

ESTIMATION OF INCREASED TRAFFIC ON HIGHWAYS IN MONTANA AND NORTH  
DAKOTA DUE TO OIL DEVELOPMENT AND PRODUCTION

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Title

Estimation of Increased Traffic on Highways in Montana and North Dakota

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Due to Oil Development and Production

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## ABSTRACT

Advances in oil extraction technology such as hydraulic fracturing have improved capabilities to extract and produce oil in the Bakken and Three Forks shale formations located in North Dakota, Montana, Manitoba, and Saskatchewan. From 2004 to the present, there has been a significant increase in oil rigs and new oil wells in these areas, resulting in increased impacts to the local, county, state, and federal roadway network. Traditional methods of rural traffic forecasting using an established growth rate are not sufficient under the changing traffic levels. The goal of this research is to develop a traffic model that will improve segment specific traffic forecasts for use in highway design and planning. The traffic model will consist of five main components: 1) a Geographic Information Systems (GIS) network model of local, county, state and federal roads, 2) a truck costing model for use in estimating segment specific user costs, 3) a spatial oil location model to estimate future oil development areas, 4) a series of mathematical programming models to optimize a multi-region oil development area for nine individual input/output movements, and 5) an aggregation of multiple routings to segment specific traffic levels in a GIS network model.

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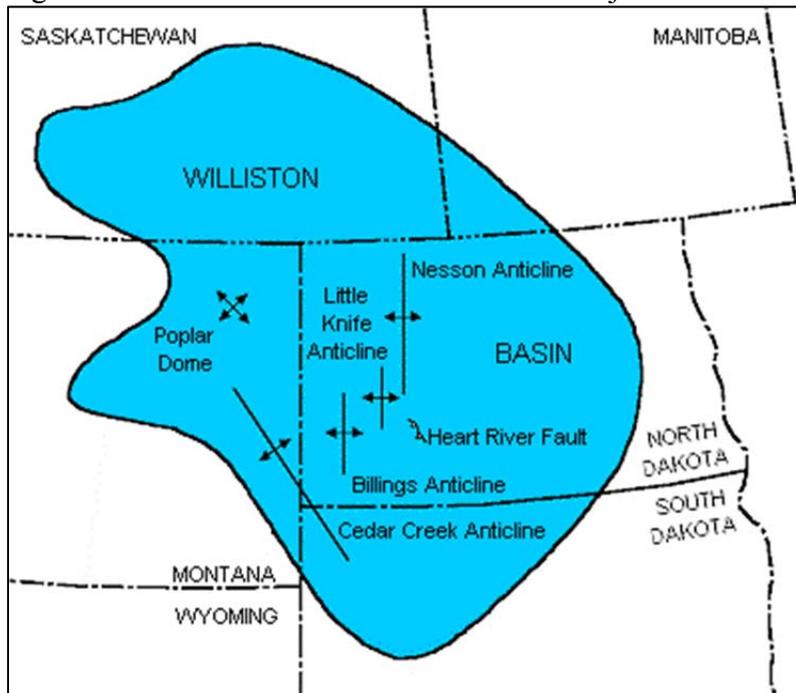
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## CHAPTER 1. INTRODUCTION

### 1.1. Background

In 1951, the Ameralda Hess Corporation drilled an oil well near on a farm owned by Clarence Iverson near Tioga, North Dakota, located in eastern Williams County. This well, known as the Clarence Iverson No.1 “gets the credit for the first major discovery in the Williston Basin” (Hintze 2011). Prior to the drilling of the Clarence Iverson No. 1, as far back as 1921, geologists had identified the potential for oil deposits within the Williston Basin. However, exploration attempts were met with varying degrees of success and oil output (Hintze 2011). The Williston basin covers portions of Montana, North Dakota, and South Dakota in the United States and Manitoba and Saskatchewan in Canada, as shown in Figure 1.

