water and oil or gas, extracted from wells can have an indefinite production period. Furthermore, wells may be converted to injection or disposal wells in which case the well becomes a destination for fluid rather an origin. Total and average volumes produced by wells can be obtained from the Manitoba Petroleum Branch and linked to well locations in mapping software. Production rates vary between and within oil fields but typically production rates decline in the first year of production for hydraulically fractured horizontal wells.

During the early stages of a new producing well the emulsion may be stored and separated on site and trucked to crude oil facilities (batteries or transload facilities). As an area within an oil field becomes more mature, wells are typically connected to the flowline network and emulsion is piped to batteries to be separated. Produced water may also be either flowlined or trucked to injection and disposal wells. The total quantity of water produced by a well is tracked by the Manitoba Petroleum Branch but the final destination for these fluids is difficult to know or predict. It is possible to determine the battery that a flowlined well is connected to, but the final destination for produced water would still be unknown.

4.2.3.1 Estimating Production Phase Truck Traffic

In comparison to development trips, production trips can more readily be estimated due to the static nature of major transload facilities and large batteries. However, rates of production can vary between wells, oil fields and over time. The density of the regional flowline network will most influence total truck trips. Figure 26 provides a flow diagram to understand truck traffic flow characteristics of the production phase.

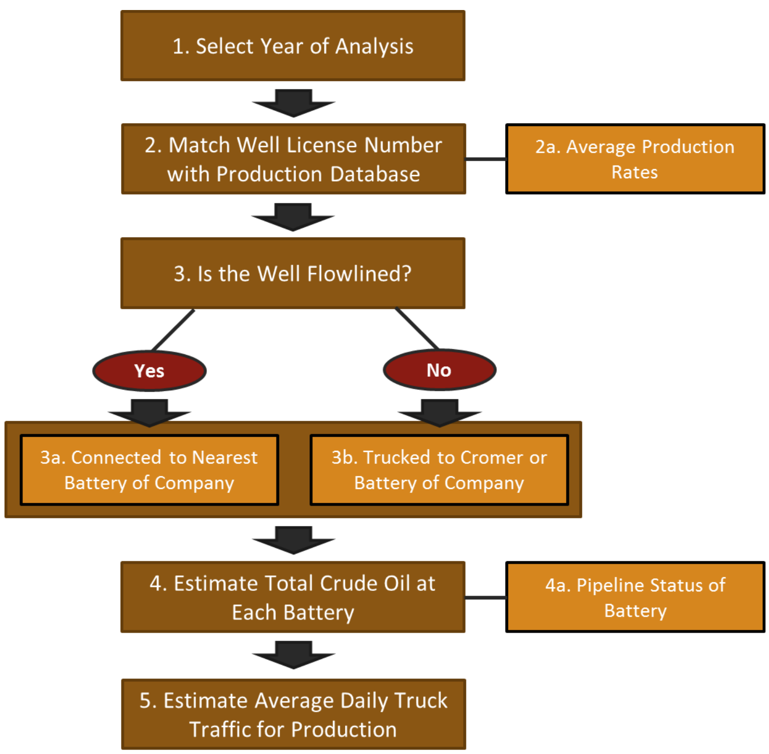


Figure 26: Decision Flow Diagram for Determining Activity from the Production Phase

Truck traffic generated by the production phase of the petroleum industry is consistent throughout the calendar year. Production of water and crude oil for each well is provided by the Manitoba Petroleum Branch and data is provided for daily, monthly, and cumulative production for each well. Further details on the five steps to estimate average daily truck traffic from the production phase follow:

1. *Select Year of Analysis*: Production rates, flowline status, and pipeline networks are subject to change with time. Production rates from directional hydraulically fractured wells are known to decline rapidly. New flowlines are regularly constructed throughout the network and pipelines and delivery contracts can change.

2. *Match Well License Number with Production Database*: The well license numbers, provided within the active wells database, can be matched with license numbers in the Manitoba Petroleum Branch production reports. The values within these reports are then averaged across the selected calendar year for each well within the geographic database (Step 2a).

3. *Is the Well Flowlined:* Flowline status of each well can be requested from the Manitoba Petroleum Branch. If a well is flowlined it will typically be connected to the nearest battery owned by the same oil and gas company as the well (Step 3a). If a well is not flowlined, the emulsion will be stored in a tank at the well site where gravity will separate the crude oil and water. Crude oil is typically trucked to a nearby battery or directly to the terminals near Cromer (Step 3b).

4. *Estimate Total Crude Oil at Each Battery*: Based on production rates of wells and connections to associated batteries, total daily crude oil stored and moved through each battery can be estimated. The estimated commodity volume can then be converted to total truck trips. Pipeline status (step 4a) indicates whether a battery is connected to the

terminals near Cromer through a pipeline. If a battery has a pipeline connection, all crude oil associated with the battery is assumed to move through pipeline. The location of each battery also provides insights into potential routes between the battery and the terminals near Cromer.

5. *Estimate Average Daily Truck Traffic for Production*: Production associated with each battery is converted to truck trips based on an average payload of 32 cubic meters obtained from industry interviews and the roadside survey.

The trips generated for the production phase are assigned to routes that connect batteries to the terminals near Cromer using shortest path assumptions that have been verified through the roadside survey. Understanding where batteries are located within a field, amount of crude oil handled, and pipeline status all assist in estimating truck traffic and routing.

4.3 EXAMPLE APPLICATIONS OF THE INTEGRATED FRAMEWORK

The framework developed in this chapter provides a structure for integrating data from multiple sources to support better understanding of truck traffic characteristics. This section provides three illustrative examples of applying the integrated framework to the petroleum industry. The examples demonstrate how specific non-traditional data sources from the four categories established in this chapter can be used to: (*a*) interpret truck traffic monitoring data (Example 1); (*b*) direct a truck traffic monitoring program so that it can better capture unique industry patterns (Example 2); and (*c*) adjust calculation procedures to reflect specific industry features (Example 3).

4.3.1 Activity and Exogenous Indicators to Interpret Classification Data

This example illustrates how the integration of activity system variables and exogenous indicators into the truck traffic monitoring process can help interpret year-over-year changes in vehicle classification distributions (VCDs) occurring within the petroleum producing region of Manitoba. Table 7 shows the change in the proportion of Class 9 and Class 10 trucks (as a percent of total truck traffic observed by an automatic vehicle classifier) from 2002 to 2012 along Highway 83, a primary highway in Manitoba that serves as a corridor between key oil fields and terminals for export. The table reveals a shift in these proportions starting around 2005 to 2006, when the fleet mix changes from Class 9 as the dominant truck type (over 30 percent of total trucks) to Class 10 comprising up to 50 percent of total trucks operating in the region. This type of classification distribution has been observed along other oil-related corridors in both Saskatchewan and Alberta (Reimer and Regehr, 2014a).

Table 7: Historical Proportion of FHWA Class 9 and 10 Vehicles to Total Trucks on a Primary Highway in Manitoba's Petroleum Producing Region
Source: Reproduced with permission from TRB from Reimer and Regehr (2014b)

Year	Class 9 (%)	Class 10 (%)
2002	35.7	19.6
2003	32.8	20.4
2004	30.4	24.2
2005	24.2	25.3
2006	24.7	26.2
2007	20.9	31.1
2008	18.8	47.8
2009	21.5	42.8
2010	20.1	42.8
2011	18.0	46.6
2012	15.4	52.0

Interpreting and validating this classification distribution trend is challenging without the integration of industry-specific data related to the level of activity in the region and other exogenous indicators. Figure 27 illustrates two types of data that can help explain the observed shift. The graph on the left shows the temporal distribution of drilling rigs operating within Manitoba's petroleum producing region. The distribution reveals a general increase in active drilling rigs starting in 2005 with annual growth through to

2012; this reflects growth of petroleum well development and related activity. The graph also highlights the seasonal distribution of drilling rig activity, most noticeably the interruption in activity during the spring weight restriction period applicable for certain roads in March and April. The number of active drilling rigs in a region has been used to project future traffic volumes under different total rig scenarios and is also an indicator of expected truck volume (Upper Great Plains Transportation Institute, 2013). The graph on the right shows the relationship between long-term trends in Manitoba crude oil production, export, and market price. Technological changes, primarily in horizontal drilling and hydraulic fracturing, became more widely used in Manitoba around 2005 to 2006 when steady historical production increases and rapid growth in the industry began. These two datasets therefore help interpret and validate the shift in vehicle classification data observed by the truck traffic monitoring program.

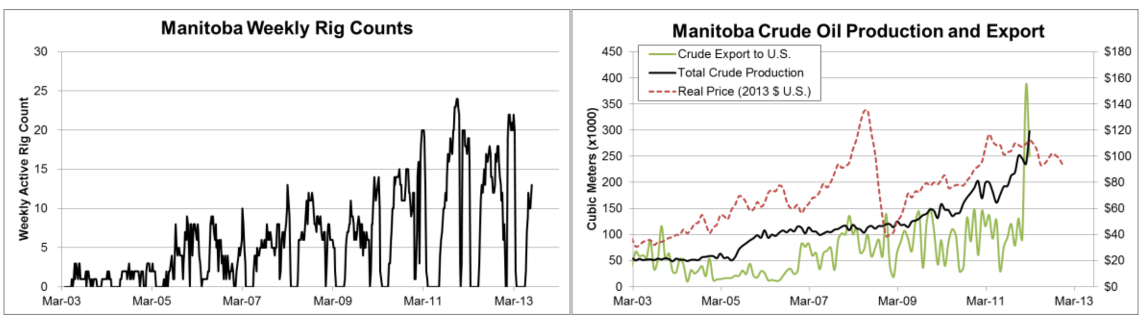


Figure 27: Trends in Manitoba Weekly Rig Counts and Crude Oil Production and Export
Source: Reproduced with permission from TRB from Reimer and Regehr (2014b)

4.3.2 Supply and Activity Variables to Direct a Truck Traffic Monitoring Program

This example illustrates how the integration of transportation supply and activity system variables helps direct adjustments to a truck traffic monitoring program so that it is better able to produce data that reflect industry patterns. Figure 28 integrates the highway and railroad transportation networks with petroleum-related land use data in a geographic information system (GIS) environment to determine the spatial extent of industry development. The map shows recently drilled wells (since 2005) and distinguishes between highways with different load classifications (primary, secondary, and tertiary routes have progressively lower axle and gross vehicle weight limits), as these designations have bearing on trip routing decisions. The GIS developed for this region also includes historical annual average daily traffic (AADT) estimates (not shown on map) for all highways, developed primarily from factored short-term counts plus some continuous count sites. Specifically, queries of these AADT estimates were used to reveal year-over-year changes (increases or decreases) in AADT for all highway segments in the region. As reliable annual truck traffic volume estimates were unavailable, these changes help to identify areas experiencing petroleum-related economic development.

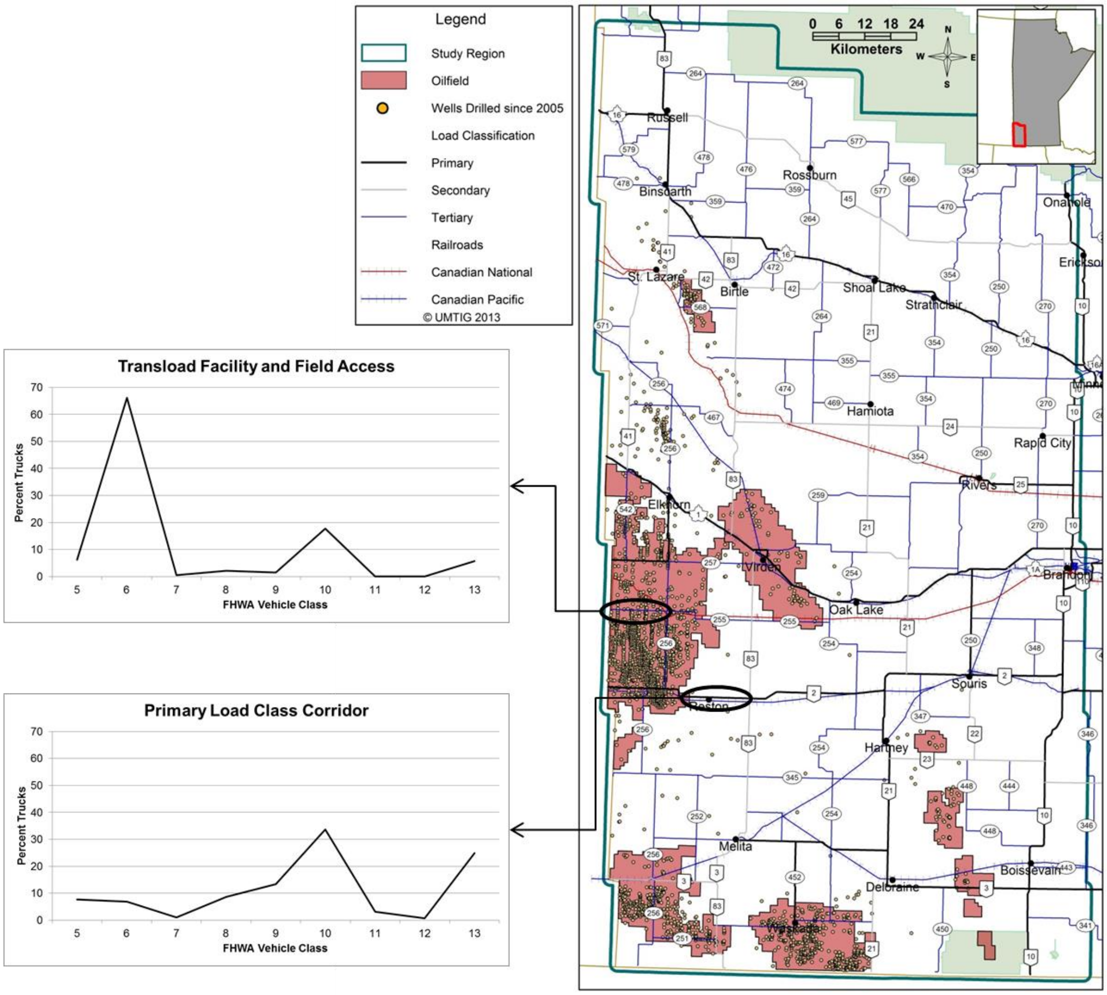


Figure 28: Petroleum-Related Activity, Transportation Supply, and Sample Vehicle Classification Distributions in Manitoba's Petroleum Producing Region
Source: Reproduced with permission from TRB from Reimer and Regehr (2014b)

The GIS enables an integrated platform for spatial and temporal visualization of developments in the region and helps direct the design of a targeted truck traffic monitoring program in the region. Among other components, this program involves a series of short-term (48-hour) classification counts conducted at 20 sites, selected with the aid of the GIS. Specific criteria for site selection follow:

- The route provides direct access to a producing oil field.
- The route connects two producing fields.

- The area is experiencing new exploration and development (as evidenced through recent well development and/or AADT increases).
- The route is in close proximity to primary destinations such as rail or pipe transload facilities.
- The route crosses jurisdictional boundaries (this helps determine cross-border traffic and tie into external datasets).
- The routes are commonly specified in oversize/overweight permit requirements.

The graphs on the left side of Figure 28 show sample VCD results from the targeted truck traffic monitoring program at two locations. The VCD in the top graph was observed on a provincial road that provides field access to the Daly-Sinclair oil field, the largest field in the region; this road also serves the nearby transload facility for crude oil export. While the total volume on this route is low, the classification distribution is representative of the traffic serving the petroleum industry. Field visits conducted during the same time period as the counts were taken confirmed that Class 6 and Class 10 trucks (primarily tanker body types carrying fluid for the well development phase and transferring crude and emulsion to a transload facility) dominate truck traffic along this route. The bottom graph shows the VCD of a provincial highway in Manitoba that is a primary corridor within the petroleum producing region. There is no continuous classification equipment along this route; however, the VCD reflects typical oil-related truck traffic classification distributions where Class 10 vehicles comprise the bulk of the fleet mix (Reimer and Regehr, 2014a). The truck traffic along this corridor would also be influenced by other local industries, particularly agriculture. The agriculture industry's influence on the VCD would be most prominent during the spring seeding and fall harvest seasons.

4.3.3 Supply and Activity Variables to Refine a Vehicle Classification Algorithm

This example illustrates how the integration of transportation supply and activity system variables supports refinements to a vehicle classification algorithm used within the truck traffic monitoring process. The VCDs shown in Figure 28 utilize Manitoba's standard 13-vehicle classification scheme. However, field evidence, permit records about oversize/overweight vehicle configurations, and visual verification of VCDs at the short-term classification sites indicate that this standard algorithm may not be appropriate for certain vehicle configurations used in the petroleum industry. Figure 29 shows two common vehicle types used in the region: a three-axle tanker truck with a four axle tanker trailer (at left) and a tandem steer truck with a permanently mounted apparatus (at right). The standard algorithm classifies these vehicles as Class 13 and Class 8, respectively. A rigid interpretation of the 13-vehicle classification scheme suggests that both vehicles may be misclassified. For the truck-trailer combination, the algorithm recognizes the seven axles and therefore places it in Class 13, even though it is not a multiple trailer combination. The tandem steer truck has four axles though not in a typical Class 7 straight truck arrangement (with a single steer and a tridem axle group) and the algorithm therefore places it in Class 8. These results may indicate a need to refine the standard algorithm, particularly when processing data collected in areas where these vehicles are common. Alternatively, it may also be appropriate to use the standard algorithm, but interpret the classification data from this region differently. For example, from the road design, operations, and maintenance perspectives, it is important to be aware that a common Class 13 vehicle in the petroleum producing region may be the seven-axle truck-trailer configuration, whereas a common Class 13 vehicle on another route may be a nine-axle turnpike double.

				Axle Group Spacing (cm)					
Photo	Axles	Length (cm)	FHWA Class	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7
Left	7	1,993	13	503	101	539	119	616	116
Right	4	747	8	204	387	155			

Figure 29: Common Truck Configurations in Manitoba's Petroleum Producing Region with Corresponding Vehicle Classification Data Record (Left Image: Class 6 Tanker Truck with Full tanker trailer, Right Image: Four-Axle Tandem Steer Truck)
Source: Reproduced with permission from TRB from Reimer and Regehr (2014b)

5. APPLICATION OF THE METHODOLOGY AND ANALYSIS RESULTS

Chapter 5 discusses the results and findings from this research, specifically the petroleum-related freight flows and the development of a data dissemination tool for transportation engineers and planners. This section provides details on: (1) data processing and analysis to develop petroleum average daily truck traffic; (2) research results; and (3) developing an interactive data dissemination tool.

5.1 DATA PROCESSING AND ANALYSIS

The dynamic nature of the petroleum industry E&P activity creates challenges to developing reliable long term estimates of freight flows and truck traffic. This section applies the methodologies outlined in Chapter 4 using data and information obtained for the year 2013. The level of development for a region, and by oil field within that region, can vary by year based on both the underlying geological formations and conditions. These variations can lead to varying intensity of development as well as levels of production leading to regional shifts in truck traffic. The Daly-Sinclair and Waskada oil fields are currently the most active fields in Manitoba and account for about two thirds of all new wells in Manitoba for 2013. The level of activity for each oil field in Manitoba over the last decade can be seen in Figure 30; since 2010 more than 500 wells have been drilled per year within the region.

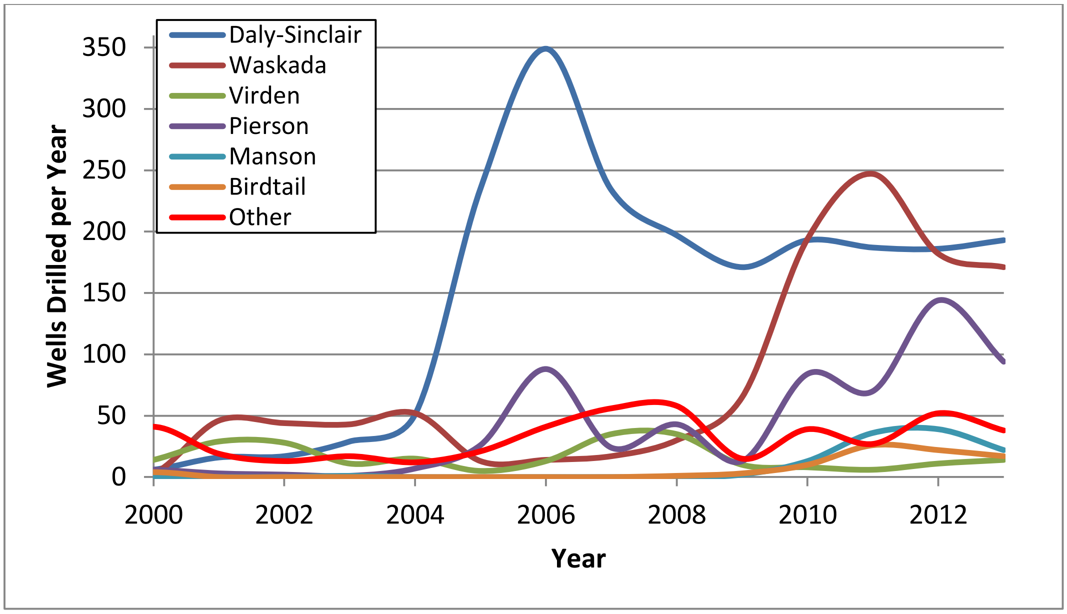


Figure 30: Change in Annual Oil Field Development Levels Since 2000

In addition to annual variations in development levels and location of that development, there are seasonal variations across the region and within each field. General patterns include higher development (typically) during the winter and summer months. Spring road restrictions from March to May essentially stop well development. Figure 31 shows the number of wells completed each week for the Waskada and Daly Sinclair fields for the year 2013 (note the sudden drop in well completions in April and May).

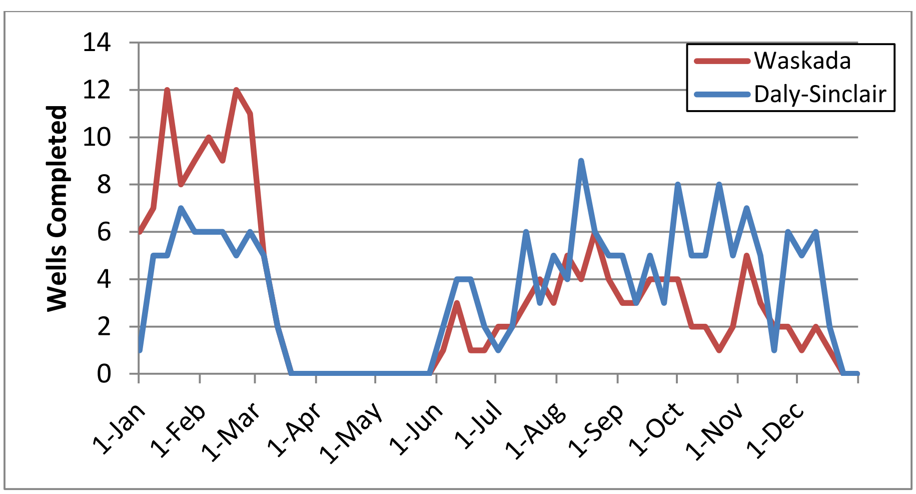


Figure 31: Weekly Well Completions for the Waskada and Daly-Sinclair Fields for 2013

In comparison to development activity, production of oil was found to operate continuously throughout the year. A defining characteristic of hydraulically fractured, directional wells is a rapid decline in production rates. Figure 32 shows the average monthly production of 55 wells drilled in February of 2013 that reported production for the duration of 2013 (Manitoba Petroleum Branch, 2014). The value for February is lower than March due to February not being a full reporting month for all wells as actual drill dates are unknown. Integrating these production volumes with flowline status determines what volume of oil gets moved by flowline or truck and provides insights into intermediate deliveries (to a battery or directly to a transload facility).

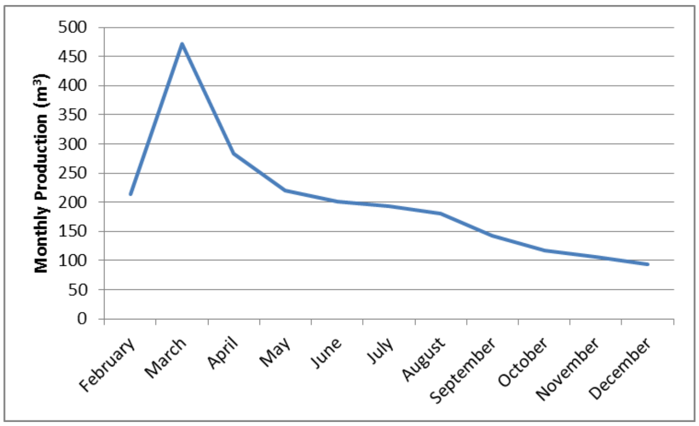


Figure 32: Monthly Crude Oil Productions Rates of Horizontal Hydraulically Fractured Wells in 2013 in Manitoba

The output of oil wells is an emulsion (mixture of oil and water) and, as Figure 33 shows, the produced water follows a similar trend to oil. However, the volume of produced water is typically higher than that of the amount of oil. Comparing the two graphs, the ratio of water to oil increases over time from a 1.5 water:oil ratio in March to a ratio of about 2.5 in December (Manitoba Petroleum Branch, 2014). The produced water must be moved from each well to a battery and then on to produced water disposal wells.

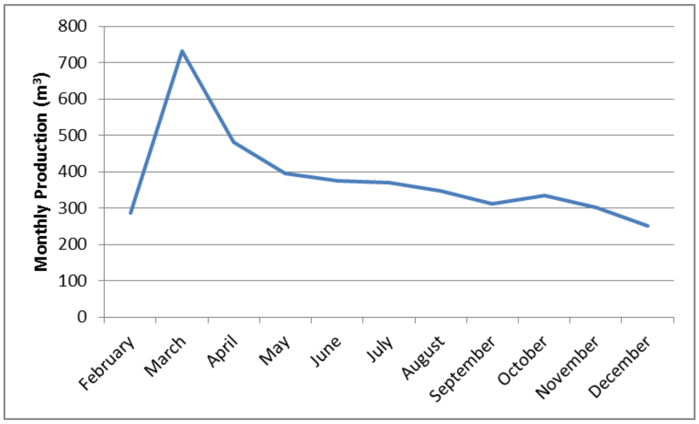


Figure 33: Monthly Produced Water Production Rates for Horizontal Hydraulically Fractured Wells in Manitoba

The number of wells developed and the associated rig activity, along with the volume of fluid moved, were integrated into the framework to assist in generating, assigning, and validating truck traffic estimates.

5.1.1 Truck Traffic Generation

Petroleum-related truck traffic generation is largely influenced by the activity system present in southwest Manitoba but is also influenced by the transportation infrastructure and exogenous factors. The primary components of the industry activity system used to interpret truck traffic are: (1) oil fields; (2) active wells; (3) batteries; and (4) terminals, materials, and equipment. From a temporal perspective, a well generates truck traffic through its life in two phases: development and production.

As highlighted earlier in Figure 7 in Chapter 2, developing a single well generates intense periods of truck traffic, particularly during the drilling and hydraulic fracturing stages. The heavy truck traffic associated with the drilling stage can be directly linked with the presence of a drill rig. Drill rig activity data are publicly available by province on the internet and are updated weekly in investor reports by Baker Hughes (Baker Hughes, 2014). Figure 34 shows weekly active drill rigs and weekly well completions for Manitoba's busiest fields in 2013. The results show that as the number of active rigs changes so do the number of wells completed. Rig activity can provide a more timely and readily available metric for oil field activity as the development phase of a well is dependent on the presence of a drill rig. However, caution should be taken when using this data source because the location of each drill rig is not provided. Expanding on the previous section, Figure 34 shows that new well development levels vary between oil fields over time within a region. The active drill rigs data are useful in determining overall region activity. Rig movements may occur within a field between lease sites, between oil fields, or cross-border between Manitoba and Saskatchewan. Exact rig movements are difficult to track, and while permit databases may provide useful insights, not all rig movements occur along provincial highways. Further insights to rig movements can be obtained from utility companies, such as electricity providers, which require move permits as a result of rigs exceeding height restrictions for electrical infrastructure (Riddell and Plaisier, 2013).

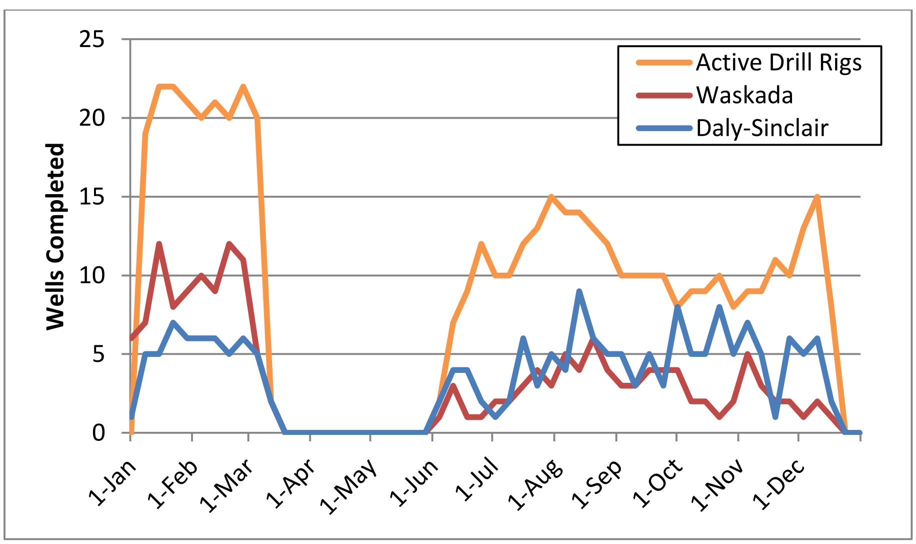


Figure 34: Waskada and Daly-Sinclair Weekly Well Completions Compared to Regional Total Active Drill Rigs

Aside from drill rig movements, water can be the largest generator of truck trips for developing a well. Water is required in both the drilling and hydraulic fracturing stages. While estimates do exist for water requirements of each stage (the two stages can combine for more than 50 loaded truck trips) they vary greatly in total trips and trip distances. Some wells may be located near a slough and pump water or obtain water from a nearby supply while others require long travel distances. This component of activity is difficult to measure as both the origin and destination cannot be determined until the activity is happening.

The second phase of the petroleum industry is the production phase when emulsion is being pumped out of wells. During this phase, centralized collection is occurring within fields and within the region itself. Activity generated during this phase is the movement of emulsion (crude oil and water). This product is moved by truck, flowline, and pipeline and the relationship between each mode of transportation and the facilities being served helps determine the overall impacts to transportation infrastructure. Flowlines reduce total truck trips generated within a field and pipelines reduce the total truck trips generated for the whole region. Regional truck trips using provincial highways are generated within each field and go between batteries and wells within the field to the export terminals near Cromer, Manitoba. Additional production trips enter the region from North Dakota and Saskatchewan.

The flow diagrams provided in Section 4.2 provide a guideline for determining and understanding the flow of petroleum-related freight within a region for both the development and production phases. Table 8 provides a summary of the results obtained from following these procedures broken down by oil field and petroleum activity phase for the 2013 calendar year. Development days are determined by calculating the number of weeks in a given year with active rigs and well completed. Each well is assumed to require approximately 25 development days and overlapping wells do not add additional days, only additional trips. The number of wells developed is multiplied by the typical number of load truck trips (140 per well) to determine a total truck traffic volume; this value is then distributed over the number of development days. The oil fields with high development activity, Waskada and Daly-Sinclair, have development all year except at industry shut down periods at Christmas and due to spring road restrictions. Production trips are assumed to occur year round and are a function of the fields' total production less the amount moved via pipeline (see Figure 26 for decision algorithm). When the values from Table 8 for truck trips are assigned to the highway network they develop a flow map of petroleum-related truck traffic. The metric used for the flow map is petroleum average daily truck traffic (PADTT) and is discussed in further detail later in this chapter.

Table 8: One-Way Petroleum Development and Production Truck Trip Statistics, 2013

Oil Field	Wells Developed	Development Days	Average Daily Development Truck Trips[1]	Average Daily Production Truck Trips	Total Petroleum Average Daily Truck Trips
Daly-Sinclair	186	280	93	87	180
Waskada	171	280	85	16	101
Pierson	93	217	60	22	82
Manson	29	168	24	12	36
Virden	14	84	23	9	32
Birdtail	15	77	27	5	32
North Non-Field	19	105	25	2	27
Whitewater	3	25	17	2	19
Regent	2	25	11	1	12
Kirkella	1	25	6	1	7
Souris	0	0	0	1	1
South Non-Field	0	0	0	1	1
Tilston	0	0	0	<1	<1
Mountainside	0	0	0	<1	<1
Lulu	0	0	0	<1	<1

NOTE 1: $Average\ Daily\ Development\ Truck\ Trips = \frac{Wells\ Developed\ x\ 140}{Development\ Days}$

5.1.2 Truck Traffic Assignment and Validation

Assigning trips to a highway segment into and out of an oil field requires an understanding of the mode of transportation taken and the location of petroleum-related infrastructure. For the development phase, all equipment and supplies are assumed to be moved to site via truck and that water will be sourced locally within the oil field (as this is more common practice). Wells drilled for the calendar year being analyzed should be mapped independently of other wells. Figure 35 shows the Waskada field with all wells drilled for 2013. Typically, shortest path decisions would be made and for this field all, or most, development trips would enter the field along PR 452 for two reasons: shortest path and highest strength rating (RTAC) highway.

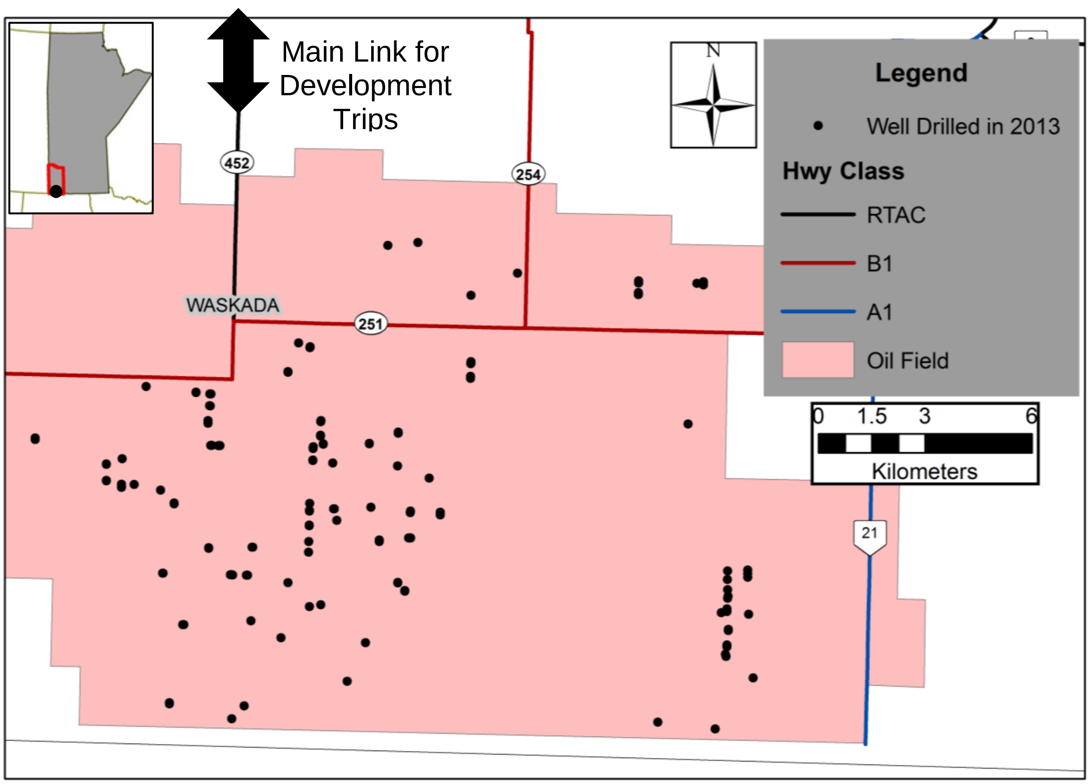


Figure 35: Waskada Oil Field Development Truck Trips Link

For the production phase, two characteristics of wells are required: flowline status and daily production. Figure 36 shows the flowline status of all wells in the Waskada field along with all batteries in the field. Linking flowlined wells with their corresponding batteries provides insights into the movement of crude oil within the field. Estimating trips between oil fields and the transload facilities at Cromer requires knowledge on pipeline connections for batteries. In the Waskada field, many of the large batteries near the community of Waskada have pipeline connections. Discussions with industry and knowledge of flowline connections to batteries, along with the results of the roadside survey, suggest that most of the crude oil in the western portion of the field is moved via pipeline. The southeast corner of the field is not connected to the transload facilities through a pipeline and therefore crude oil from this region is moved by truck.

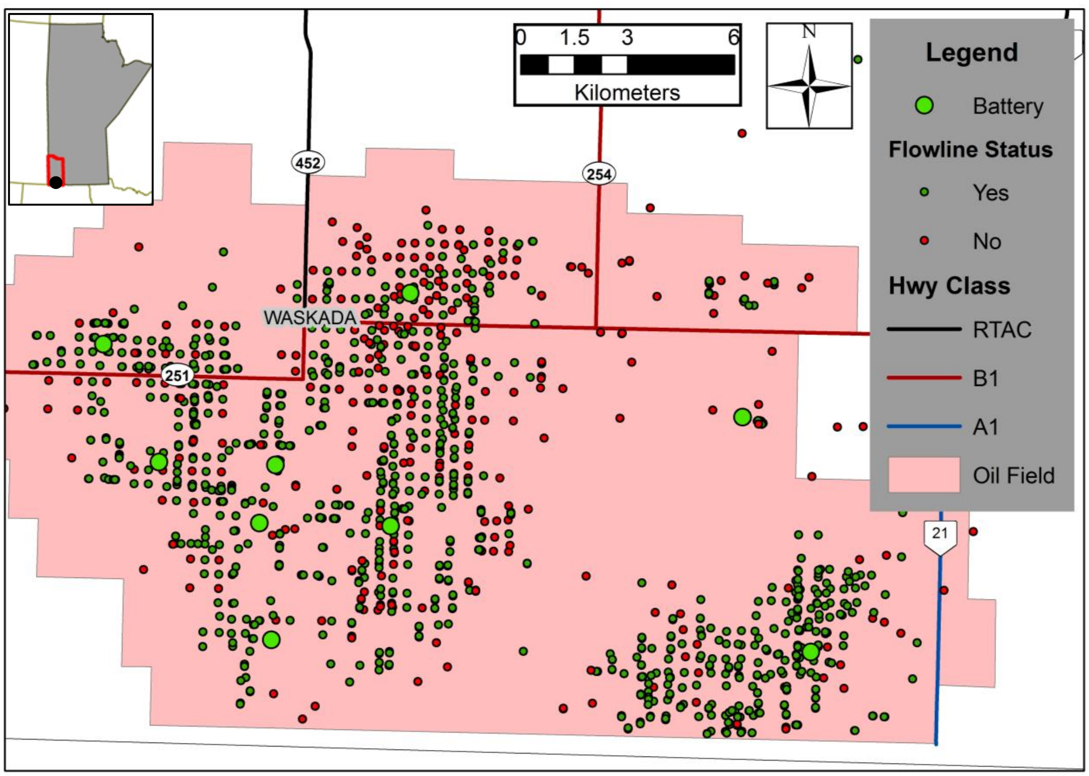


Figure 36: Flowlined Wells and Major Batteries in the Waskada Field, 2013

Total daily truck trips, a function of the development and production activity, are assigned to the highway segments nearest the activity generator and closest to ODs for that product/material/equipment. For 2013, the Waskada field had two highways capable of moving traffic in and out of the field because the Coulter Bridge on PR 250 was out of service. PR 452 is assumed to carry all development related trips and some production trips. PTH 21 is assumed to carry all production related trips from that area of the Waskada field. These estimates were validated against classification coverage counts established along both highway segments. A review of the individual vehicle data from the classification coverage counts shows indications that each highway segment was carrying the traffic that was estimated and assigned to it:

- *PR 452* showed evidence of truck configurations known to serve the petroleum industry during the development phase and total truck traffic counted was equal to the estimated 85 development trips generated by new wells. The 48-hour count was conducted when the agriculture industry would not typically be very active and few other industries operate in the region. Therefore, total truck traffic at this site should be equivalent to total estimate petroleum-related truck traffic.
- *PTH 21* has a lower total and truck volume than PR 452 with a broader mix of traffic as a connection to the U.S. border crossing. Vehicles expected and noted in the VCD at this location included Class 10 and Class 13. Class 13 axle counts and spacing suggested many of these vehicles were a Class 6 with a full trailer commonly used to haul crude oil to transload facilities and batteries.

The above process was completed for each of the major oil fields in Manitoba including Pierson, Daly-Sinclair, Virden, Manson, and Birdtail. The remaining fields have little to no development and did not require the same level of effort for estimation. The major oil fields were used to select the location of classification coverage count sites, as shown in Figure 37. These counts were performed in the summer of 2013 and sites were selected based on the previous year's level of development and AADT annual changes from the Manitoba Highway Traffic Information System. As discussed, the classification counts, although only short term counts, help validate truck traffic estimates obtained through freight demand modeling processes.

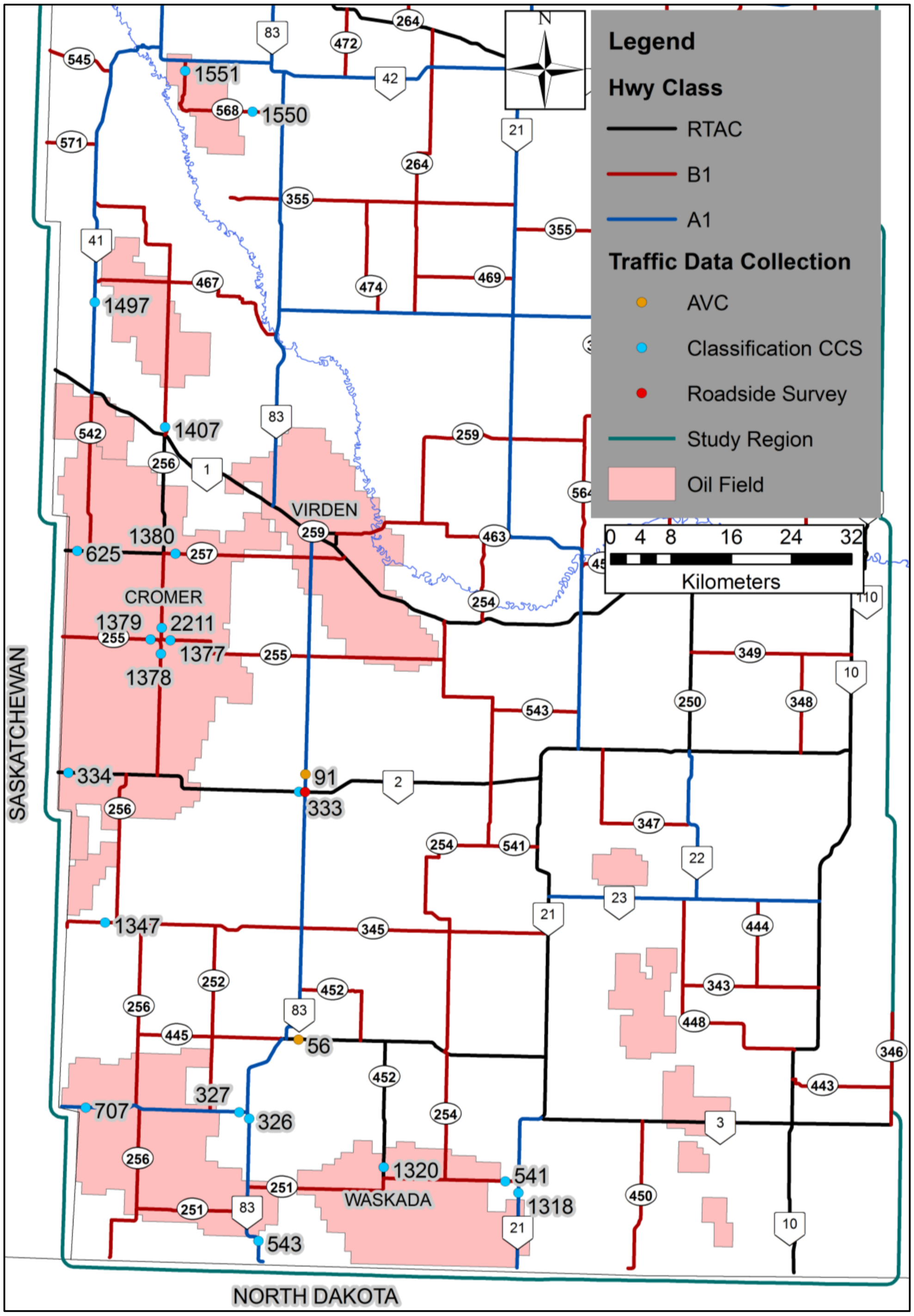


Figure 37: Truck Traffic Monitoring Program Established to Observe Petroleum-Related Trucking Characteristics
Source: Traffic data adapted from the *Manitoba Highway Traffic Information System* by M.Reimer

In some instances, an oil field may have a broader network of highways that provide access for development and production trips (when compared to the Waskada field example). The Pierson and Daly-Sinclair fields are examples where higher volumes of through traffic may exist that bring petroleum-related equipment and supplies into that field as well as to other fields. Figure 38 shows the Pierson Field and location of classification coverage count stations with their associated VCDs. PTH 3 goes through the field and into Saskatchewan and equipment and supplies destined for the field may originate east or west of the field. To assist in determining which trucks were destined for the field, the distance between the counters was measured and average truck speeds used to compare identical vehicle configurations. If the timestamp at one counter (location 1) minus the timestamp at the second counter (location 2) represents the travel time of the vehicle to cover the distance between the two counters then the vehicle is assumed to be passing through and not destined for a location within the oil field.

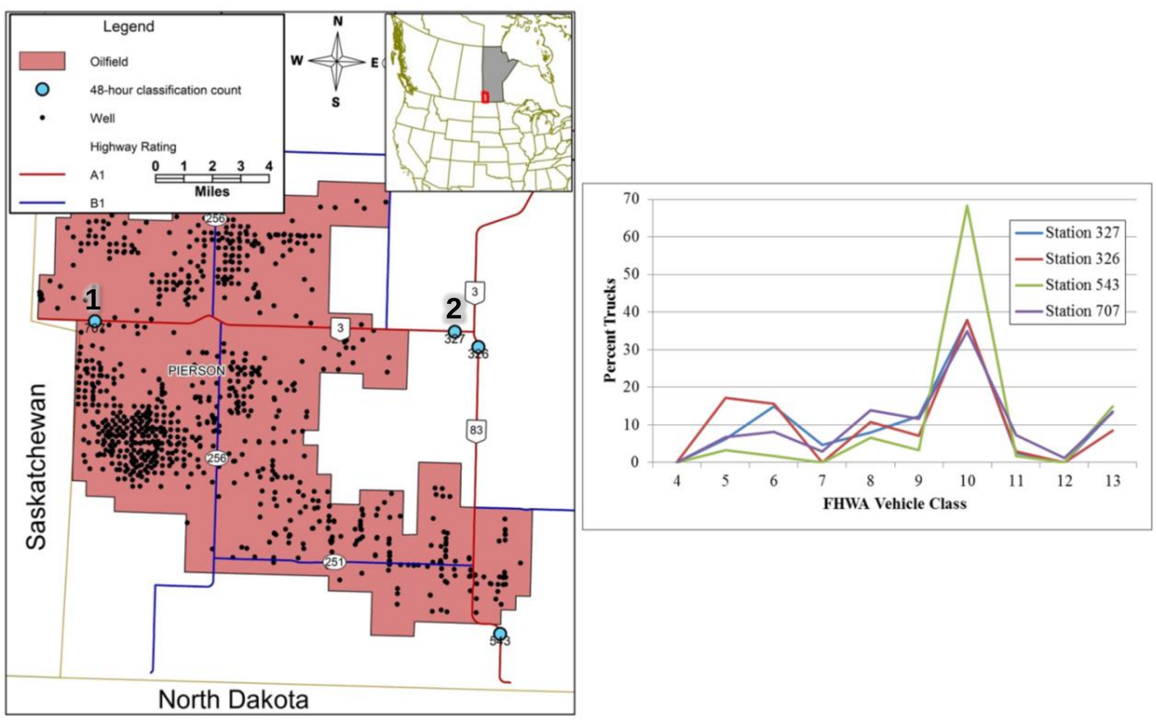


Figure 38: Classification Coverage Counts for the Pierson Field with Associated VCDs
Source: Used with permission from ASCE from Reimer, Regehr, and McKee (2014)

Complexities enter into estimating and assigning petroleum-related truck traffic due to the presence of a dense municipal road network. Estimates were not provided for the municipal road network but in all likelihood additional traffic is added to the highway network outside of the locations of count stations.

5.1.3 Intersection Analysis

Intersection analysis is required to provide estimates through intersections and along corridors connecting fields to major ODs. Figure 37 shows the segments of highway where a classification coverage count was conducted for this research. Where a classification coverage count exists, estimates were directly assigned through a combination of freight demand calculations and traffic monitoring counts. Typically, these segments are directly connected to an oil field. Petroleum-related truck traffic is then distributed through the network using routing information obtained from the roadside survey, industry interviews, and shortest path decision making.

Figure 39 shows an example intersection near the community of Melita, located between the Pierson and Waskada fields. The petroleum-related truck traffic (referred to as PADTT on the map) was assigned to highway segments working out from each oil field towards other fields and major ODs, such as the transload facilities at Cromer. The values shown in Figure 39 were calculated from the Waskada and Pierson fields. After calculating estimated traffic in and out of the intersection based on the travel demands of the Waskada and Pierson fields, the remaining trucks are assigned to PTH 83 north of Melita. At the intersection, the turning movements show that a PADTT of 115 is associated with movements between Waskada and the Daly-Sinclair and Virden area and the remaining PADTT of 110 with the Pierson area and Saskatchewan. A PADTT of 45 is associated between the Pierson area and the Daly-Sinclair and Virden area.

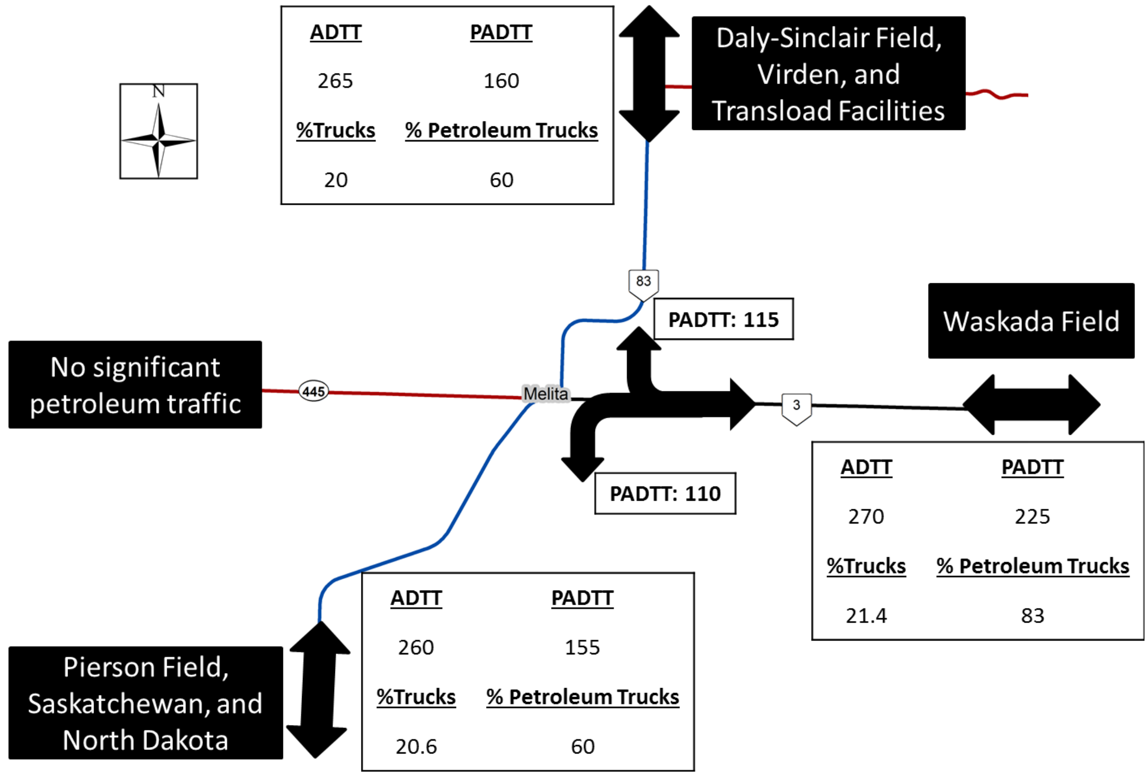


Figure 39: Example Intersection Analysis

Percent trucks and average daily truck traffic (ADTT) were taken from traffic estimates provided by the *Manitoba Highway Traffic Information System* and combined with estimates for total and petroleum-related truck traffic from counts and work performed as part of this research. The percent petroleum trucks metric is the ratio of petroleum trucks to total trucks. Typically for an intersection, both directions are assumed to carry equal volumes of daily petroleum-related truck traffic. In some instances, additional information is available from industry or count stations that suggested this was not true and petroleum-related truck traffic was routed along appropriate corridors. For example, PTH 83 north of the Pierson field and south of Melita has the following characteristics to consider:

- Development trips originate in Saskatchewan and the Pierson Field and may be destined for north of Melita or to the Waskada Field;

- Production trips on PTH 83 south of Melita can originate from Saskatchewan, the Pierson Field, and North Dakota; and
- North Dakota production trips travel north on PTH 83 while loaded but typically return empty on a different route (PR 256).

Development and production trips were kept separate through the process of routing traffic as production trips have a designated known destination. Each intersection was balanced for petroleum-related truck traffic to ensure that what enters an intersection is equal to what goes out. When directional information was unavailable, the total daily truck traffic was split equally in both directions. The final ADTT and petroleum average daily truck traffic (PADTT, discussed in the next section) values are combined directions and used to develop the flow map in this research.

5.1.4 Petroleum Average Daily Truck Traffic

The final truck traffic volumes assigned to the highway network within the study region are based on estimated daily truck trips from the development and production phases. These trips were assigned and validated through intersection analyses, validation through traffic monitoring, and industry knowledge obtained through the roadside survey and industry interviews. The petroleum-related truck traffic metric is termed petroleum average daily truck traffic (PADTT). PADTT is an estimate of the average number of trucks per day passing a point on the roadway resulting from petroleum-related activity. An important note on this metric is that it represents petroleum-related activity when oil fields are undergoing the development and production phases. The PADTT metric is reflective of “business-as-usual” through the entire region and assumes that all fields are experiencing development activity simultaneously. During periods of no development, such as during spring road restrictions, regional truck traffic flow would be much lower throughout the entire network as the development trips are removed from the system.

5.2 ANALYSIS RESULTS

This section outlines the results from the analysis and approach used to characterize petroleum-related truck traffic and freight flow through the study region.

5.2.1 Geographic Distribution

Figure 40 shows the distribution of PADTT throughout the study region. Petroleum-related truck traffic is primarily associated with the Daly-Sinclair field (including the terminals near Cromer), Waskada field, and Virden. Cross-border traffic with Saskatchewan includes truck trips associated with both the development and production phases and occurs along PTH 2 and PTH 3. The highest PADTT is along PR 256 which provides access to wells and batteries within the Daly-Sinclair field and serves the majority of all production-based trips ending at the transload terminals. The Waskada field, second to Daly-Sinclair in development activity, has most trips enter the field through PR 452. Figure 40 also displays the distribution of new wells added to the system in the 2013 calendar year.

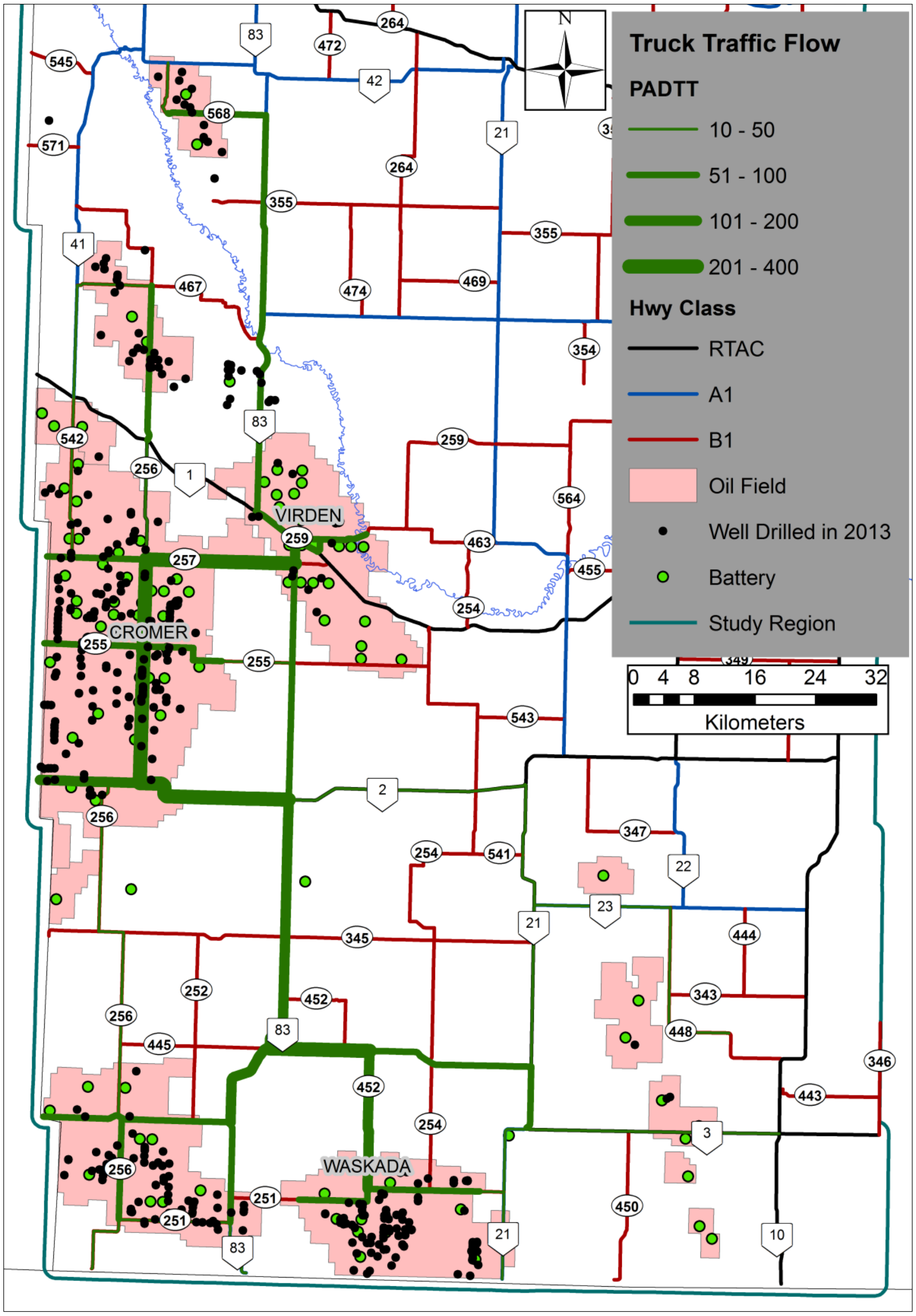


Figure 40: PADTT Flow Map for Southwest Manitoba

This same highway network is also classified in terms of functionality to the petroleum industry. Figure 41 shows the highway network by the two functionality classes. The definitions of the two functionality classes are:

- *Class A*: Primary corridor for the petroleum industry that serves both development and production phase trips into, out of, or between oil fields. PADTT for these routes are typically over 100 trucks per day. In some instances, these routes may provide the only means of access to an origin or destination. Gravel roads that carry petroleum-related truck traffic within fields and have higher volumes of trucks per day typically fall into this class as well.
- *Class B*: Secondary corridor for the petroleum industry that serves only production phase trips or low volume production and development phase trips. PADTT for these routes are typically less than 100 trucks per day. These corridors often connect smaller fields with low activity to the broader petroleum-related network.

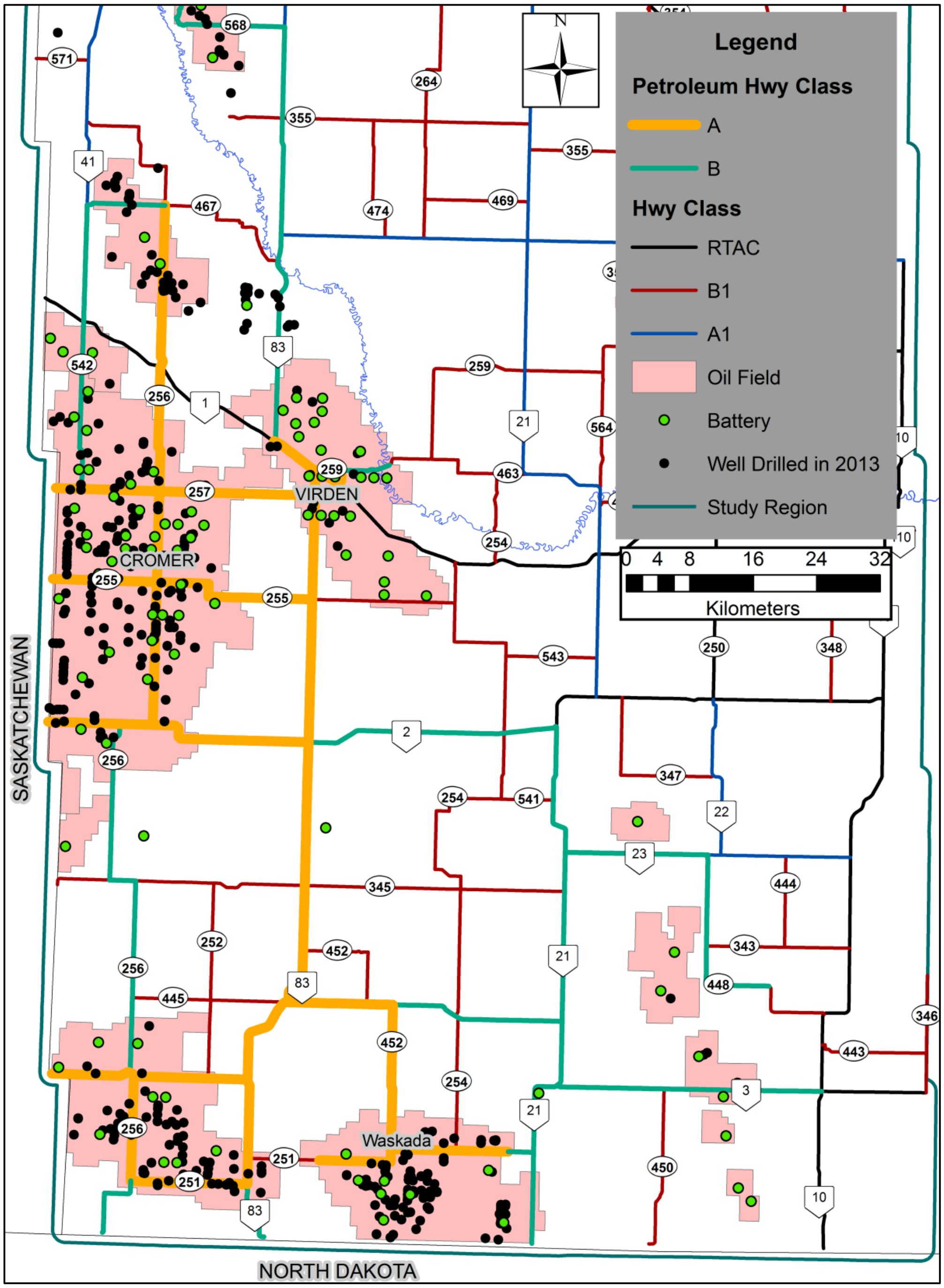


Figure 41: Highway Classification for Petroleum-Related Truck Traffic

Both classes of functionality are influenced by highway weight classification. Highways classified as B1, with a GVW of 47,630 kg, are typically assigned a functionality class B as the lower weight limits make them less likely to serve development phase trips and have lower volumes. One exception to this is PR 256 both north and south of transload facilities at Cromer. These highway segments experience the highest petroleum-related truck activity because this highway serves as the main access point for development in the Daly-Sinclair field and the final destination for crude oil produced throughout the region.

5.2.2 Temporal Distribution

The petroleum industry operates year-round and, during some stages of well development, may operate 24 hours per day. As shown in Figure 34, well completions and rig activity peak during the winter months, do not occur during spring road restrictions, and remain relatively consistent for the remainder of the year. These characteristics can create variations in average daily truck traffic volumes because development trips make up the bulk of petroleum-related truck traffic. Figure 42 shows truck traffic volumes from an automatic vehicle classifier (AVC) located on PTH 83 north of PTH 2. The daily truck traffic volumes peak during the spring road restrictions, possibly due to PR 256 having a Level 2 weight restriction. Truck traffic related to the production phase is routed through PTH 83 and PR 255 during this period; six-axle class 10 trucks are typically used for production trips.

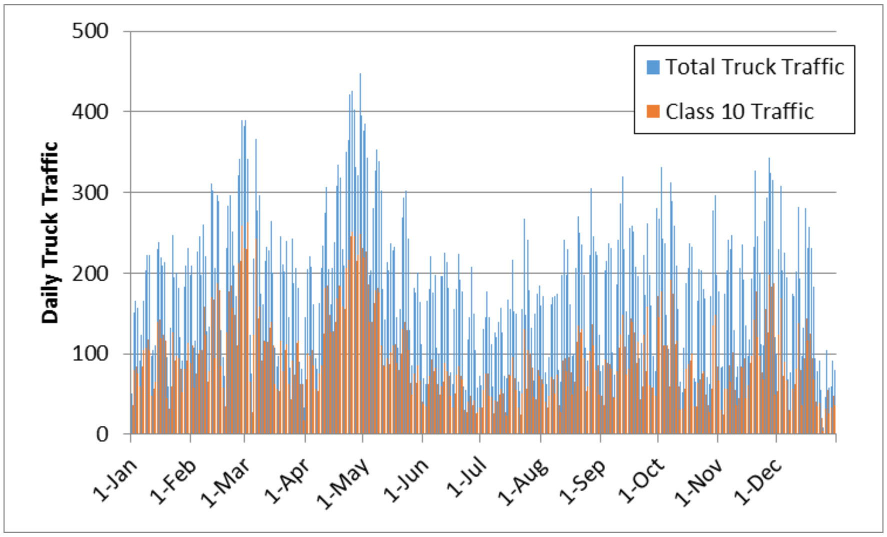


Figure 42: Daily Total Truck Traffic and Daily Class 10 Truck Traffic of Permanent Classification Count Station 91 in Southwest Manitoba

Source: *Manitoba Highway Traffic Information System* (2014)

The hourly distribution of truck traffic within the oil fields varies between locations. Figure 43 shows truck traffic hourly distributions from a coverage classification count site (Station 1378) near the Cromer terminals on PR 256 where truck traffic is influenced by production-based trips. Hourly distributions and a map showing the locations of all 20 classification coverage count sites can be found in Appendix E. The coverage classification counts are numbered with their corresponding coverage count site numbers, as designated by MIT. One challenge with selecting a time and location for a classification coverage count is the dynamic nature of the industry. Daily truck volumes can exhibit considerable variation depending on the level of development occurring during the period of data collection. When data collection does not capture typical field activity, knowledge of the annual activity level for a field and corresponding highway route can assist in understanding which traffic counts may be outliers.

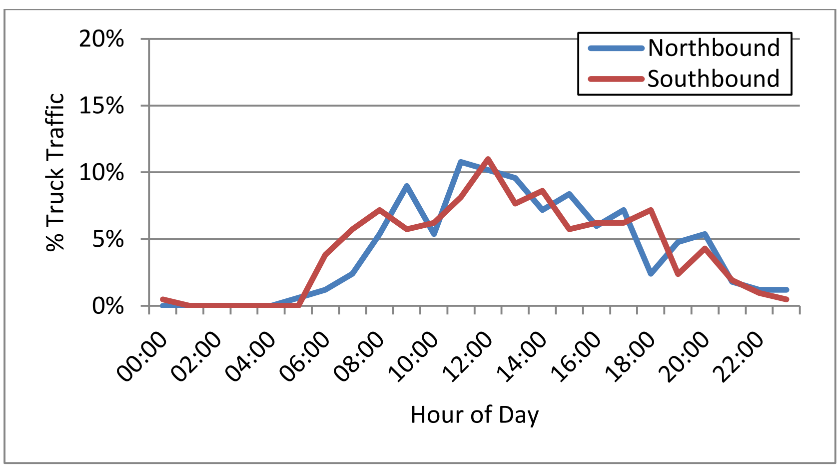


Figure 43: Hourly Distribution of Truck Traffic for Station 1378

5.2.3 Vehicle Class Distribution

The petroleum industry across Alberta, Saskatchewan, and Manitoba is typically characterized by classification distributions dominated by FHWA Class 10 vehicles (tractor with a tridem axle group on the semitrailer) (Reimer and Regehr, 2014a). Across the 20 coverage classification count stations established in this study, the dominant vehicle classes were Class 6, Class 10, and Class 13. Class 6 vehicles include service vehicles and tankers to haul emulsion, crude oil, or water. Class 10 vehicles may be any body type but typically consist of tankers for hauling liquids or flat decks hauling equipment or performing special permit rig moves. Class 13 vehicles specific to the oil fields are Class 6 tankers with a four axle trailer consisting of two tandems (referred to as 'quads' by industry but are really full trailers – see Appendix C for vehicle characteristics). The left side of Figure 44 shows a vehicle class distribution (VCD) on PR 256 indicative of high production-based truck trips. The right side of Figure 44 shows a VCD on PR 452 indicative of high development-based truck trips. Vehicles in the second VCD that suggest development-based trips include Class 8 and 11 (often service rigs) and Class 10 vehicles are frequently 7-axle trucks used in rig moves. Characteristics in the second VCD that are not apparent can be identified in the raw data through a review of individual vehicle entries and axle spacing. The Class 10 vehicles in the second VCD contain 7-axle tractor-trailers common with rig moves whereas the Class 10 vehicles in the first VCD are typically 6-axle tanker trucks. A map of truck traffic data collection sites and their corresponding VCDs can be found in Appendix E. An inventory of vehicles operating in the oil fields and selected characteristics can be found in Appendix C.

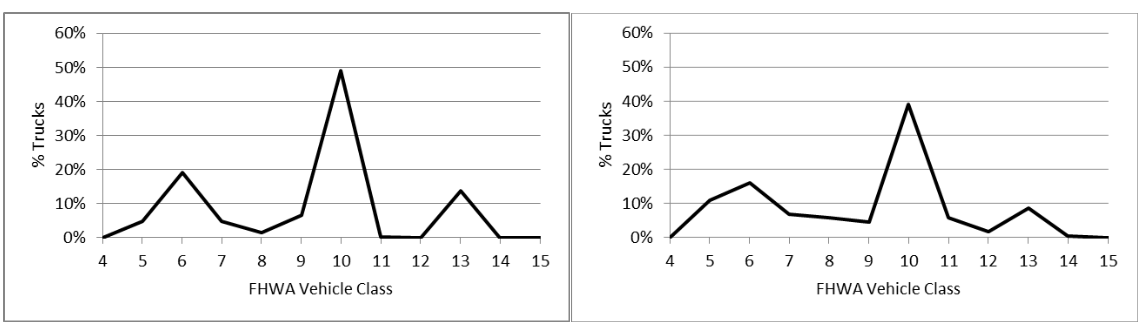


Figure 44: VCDs for production (left image) and development (right image) Phases on Select Highways

5.2.4 Directional Characteristics

Generally, truck traffic into a field is similar to truck traffic leaving a field. While weight data were not collected comprehensively through the network, industry intelligence suggests that development trips are loaded into a field and empty returning. In some cases, such as the movement of equipment, trips can be loaded in both directions for a single well. Figure 45 shows that northbound and southbound VCDs for the classification CCS on PR 452 north of Waskada have similar characteristics to each other. In some instances, such as the VCD shown in Figure 46, trucks may take a more circuitous route and not return along the same corridor. The northbound VCD is a result of loaded northbound crude oil tankers crossing the U.S.-Canada border on PTH 83 but selecting a different return route through PR 256 or Saskatchewan. Directional characteristics may vary based on highway weight restrictions, municipal road use, or field characteristics for picking up and delivering materials.