Figure 1. Extent of the Williston Basin with major structures shown (Heck, et al. 2002)



The Williston Basin consists of numerous oil formations as shown in Figure 2. Each formation is arranged in sequence of timeframe of deposition. In 2002, the Madison formation

was the most productive oil formation in North Dakota, producing 60% of all oil in the state to date, followed by the Duperow (9.7%), Red River (8.4%), Tyler (5.8%), Spearfish (3.7%), and Bakken (3.1%) (Heck, et al. 2002). With the introduction of new exploration and extraction technologies, the relative productivity of these formations has changed. As of December 2011, the Madison formation had contributed 46% of historical production, followed by the Bakken (16.5%), Red River (5.3%), Devonian (4.9%), Silurian (3.2%), and Duperow (2.5%) (North Dakota Industrial Council, Oil & Gas Division n.d.). Of note is that the largest producing oil formations were formed during the late Devonian and Mississippian systems.

Figure 2. Generalized stratigraphic column for the Williston Basin (Heck, et al. 2002)

Systems	Rock Units				
Quaternary	Pleistocene		Permian	Minnekahta	
	White River		Pennsylvanian	Opeche	
	Golden Valley			Broom Creek	
Tertiary				Amsden	
	Fort Union Group		Mississippian	Tyler	
				Otter	
		Kibbey			
Cretaceous	Hell Creek			Madison Group	Charles
	Fox Hills				Mission Canyon
	Pierre				Lodgepole
	Judith River			Devonian	Bakken
	Badre				Three Forks
	Niobrara				Birdbear
	Carlile				Duperow
	Greenhorn		Souris River		
	Belle Fourche		Dawson Bay		
	Mowry		Prairie		
	Newcastle		Winnipegosis		
	Skull Creek		As hern		
	Inyan Kara		Silurian		Interlake
Swift		Stonewall			
Jurassic		Ordovician	Stony Mountain		
	Rierdon			Red River	
Piper			Winnipeg Group		
Triassic	Spearfish	Cambrian	Deadwood		
Permian			Precambrian		

While historical oil development has been centered in the Mississippian system, primarily in the Madison Lodgepole and Mission Canyon formations, recent development has been centered in the late Devonian system. Within this system, the Duperow formation had been the largest area of productive exploration and development until the early 2000s, but beginning in the mid-2000s, the focus has been on the Bakken formation located in the late Devonian and early Mississippian systems. The extent of the Bakken formation in the United States is shown in Figure 3. A 2008 United State Geological Survey (USGS) study of the Bakken formation suggests large previously undiscovered volumes of oil, with a mean estimate of 3.65 billion barrels (United States Geological Survey 2008). Continental Resources, Inc. estimated the recoverable oil at 24 billion bbl in 2011 (OGJ editors 2011). The USGS began reevaluating Bakken reserves in 2012, and updated estimates are expected during the 2014 fiscal year (United States Department of the Interior 2011).