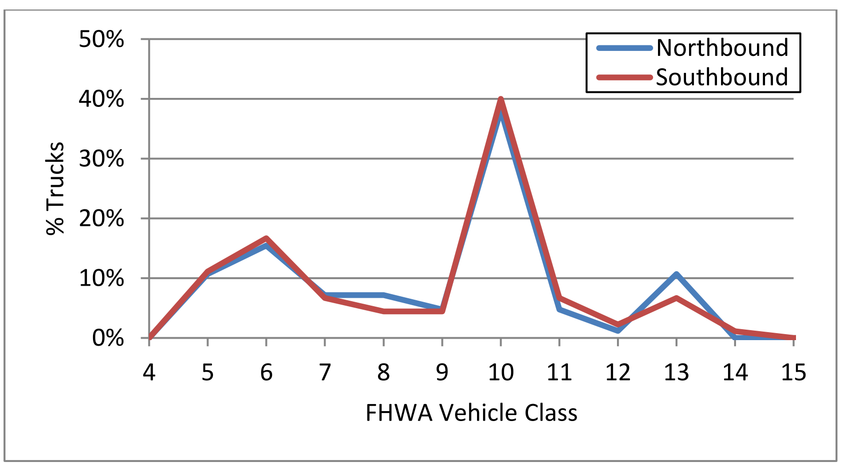


Figure 45: Directional VCDs for Station 1320 on PR 452 (Access to Waskada Field)

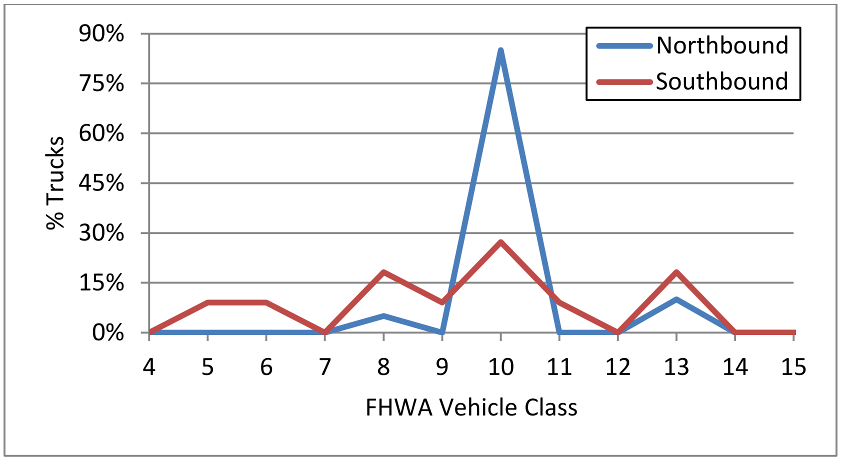


Figure 46: Directional VCDs for Station 543 on PTH 83 (Production Trips from U.S.)

5.2.5 Roadside Survey

Results of the roadside survey provided useful information on origins and destinations as well as vehicle and trip characteristics. Figure 47 provides details on freight movement in the study region broken down into three categories: (1) traffic destined for or originating from the study region, (2) internal truck trips, and (3) through traffic. From the roadside survey, it was found that 22 percent of truck trips are through traffic but the majority of traffic is intra-regional (39 percent) or between Manitoba and neighboring jurisdictions (39 percent) Saskatchewan and North Dakota. Data on the route being travelled by each truck were provided along with the origin, destination, and commodity being transported.

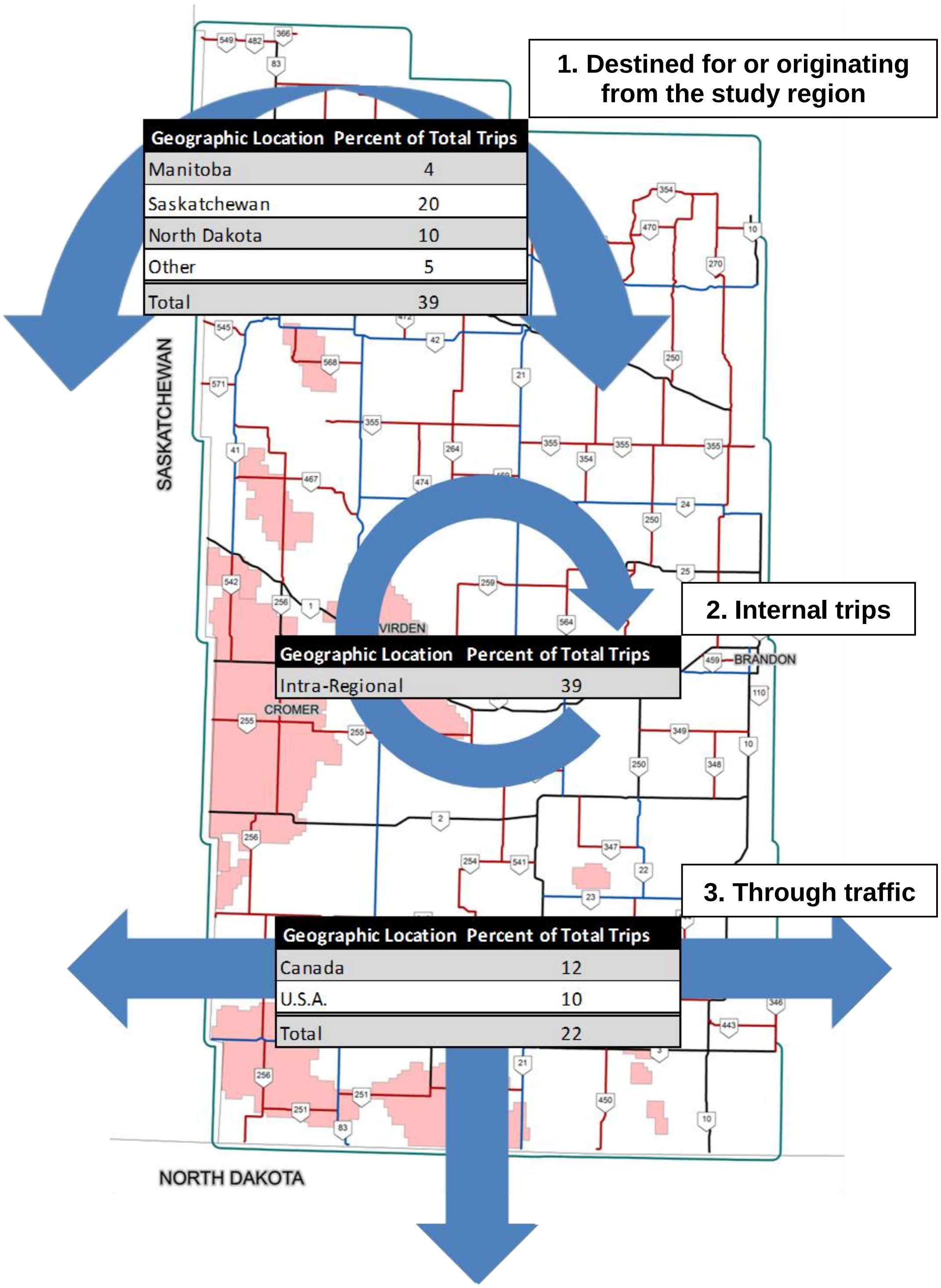


Figure 47: Origin and Destination Characteristics Obtained Through the Roadside Survey (n=84)

Furthermore, the roadside survey provided information on the type of industry served by truck traffic in the region. Figure 48 shows the breakdown in truck traffic by industry served. Petroleum-related truck traffic consisted of crude oil, freshwater, contaminated soil, and equipment and supplies. Agriculture-related truck traffic, part of the regional latent truck traffic, is likely high because the survey was conducted in September during the harvest season; petroleum-related traffic may comprise a larger portion of the total truck traffic fleet mix during other times of the year. Most of the petroleum-related truck traffic intercepted was destined for the crude oil transload terminals at Cromer or the hazardous material facility north of Virden. Crude oil was being transported through this intersection from the southern fields in Manitoba and from across the U.S.-Canada border in North Dakota. Contaminated soil destined for the hazardous material facility was primarily sourced from Saskatchewan.

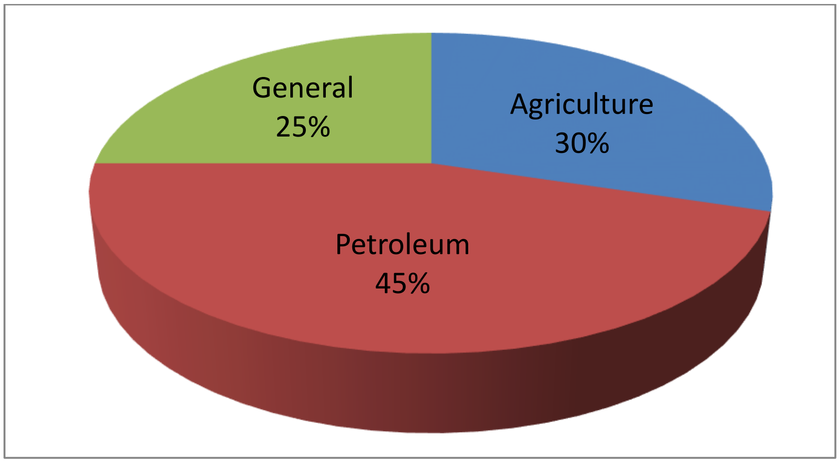


Figure 48: Breakdown of Vehicles Surveyed Based on Industry Served (n=84)

5.3 DEVELOPMENT OF A DATA DISSEMINATION TOOL

The data and information presented in the thesis assisted in developing a data dissemination tool for use by transportation engineering and planning professionals. This tool uses Google Earth® software, an easy-to-use GIS environment, to allow practitioners to navigate through a region of interest, select components, and view attributes. The Google Earth® data dissemination tool contains information on the three components of the petroleum-related transportation system analysis: (1) transportation supply; (2) activity system; and (3) flow. Details on the components, attributes, and the source data are available in Appendix F of the thesis. GIS analysis and editing were performed using the ArcMAP® software developed by ESRI. The GIS data was then exported from the ArcMAP® environment to the Google Earth® keyhole markup language (.kml) using built-in tools found within the ArcMAP® software. Minor editing was required within the Google Earth® software to organize visible GIS layers. The final product is a series of files that are stored in internet-based cloud storage. The advantage of using cloud storage is to enable centralized updating of GIS layers without requiring redistribution to all users of the data dissemination tool.

Figure 49 provides a screenshot of the transportation supply GIS layers included within the Google Earth® tool. The supply of transportation includes the infrastructure used to support the petroleum industry in developing new wells and enabling continued petroleum production. Layers included in the tool are: provincial highways and roads; municipal road network; bridges and other structures; railroads; and pipelines. The tool is intended for use by highway engineering, planning, and maintenance professionals and thus is focused on the highway infrastructure. Highway and bridge infrastructure are selectable and include attributes on characteristics such as surface, width, and weight rating. Details on the data sources and GIS layer attributes related to the transportation supply are provided in Appendix F.

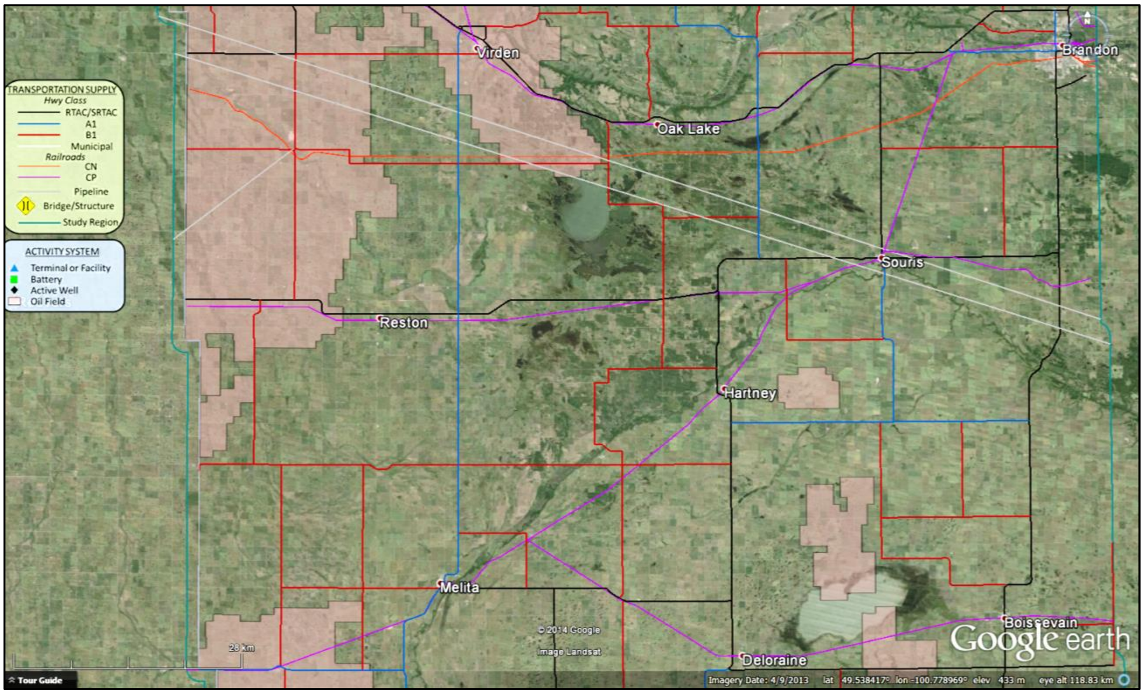


Figure 49: Google Earth® Data Dissemination Tool Showing the Transportation System

Figure 50 provides a screenshot of the activity system GIS layers included within the Google Earth® tool. The activity system impacts the regional transportation supply and, when visualized with the transportation supply, helps identify where this activity is most dense. A dense activity system likely indicates areas that generate and attract truck traffic. The four general components of the activity system, as visualized within the Google Earth® tool, include: (1) designated oil fields; (2) active wells; (3) batteries; and (4) terminals and materials/equipment sources. All four components interact with each other and represent the origins and destinations within the petroleum producing region of Manitoba. Details on the data sources and GIS layer attributes related to the transportation supply are provided in Appendix F.

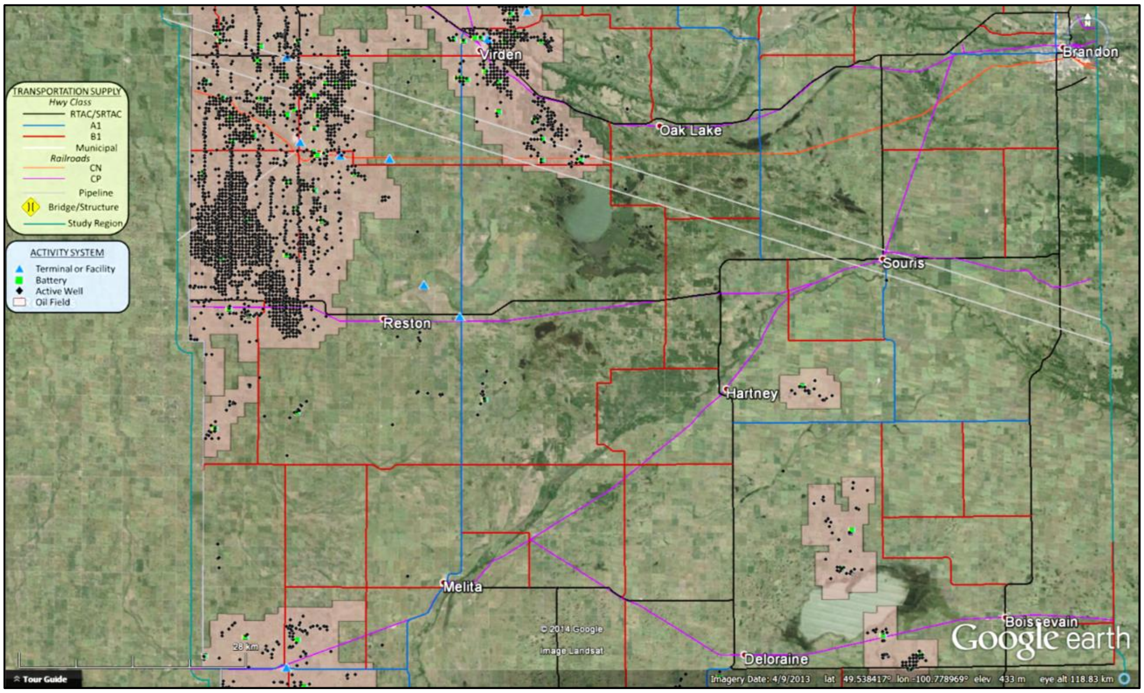


Figure 50: Google Earth® Data Dissemination Tool Showing the Petroleum Activity System

Figure 51 provides a screenshot of the flow system GIS layers included within the Google Earth® tool. These layers represent the results of the estimation and analysis component the thesis that characterized petroleum-related truck traffic. The primary intent of these components is to represent the PADTT using increasing line thicknesses to represent higher truck traffic volumes. The flow system also includes information from truck traffic data collection including VCDs and temporal distributions obtained from AVCs and Classification CCSs. The data from the roadside survey are also summarized directly within the tool. Each component from the truck traffic data collection is selectable and will provide the data sheets from Appendix E that summarize the data analysis performed at that location.

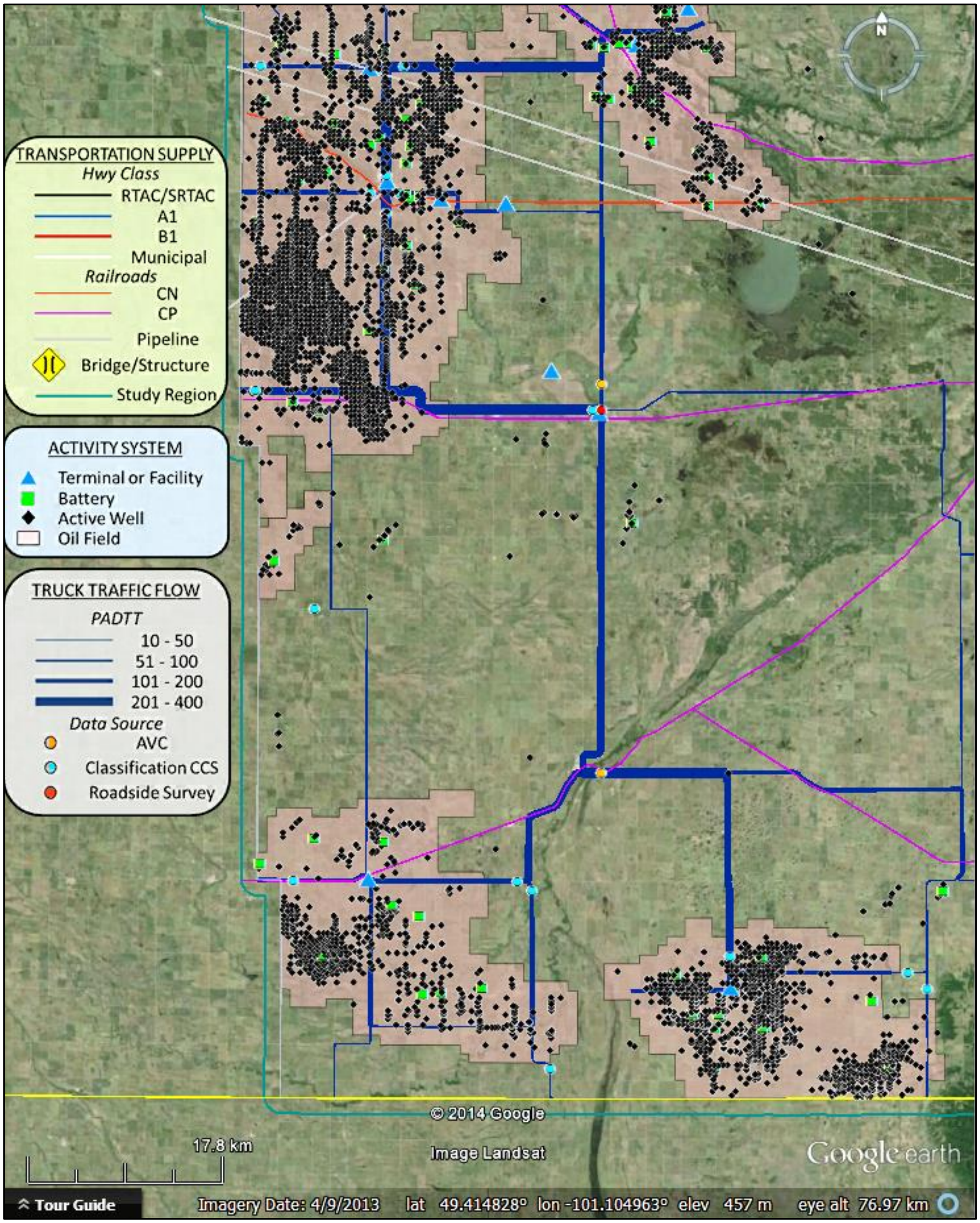


Figure 51: Google Earth® Data Dissemination Tool Showing PADTT

5.4 IMPLICATIONS FOR TRANSPORTATION ENGINEERING

The methodology and results from this research create a framework for estimating petroleum-related freight flows but also illustrate the challenges of this industry for transportation engineering and planning. The complex freight demands and rapid growth in petroleum production due to increased development activity places significant strain on local and regional roads and highways. This development results in regional shifts in truck traffic volume, the types of truck being used, and trip-making characteristics. These shifts can create immediate challenges in highway infrastructure maintenance, highway planning and design, and ongoing asset management. Understanding the development and production phases of the petroleum industry can assist in accommodating and planning for shifting truck traffic characteristics.

The development phase of petroleum industry activity involves drilling new wells to increase (or maintain) production levels and exploration for new oil reservoirs. This phase challenges transportation engineering and planning due to the short-term, intense truck traffic volumes that reflect the dynamic spatial and temporal patterns of the industry itself. Transportation analysts need to understand the characteristics of the drilling and hydraulic fracturing stages of well development because these stages generate most of the truck traffic for this phase. Furthermore, understanding of the local geology, well depth, well length, and drilling techniques applied provide insights into expected truck trips and likely development regions.

The truck traffic associated with the development phase includes OS/OW vehicles that exceed GVW limits and lane widths on many of the low-volume rural highways in the region. The characteristics of these vehicles can create safety challenges when experiencing meets with other vehicles on narrow highways with little to no road shoulders. The condition of the shoulders can also create safety concerns for vehicle operations as the high weights can cause the vehicle to become unstable if there is a drop between the paved surface and a gravel shoulder. Lastly, aging bridge infrastructure can create network limitations for the industry when no overweight vehicles are permitted to cross. Transportation engineers and planners should be aware of the safety concerns and network connectivity issues for the unique vehicles of the industry.

The second phase of the petroleum industry activity is the production of petroleum products and associated by-products. This phase of the industry is more predictable than the development phase because most of the infrastructure is already in place and reliable freight estimates can be obtained through public agencies. Spatial and temporal characteristics are more consistent throughout the year and activity levels do not fluctuate intensely within a single year. However, up-to-date information can be difficult to obtain for flowline and pipeline status. The use of non-current flowline and pipeline status will result in an over-estimation of total truck traffic generation. This estimate can become more reliable with the use of industry knowledge to confirm when and where wells may, or may not, be flowlined as supplement to the databases with a time lag.

Understanding the characteristics of these two distinct phases of the petroleum industry is a key component to applying the methodologies outlined in this research. The integrated framework is more powerful when the analyst has a thorough understanding of the industry because regions of high freight activity versus lower freight activity can be identified. The research in this thesis, due to limited resources, timing constraints, and being a pilot study, collected traffic count data prior to performing analysis of freight demand data. If this analysis had been performed before collecting traffic data, the short-term classification counts could have been set up and placed at locations to more accurately collect data on the temporal and spatial patterns of the petroleum industry.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the research, highlights major findings and provides recommendations for future research.

6.1 CONCLUSIONS

This research develops and applies a methodology to characterize and estimate petroleum-related freight flows to understand truck traffic patterns within a region. The petroleum industry has experienced rapid growth recently due to hydraulic fracturing and directional drilling. Industry characteristics such as local geology, extraction techniques, and market trends can help explain regional activity in oil and gas exploration and production. In addition, the petroleum industry has complex freight transportation demands with dynamic temporal and spatial truck traffic characteristics operating within a multimodal transportation network. This research used an integrated framework that takes advantage of the common goals of truck traffic monitoring programs and freight demand modeling to characterize petroleum-related freight flow and truck traffic.

The petroleum industry has experienced increasing development activity (drilling of new wells) and higher total crude oil production, both of which can place significant strain on local and regional roads and highways. In total, a single well may generate approximately 140 one-way loaded truck trips over a span of at least 25 days. The majority of these trips are made during the most intense stages that span only eight days. During the spring season development is essentially stopped due to spring road restrictions and difficult field conditions. In comparison, the production phase of the petroleum industry operates year round and generates truck traffic based on flowline and pipeline status and average daily production of each well.

Estimating petroleum-related truck traffic flow in the region requires an understanding of the regional transportation supply, petroleum-related activity system, and exogenous factors that influence the industry. This research adopted an integrated framework to characterize and assign petroleum-related truck traffic to a regional highway network. The framework integrates components of freight demand modeling and truck traffic monitoring processes to characterize and understand truck traffic flow characteristics of the petroleum industry. The freight demand modeling process was used to integrate key metrics specific to the petroleum industry to determine trip generation and link commodity movements with truck traffic. Commodity movements, including equipment, are transported primarily on trucks classified as FHWA class 6 (single unit), class 10 (single trailer), and class 13 (multi-trailer), however, unique configurations are used to move specialized equipment. Elements of the freight demand modeling process can help forecast truck traffic characteristics, though this is not the objective of this research. The truck traffic monitoring data provides details on highway traffic and truck traffic volumes, vehicle classification, and temporal and directional characteristics.

The research applies two decision flow diagrams to process and analyze petroleum-related activity related to the development and production phases. Application of the methodologies discussed in the thesis resulted in approximately 140 one-way development trips per new well drilled and varying total production trips based on oil field characteristics. The decision flow diagrams assist in determining temporal and spatial characteristics of truck trips into and out of each oil field on the provincial highway and road network. The resulting distribution and assignment of truck traffic, termed *Petroleum Average Daily Truck Traffic* (PADTT), is an estimate of the average number of trucks per day passing a point on the roadway resulting from petroleum-related activity when fields are undergoing both the development and production phases.

Throughout the study region, PADTT ranged from over 300 on primary corridors near key facilities (Cromer Transload Facility) to under 50 in low activity fields at the edge of petroleum producing region. The PADTT metric is reflective of “business-as-usual” throughout the whole region when operating through development days. During periods of no development truck traffic volumes would be lower as development trips are removed from the highway network.

The methodologies and approach used in the research to characterize petroleum-related freight flows and truck traffic support transportation engineering and planning activities in jurisdictions impacted by rapid petroleum developments. The research illustrates the need to understand regional transportation systems and how petroleum industry activities interact with supporting transportation infrastructure. Furthermore, the exogenous factors that affect the industry (such as crude oil pricing) influence industry activity levels that produce truck traffic flow. The thesis highlights the complexity of the industry and how integrating multiple datasets across exogenous factors, activity variables, and transportation supply variables is required to plan for petroleum industry impacts on regional transportation networks. While certain components and details of this research are specific to the petroleum industry in southwest Manitoba, the methodology and approach is transferable to other petroleum-producing regions. In addition, the methodology and approach can be applied beyond the petroleum industry to help transportation planners, analysts, and engineers understand the impacts of other industry-specific developments.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

This research identified the following opportunities for future work:

- Enhance truck traffic monitoring programs by identifying temporal and spatial patterns of specific industry activity. This research developed a truck traffic monitoring program for the petroleum industry in Manitoba based on activity levels and changes in traffic volumes along selected highway segments. The thesis built a knowledge base from this monitoring program that could be expanded upon and changed in response to shifting industry patterns. Furthermore, this approach to truck traffic monitoring programs could be expanded to the wider network within a jurisdiction to improve understanding for any specific industry.
- Refine petroleum-related truck traffic estimates in response to industry changes on an annual or bi-annual basis. Due to the dynamic nature of the industry, estimates and analyses should be regularly updated. First, well-specific truck traffic estimates should be updated as target geological formations and drilling techniques are subject to change, thus altering the required inputs. Secondly, changes in the multimodal transportation network may occur, such as flowline network expansion, which can shift truck traffic characteristics. Lastly, origins and destinations shift for both material and equipment inputs and crude oil production infrastructure. This information is important in distributing and assigning petroleum-related truck traffic to the highway network and will influence highway engineering and planning activities.
- Develop and evaluate the impacts of increased truck traffic volumes on highway infrastructure. Most of the petroleum-related activity is occurring on low-volume highways that have traditionally served the agriculture industry. This thesis

developed estimates for average daily truck traffic and provides some example vehicle class distributions. However, little weight data are available for trucks operating through this region to assess the physical impacts of increased petroleum-related truck traffic.

- Much of the petroleum industry activity starts or ends on the municipal road network. This dense network extends across multiple jurisdictions because each municipality is responsible for the network within their boundaries. Categorizing the municipal road infrastructure and distributing petroleum-related truck traffic through this network would improve overall understanding of the industry's impact on regional infrastructure.

7. BIBLIOGRAPHY

Abel, Jennifer [Chief Petroleum Engineer at the Manitoba Petroleum Branch of Innovation, Energy and Mines] and Gervin, Allan [Petroleum Inspector at the Manitoba Petroleum Branch of Innovation, Energy, and Mines]. Personal Interview. 26 June 2013.

Abel, Jennifer [Chief Petroleum Engineer at the Manitoba Petroleum Branch of Innovation, Energy, and Mines] and Gervin, Allan [Petroleum Inspector at the Manitoba Petroleum Branch of Innovation, Energy, and Mines]. Personal Interview. 21 March 2014.

ALL Consulting (2012). "The Modern Practices of Hydraulic Fracturing: A Focus on Canadian Resources," prepared for Petroleum Technology Alliance Canada (PTAC) and the Science and Community Environmental Knowledge Fund (SCEK).

Baker Hughes (2014). *North America Rig Count* Retrieved from the Baker Hughes Investor Relations website: phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-reportsother

Canada. National Energy Board (2011). *Energy Briefing Note on Tight Oil Developments in the Western Canada Sedimentary Basin*. Retrieved December 12, 2013 from http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/l/tghtdvlpmntwcsb2011/tghtdvlpmntwcsb2011-eng.pdf

Canada Gazette (2014). *Regulations Amending the Transportation of Dangerous Goods Regulations (Update of Standards)*. Retrieved July 29, 2014 from: http://www.gazette.gc.ca/rp-pr/p2/2014/2014-07-02/html/sor-dors152-eng.php

Canadian Association of Petroleum Producers (2013). *2013 Crude Oil Forecast, Markets & Transportation.* Calgary, AB.

Canadian Association of Petroleum Producers (2014). *Transporting Crude Oil by Rail in Canada.* Calgary, AB.

Canadian Energy Pipeline Association (2014). *Regulations and Standards*. Retrieved July 29, 2014 from: http://www.cepa.com/about-pipelines/pipeline-design-construction/regulation-and-standards

Canadian Energy Research Institute (2012). “Tight and Shale Oil Plays in the Western Canadian Sedimentary Basin,” published in the 2013 Manitoba Oil & Gas Review.

Day, Dennis [Executive of FAST Trucking and founder of General Well Servicing]. Personal Interview. 4 February 2014.

Federal Highway Administration (2013). *Traffic Monitoring Guide.* Washington, D.C.: U.S. Department of Transportation.

Fox, J. and Nicolas, M.P.B. (2012). “Oil in Manitoba: Exploration, production, reserves and revenues,” Manitoba Innovation, Energy and Mines Mineral Resources Division. Presentation given at APEGM Professional Development Seminar, Winnipeg, MB.

Hart, M., Adams, T., and Schwartz, A. (2013). “Shifting Sands: Emerging Transportation Impacts of Frac Sand Mining and Shale Gas Drilling,” Transportation Research Board Annual Meeting, Washington, D.C.

Holguin-Veras, J. and Thorson, E. (2000). Trip Length Distributions in Commodity-Based and Trip-Based Freight Demand Modeling. In *Transportation Research Record:*

Journal of the Transportation Research Board, No. 1707, Transportation Research Board of the National Academies, Washington, D.C., 2000, pp. 37-48.

Karsinski, D.R. (2006). "Sedimentology and Hydrocarbon Potential of the Devonian Three Forks and Mississippian Bakken Formations, Sinclair Area, Southeast Saskatchewan-Southwest Manitoba," master's thesis, University of Manitoba, Winnipeg, Manitoba.

Li, J. and Morozov, I. (2007). "Geophysical Investigations of the Precambrian Basement of the Williston Basin in south-eastern Saskatchewan and south-western Manitoba," University of Saskatchewan, Williston Basin TGI. Retrieved December 10, 2013 from http://seisweb.usask.ca/Reports/TGI2/TGI2_report-Feb_2007.pdf

MacAdam, L. (2014). "Addressing Transportation Impacts from Shale Oil and Gas Development in Ohio's Utica," American Society of Civil Engineering Shale Energy Engineering Conference, Pittsburgh, PA.

Manheim, M.L. 1979. Fundamentals of Transportation Systems Analysis: Volume 1: Basic Concepts. Cambridge, MA: MIT Press.

Manitoba (2014a). *The Oil and Gas Act*. Retrieved from the Department of Justice Manitoba website: http://web2.gov.mb.ca/laws/statutes/ccsm/_pdf.php?cap=o34

Manitoba (2014b). *Manitoba Petroleum Fiscal Regime*. Retrieved from the Manitoba Mineral Resources website: http://www.gov.mb.ca/iem/petroleum/infonotes/14-03.pdf

Manitoba 511 (2014). *Road and Traveller Information*. Retrieved from the Manitoba Government website on July 30, 2014: http://web20.gov.mb.ca/RI/Map?lng=-99.99&lat=49.8&z=8

Manitoba Mineral Resources (2014). *Informational Notice 14-03 – Spatial Data Requirements for Flowline Submissions*. Retrieved from the Manitoba Petroleum Branch website: http://www.gov.mb.ca/iem/petroleum/infonotes/14-03.pdf

Manitoba Petroleum Branch (2014). *Production Reports.* Data retrieved from the Manitoba Petroleum Branch website: http://www.manitoba.ca/iem/petroleum/reports/index.html

Matter, M. and Voda, J. (2014). "Protecting PennDOT's Infrastructure," American Society of Civil Engineering Shale Energy Engineering Conference, Pittsburgh, PA.

Miller, T., and Sassin, J. (2013). "Assessing the Impacts of Energy Developments on Rural Texas Highway Infrastructure," Transportation Research Board Annual Meeting, Washington, D.C.

National Cooperative Highway Research Program (2008). *NCHRP Report 606: Forecasting Statewide Freight Toolkit.* Transportation Research Board of the National Academies, Washington, D.C.

Nicolas, M. (2006). "Petroleum Geology of the Devonian Three Forks Formation, Sinclair Field and Surrounding Area, Southwestern Manitoba," in E.H. Nickel (ed), Saskatchewan and Northern Plains Oil & Gas Symposium Core Workshop Volume, Saskatchewan Geological Society Special Publication 20, p32-49.

Nicolas, M. (2007). "The Devonian Three Forks Formation: Manitoba's Newest Oil Play," presentation given to the Manitoba Geological Survey.

Nicolas, M.P.B, and Barchyn, D. (2008). "Williston Basin Project (Targeted Geoscience Initiative II): Summary report on Paleozoic stratigraphy, mapping and hydrocarbon assessment, southwestern Manitoba," Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Geoscientific Paper GP2008-2.

Northern Tier Regional Planning and Development Commission (2011). *Marcellus Shale Freight Transportation Study.* November 2011.

Quiroga, C. (2014). "State of the Practice and Research Needs," American Society of Civil Engineering Shale Energy Engineering Conference, Pittsburgh, PA.

Quiroga, C., Fernando, E., and Oh, J. (2012). "Energy Developments and the Transportation Infrastructure in Texas: Impacts and Strategies," Report FHWA/TX-12/0-6498-1, Texas Transportation Institute, College Station, Texas.

Regehr, J.D., Montufar, J., and Clayton, A. (2009). "Lessons learned about the impacts of size and weight regulations on the articulated truck fleet in the Canadian prairie region." *Canadian Journal of Civil Engineering*, vol. 36: 607-616.

Reimer, M. and Regehr, J.D. (2014a). "A Hybrid Approach for Clustering Vehicle Classification Data to Support Regional Implementation of the Mechanistic-Empirical Pavement Design Guide." In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2339 Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 112-119.

Reimer, M.J. and Regehr, J.D. (2014b). "A framework for characterizing truck traffic related to petroleum well development and production in unconventional shale plays." In *Transportation Research Record: Journal of the Transportation Research Board,* No. 2410 Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 1-9.

Reimer, M.J., Regehr, J.D., and McKee, J. (2014). “Issues and Options for Oversize/Overweight Permitting of Petroleum-Related Trucks in a Performance-Based Regulatory Context: The Manitoba Experience.” In *Shale Energy Engineering Conference Proceedings*¸ American Society of Civil Engineering, Pittsburgh, PA, 2014, pp. 552-564.

Riddell, Ryan [Supervisor for Oil Field Planning and Construction Services at Manitoba Hydro] and Plaisier, Bruce [Customer Service Manager at Manitoba Hydro]. Personal Interview. 19 April 2013.

Selly, R.C. (1998). “Elements of Petroleum Geology (2nd ed.),” San Diego, CA: Academic Press.

Smith, K. Risk and Reward from the US Fracking Boom. In *International Railway Journal*, Vol. 53, Issue 9, pp. 22-26. September 2013

Statistics Canada (2014). No date. Table 404-0002 Railway carloadings statistics, by commodity, monthly. Accessed: June 12, 2014.

Tidd, L. (2013). “Consideration of Shale Gas Development Impacts in Long-Range Transportation Planning,” Transportation Research Board Annual Meeting, Washington, D.C.

Tolliver, D. (2013). “Effects of Oil & Gas Development on Highway Infrastructure Investments: Case Study of the Bakken Shale,” Transportation Research Board Annual Meeting, Washington, D.C.

U.S. Energy Information Administration (2013). *Annual Energy Outlook 2013.* Washington, D.C.

United States of America (2011). U.S. Department of Energy. *Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays*. Washington, D.C.

Upper Great Plains Transportation Institute (2010). *Additional Road Investments Needed to Support Oil and Gas Production and Distribution in North Dakota.* North Dakota Department of Commerce. December, 2010.

Upper Great Plains Transportation Institute (2013). *Impacts to Montana State Highways due to Bakken Oil Development.* Montana Department of Transportation, February, 2013.

Upper Great Plains Transportation Institute (2014). *Infrastructure Needs: North Dakota's County, Township and Tribal Roads and Bridges: 2015-2034.* Draft Final Report to the North Dakota Legislative Assembly, July 8, 2014.

Wilke, P. and Harrel, M. (2011). "Assessment of Impact of Energy Development Projects on Local Roads," *Transportation Association of Canada 2011 Annual Meeting*, Edmonton, Alberta.

Woodrooffe, J., Sweatman, P., Middleton, D., James, R., and Billing, J.R. (2010). "Review of Canadian Experience with the Regulation of Large Commercial Motor Vehicles." *NCHRP Report 671*, Transportation Research Board, Washington, D.C.

Young, H.R., Li, R., and Kuroda, M. (2012). Silicification in Mississippian Lodgepole Formation, Northeastern Flank of Williston Basin, Manitoba, Canada. *Journal of Earth Science, Vol. 23, No. 1*, pp. 1-18.

APPENDIX A

DETAILED PETROLEUM GEOLOGICAL CHARACTERISTICS

OF SOUTHWEST MANITOBA

This appendix reiterates and expands on the topics covered in section 2.1 of this thesis.

Geological Setting

Within the Williston Basin are geological structural elements which trap hydrocarbons (the organic compounds that make up petroleum products) and create reservoirs (Li and Morozov, 2007). The basin itself, along with major geological structures can be seen in Figure 1. Geological formations (layers of sediments) within the basin contain carbonate and evaporitic (water soluble minerals) sedimentary sequences that are indicative of the late Devonian era (375 million years ago) to the middle Cenozoic era (65 million years ago) (Nicolas and Barchyn, 2008). The Bakken formation is one sequence within this region and it acts as an oil source rock, reservoir, and trap.

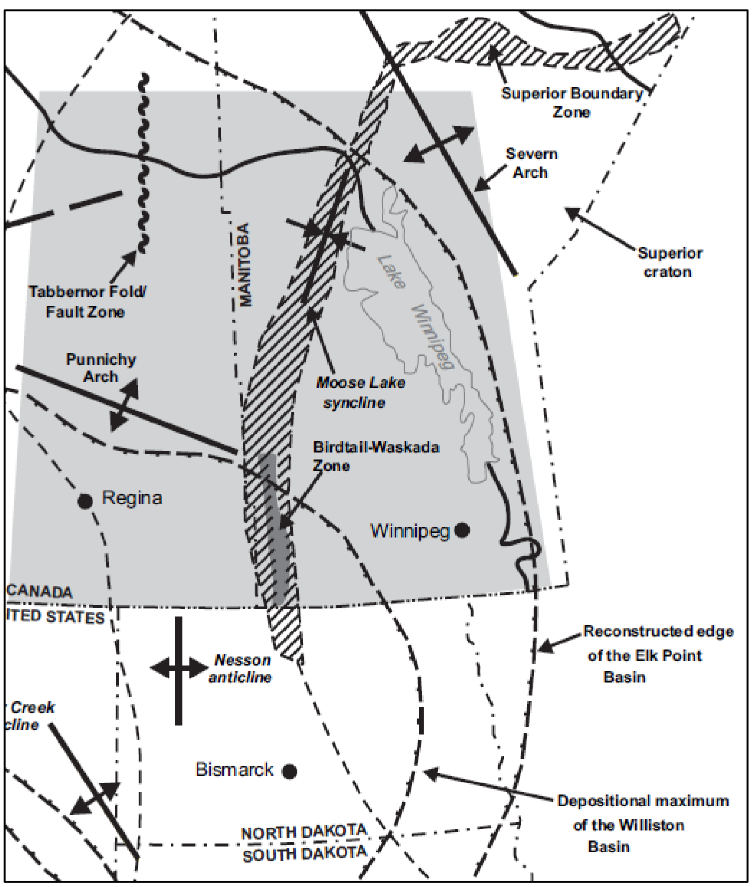


Figure 1: Williston Basin Location Map with Key Geological Structures
Source: Reproduced from Government of Manitoba with permission from Manitoba Mineral Resources from Nicolas and Barchyn (2008)

The geological sequences in the Basin include Paleozoic, Mesozoic, and Cenozoic aged strata and reach a maximum depth of 2.3 km in the southwestern most corner of the province; this dip creates a geological wedge through the region. Within the Manitoba portion of the basin there are major angular unconformities caused by tectonic shifting; of these, the most relevant to the oil producing region is the Precambrian Superior Boundary Zone (SBZ). The SBZ influenced the area by creating localized effects through basement reactivation, creating depositional environment edges, and imposing preferential salt-dissolution zones (Li and Morozov, 2007). The SBZ is shown running north-south in Figure 1 and is approximately 50 km wide. Basement reactivation is critical to the petroleum system in that it creates numerous faults, generates porosity variations and dissolution anomalies caused by fluid movement. Above the SBZ is the Birdtail-Waskada Axis (BWA) – a salt collapse with structural and stratigraphic irregularities – that runs through the southern portion of the SBZ. Together, these two zones create traps to create petroleum reservoirs and assist the movement of fluids (hydrocarbons). The location of these zones and the structural irregularities created by them locally control oil saturation, migration, and reservoirs (Nicolas, 2006).

The primary strata yielding significant petroleum production in the Williston Basin exist in the Paleozoic sequence. The Mississippian layer is the most productive in Manitoba but recent developments in extraction techniques and an improved understanding of the region have moved exploration into the deeper Devonian and Cambrian sequences (Li and Morozov, 2007).There are four formations that are the primary targets for petroleum exploration and production. These formations include, from oldest to youngest geologically, the Three Forks, Bakken, Lodgepole, and Lower Amaranth. Characteristics of the four formations are discussed below.

Three Forks

The Three Forks formation was deposited near the end of the Devonian period in the Elk Point Basin during a nearshore/shallow marine environment (Li and Morozov, 2007). Pre-Mississippian and pre-Jurassic erosion thinned the Three Forks at the eastern and northern edges. Further thinning occurs adjacent to the BWA and SBZ and effectively creates a boundary to the formation and oil reservoir potential. Oil production in this formation is related to the sandy clean parts where the unit subcrops and is in communication (comingled) with the permeable middle Bakken sandstone (Nicolas, 2007). The Three Forks works more as an addition to the storage volume and production of the overlying Bakken. The second, deeper unit in the Three Forks formation is a secondary reservoir and a poorer source of oil than the primary unit (Nicolas, 2006).

Bakken

The Mississippian Bakken formation consists of three members: Upper, Middle, and Lower. The Upper and Lower formations are a bituminous shale while the Middle formation consists of siltstone and sandstone. In Manitoba, the Lower Bakken has essentially been eroded away and exists only in sinkholes resulting from salt-collapse structure in the southern oil fields near the U.S. border. Throughout most of the region the middle member is comingled with the Three Forks formation. Similarly to the Three Forks, the layer thins east and north at the edge of the Williston Basin, with thickening occurring further south. Unlike North Dakota and parts of Saskatchewan, where the Lower Bakken formation is present, hydrocarbon production from the Middle Bakken is highly reliant on the Three Forks formation.

The Middle Bakken formation was deposited after a Late Devonian regression (falling sea level) and erosion event and contains dolomites and sandstones. Diagenetic processes (which create changes to sedimentary rocks) such as dolomitization, mineral precipitation, and porosity development have occurred within the Middle Bakken formation (Karsinski, 2006). The depositional environment for the Bakken layers was the result of Mississippian seas transgressing (rising) east. The high organic content of both the Upper and Lower Bakken indicate that anoxic (low oxygen) conditions required for hydrocarbon generation were achieved (typical of deep water bodies). Regressive seas created the erosional environment that removed the Lower Bakken from the area. The depositional environment and concomitant change in sea level are shown in Figure 2.

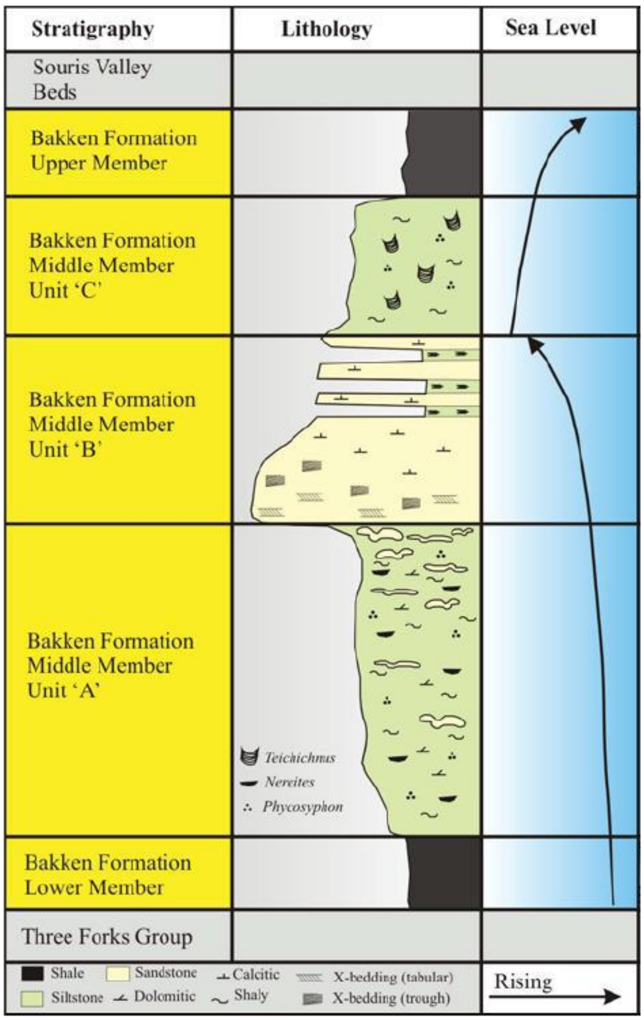


Figure 2: Lithology of the Bakken Formation
Source: Reproduced with permission from Canada (2011)

The shale of the Bakken is one of the major source rocks of hydrocarbons within the Williston Basin. The Lower and Upper Bakken were heated during continued burial which assists in generating oil and gas from organic matter (Canada, 2011). The Middle Bakken is a productive reservoir due to expulsion from both the top and bottom layers and enables the hydrocarbons to migrate to Saskatchewan and Manitoba from the deepest points of the basin in North Dakota. In Manitoba, the Middle Bakken itself is considered a poor reservoir and has low production due to anhydrite cementation. This cementation results in the Middle Bakken being classified as a tight oil formation which benefits from the application of hydraulic fracturing. The light crude oil extracted from the Bakken formation is in the range of 30 to 42 degrees API gravity and has a very low gas-to-oil ratio, which makes it a desirable product (Canadian Energy Research Institute, 2012). Degrees API gravity is an American Petroleum Institute (API) measure of the density of oil in comparison to water. The high API gravity indicates that Manitoba is producing light crude oil.

Bakken-Three Forks

The comingled Bakken-Three Forks formation accounts for about 15 percent of cumulative oil production in Manitoba and is rapidly growing. The two formations are hydraulically connected and display very similar diagenetic features – primarily a process known as dolomotization. Dolomotization causes significant shrinkage of a formation’s original volume and increases the interconnected porosity (Selly, 1998). The same process can generate irregular traps and prevents further oil migration. Several other features within these formations show evidence of diagenetic processes and the existence of pyrite suggests the presence of organic matter, an anoxic low temperature environment, and the existence of sulfur (Karsinski, 2006). These three features are relevant to petroleum generating source rocks and the production of hydrogen sulfide (H_2S), a common by-product of oil wells in Manitoba.

Late-stage diagenesis is also evident in the Bakken and Three Forks formations. This is indicated by pore-filling by pyrite developed during the late stages and secondary porosity created by dissolved feldspar grains from acidic fluids in carbon dioxide production. Carbon dioxide production is an indicator of hydrocarbon generation and can be linked to the Bakken shales from the Late Cretaceous. Other late-stage diagenesis features include cementation and mineral precipitation. These late-stage processes reduce permeability of the layer and lower its potential for hydrocarbon extraction. Hydraulic fracturing helps connect the porosity of the layer and increase permeability.

Lodgepole

The Lodgepole formation is part of the Lower Mississippian and follows a similar trend to the other formations with the sequence thinning towards eastern and northern edges of the basin. This formation was one of the first producers in Manitoba and these reservoirs developed where trapping occurred due to stratigraphic and structural features in the Daly and Virden fields. The Lodgepole was deposited in oxygenated conditions through a major transgression event leading to a period of open marine environments and normal-marine carbonate sedimentation. The material found in the formation is representative of an open water shelf break and is coincidental with the BWA, which marks the erosional edge of the Lodgepole, in a north-south direction that creates structural and isopach anomalies (potential hydrocarbon bearing zones) (Young, et al. 2012). Historically, this formation has accounted for over two thirds of cumulative oil production in Manitoba since production first began.

Lower Amaranth

The Lower Amaranth, also known as the Manitoba Spearfish, is a sandstone and siltstone formation that was deposited above an erosional surface during low sea levels in the Triassic age. Hydrocarbons found in this formation have been generated in the lower oil-rich shale at the erosional surface. The sandstone of this formation is at a relatively shallow depth (800 to 1000 metres below ground elevation) with low permeability but has been made economical due to multi-stage horizontal hydraulic fracturing (Canada, 2011). This layer produces approximately 30 percent of Manitoba's oil and yields a sweet, light crude oil. It has been an active formation since 2010 (Canadian Energy Research Institute, 2012).

Geographic setting

Manitoba is home to 13 designated oil fields and has over 200 oil pools, all located in the southwest corner of the province. Typical depths of hydrocarbon reservoirs are up to 2300 metres, but most production occurs no deeper than 1200 metres. The oil fields and producing wells (there are over 4000 producing wells in Manitoba) are shown in Figure 3. Since the first well was drilled in 1951, Manitoba has produced over 300 million barrels of oil and recent development has increased rapidly with improved technology; production values are illustrated in Figure 3 (production was steady until about 2005 with previous “oil booms” occurring in the 1950s and 1960s).

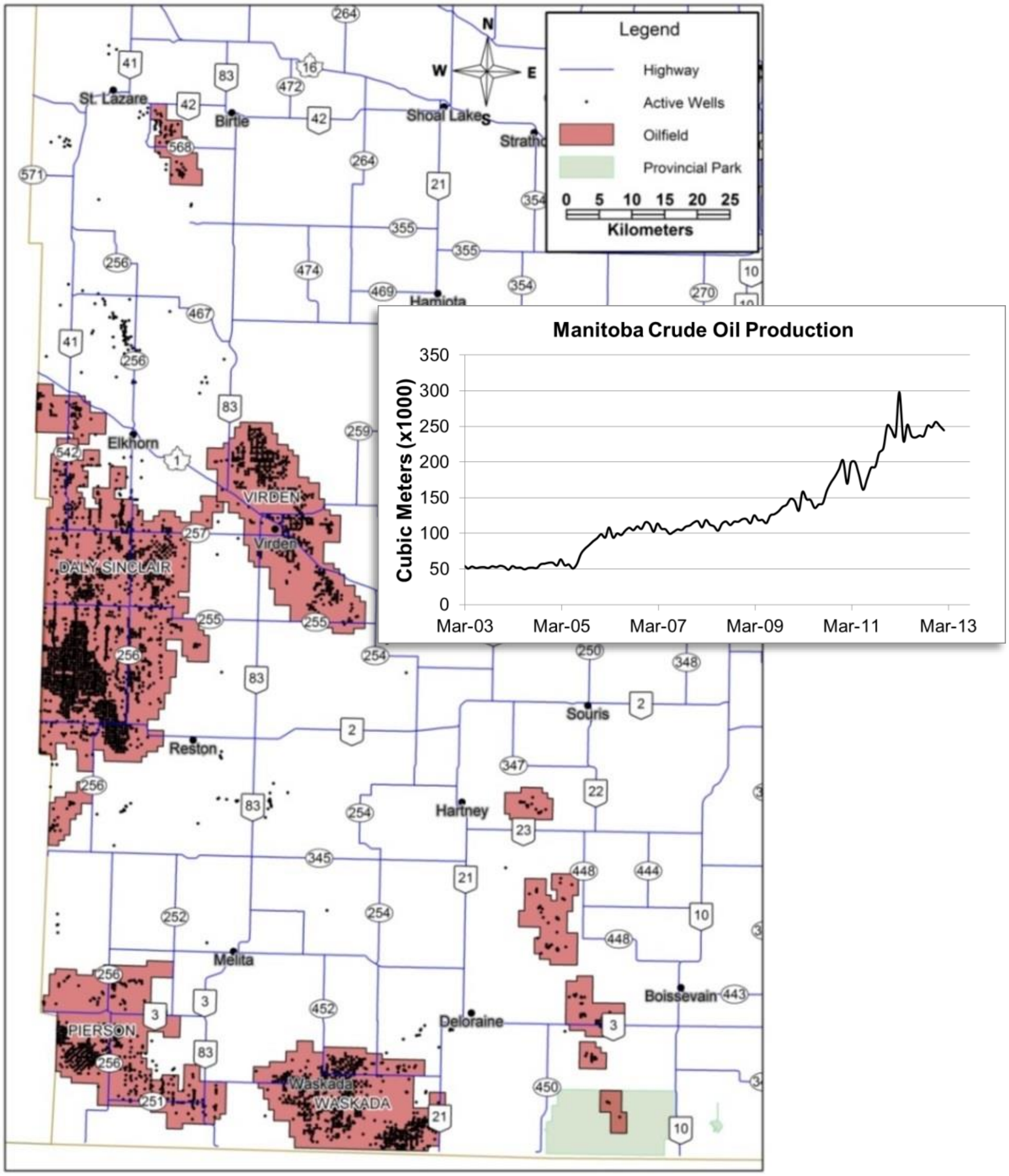


Figure 3: Manitoba oil Fields, Active Wells, and Productions Statistics

Daly-Sinclair Field

The largest field in Manitoba is the Daly-Sinclair. This field is located along the Saskatchewan border and south of the Trans-Canada highway. The Daly field (northern portion) was the location of the first producing well put in service in 1951. Currently, drilling in this field occurs in the Three Forks formation where the thickness of the geological sequence ranges from 35 to 52 metres and is comingled with the Middle Bakken, which is no thicker than six metres. Table 1 shows some of the key characteristics for the reservoirs in the region. The comingled or Three Forks formations are ideal candidates for drilling and will result in the highest production rates compared to the Middle Bakken (Karsinski, 2006). In the Daly region of the field, drilling is occurring in the Lodgepole formation where hydrocarbon traps are stratigraphic and structural. The Daly-Sinclair field may be limited in its potential for expansion due to the geological sequence thinning to the east as it reaches the boundary with the Birdtail-Waskada Axis (Nicolas, 2006).

Table 1: Characteristics of Geological Formations in the Daly-Sinclair Field
Source: Karsinski (2006)

	Porosity (%)	**Permeability (%)**	**Oil Saturation (%)**
Comingled	12.8 to 17.9	1.3 to 9.5	6.4 to 31.8
Three Forks	14.2 to 16.9	2.9 to 8.6	7.0 to 34.0
Middle Bakken	11 to 16.5	0.2 to 2.7	1.4 to 18.8

Waskada Field

The Waskada field is located at the southern edge of the region adjacent to the U.S. border. Wells in this region are mostly drilled to the Lower Amaranth with some drilling occurring to the lesser explored Mission Canyon. Development began in the 1980s but has seen recent growth in production due to directional drilling and hydraulic fracturing. A snapshot of the Waskada region is shown in Figure 4 along with the orientation of horizontal wells and locations of other essential support infrastructure such as water sources, saltwater disposal, and batteries. Horizontal wells crossing each other in Figure 4 are targeting different geological formations. Unique to the Waskada field in Manitoba is the clustering of horizontal wells, often with four or more wells to a pad, and horizontal legs half the length of typical wells in other fields. These features are due to the tightness of the geological formation and can be seen on Figure 4 as a fanning out of horizontal legs from a single point (Abel, 2014). Potential subcrop plays in the Lodgepole formation may increase oil production from this formation in future exploration.

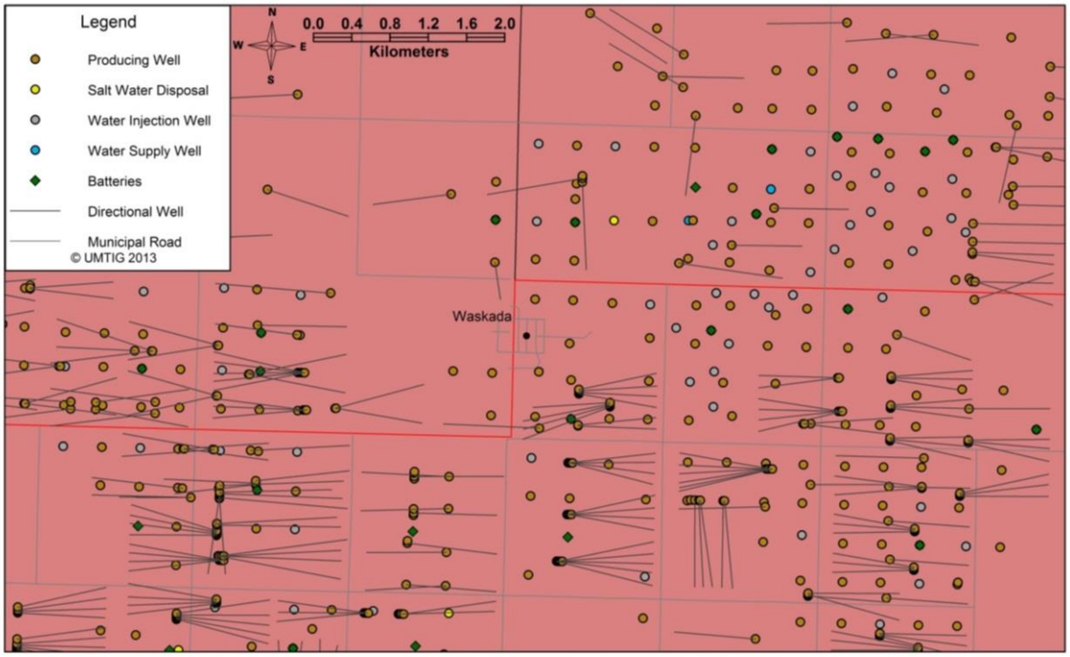


Figure 4: Petroleum-Related Infrastructure in the Waskada Field

Pierson Field

The Pierson field is located in the southwest corner of Manitoba's oil producing region, adjacent to the Saskatchewan and North Dakota borders. The Pierson field has lower production levels than Waskada but has seen similar development and drilling patterns with recent growth occurring due to directional drilling and hydraulic fracturing. The same subcrop features as the Waskada field may result in further development and drilling in the Lodgepole formation.

Virden Field

The Virden field was historically the main field in Manitoba where production came from the Mississippian formations – primarily the Lodgepole where traps were stratigraphic and structural. Currently there is little development occurring in this field but some drilling companies believe there is still room for growth and have recently begun exploration in the area using modern drilling techniques (Abel, 2014). The major oil E&P occurred during booms in the 1950s and 1960s with some increase in production seen in the mid-2000s.

Other Fields

Several other smaller fields exist throughout Manitoba and well development is growing north of the Trans-Canada highway in the Manson field. Most of the development in these minor fields is in the Lodgepole, Melita (Jurassic), and Three Forks formations. In the smaller fields at the eastern extent of the region, the Lodgepole has porous subcrops and is capped by the Amaranth formation. These features may lead to increased production from the Lodgepole in the future. The Kirkella field, due north of the Daly-Sinclair field, has wells being drilled to the comingled Bakken-Three Forks formation.

Current development in the petroleum producing region of Manitoba is focused on drilling in the Bakken-Three Forks formation. Production is also rapidly growing in the Lower Amaranth, but all other formation production is negligible.

Extraction Techniques

Basins in North America are seeing increased levels of production as new technologies, including directional drilling, hydraulic fracturing, and earth imaging, have made E&P more economically feasible. When used in combination, the two technologies increase the ability of producers to profitably extract oil and gas from low-permeability geological plays like shale plays or tight sedimentary layers (United States of America, 2011). In Manitoba, hydraulic fracturing has been performed since the 1950s and some directional drilling was performed as early as 1991. Around 2005, horizontal wells began taking a larger share of the total wells drilled in Manitoba and by 2009 accounted for at least 90 percent of all new wells drilled in the region.

The hydrocarbon bearing formations of Manitoba can, for the most part, be considered 'tight' oil formations. This classification is a result of late-stage diagenesis activity and the occurrence of anhydrite cementation, which reduces porosity and permeability. The cementation has reduced pore space and size and the amount of interconnected pores. These tight formations are spread over a wide region where oil is not typically pooled and therefore may be considered as continuous resources. Tight oil comes in two forms:

1.) oil located in the original shale source rock with very low permeability; and

2.) oil that has migrated and is trapped in tight formations.

The second condition is present in Manitoba and can benefit from directional drilling and hydraulic fracturing while requiring less input resources (such as frack sand and water) than the first condition, as drillers are dealing with dolostone and sandstone rather than shale. The combination of directional drilling and hydraulic fracturing in this type of geological setting greatly increases a well's exposure to the producing formation and increases production rates (Canada, 2012).

Hydraulic fracturing, or fracking for short, is a method of oil and gas extraction that creates fractures in geological formations to enable hydrocarbons to flow more easily out of otherwise impermeable shale layers or other low permeability rock formations (tight formations). Fracking requires a mixture of water, sand or other proppants, and carefully engineered chemical additives to prop open fractures, protect the boreholes, and improve extraction rates. The use of each component of the fracking mixture and its purpose is as follows:

- *Water*: large volumes are required to carry chemicals and proppants through the borehole and fractures.
- *Chemicals*: additives help prevent bacterial growth, reduce friction, and improve effectiveness of oil extraction.
- *Proppants*: material such as sand or ceramic beads are pushed into cracks and fissures at high pressure to keep fractures open as pressure dissipates.

The process increases the hydraulic conductivity in the formation and creates higher flow rates of hydrocarbons. The process is not new and has been applied beyond hydrocarbon extraction to improve drinking water wells, dispose of waste, and enhance geothermal energy sources (ALL Consulting, 2012). It is a standard process for extraction from unconventional sources but only recently has it been applied to conventional sources to help improve productivity. The process is the same for both types of hydrocarbon sources, but when applied to a conventional source requires significantly fewer inputs.

Wells within Manitoba are considered conventional oil wells and the applied hydraulic fracturing process is on a much smaller scale than other regions across North America where unconventional wells are drilled (as is the case in shale oil plays). In this region, hydraulic fracturing has been applied since the 1950s to vertical wells to help increase conductivity. With the increased use of directional drilling, hydraulic fracturing has helped make hydrocarbon production in southwest Manitoba economically feasible and spurred rapid development.

The use of directional drilling is economically advantageous as it reduces the total number of wells and the overall cost of production. To complete a horizontal well, drilling is performed to a determined depth and then kicked (or curved) out to the target geological formation. From this point, the horizontal leg of the well may be anywhere from a few hundred metres up to two kilometres along the target formation. This process helps increase the amount of exposure the well has to the producing rock formation. The horizontal leg greatly increases the productivity of a well when compared with a vertical well and allows for a much greater number of fracture stages. The continuous nature of hydrocarbon resources in tight formations requires planning and strategy in terms of well spacing, well lengths, and frack sizes to ensure efficient recovery. Typically, in Manitoba, well spacing is four to eight wells per land section (one square mile). The hydraulic fracture stages are done in 10-metre intervals through the extent of the well with approximately 25-metre spacing between each stage (Abel, 2014).

The drilling stage of a well is only one of many stages to well development, as is the hydraulic fracturing process. Figure 5 shows the stages a typical well in Manitoba goes through before production of hydrocarbons begins (Abel, 2013). The use of hydraulic fracturing with directional drilling has helped decrease the total number of wells required by increasing each wells exposure to the formation and therefore decreasing total development costs, despite each well being more expensive. The technology applied in each geographic location is dependent on the underlying geology in terms of the target formation and the interaction of stresses, pressures, and temperatures within the formation; essentially subsurface conditions play the greatest role in determining how the process is applied (ALL Consulting, 2012). One major advantage of horizontal drilling is its ability to follow the geological formation for the well’s entire length, regardless of how the formation may change over a distance.

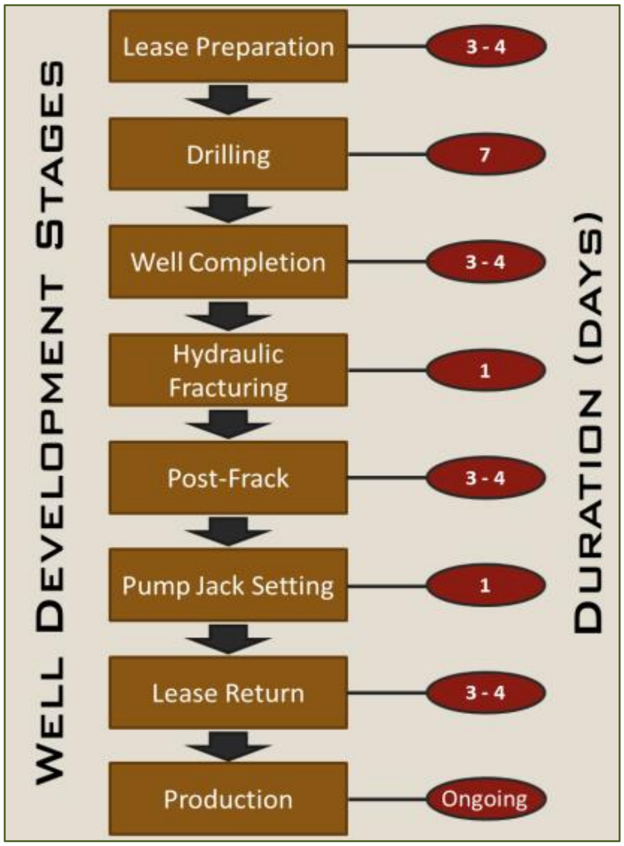


Figure 5: Development Stages for a Hydraulically Fractured Well

Where hydraulic fracturing and directional drilling is most effective is in source rocks where geological pore spaces are not connected. In many formations in Manitoba, this is the condition due to late-stage diagenetic processes that have reduced porosity and permeability. The fracturing process creates a network of fractures that helps connect this porosity and the horizontal drilling expands the network and increases well exposure to the emulsion. As mentioned, the formations in Manitoba that are hydrocarbon bearing are not very thick (52 metres for the Three Forks). Thus, the pay region (area of a well that emulsion can flow to) is limited for a vertical well whereas for a horizontal well the pay region can be increased by more than 10 times (ALL Consulting, 2012).

The process of hydraulic fracturing requires data on the characteristics of the reservoir and the stress relationships within the rock formation. This data includes porosity, permeability, and lithology of the producing rock along with fluid saturation data and existing fractures within the formation. Fracture information includes data related to orientation, fracture width, and permeability and is used to determine the type of treatments (sand, fluid, chemicals, pressure) required to perform efficient hydraulic fracturing (Abel, 2013). The fracturing process typically creates vertical fractures through the formation as separating the formation is easier than lifting all of the overlying formations. Vertical fractures within a rock formation run parallel to the maximum horizontal stresses. An understanding of the producing rock formation is important when designing and planning hydraulic fracture processes to optimize well placement and horizontal well orientation.

Hydraulic fracturing can also be done multiple times for one well to re-stimulate the well and producing formation. One of the major ongoing challenges in the Bakken, and for most hydraulically fractured wells in tight plays, is the significant drop-off in production rates. Rapid decline of production rates in tight oil formations is common within the first year of producing wells. Pressure decreases in the producing formations contribute to these declines. However, in Manitoba and other regions, enhanced oil recovery (EOR) can help increase production rates. EOR is performed by converting low producing wells into water or gas injection wells to water flush the producing formation and push oil towards selected wells.

APPENDIX B

FHWA VEHICLE CLASSIFICATION SCHEME

	FHWA Class 1 - Motorcycles
	FHWA Class 2 - Passenger Vehicles (With 1- or 2-Axle Trailers)
	FHWA Class 3 - 2-Axles, 4-Tire Single Units, Pickup or Van (With 1- or 2-Axle Trailers)
	FHWA Class 4 - Buses
	FHWA Class 5 - 2D - 2 Axles, 6-Tire Single Units (Includes Handicapped-Equipped Bus and Mini School Bus)
	FHWA Class 6 - 3 Axles, Single Unit
	FHWA Class 7 - 4 or More Axles, Single Unit
	FHWA Class 8 - 3 to 4 Axles, Single Trailer
	FHWA Class 9 - 5 Axles, Single Trailer
	FHWA Class 10 - 6 or More Axles, Single Trailer
	FHWA Class 11 - 5 or Less Axles, Multi-Trailers
	FHWA Class 12 - 6 Axles, Multi-Trailers
	FHWA Class 13 - 7 or More Axles, Multi-Trailers

Figure 1: FHWA 13 Vehicle Classification Scheme

Source: *Manitoba Highway Traffic Information System* (2014)

APPENDIX C

PETROLEUM-RELATED TRUCK TRAFFIC INVENTORY

Coil Tubing Service Rig

Purpose: Well servicing activities and hydraulic fracturing

Sample values from permit database:
- Width: 3.4 m
- Height: 4.7 m
- Length: 37.0 m
- GVW: 91,000 kg

Axles in Group	1	3	2	3	1
# of Wheels	2	12	8	24	4
Weight (kg)	7300	27000	20088	27500	9100
			Jeep		Booster

NOTE: This vehicle is found in many different configurations and GVWs

NOTE: As shown, this rig was operating without a jeep or booster; measured weights from portable weigh scales are below.

Axles in Group	1	3	3
# of Wheels	2	12	24
Weight (kg)	8220	26820	39460

GVW: 74,500 kg

Picker Truck

Purpose: Support vehicle for drilling and other oilfield activities

Sample values from permit database:
- Width: 2.6 m
- Height: 4.15 m
- Length: 13.8 m (without trailer)
- GVW: 31,549 kg

Axles in Group	2	3
# of Wheels	4	12
Weight (kg)	14830	16719

NOTE: This vehicle is found in many different configurations and GVWs

NOTE: As shown, loaded picker truck with semi-trailer; measured weights from portable weigh scales are below.

Axles in Group	2	3	3
# of Wheels	4	12	8
Weight (kg)	14190	23490	7450

GVW: 45,130 kg

Winch Truck

Purpose: Move drill rig and drill rig support infrastructure

Sample data from permit database:

Width: 5.49 m
Height: 5.18 m
Length: 37.5 m
GVW: 99,690 kg

Axles in Group	1	3	2	3	2
# of Wheels	2	12	24	16	8
Weight (kg)	8190	21000	25000	27500	18000

NOTE: This vehicle is used for moving different pieces of equipment and therefore configurations and weights will vary.

NOTE: Image shown is an empty winch truck at a drill site. Equipment is pulled on to the trailer using the cable shown lying on the flat deck. The drill rig is the heaviest piece moved to a drill site. A typical well will require about eight winch trucks.