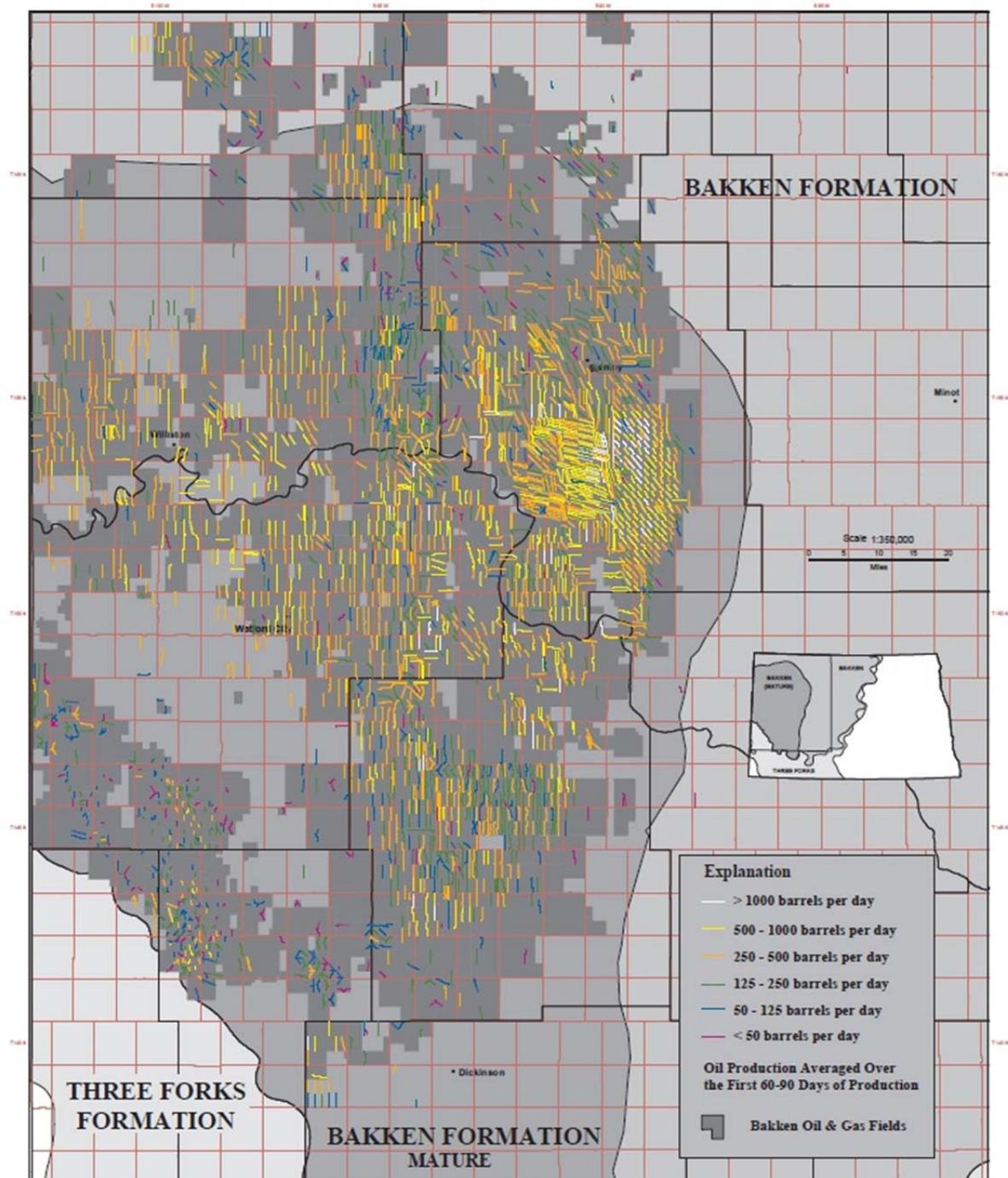
The Bakken formation consists of three members. “the Upper Member, a 23-foot thick black marine shale; the Middle Member, an 85-foot thick interbedded layer of limestone, siltstone, dolomite, and sandstone; and the Lower Member, a 50-foot thick black marine shale” (Grape 2006). Early exploration focused on the upper and lower members that consisted of shale, and recent exploration has been focused on the middle member, which is located approximately two miles below the surface, varying in depth by geographic area. The Bakken formation is located between two tight formations: the Lodgepole above and the Three Forks below. The Lodgepole is a limestone formation that is 900 feet thick, and the Three Forks is a 250-foot formation. Each of these formations consists of low-permeability carbonates, which effectively act as a seal on each edge of the Bakken, thereby creating increased pressures and temperatures. This combination of pressure and temperature converts the kerogen content of the