Conventional Service Rig

Purpose: Well servicing activities and hydraulic fracturing

Sample data from Permit Database:

Width: 2.98 m
Height: 4.23 m
Length: 21.59 m
GVW: 36,231 kg
Overhang: 5.52 m

Axles in Group	2	2
# of Wheels	4	8
Weight (kg)	14390	21841

NOTE: Service rigs may be different configurations and have varying overhangs and axle/GVW weights. The depth and length of wells can influence the type and size of service rig required.

Bed Truck

Purpose: Support vehicle for drilling and other oilfield activities

Sample data from permit database:
Width: 3.05 m
Height: 4.15 m
Length: 14.0 m
GVW: 31,500 kg

Axles in Group	2	2
# of Wheels	4	8
Weight (kg)	15500	16000

NOTE: Image shown is an empty bed truck with similar characteristics to the example permitted data. Bed trucks operate in a variety of configurations and weights. Bed trucks may operate with trailers and single steers (details of a bed truck moving a derrick are below).

Sample data from permit database:
Width: 5.49 m
Height: 5.18 m
Length: 48.0 m
GVW: 54,300 kg

Axles in Group	1	2	2
# of Wheels	2	8	16
Weight (kg)	6800	20000	27500

Straight Truck and Full Trailer

Purpose: Move crude oil and water

Sample data from permit database:
Width: 2.6 m
Height: 4.15 m
Length: 23.0 m
GVW: 47,630 kg

NOTE: As shown, this vehicle is moving crude oil but this vehicle type may also carry water. The dangerous goods placard on the side of the vehicle and trailer will be labelled "1267,3" when moving crude oil. Observed vehicles were hauling approximately 30 to 35 cubic metres of crude oil. Crude oil is more typically moved by traditional tridem tanker trailers.

Axles in Group	1	2	2	2
# of Wheels	4	8	8	8
Weight (kg)	6800	13650	15850	12800

GVW: 49,100

APPENDIX D

ROADSIDE SURVEY QUESTIONNAIRE

University of Manitoba Commercial Vehicle Survey	Surveyor Name: ___________________ Time: ___:___ am / pm Location: ____________

The University of Manitoba Department of Civil Engineering is conducting a roadside survey to gain insight into the characteristics of truck trips and commodities being moved in Manitoba. Participation in this survey will assist one master's student with data collection for their thesis and provide valuable information to MIT for infrastructure planning. The survey will take about 5 minutes.

Do you agree to participate in this survey?
a. Yes
b. No, reason: ________________________

Truck Characteristics

What is the truck configuration?
a. 2 (single unit)
b. 3 (single unit)
c. 3-S2
d. 3-S3
e. 3-S2-S3
f. 3-4 (straight truck with trailer)
g. Other: _________________
NOTE: Specify axles with number and semi-trailer with 'S'

Are there oversize cargo markings? Y / N

What is the truck body type?
a. Van
b. Hopper
c. Tanker
d. Flat deck
e. Permanently mounted equipment
f. Dump
g. Other: _________________ (i.e., frack tanks)
If trailers are different body types, specify:
1st trailer: _______________
2nd trailer: _______________

What dangerous goods UN and placards are on the truck?

Placard 1	*Placard 2*
a. None	**a.** None
b. Class, UN:________	**b.** Class, UN:________
c. Danger	**c.** Danger
d. Other:__________	**d.** Other:__________

What type of connection is between the trailers?
a. 'A' **b.** 'B'
c. 'C' **d.** N/A
e. Other: _________________

Are there lift axles on the truck or trailer(s)? Y / N
Which axles? 2 3 4 5 6 7 8 9 10 11 12 13

Load and Commodity Characteristics

Is the truck loaded, empty, or carrying returns?
a. Carrying cargo
b. Empty
c. Returning racks/bins
d. Carrying permanently mounted apparatus/non-cargo
e. Other:_____________________

What is the total weight of cargo?
______________________ Unit:______________

How much of each trailers capacity is in use?

Trailer 1		*Trailer 2*
☐	Empty	☐
☐	25%	☐
☐	50%	☐
☐	75%	☐
☐	100%	☐

How is the trailer capacity determined?
a. By space **b.** By weight

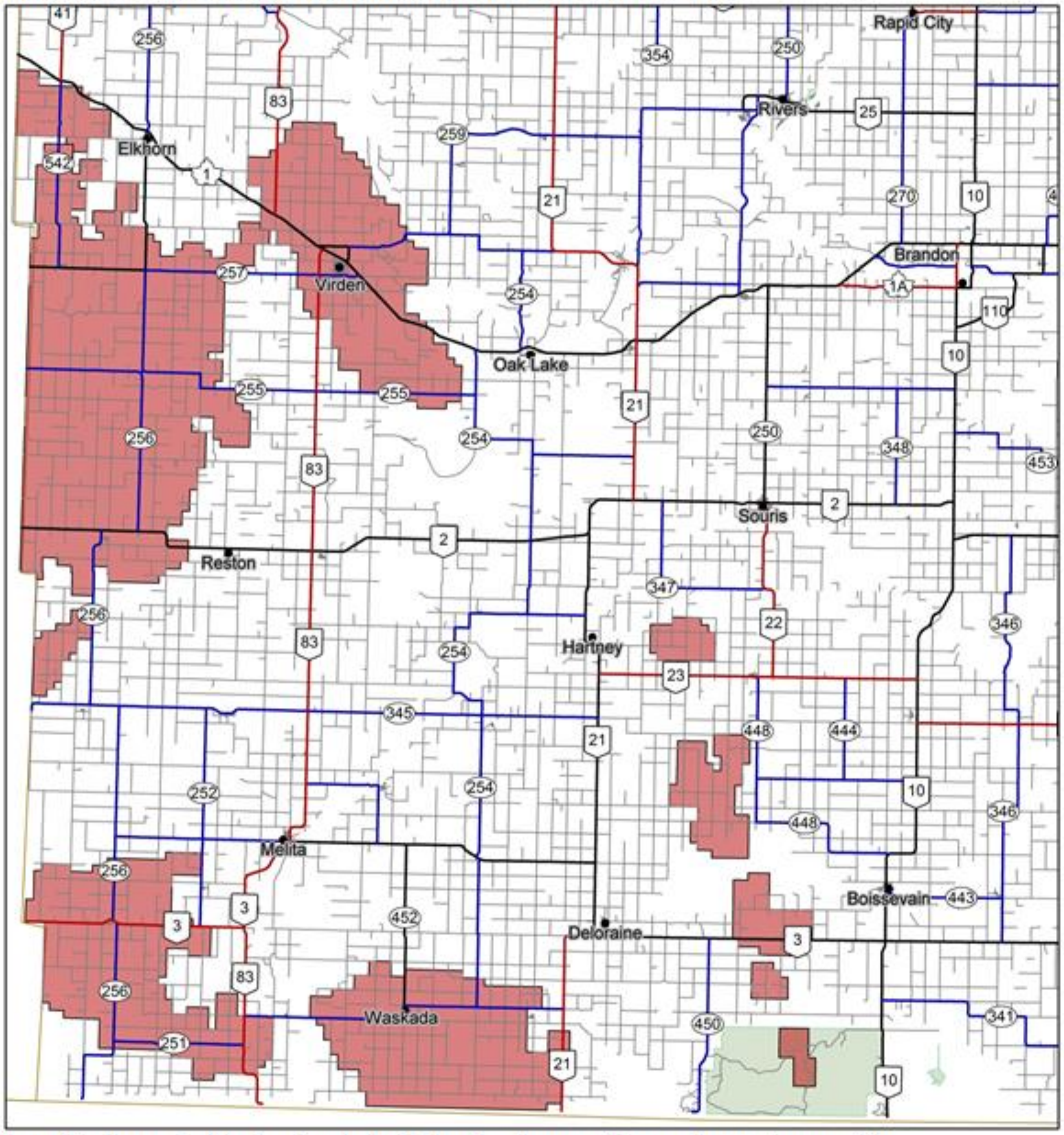
What is the commodity/product being transported?

a. Emulsion	**b.** Crude	**c.** Sand
d. Gravel	**e.** Equipment: ______________	**f.** Water (fresh / waste)
g. Specialized vehicle: __________	**h.** Agriculture: ______________	**i.** Other:__________________

Trip Routing

Highlight the route you are taking on the map below. Please indicate the location of any facilities/terminals where dropoff or pickup occurred along with any provincial or international border crossings taken.

If your trip is recurring, please indicate how frequently this trip occurs in a week: ___________



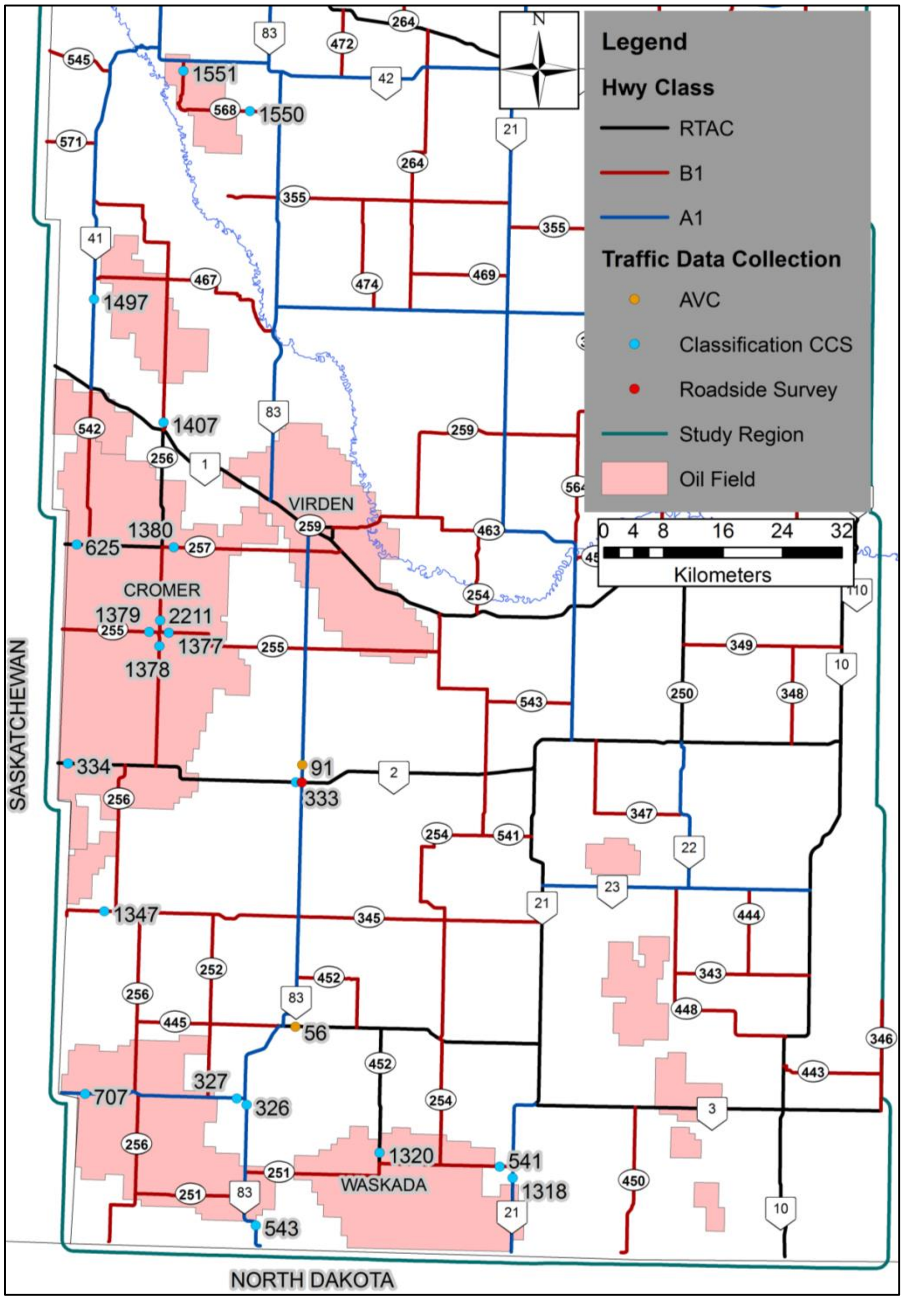
If your trip does not originate or terminate at a location shown on the map above, please specify:

Origin: ________________________ **Destination:** ________________________

APPENDIX E

TRUCK TRAFFIC MONITORING DATA SUMMARY

This appendix provides summary sheets for two automated vehicle classifiers, 20 classification coverage counts, and one roadside survey. Below is a reference map for the locations of each component of the truck traffic monitoring data collection. This information is also located within the Google Earth® data dissemination tool.

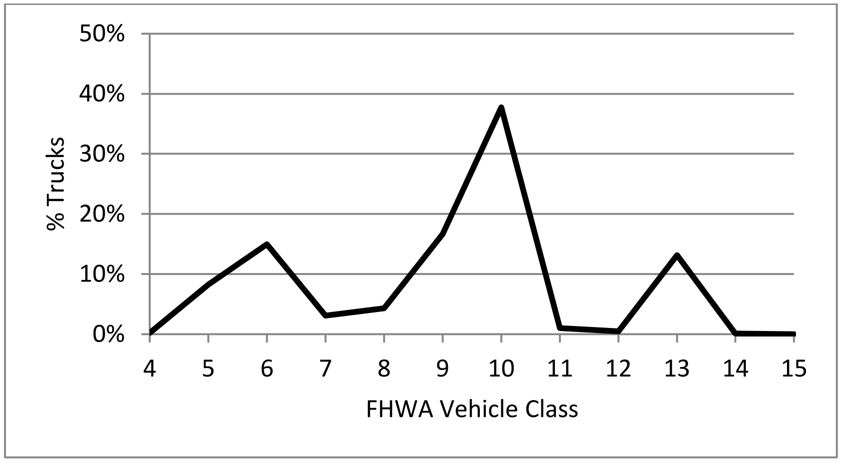


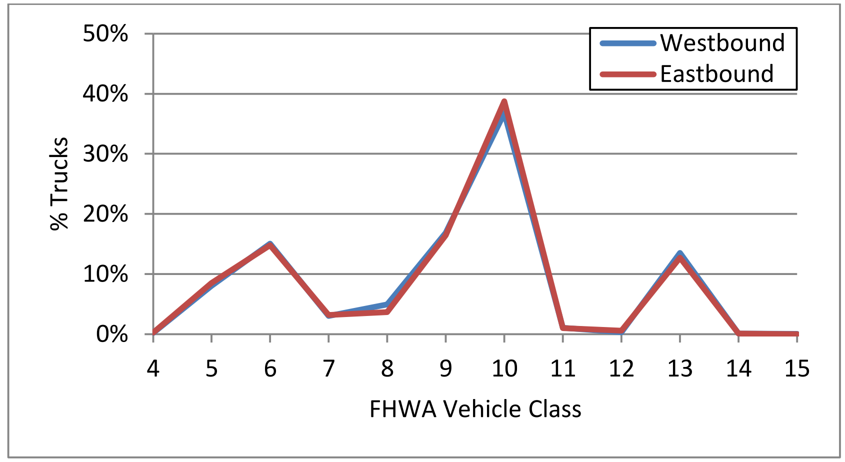
• Station 56 •

Location: PTH3 – East of North Junction with PTH83
Flow: WB-EB
Date: 2013

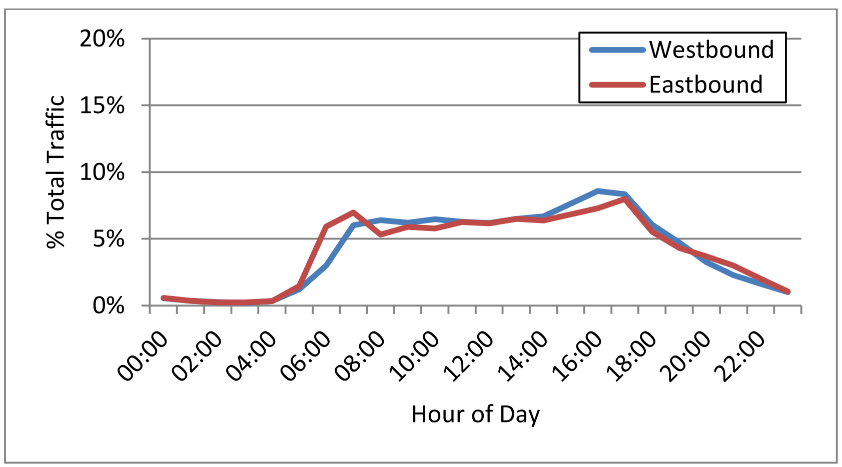
AADT: 1150
AADTT: 220
PADTT: 220

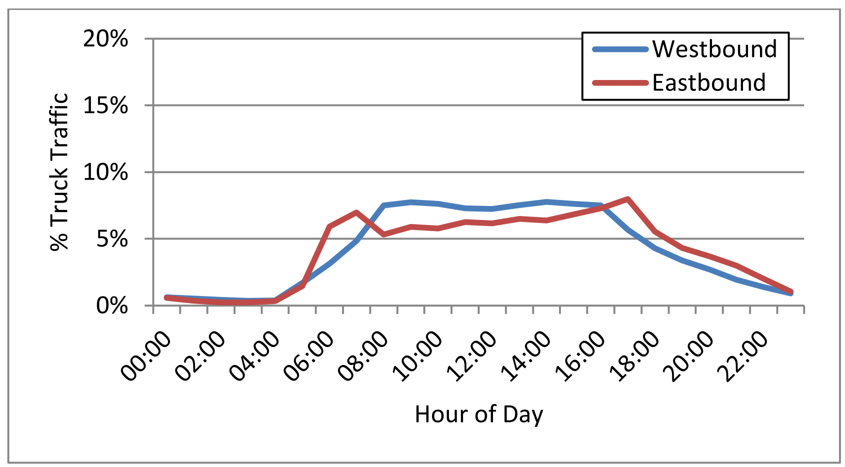
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

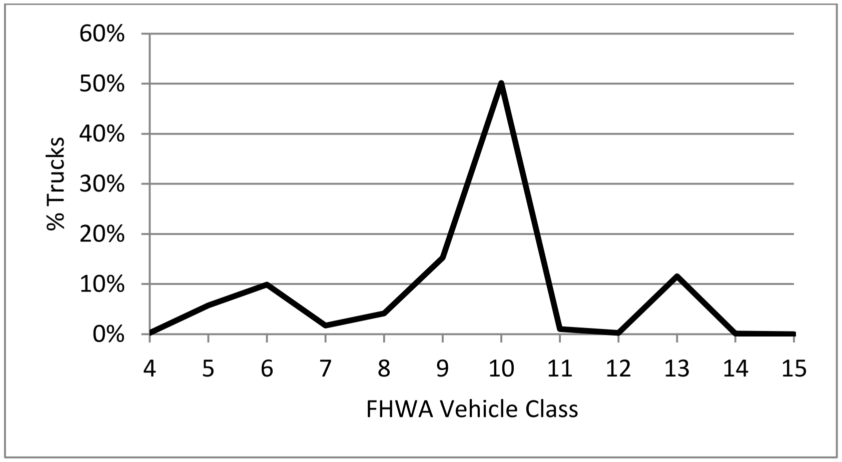


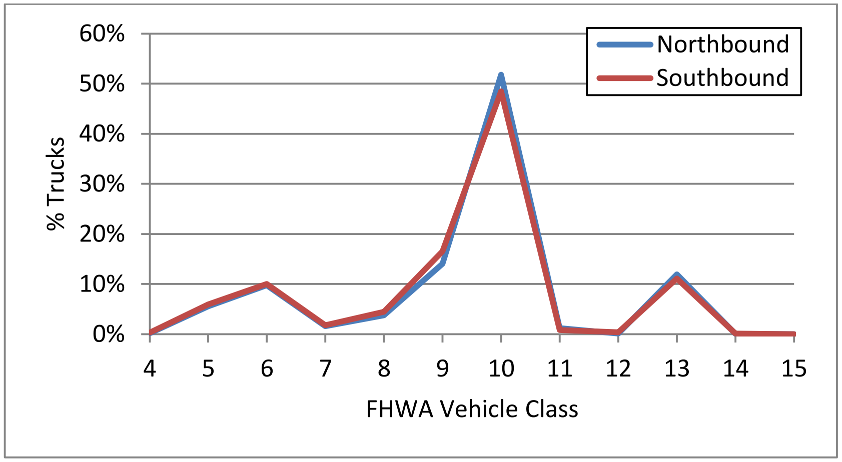


• Station 91 •

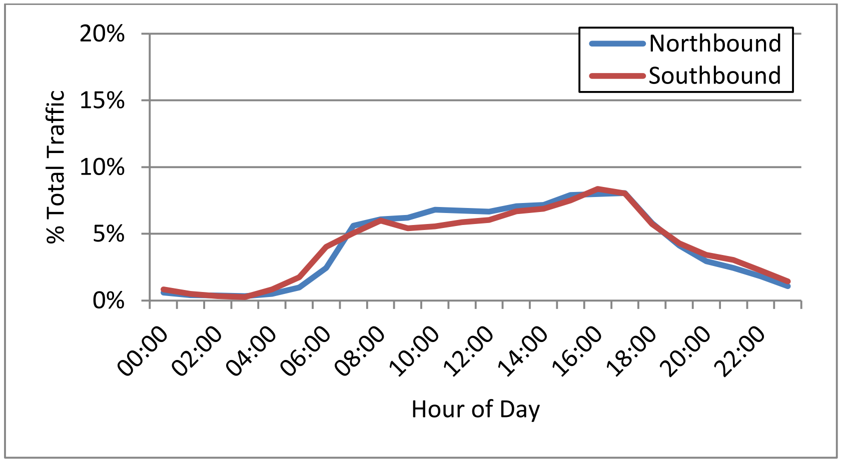
Location:	PTH83 – North of PTH2	**AADT:**	1020
Flow:	NB-SB	**AADTT:**	180
Date:	2013	**PADTT:**	80

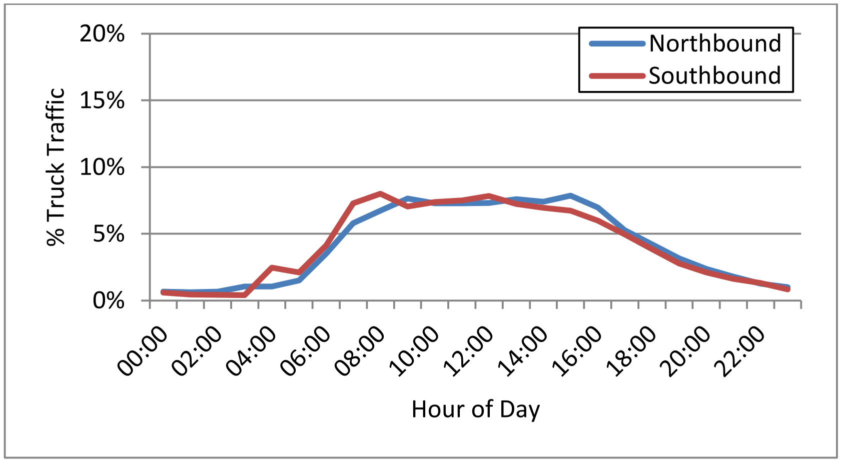
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



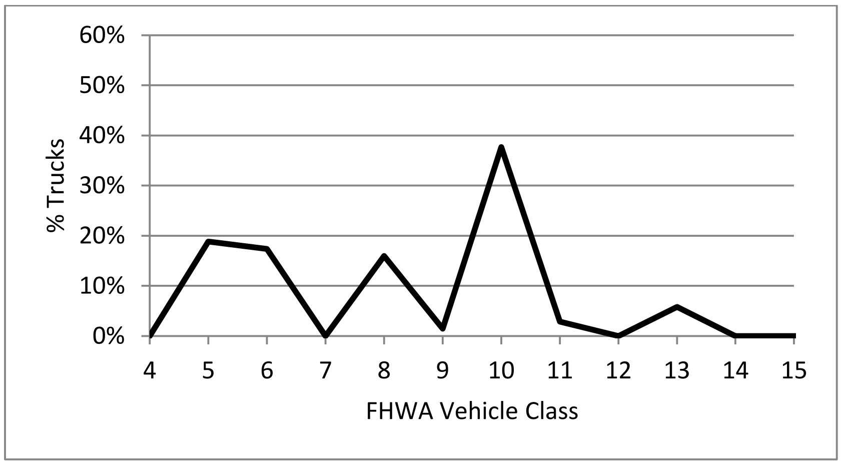


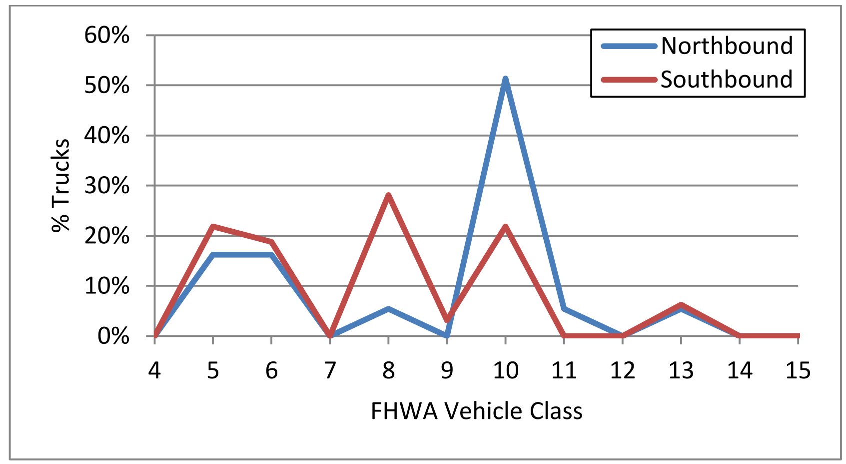
• Station 326 •

Location: PTH83 – South of PTH3 South Junction
Flow: NB-SB
Date: September 23-25, 2013

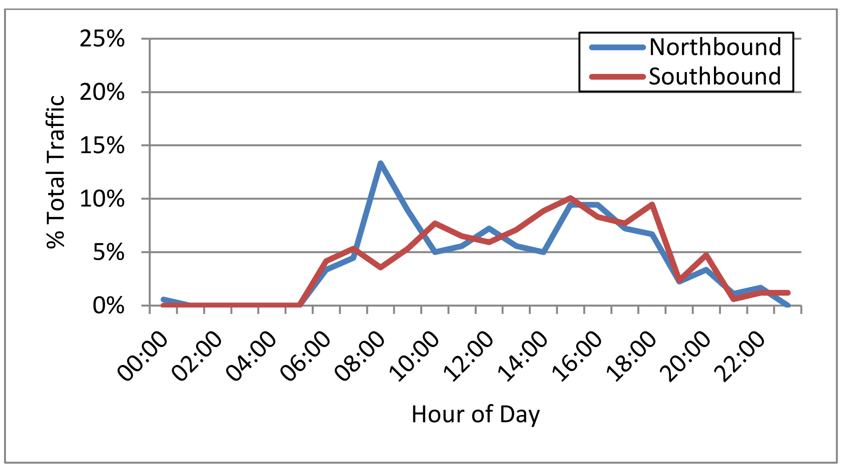
ADT: 350
ADTT: 70
PADTT: 60

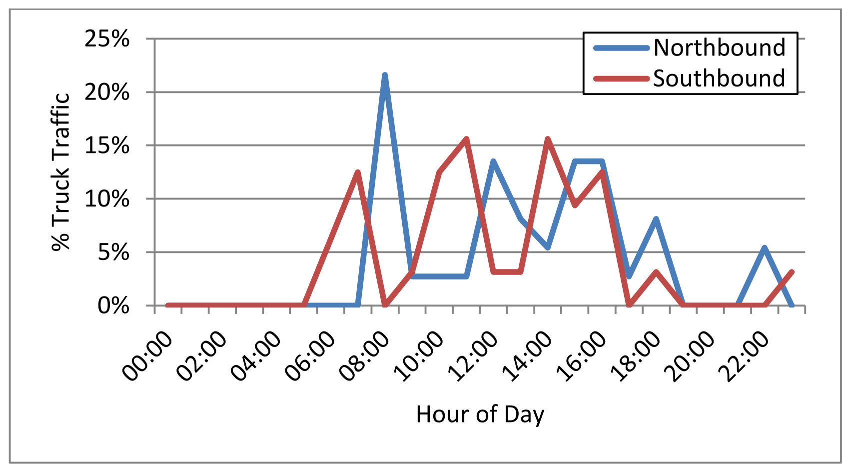
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

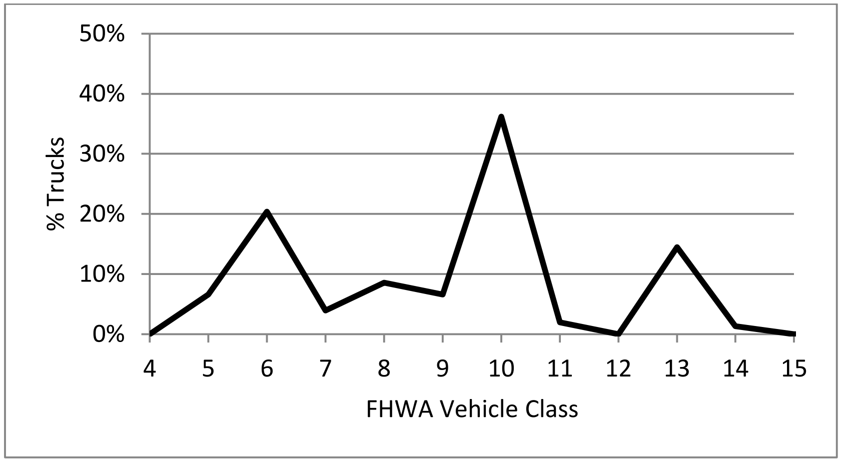


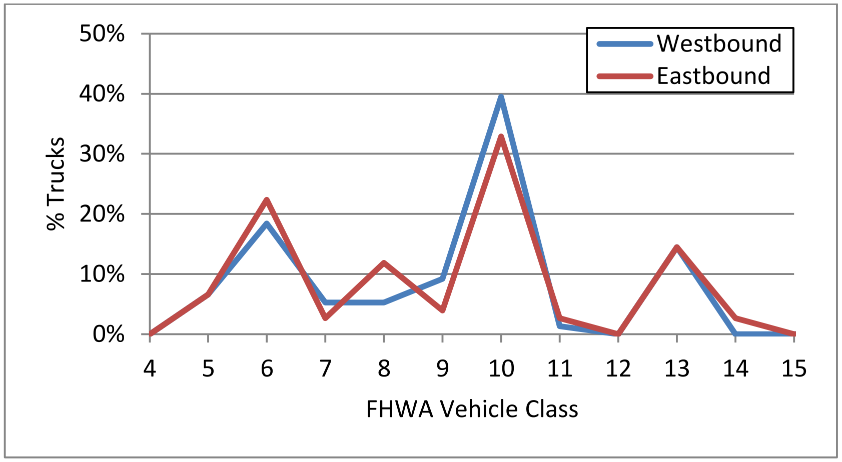


• Station 327 •

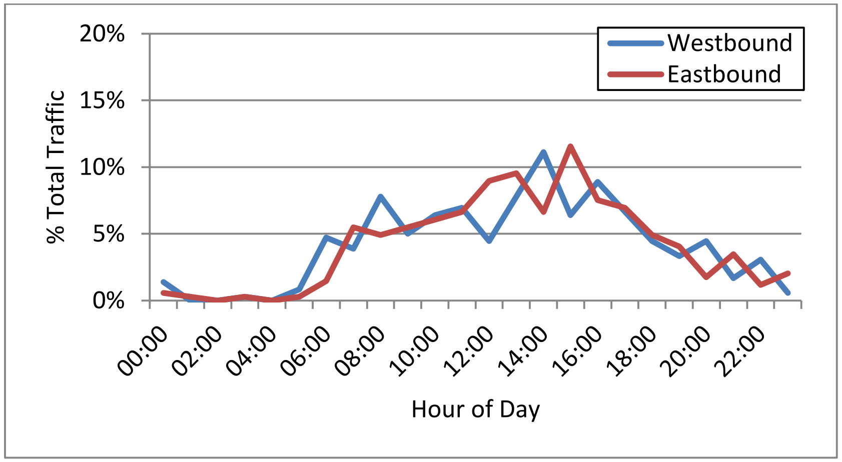
Location:	PTH3 – West of PTH83 South Junction	**ADT:**	690
Flow:	WB-EB	**ADTT:**	140
Date:	September 23-25, 2013	**PADTT:**	100

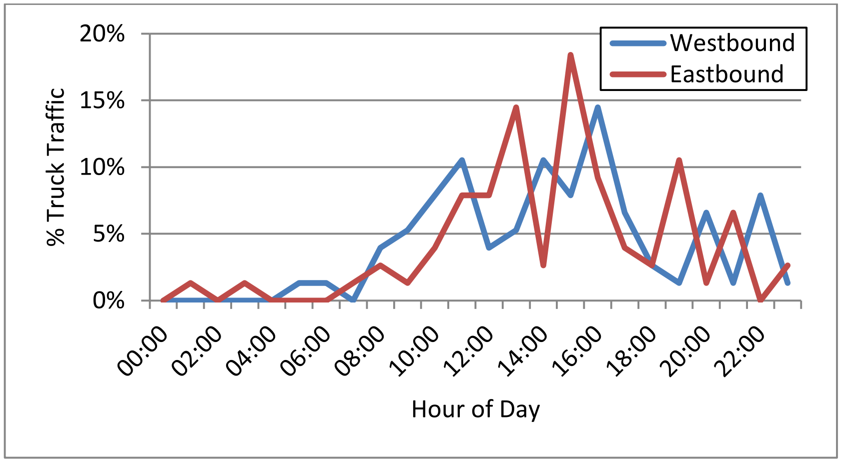
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

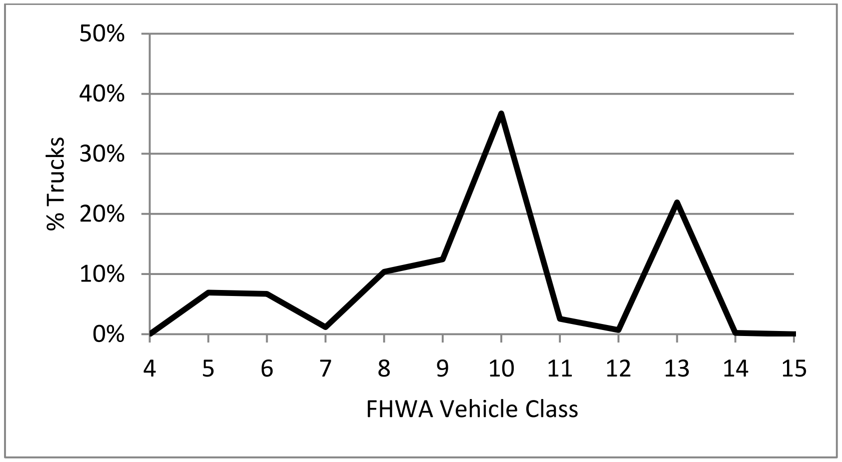


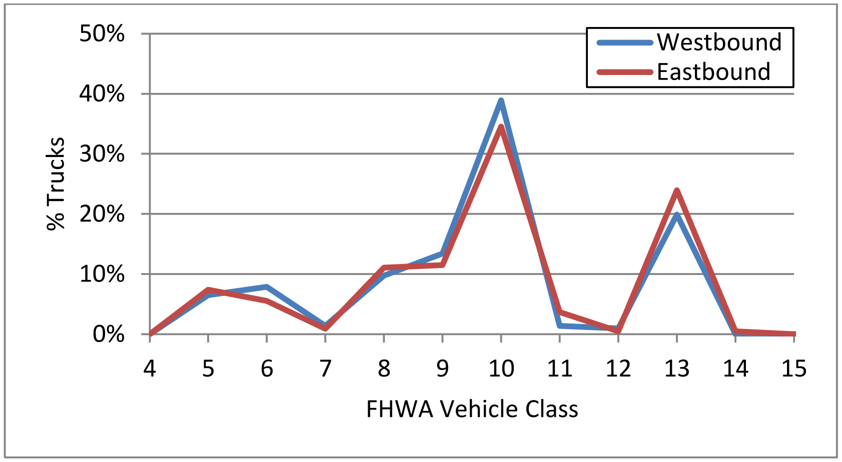


• Station 333 •

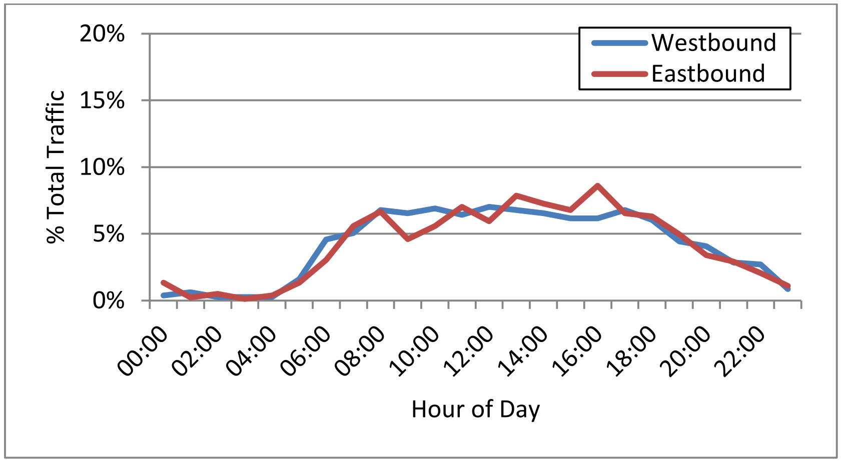
Location:	PTH2 – West of PTH83 intersection	**ADT:**	1690
Flow:	WB-EB	**ADTT:**	410
Date:	June 18-20, 2013	**PADTT:**	210

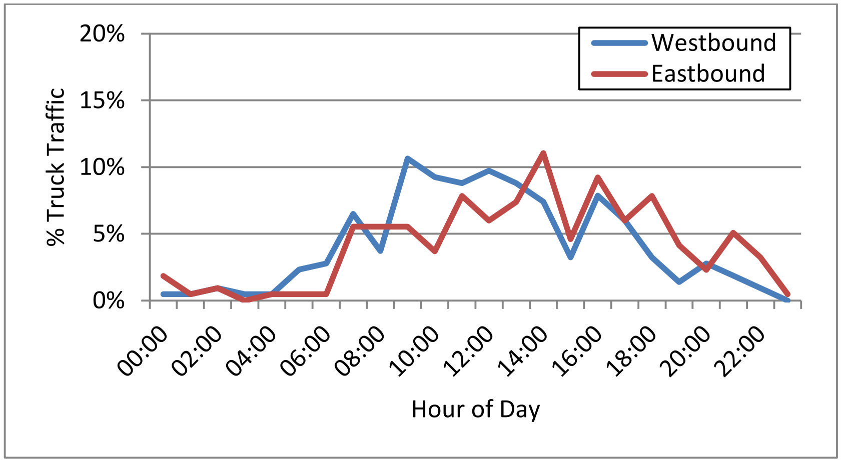
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

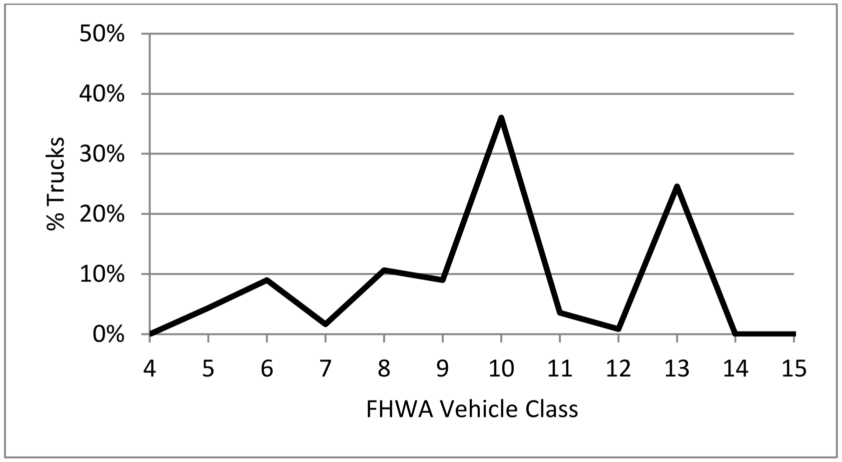


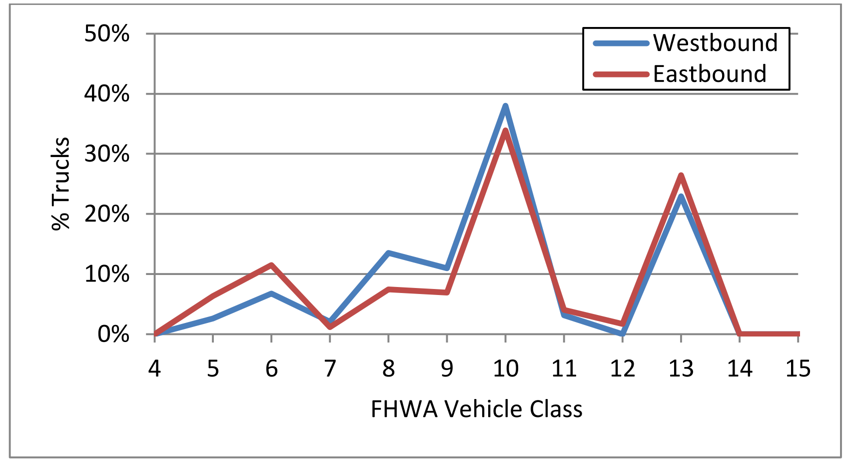


• Station 334 •

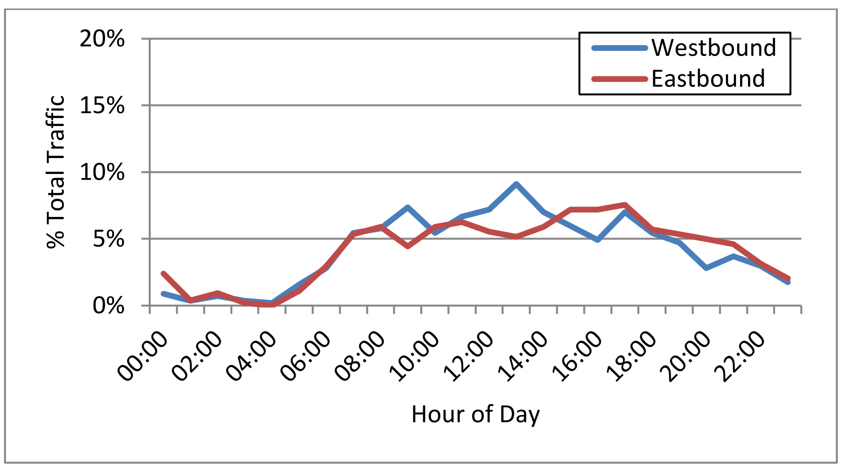
Location:	PTH2 – East of Saskatchewan border	**ADT:**	1130
Flow:	WB-EB	**ADTT:**	360
Date:	June 18-20, 2013	**PADTT:**	170

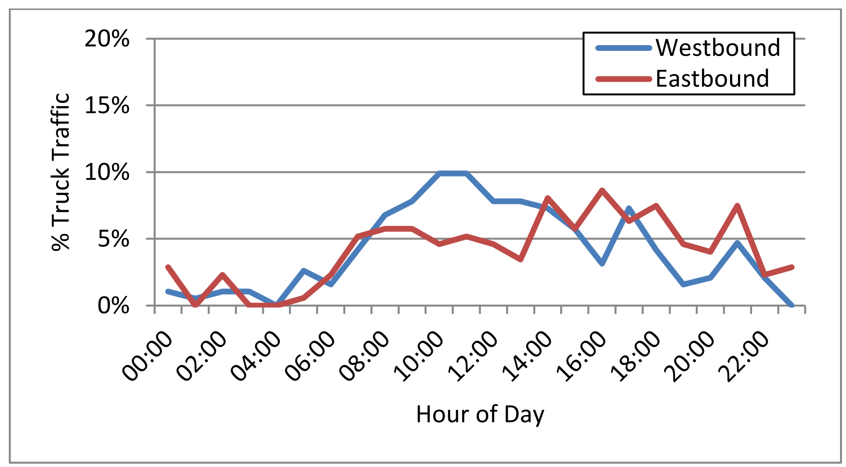
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

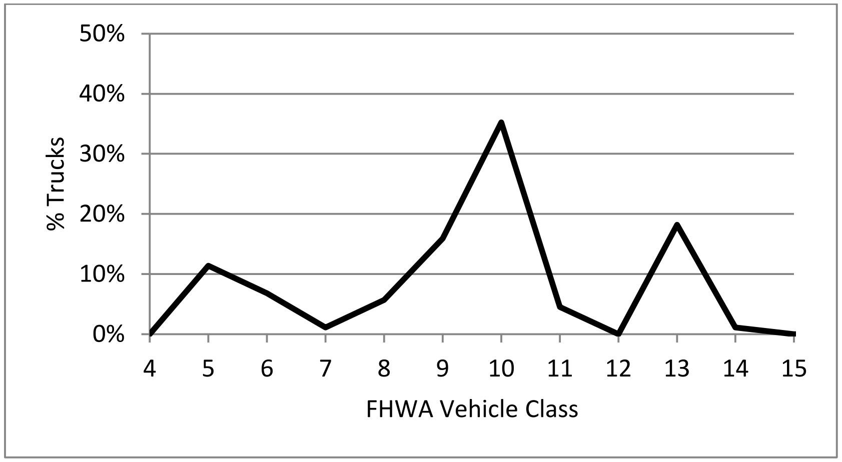


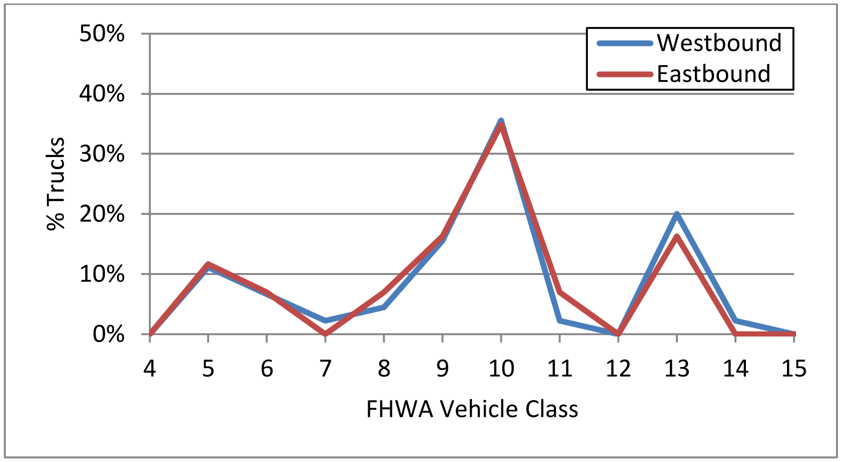


• Station 541 •

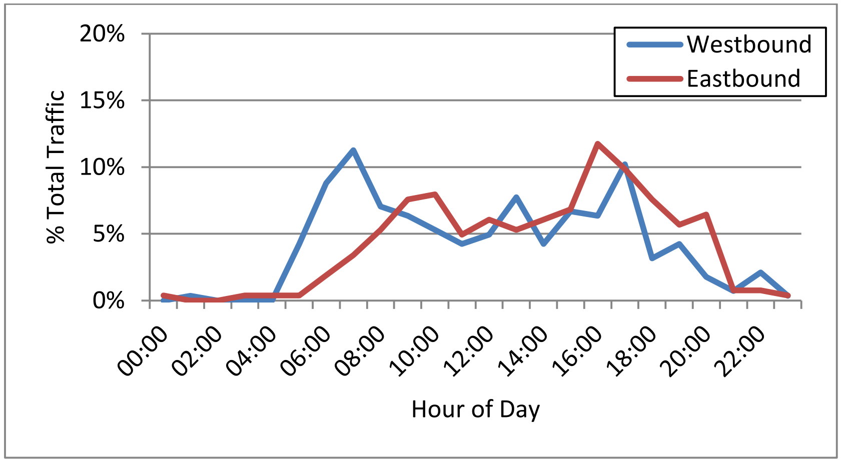
Location:	PR251 – West of PTH21	**ADT:**	530
Flow:	WB-EB	**ADTT:**	70
Date:	September 23-25, 2013	**PADTT:**	40

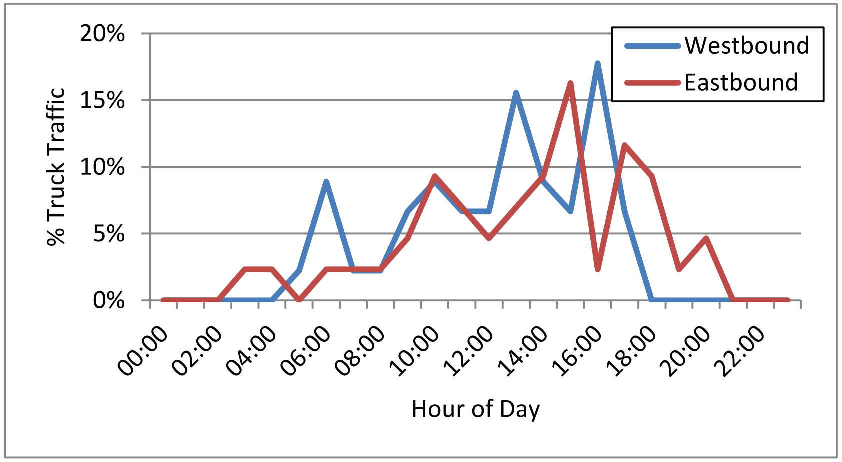
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



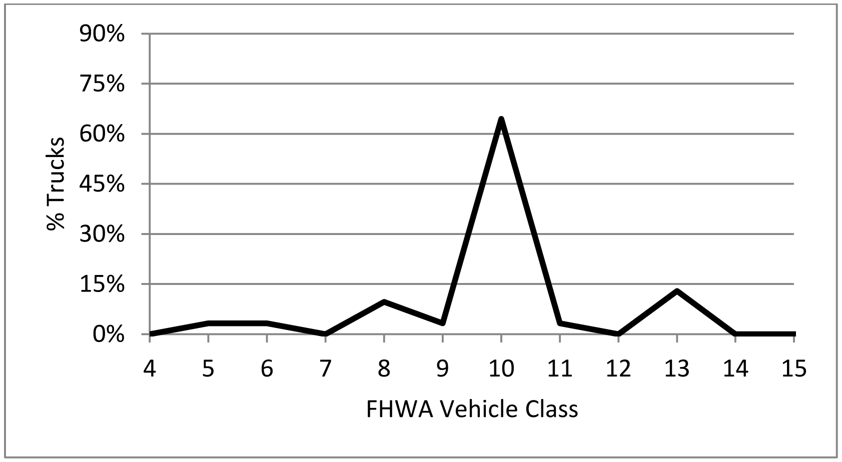


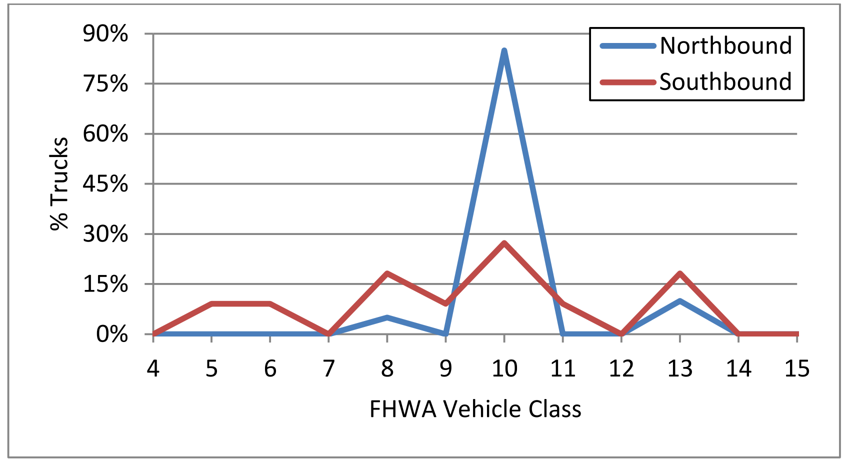
• Station 543 •

Location: PTH83 – North of U.S.A. Border
Flow: WB-EB
Date: September 23-25, 2013

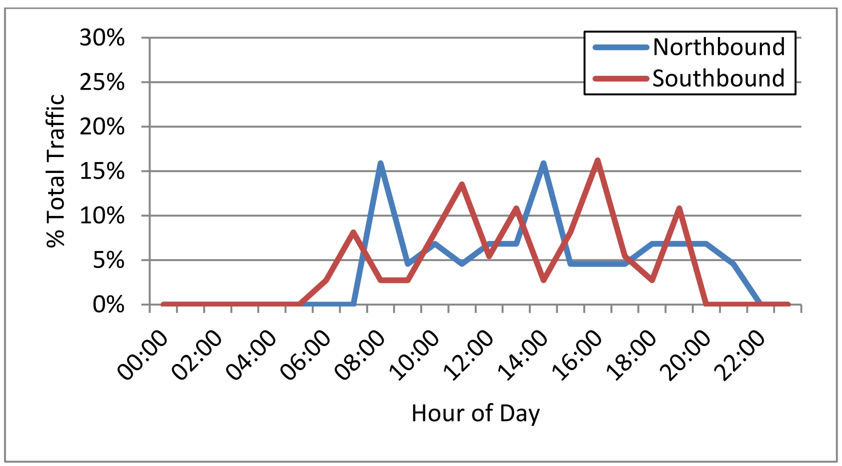
ADT: 90
ADTT: 30
PADTT: 30

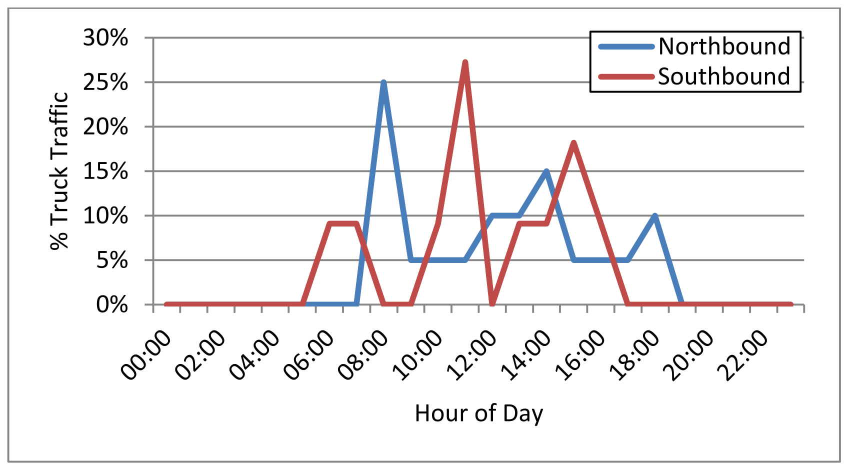
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

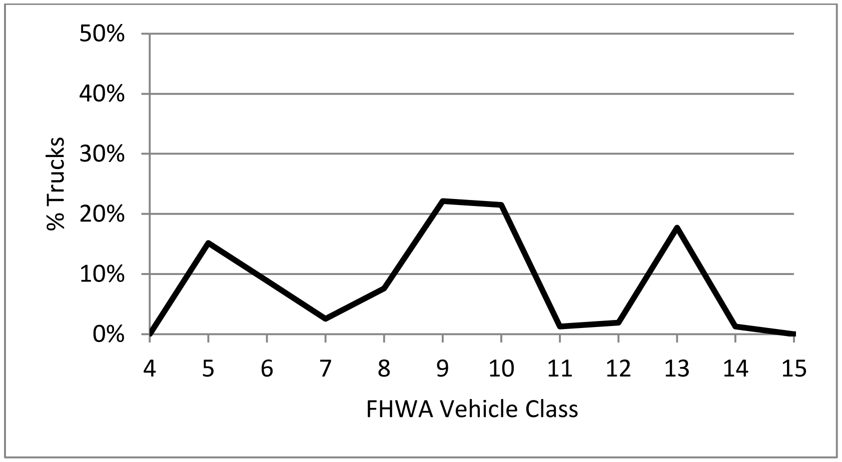


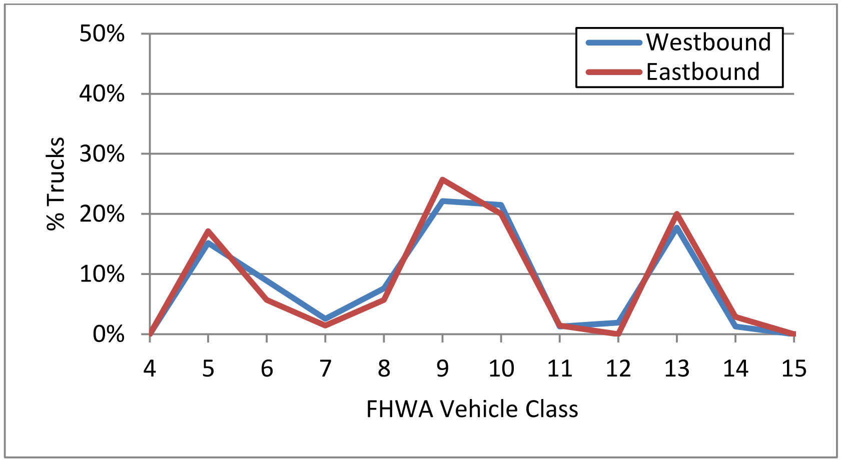


• Station 625 •

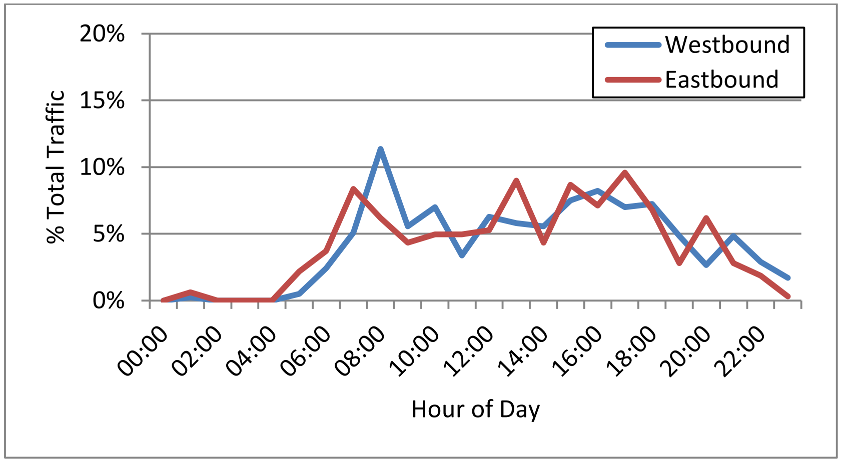
Location:	PR257 – East of Saskatchewan border	**ADT:**	750
Flow:	WB-EB	**ADTT:**	160
Date:	June 18-20, 2013	**PADTT:**	100

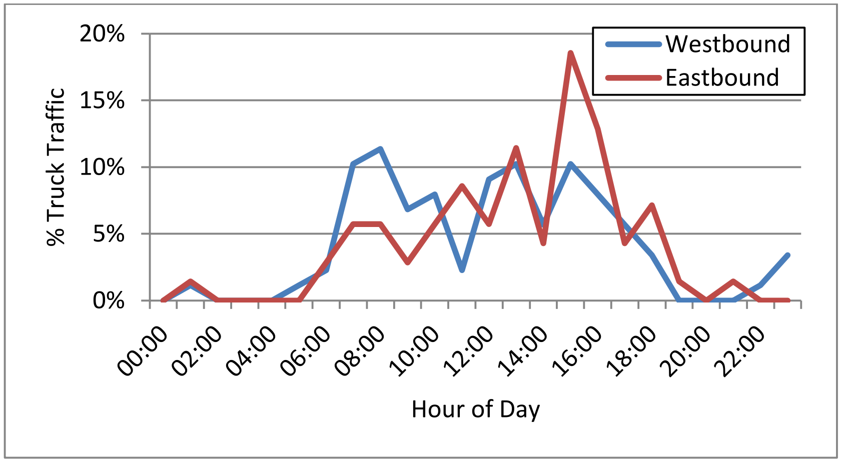
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

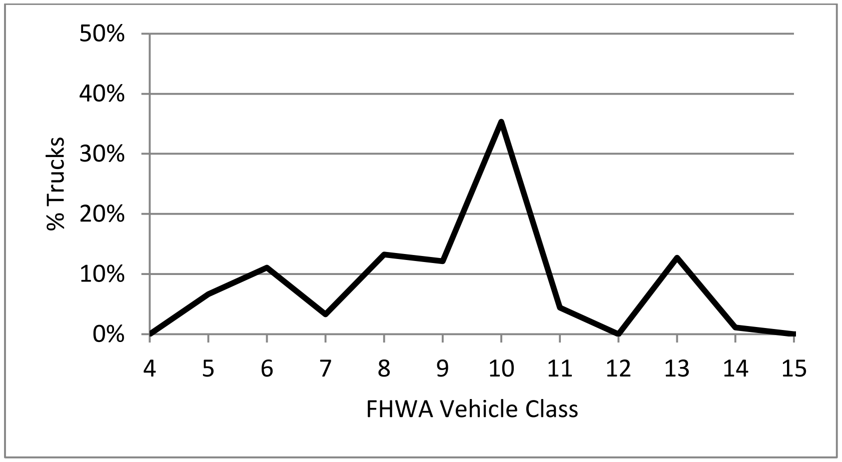


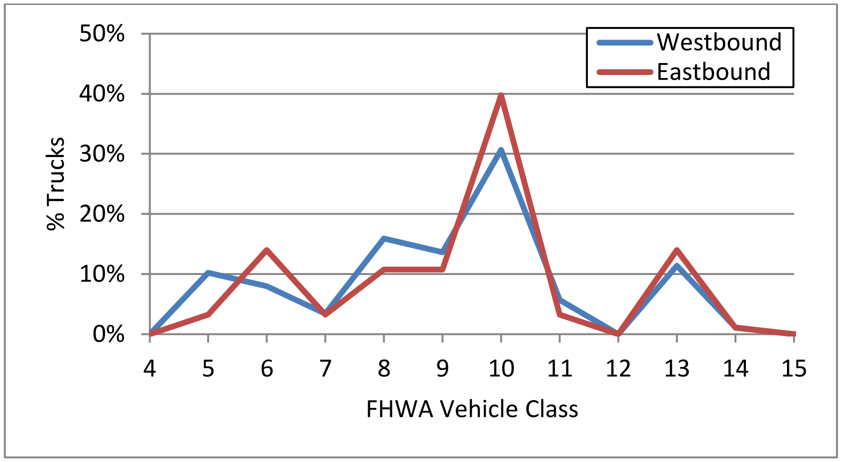


• Station 707 •

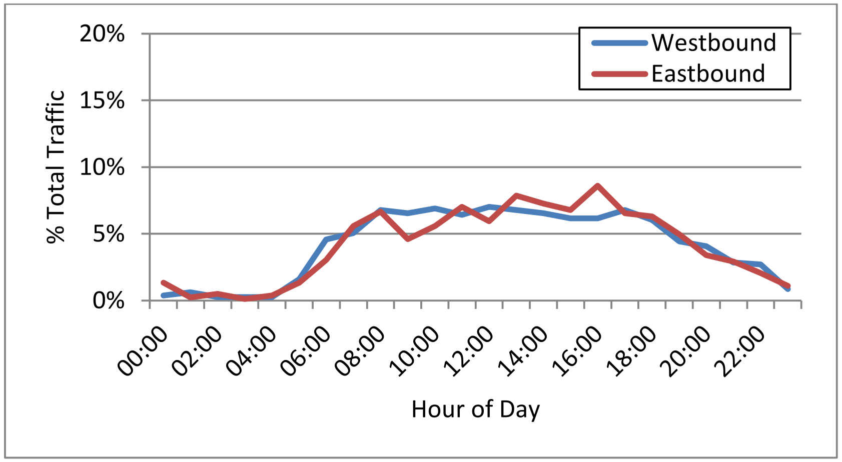
Location: PTH3 – East of Saskatchewan Border | **ADT:** 1690
Flow: WB-EB | **ADTT:** 410
Date: September 23-25, 2013 | **PADTT:** 210

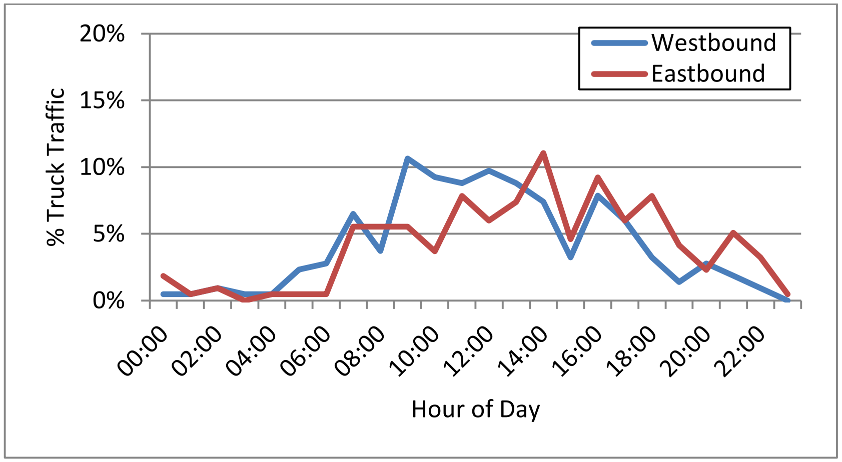
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



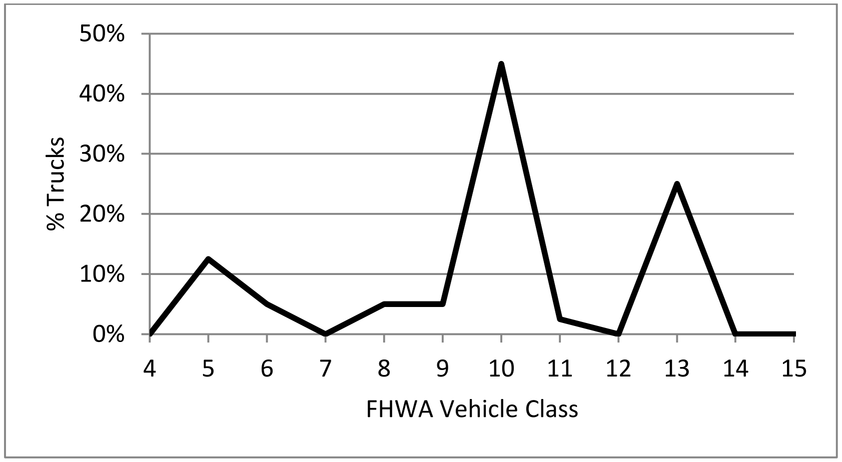


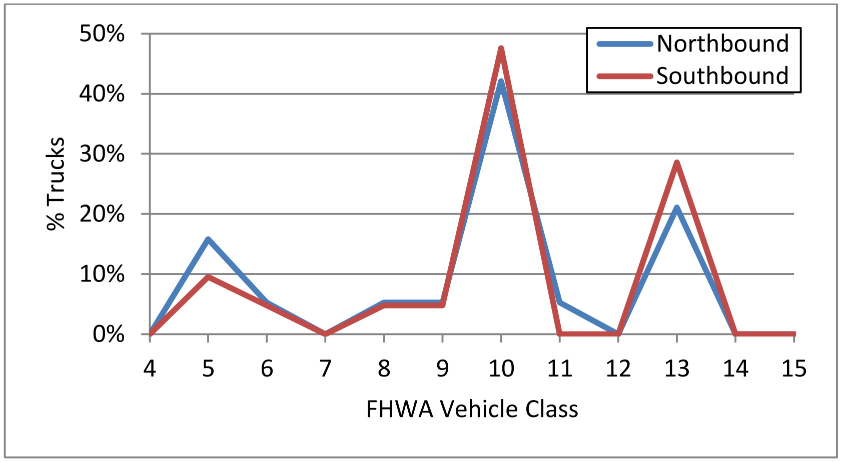
• Station 1318 •

Location: PTH21 – South of PR251
Flow: NB-SB
Date: September 23-25, 2013

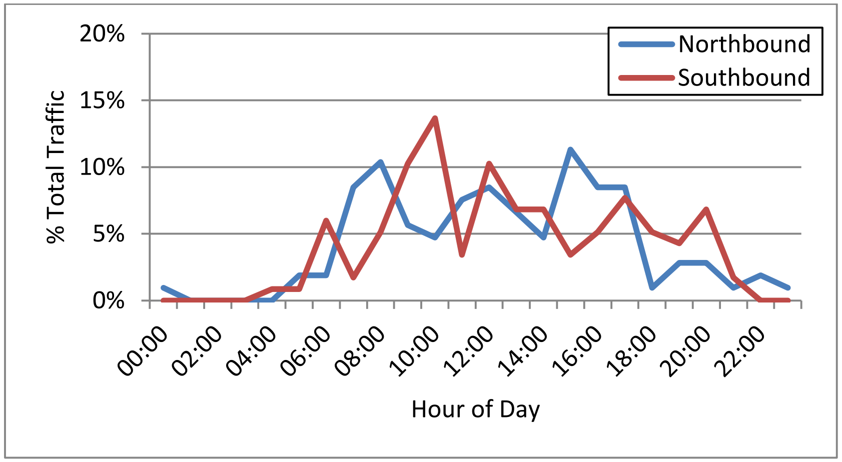
ADT: 200
ADTT: 40
PADTT: 40

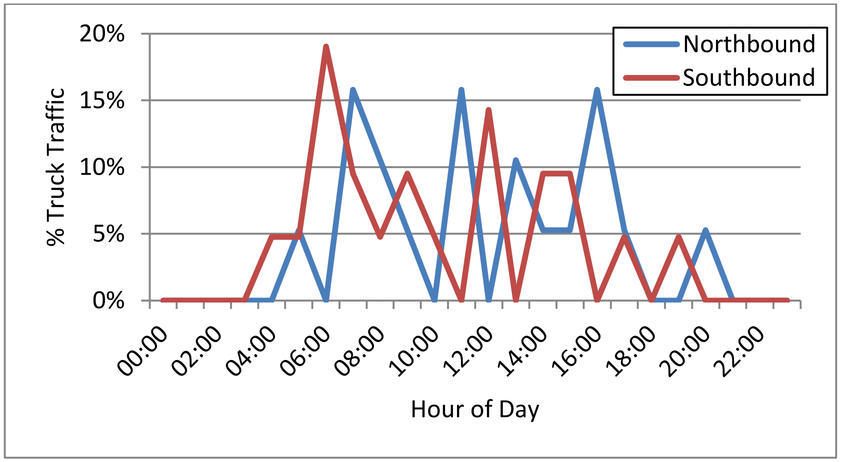
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



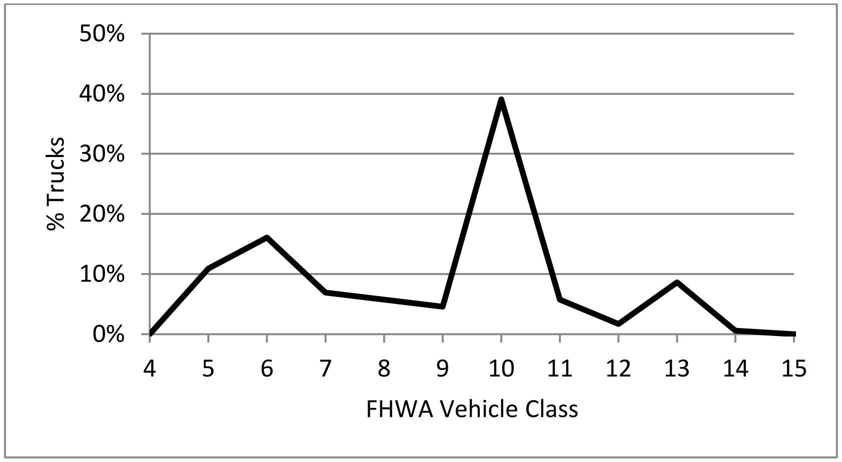


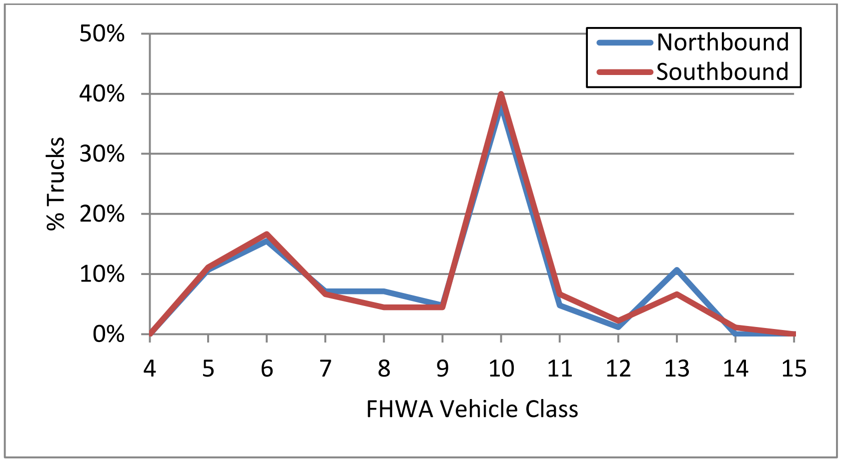
• Station 1320 •

Location: PR452 – North of PR251
Flow: NB-SB
Date: September 23-25, 2013

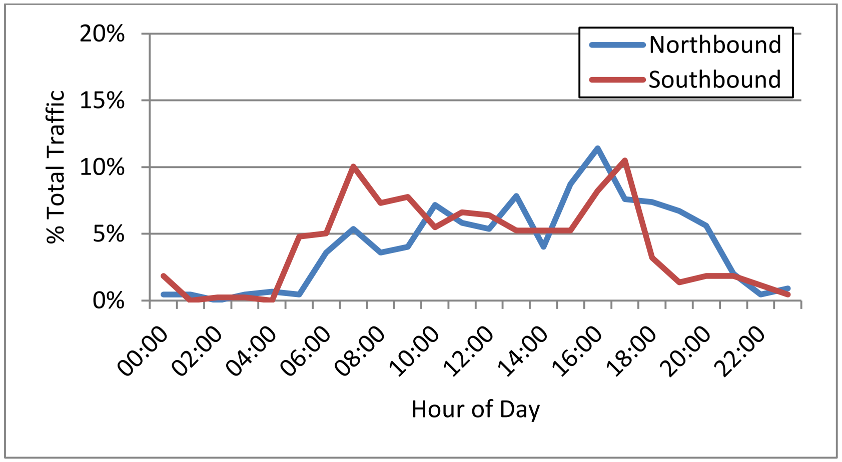
ADT: 850
ADTT: 170
PADTT: 160

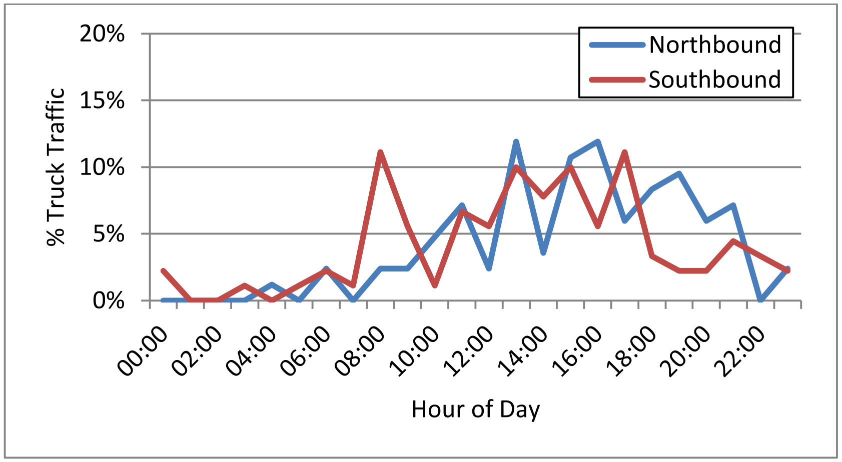
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



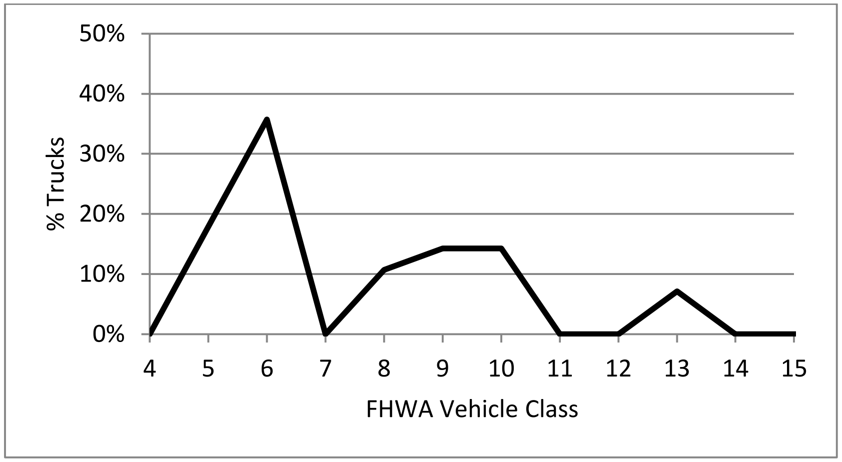


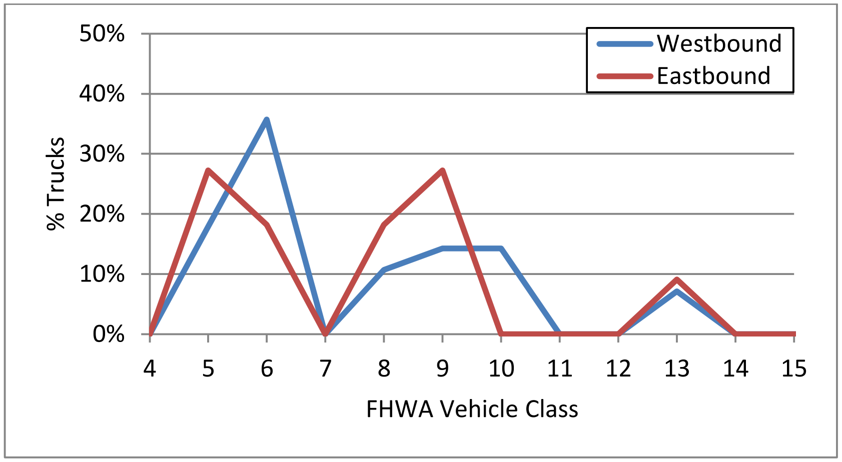
• Station 1347 •

Location: PR345 – East of Saskatchewan Border
Flow: NB-SB
Date: September 12-14, 2013

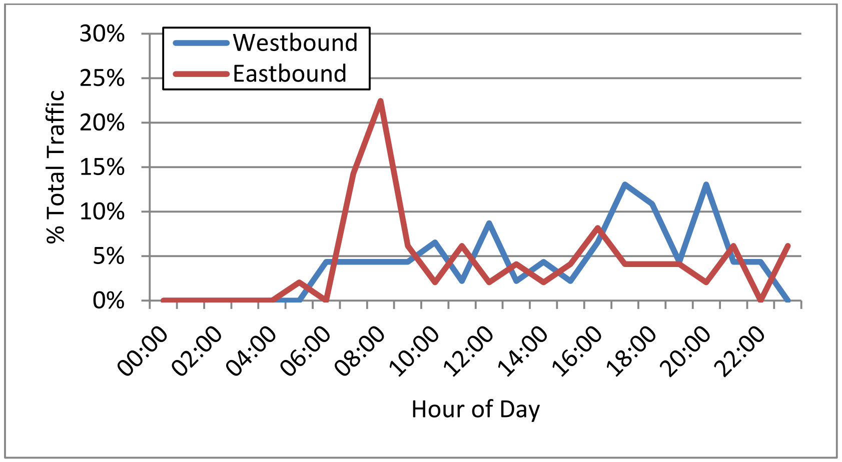
ADT: 100
ADTT: 20
PADTT: 0

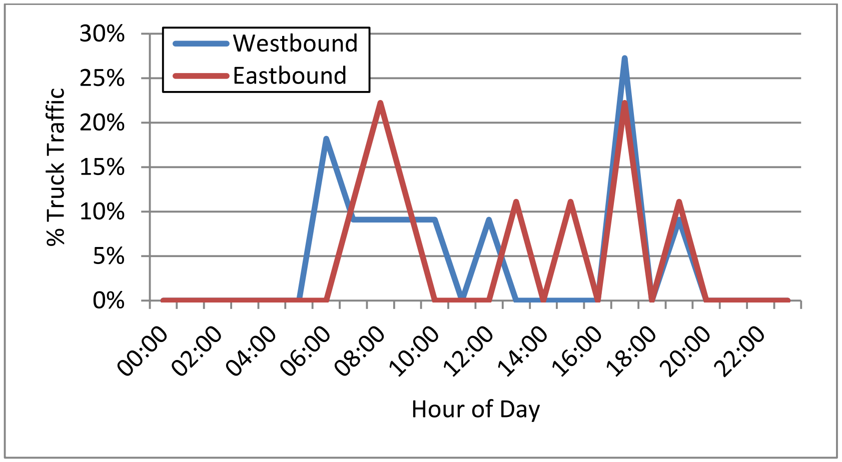
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

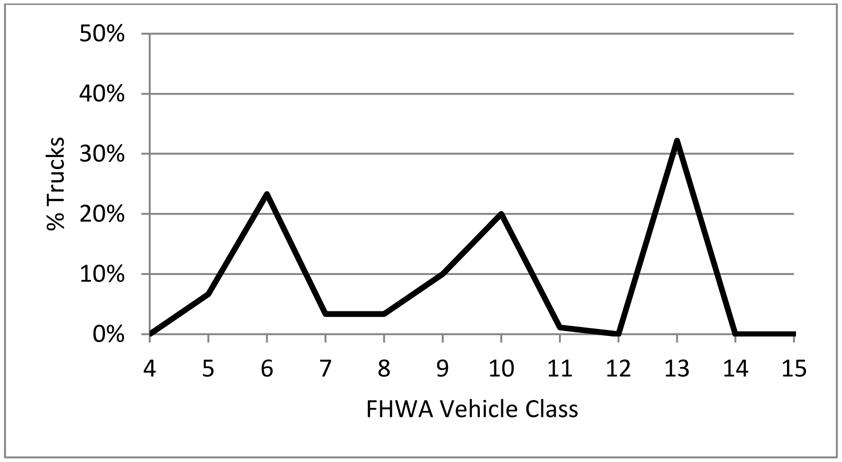


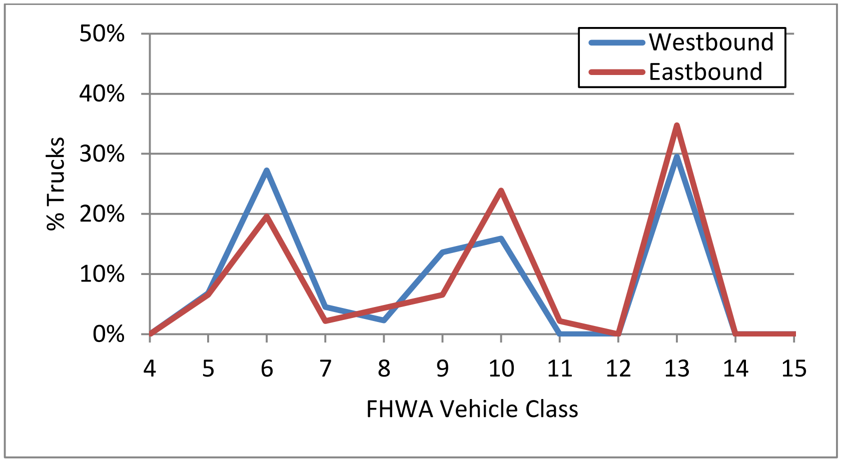


• Station 1377 •

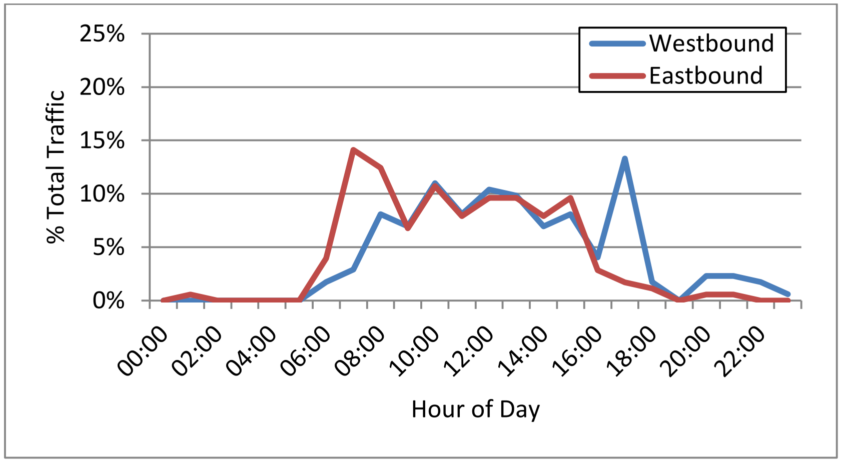
Location:	PR255 – East of Enbridge and Tundra Terminals	**ADT:**	300
Flow:	WB-EB	**ADTT:**	80
Date:	September 10-12, 2013	**PADTT:**	80

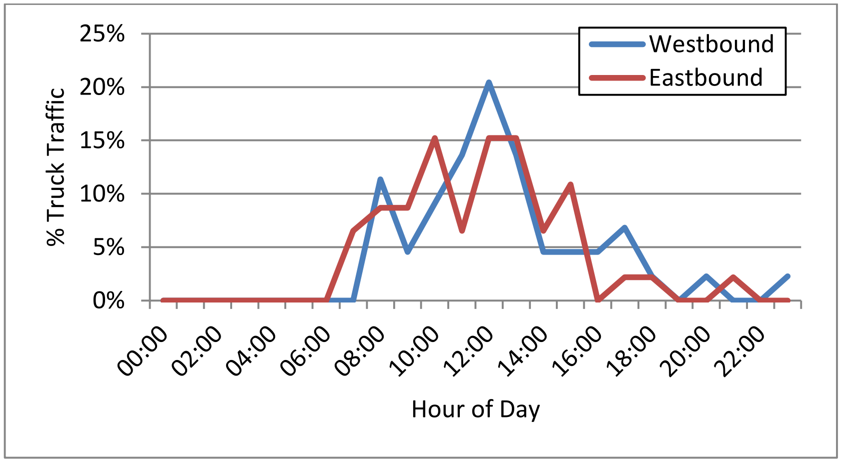
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

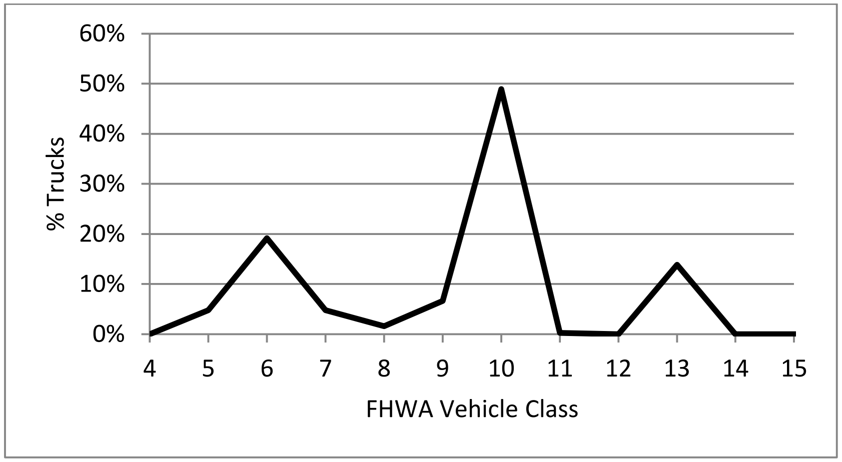


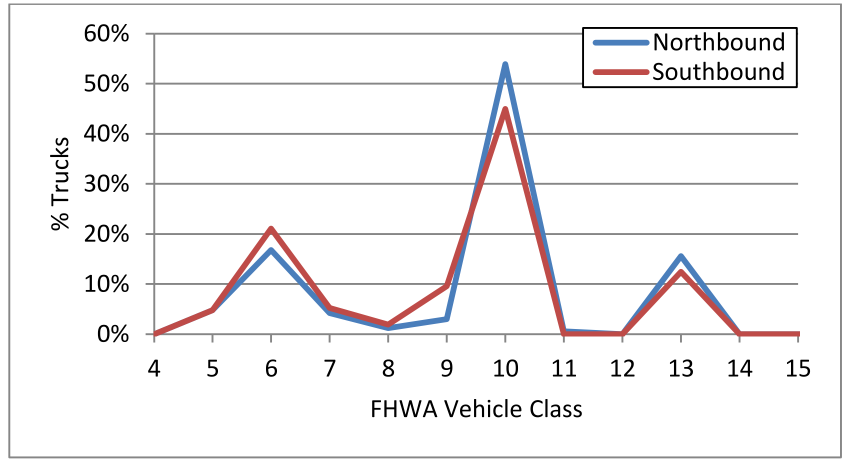


• Station 1378 •

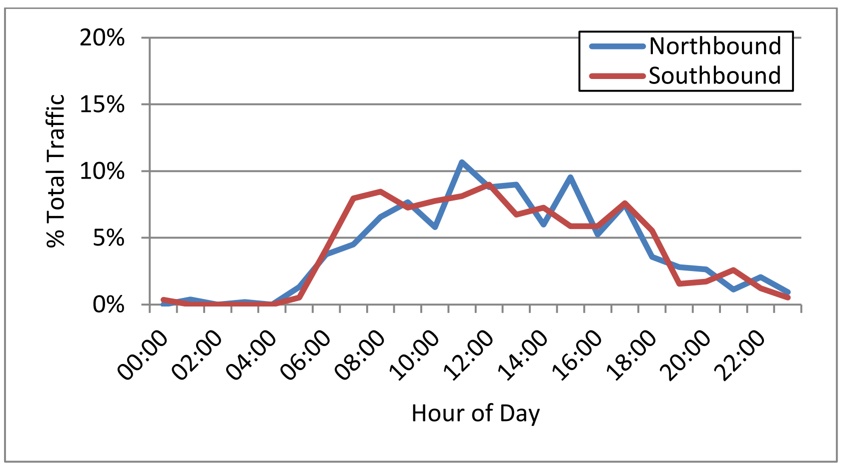
Location:	PR256 – South of Enbridge and Tundra Terminals	**ADT:**	1050
Flow:	NB-SB	**ADTT:**	380
Date:	September 10-12, 2013	**PADTT:**	340

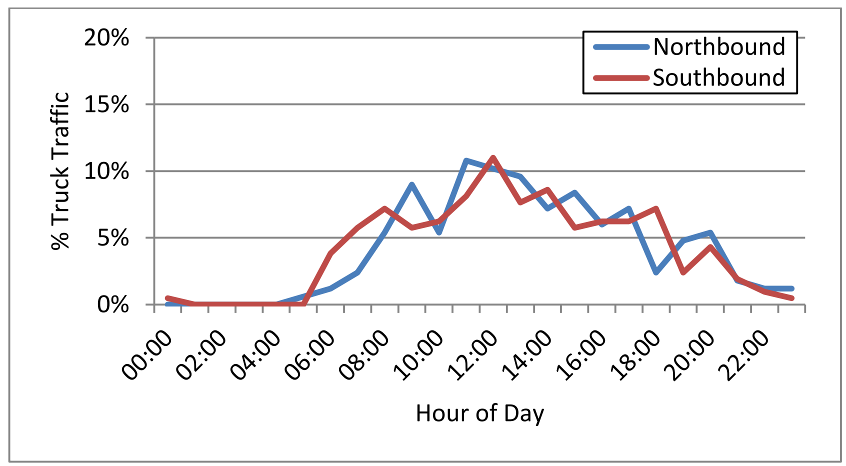
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

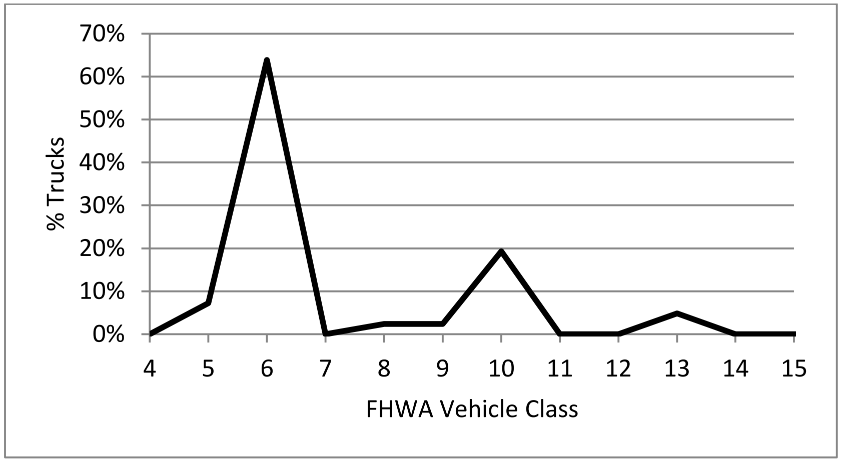


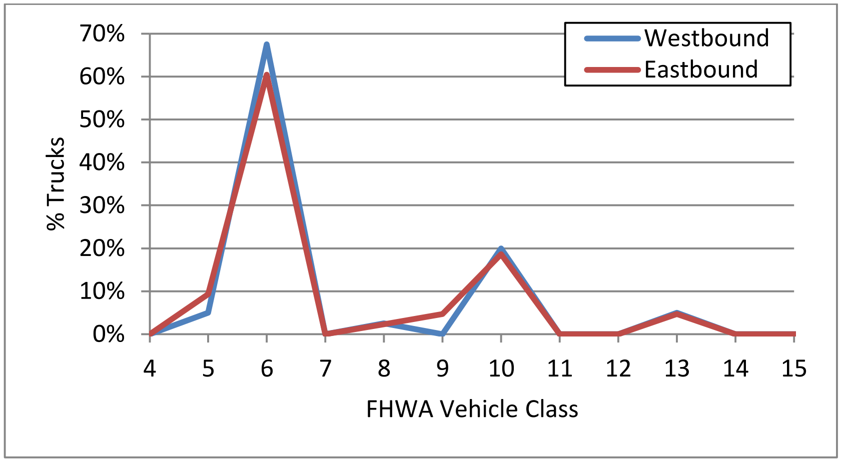


• Station 1379 •

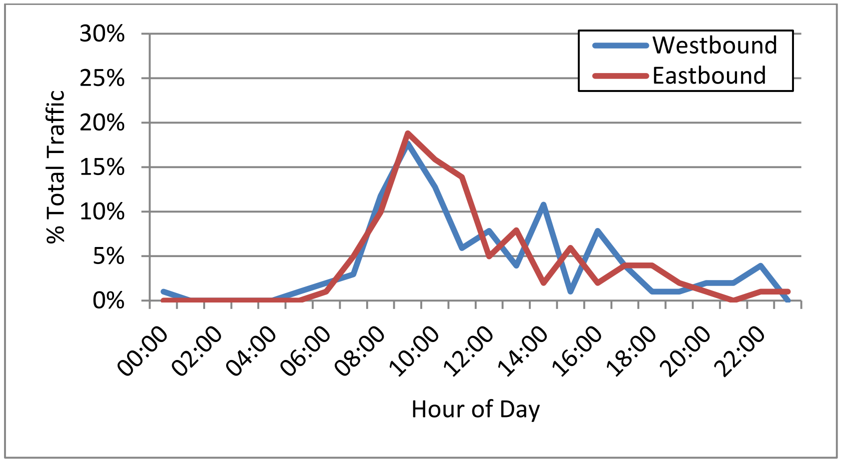
Location:	PR255 - West of Enbridge and Tundra Terminals	**ADT:**	230
Flow:	WB-EB	**ADTT:**	100
Date:	June 19-21, 2013	**PADTT:**	80

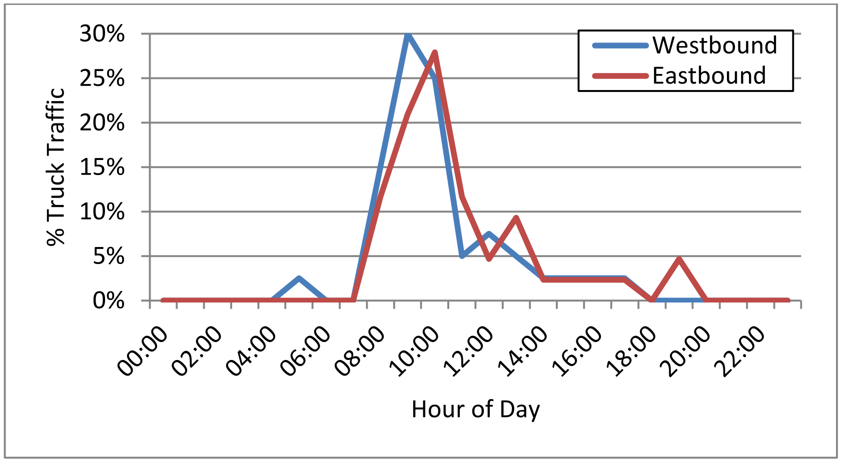
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



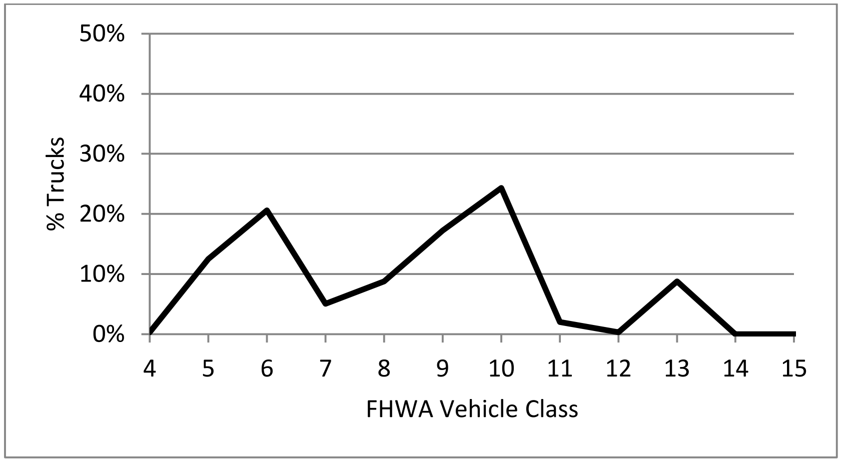


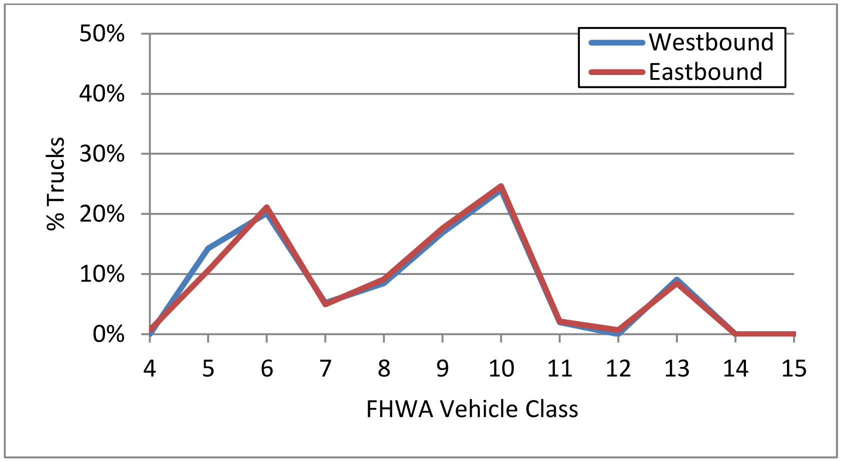
• Station 1380 •

Location: PR257 – East of PR256 Intersection
Flow: WB-EB
Date: September 10-12, 2013

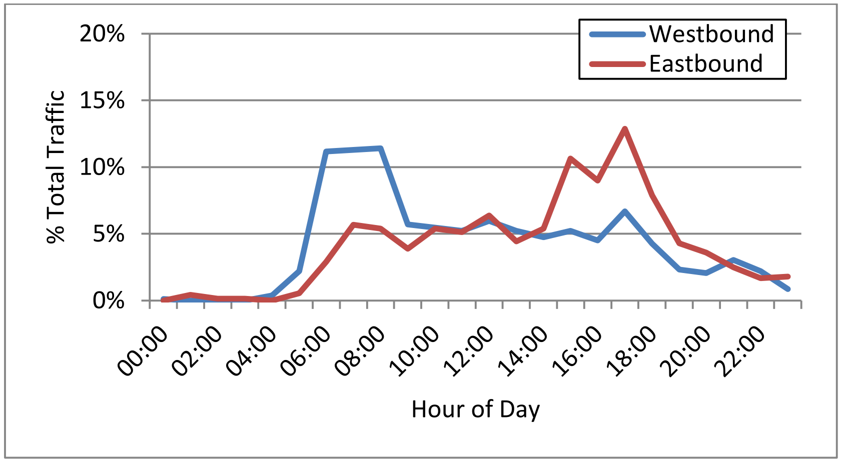
ADT: 1550
ADTT: 290
PADTT: 240

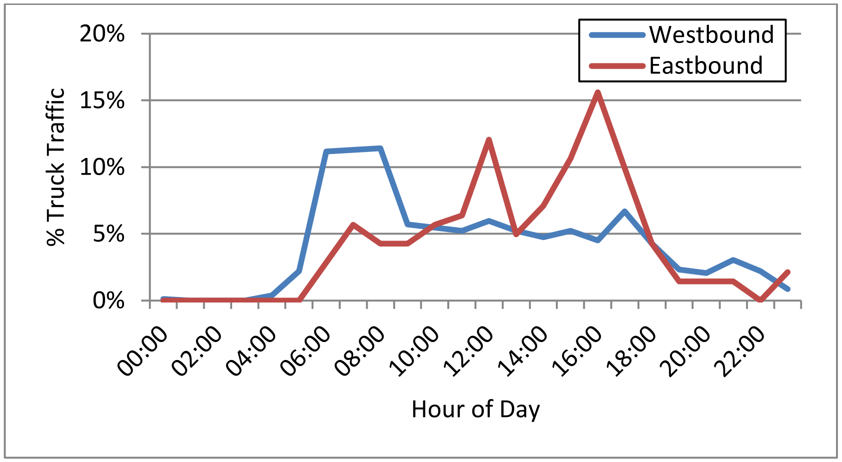
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)



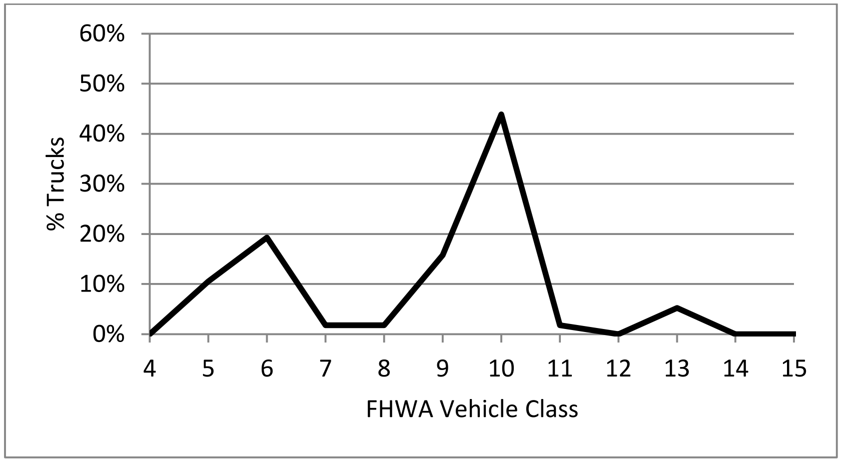


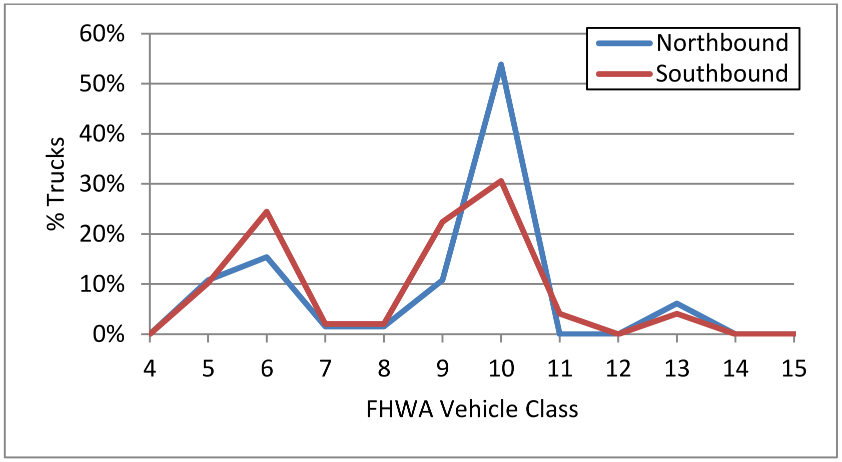
• Station 1407 •

Location: PR256 – North of PTH1
Flow: NB-SB
Date: September 12-14, 2013

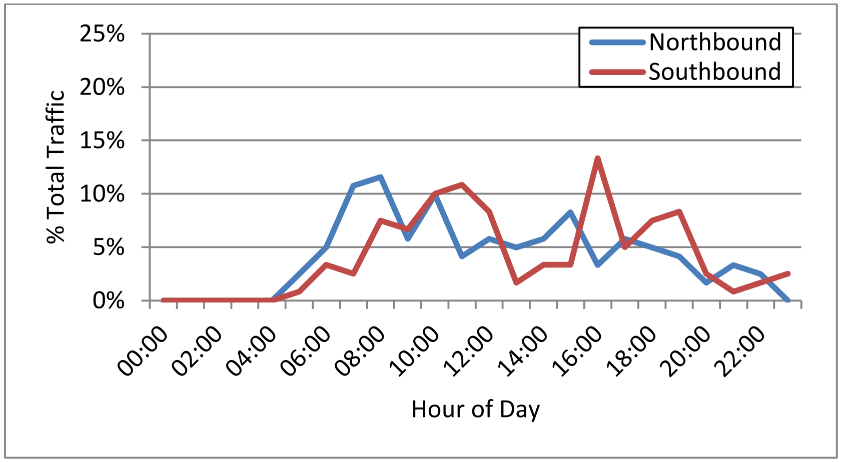
ADT: 240
ADTT: 70
PADTT: 60

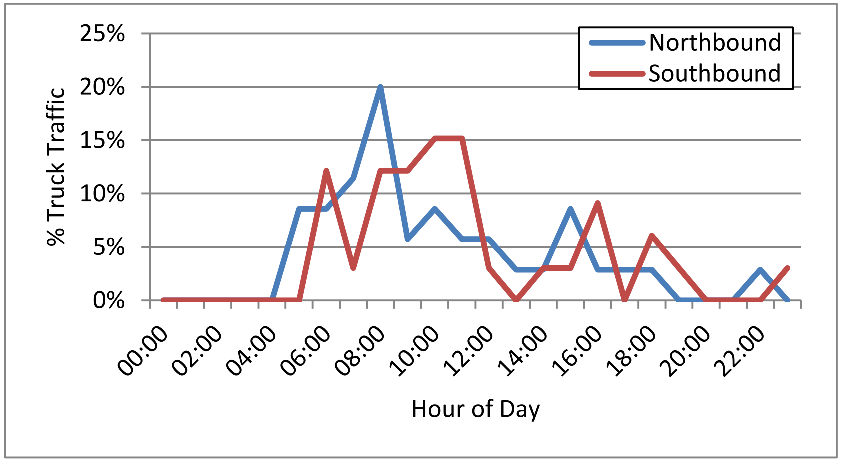
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

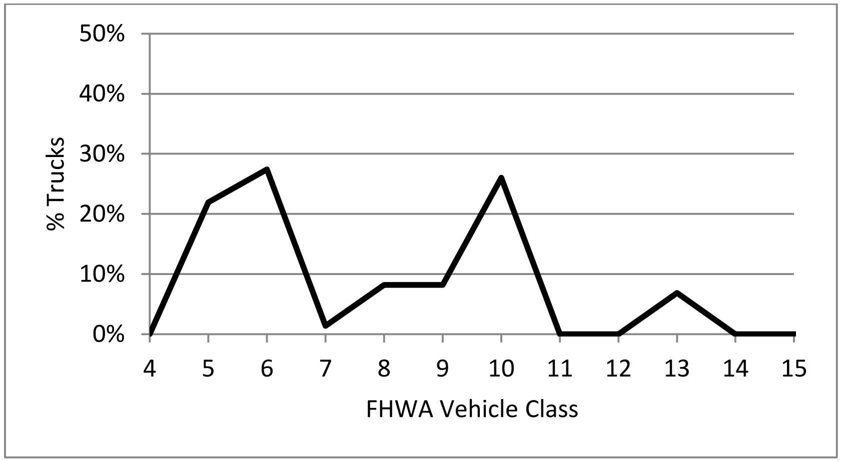


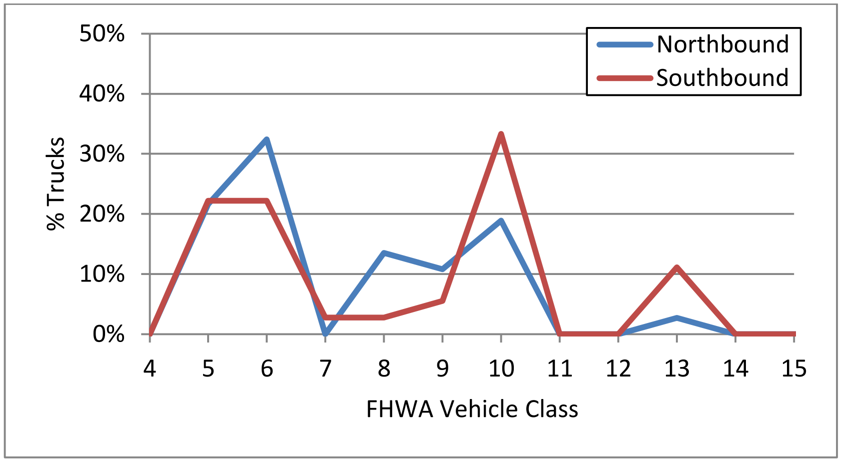


• Station 1497 •

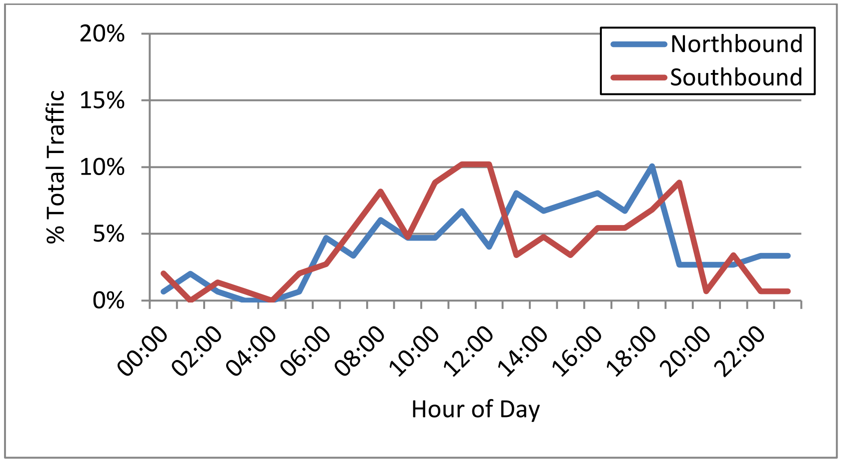
Location:	PTH41 – South of PR467	**ADT:**	280
Flow:	NB-SB	**ADTT:**	40
Date:	June 25-27, 2013	**PADTT:**	20

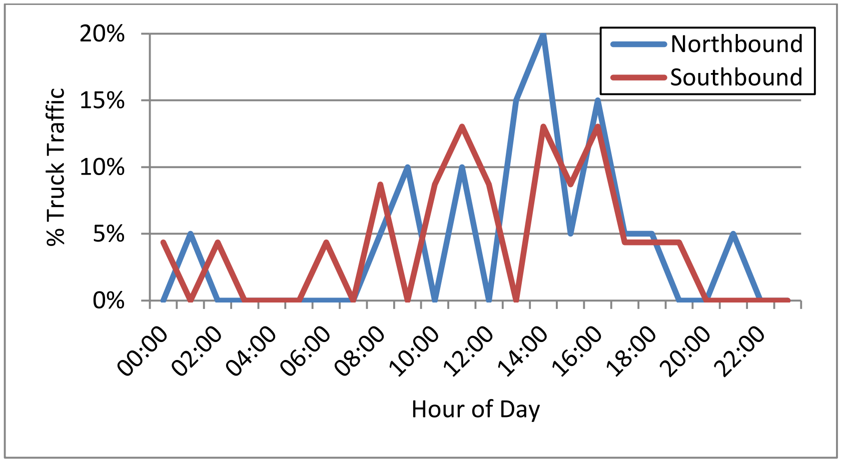
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

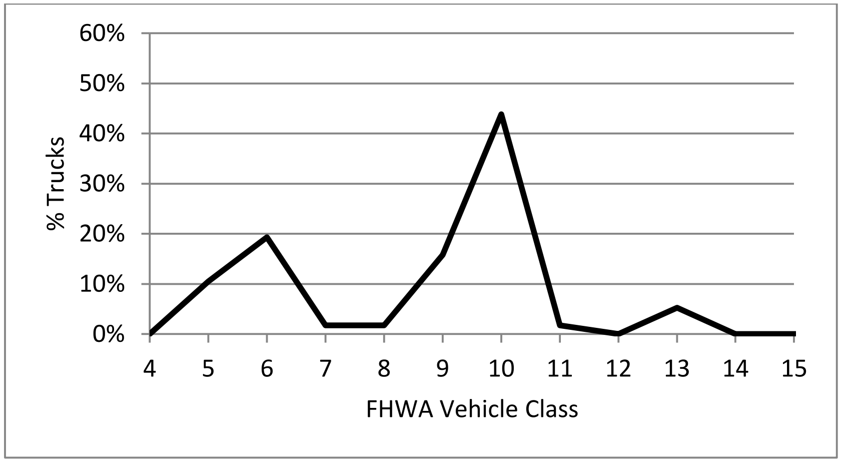


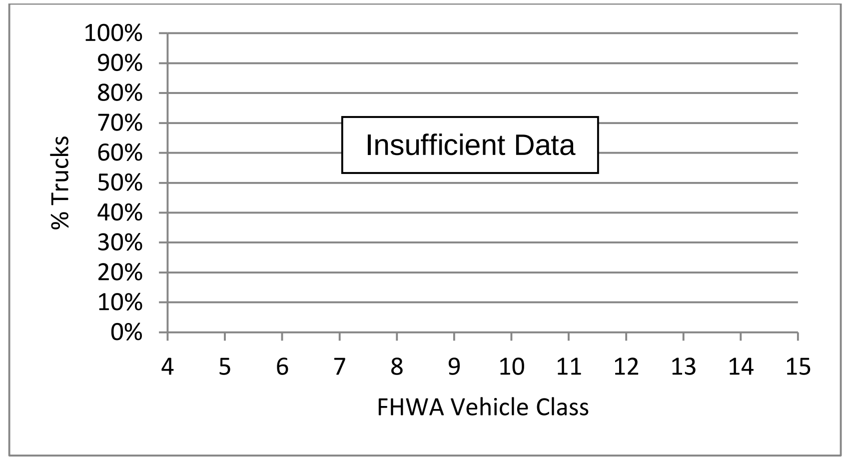


• Station 1550 •

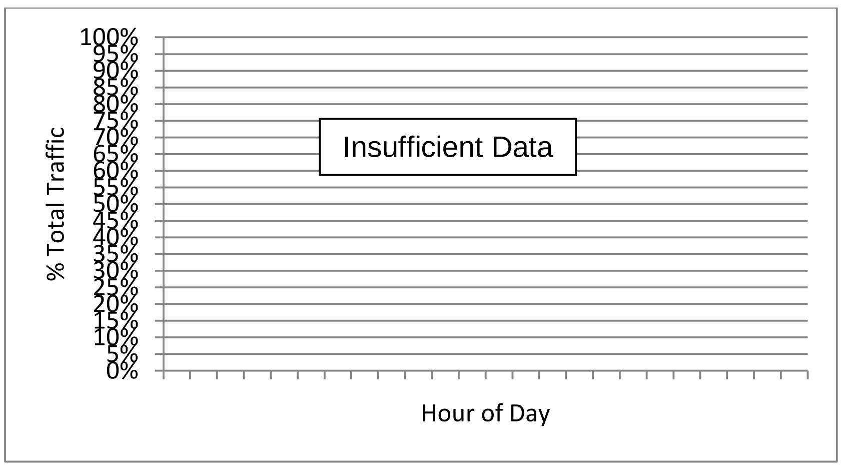
Location:	PR568 – West of PTH83	**ADT:**	Insufficient Data
Flow:	WB-EB	**ADTT:**	Insufficient Data
Date:	June 25-27, 2013	**PADTT:**	60

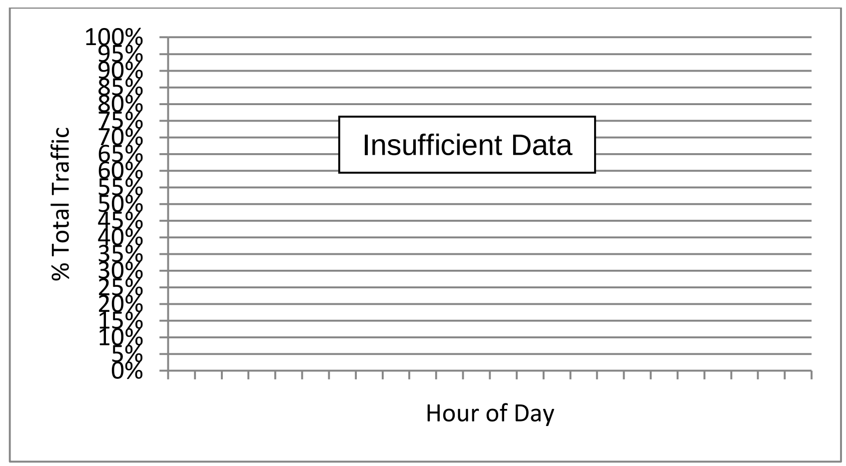
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

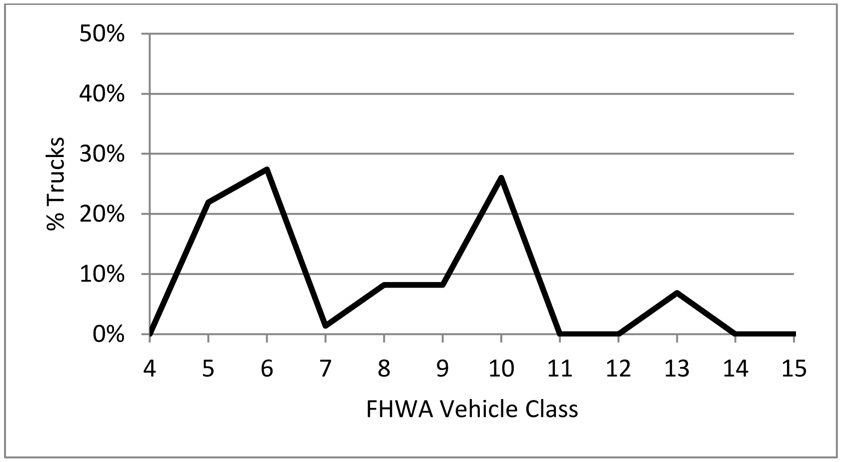


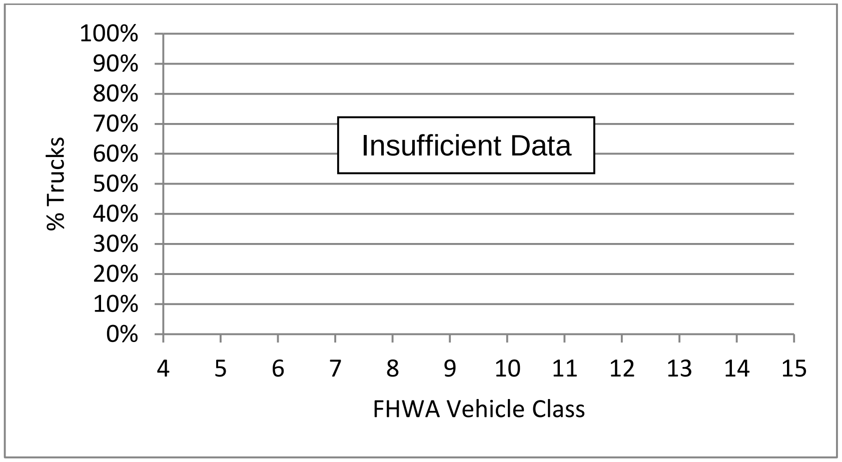


• Station 1551 •

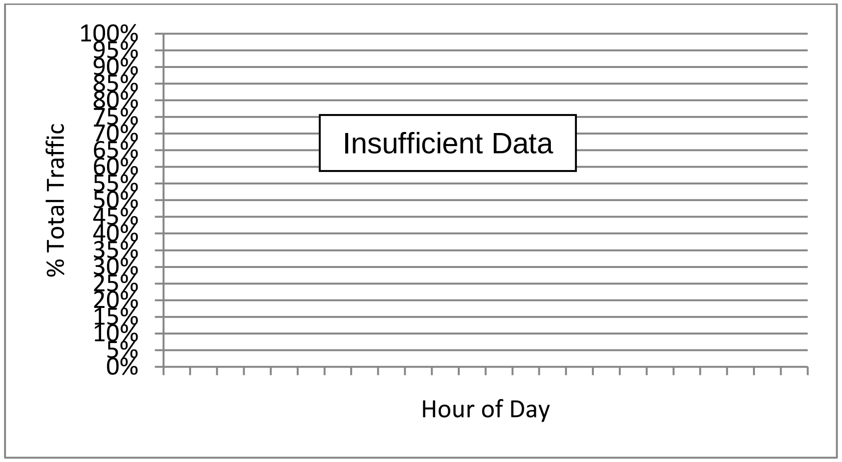
Location:	PR568 – South of PTH42	**ADT:**	Insufficient Data
Flow:	NB-SB	**ADTT:**	Insufficient Data
Date:	June 25-27, 2013	**PADTT:**	20

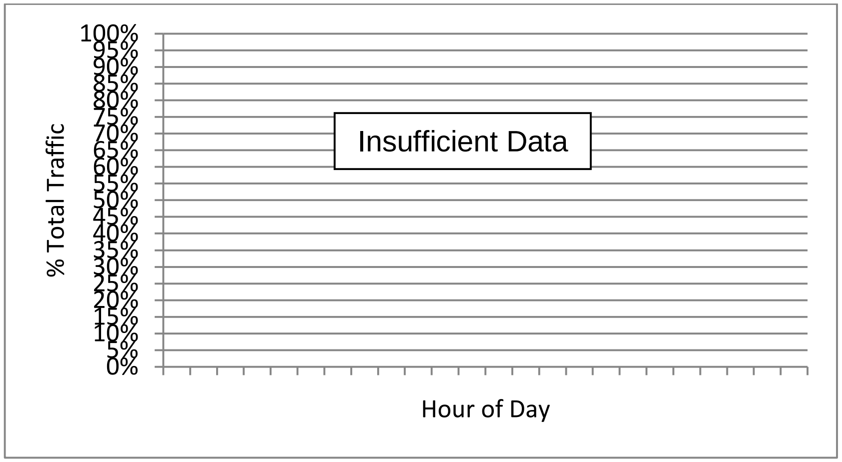
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)

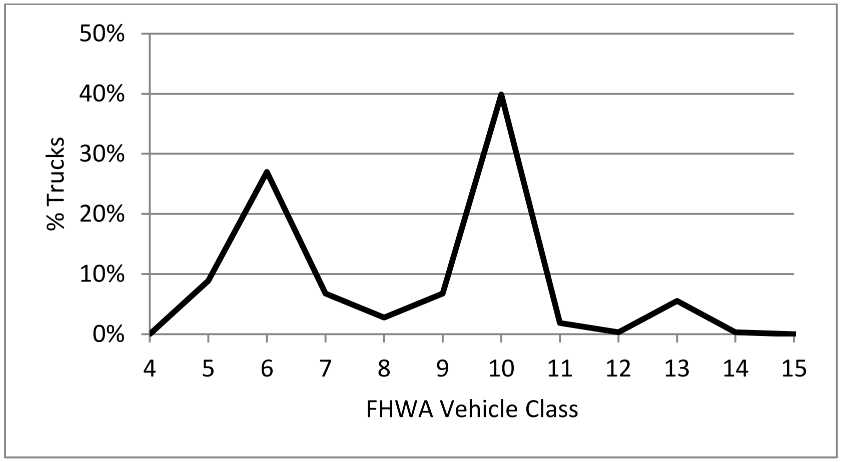


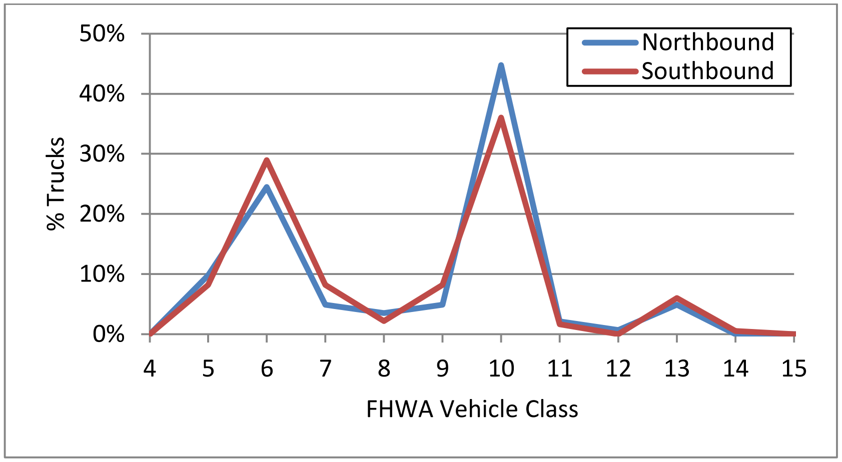


• Station 2211 •

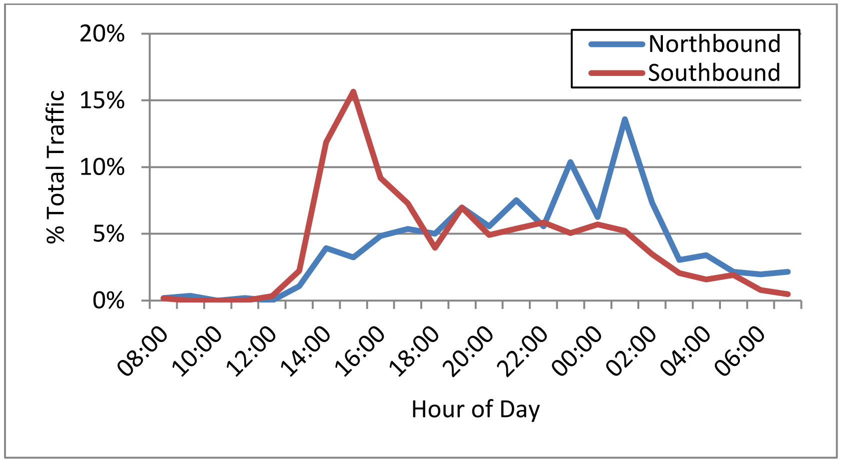
Location:	PR256 - North of Enbridge and Tundra Terminals	**ADT:**	1060
Flow:	NB-SB	**ADTT:**	300
Date:	September 10-12, 2013	**PADTT:**	290

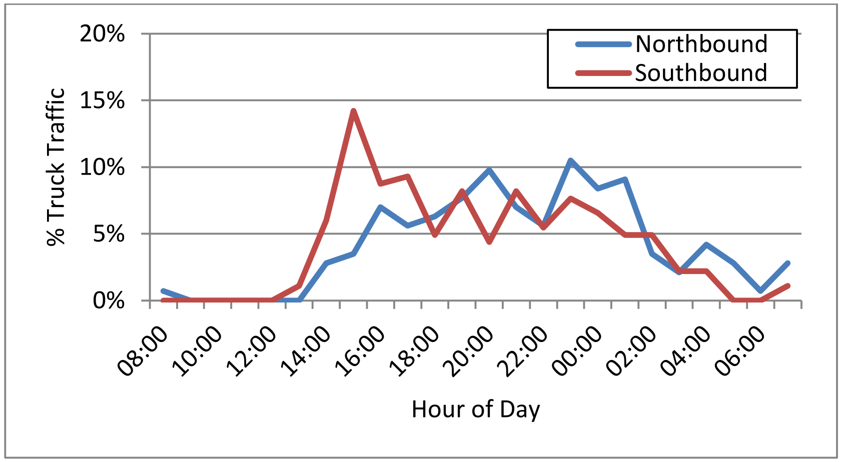
Vehicle Class Distribution (total and by direction)





Hourly Traffic Distribution (total traffic and truck traffic only)





APPENDIX F

DATA SOURCES AND SUPPLEMENTAL INFORMATION ON THE GOOGLE EARTH® DATA DISSEMINATION TOOL

Description of Transportation Supply Data Sources

Data concerning transportation supply for Manitoba was obtained from publicly available sources. Table 1 provides a summary of the data sources used for each component of transportation supply. The linear reference system for each component was adapted and modified from a wider region (Manitoba, Canada, or North America) to represent only the region of interest. The reference systems were either in, or converted to, North American Datum 1983 (NAD83) and Universal Transverse Mercator Zone 14 north (UTM14N). Attributes were selected on the basis of what was considered important to the results of the study and additional information not required was trimmed from any dataset. For each component, the information required was either freely available on the internet or through requests of public agencies (i.e., Manitoba Infrastructure and Transportation or Manitoba Petroleum Branch).

Table 1: Transportation Supply Data and Data Sources

	Data	*Data Source*
Highways, Roads, and Structures	Linear Reference System	Adapted from the Manitoba Highway Traffic Information System by M.Reimer
	Attributes	Manitoba Infrastructure and Transportation
	Bridges and Structures	Manitoba Infrastructure and Transportation
	Municipal Roads	Adapted from the Manitoba Land Initiative by M.Reimer
Rail	Linear Reference System	Adapted from GeoBase by M.Reimer
	Attributes	CN and CP investor handbooks
Pipelines and Flowlines	Linear Reference System	Adapted from U.S. Energy Information Administration by M.Reimer
	Attributes	Enbridge and Transcanada websites, Manitoba Petroleum Branch
	Flowline Information	Manitoba Petroleum Branch

Manitoba Highways, Roads, and Structures

Figure 1 shows a screenshot of the balloon found in Google Earth® when a highway is selected. The title of the balloon is referenced to the highway type and number. The attributes and their definitions are provided in Table 2. A detailed explanation of PADTT is provided in Chapter 5 of this thesis. Municipal roads do not contain attribute information and are provided only as spatial data to illustrate connectivity between petroleum-related activity and the highway network. The surface and shoulder attributes provided in Google Earth® are those typically seen along a highway control section (i.e., conditions seen for the longest distance on a control section).

PR 452

PR 452	
HWY_TYPE	PR
HWY_NO	452
CS_KEY	03452010HU
SEQ	20
HWY_CLASS	RTAC
MAX_GVW	62500
SRR	N/A
PADTT	160
FUNCTIONAL	Collector
AV_SURF_T*	Bituminous (Bpm)
AV_SURF_W*	7.4
AV_SHLD_T*	Fully Paved
AV_SHLD_W*	0.8
2013_AADT	710

Figure 1: Screenshot of attributes of roads and highways

Table 2: Attributes and definitions for Manitoba Highways

Attribute	*Definition*
HWY_TYPE	Highway type (PTH or PR)
HWY_NO	Highway number
CS_KEY	Control section
SEQ	Control section sequence
HWY_CLASS	Highway classification (RTAC, A1, etc.)
SRR	Spring road restriction level
PADTT	Petroleum average daily truck traffic
FUNCTIONAL	Functional planning classification
AV_SURF_T*	Average surface type of control section
AV_SURF_W*	Average surface width in metres
AV_SHLD_T*	Average surface type for outside shoulder
AV_SHLD_W*	Average width of outside shoulder in metres
2013_AADT	2013 AADT reported by MHTIS

*NOTE: Surface and width can change multiple times for a single control section. Due to sequence differences between this system and the MIT Highway Information System, values given are those of the longest distances within the MIT system.

Bridges and structures, as maintained by Manitoba Infrastructure and Transportation, are included within the Google Earth® data dissemination tool. Figure 2 shows a screenshot of the balloon found in Google Earth® when a bridge is selected. The attributes and their definitions are provided in Table 3. Structures included in this layer include bridges, culverts, and dams that are crossed by vehicles and monitored by MIT.

×

945

945	
SITE	945
STRUCTURE	Timber Bridge with Reinforced Concrete Abutments
TYPE	Minor Bridge
CLASS_TYPE	2nd Class
ROAD_NO	083
LENGTH_M	43.891
MUNICIPALI	Pipestone
LEGAL	SE-29-07-26
FEATURE	Pipestone Creek
DESIGN_LOA	HS20
MAX_SPAN_L	10.058
DECK_WIDTH	9.144
ROADWAY_WI	7.315
YEAR_BUILT	1955
MODIFICATI	
SKEW_ANGLE	0
MAIN_SPANS	5
Inv_RF	0.747
Op_RF	1.134
Date_RF	23/07/2009
LRFR_Strai	0.906
LRFR_Trail	0.949
LRFR_Train	0.949
Date_LRFR	23/07/2009
Long_Term	
Vertical_C	

Directions: To here - From here

Figure 2: Screenshot of attributes for bridges, culverts, and dams

Table 3: Attributes and definitions for bridges and structures

Attribute	*Definition*
SITE	Reference number of structure
STRUCTURE	Type of structure
TYPE	Major or minor structure type
CLASS_TYPE	Class of structure
ROAD_NO	Road number structure is located on
LENGTH_M	Total length in metres (bridges only)
MUNICIPALI	Municipality structure is located in
LEGAL	Legal location
FEATURE	Geographic feature crossed by structure
DESIGN_LOA	Design load used for structure
MAX_SPAN_L	Length in meters of maximum span (bridges only)
DECK_WIDTH	Width deck in metres (bridges only)
ROADWAY_WI	Width of roadway over structure in metres
YEAR_BUILT	Year structure was built
MODIFICATI	List of modifications performed on structure since construction
SKEW_ANGLE	Skew angle in degrees
MAIN_SPANS	Number of main spans (bridges only)
Inv_RF	Inventory Rating Factor (bridges only)
Op_RF	Operating Rating Factor (bridges only)
Date_RF	Date of most recent rating factor calculation
LRFR_Strai	Load and Resistance Factor Rating for straight truck (bridges only)
LRFR_Trail	Load and Resistance Factor Rating for truck with trailer (bridges only)
LRFR_Train	Load and Resistance Factor Rating for multiple trailer truck (birdges only)
Date_LRFR	Date of Load and Resistance Factor Rating calculations
Long_Term	List of long term restrictions or conditions at structure
Vertical_C	Vertical clearance (if applicable) at structure

Railroads

Figure 3 shows a screenshot of the balloon found in Google Earth® when a railroad is selected. The title of the balloon is referenced to the name of the railroad company. The attributes and their definitions are provided in Table 4. The acronym MGTM (million gross tons per mile) is a railroad metric for the weight of all cars and locomotives that travel along the network. Load restriction refers to the maximum weight allowable by freight carrying rail cars along the Subdivision.

Canadian National

Canadian National	
RAILWAY_NA	Canadian National
SUBDIVISIO	Cromer
TRACK_TYPE	Main Single
LOAD_RESTR	263,000 LBS
MGTM	<5

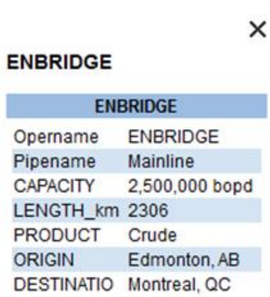
Figure 3: Screenshot of attributes for railroads

Table 4: Attributes and definitions for railroads

Attribute	*Definition*
RAILWAY_NA	Name of railroad owner
SUBDIVISIO	Name of railroad Subdivision
TRACK_TYPE	Classification of railroad track
LOAD_RESTR	Load restriction (in pounds) for cars carried on Subdivision
MGTM	Annual million gross tons per mile

Pipelines and Flowlines

Figure 4 shows a screenshot of the balloon found in Google Earth® when a pipeline is selected. The title of the balloon is referenced to the name of the pipeline operator. The attributes and their definitions are provided in Table 5. The pipelines shown in the Google Earth® tool are only major lines that carry crude oil between regions. The origin and destination of a pipeline are provided to show direction of flow. Internal pipelines and the flowline network of the study region are not publicly available in the form of GIS data and therefore were not included in this research.



ENBRIDGE

ENBRIDGE	
Opername	ENBRIDGE
Pipename	Mainline
CAPACITY	2,500,000 bopd
LENGTH_km	2306
PRODUCT	Crude
ORIGIN	Edmonton, AB
DESTINATIO	Montreal, QC

Figure 4: Screenshot of attributes for pipelines

Table 5: Attributes and definition for pipelines

Attribute	*Definition*
Opername	Name of pipeline operator
Pipename	Name of pipeline
CAPACITY	Total pipeline capacity in barrels of oil per day (BOPD)
LENGTH_km	Total length of pipelinen from origin to final destination
PRODUCT	Commodity carried by pipeline (this study only looked at crude oil lines)
ORIGIN	Starting point of pipeline
DESTINATIO	Ending point of pipeline

Description of Activity System Data Sources

Data for Manitoba for the activity system was obtained almost exclusively from the Manitoba Petroleum Branch. In some instances, information and data were manually developed through conversations with industry experts and field observations. Table 6 provides a summary of the data sources used for each component of the activity system. The datum and coordinate system for each component is NAD83 (UTM14N). Attributes were selected and summarized from larger datasets pertaining to the area of interest. Data included in the Google Earth® tool was selected to reflect the year of study (2013) and to provide summaries of characteristics (such as production and number of wells drilled in a field) that influence the transportation network. For each component, the information required was either freely available on the internet, through requests of public agencies, or through interviews with industry experts.

Table 6: Activity System data and data sources

	Data	*Data Source*
Oil Fields	Spatial Reference System	Manitoba Petroleum Branch
	Attributes	Adapted from Manitoba Petroleum Branch and industry interviews by M.Reimer
Active Wells	Spatial Reference System	Manitoba Petroleum Branch
	Attributes	Adapted from Manitoba Petroleum Branch by M.Reimer
Batteries	Spatial Reference System	Adapted from Manitoba Petroleum Branch by M.Reimer
	Attributes	Adapted from Manitoba Petroleum Branch by M.Reimer
Terminals, Materials, and Equipment	Spatial Reference System	Developed by UMTIG through industry interviews by M.Reimer
	Attributes	Developed by UMTIG through industry interviews by M.reimer

Oil Fields

Figure 5 shows a screenshot of the balloon found in Google Earth® when an oil field is selected. The title of the balloon is referenced to the name of the oil field. The attributes and their definitions are provided in Table 7. A comparison in drilling activity is provided between 2005 (beginning of current industry growth period) and the most recent year of data collected in 2013. Development trips (one-way loaded truck trips) required to drill all wells in a year can be spread over the number of development days. The number of development trips for an oil field is the product of the total number of wells drilled multiplied by industry estimates of total trips required per well. Development days are estimated from the number of weeks where wells were completed within an oil field. As discussed in Chapter 2 of this thesis, the industry does not drill new wells during spring road restrictions and during the Christmas holidays and in 2013 the maximum number of development days available in a year is approximately 280 (this will vary based on weather conditions each year).

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WASKADA

WASKADA	
Field_Name	WASKADA
FIELD_CODE	03
Dril_Wells	1857
Acti_Wells	1409
Batteries	9
2005_Drill	13
2013_Drill	171
Dev_Trips	23770
Dev_Days	280
Prod_Trips	16

Figure 5: Screen shot of attributes for oil fields

Table 7: Attributes and definitions for Manitoba oil fields

Attribute	*Definition*
Field_Name	Name of oil field
FIELD_CODE	Two-digit code that represents oil field in databases
Dril_Wells	Total number of wells drilled within field since discovered
Acti_Wells	Total number of wells designated as active
Batteries	Number of batteries in operation within field
2005_Drill	Number of wells drilled in 2005
2013_Drill	Number of wells drilled in 2013
Dev_Trips	Estimated one-way loaded truck trips to develop all wells in 2013
Dev_Days	Estimated number of days used to develop all wells in 2013
Prod_Trips	Estimated daily truck trips required to move crude oil to Cromer terminals

Active Wells

Figure 6 shows a screenshot of the balloon found in Google Earth® when an active well is selected. The title of the balloon is referenced to the type of well. The attributes and their definitions are provided in Table 8. When viewing attributes of an active well, the amount of fluid produced and whether the well is flowlined are important features in determining the number of trucks generated by a well during its production life. As discussed in this thesis, a flowlined well will move emulsion from the well to a centralized collection point but when not flowlined the crude oil and water must be moved by truck.

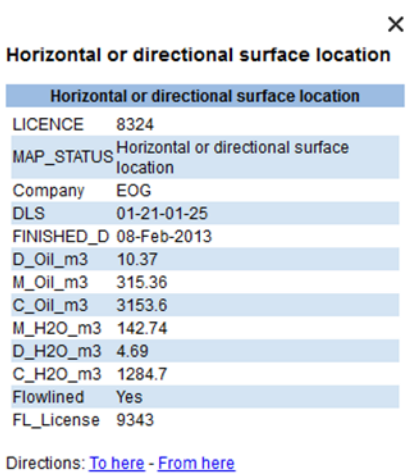

Figure 6: Screenshot of attributes for active wells

Table 8: Attributes and definitions for active wells

Attribute	*Definition*
LICENCE	License number of well used as a reference in larger databases
MAP_STATUS	Type of well
Company	Name of company operating well
DLS	Dominion land survey location
FINISHED_D	Date well was finished
D_Oil_m3	Average daily crude oil production in cubic metres (for 2013)
M_Oil_m3	Average monthly crude oil production in cubic metres (for 2013)
C_Oil_m3	Cumulative crude oil production in cubic metres since well was completed
D_H2O_m3	Average daily water production in cubic metres (for 2013)
M_H2O_m3	Average monthly water production in cubic metres (for 2013)
C_H2O_m3	Cumulative water production in cubic metres since well was completed
Flowlined	Flowline status of well
FL_License	License number for flowline used as a reference in larger databases

Batteries

Figure 7 shows a screenshot of the balloon found in Google Earth® when a battery is selected. The title of the balloon is referenced to the name of the company that operates the battery. The attributes and their definitions are provided in Table 9. Batteries, collection points for emulsion from active wells, separate crude oil from water. The pipeline status of a battery dictates whether crude oil is moved by pipeline or trucked to the export terminals at Cromer.

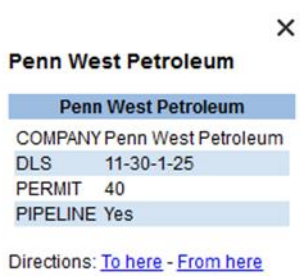

Figure 7: Screenshot of attributes for batteries

Table 9: Attributes and definitions for batteries

Attribute	*Definition*
COMPANY	Name of company that operates battery
DLS	Dominion land survey location
PERMIT	Battery permit number used as a reference in larger databases
PIPELINE	Indicates if a battery is connected to a pipeline

Terminals, Materials, and Equipment

Figure 8 shows a screenshot of the balloon found in Google Earth® when a facility is selected. The title of the balloon is referenced to the type of facility. The attributes and their definitions are provided in Table 10. This layer provides the locations of important origins and destinations that support the petroleum industry.

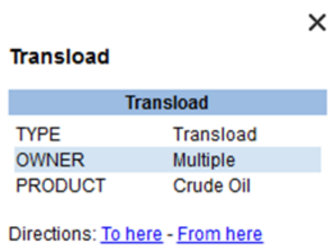

Figure 8: Screenshot of attributes for terminals, materials, and equipment

Table 10: Attributes and definitions for terminals, materials, and equipment

Attribute	*Definition*
TYPE	Type of facility selected
OWNER	Name of facility owner or indicates multiple owners
PRODUCT	Type of material, equipment, or supplies handled at facility

Description of Transportation Flow Data Sources

Petroleum Average Daily Truck Traffic (PADTT) is the estimated average number of trucks per day passing a point on the roadway resulting from petroleum-related activity when fields are undergoing typical development and production activity. The PADTT metric is reflective of "business-as-usual" throughout the whole region when operating through development days. During periods of no development truck traffic volumes would be much lower as the development trips are removed. This is the truck traffic assigned to a highway segment when oil fields are drilling new wells and reflects the varying levels of activity seen throughout the region and the different fields. Selecting an oil field within the Google Earth® tool will inform the user of the number of wells drilled, development trips generated, development days, and daily production trips (highlighted in Chapter 2 of this thesis). Within the Google Earth® tool, increasing PADTT is designated with a thicker line and shown in the "Truck Traffic Flow" legend (Figure 9). This data is also reflected in the highways component of the Transportation Supply layer.

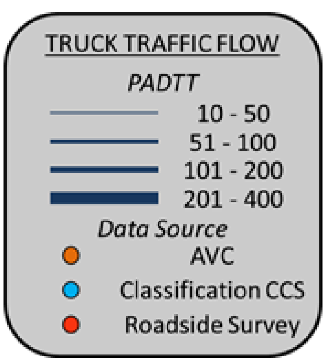

Figure 9: Google Earth® legend for Truck Traffic Flow