Figure 3. Map showing Williston Basin Province boundary and the Bakken-Lodgepole system in Montana, North Dakota, and South Dakota. (United States Geological Survey 2008)



shales to petroleum. Additionally, the pressure and temperature conditions result in natural fracturing of the shales and the middle member, resulting in an overpressured formation capable of high production rates. Once areas within the formation exceed 100 degrees celsius, they are considered thermally mature or effectively heated sufficiently to produce crude petroleum (Grape 2006). The thermally mature boundaries dictate the likelihood of successful exploration and production. Figure 4 shows the boundaries of the thermally mature areas of the Bakken in North Dakota. Within these boundaries, significant crude oil reserves are known to exist. However, using traditional vertical drilling techniques, much of these reserves cannot be extracted in an economically viable fashion.

Figure 4. Existing oil wells in relation to thermal maturity (Nordeng 2010)



### 1.1.1. Drilling Technology

Traditional methods of oil extraction involve drilling a vertical well to an underground oil pool and extracting the oil directly. As mentioned above, early drilling of the Bakken focused on

the upper and lower shale members. “Success in these efforts hinged on connecting conventional vertical wellbores with an existing natural fracture system while not ruining the wellbore in the process with introduced drilling fluids. The shale itself is highly reactive with water and swells when exposed to it, which can seal off a productive fracture system” (Grape 2006). The natural fractures release crude oil so that it may be extracted; therefore, locating these fractures was essential.

A limitation of drilling at natural fractures is that the natural fracturing process only releases a portion of the available crude oil. However, a new technique known as hydraulic fracturing was introduced in the 1920s (Grape 2006). Hydraulic fracturing is an artificial method of well stimulation used to maximize the availability of crude oil. Within the Bakken formation, it is commonly used to enhance existing fracture systems to allow the oil to flow freely within the formation. A combination of water and chemical additives are pumped into the formation at high pressure. When the pressure exceeds the strength of the rock, additional fractures are created, often hundreds of feet from the wellbore. At this point, a proppant is introduced to the fractures to keep them from closing when pumping pressure is released (United States Environmental Protection Agency 2012).

More recently, technological advances have further improved the economic viability of Bakken wells: directional or horizontal drilling. Directional drilling involves the drilling of any non-vertical wellbore. Initial directional drilling was known as slant drilling, as the wellbore was drilled at a diagonal. This allowed the extraction of oil reserves underneath an already developed surface area, or in certain cases, outside the existing boundaries of the oil field. Within the Bakken formation, the practice of horizontal drilling is commonplace. Horizontal drilling consists of an initial vertical wellbore which, at a specified depth, is deviated at an angle that is

adjusted until the final wellbore is a horizontal lateral wellbore. As the middle member of the Bakken is a relatively narrow 85 feet, this allows a much larger contact area between the wellbore and the formation, which is greatly enhanced through hydraulic fracturing.

A portion of the vertical alignment of the wellbore is enclosed in a concrete casing, thereby preventing contamination of groundwater formations during the fracturing process. The horizontal lateral portion of the wellbore is perforated to allow maximum contact area between the liner and the formation. Once in place, the hydraulic fracturing process commences with the end result of longitudinal fractures along the horizontal lateral. Multiple fracturing stages ensure that fractures occur along the entire horizontal alignment.

North Dakota Industrial Commission Oil and Gas Division statistics show that traditional methods (vertical drilling) of oil extraction from 1970 to 1990 in North Dakota had resulted in an average daily production range of 25-32 barrels (BBLs) of crude oil per well. Within two years of the introduction of horizontal drilling, coupled with hydraulic fracturing in North Dakota, the average daily production rate rose to 49-55 BBLs of crude oil. By the end of 2012, the average well production rose to 87 BBLs of crude per day, for an average production of 575,490 BBLs statewide daily. Over the same timeframe, the total number of producing wells more than doubled from 3,212 to 6,636 (North Dakota Industrial Commission, Oil and Gas Division 2012).

#### 1.1.2. Freight Traffic Generation

With the move to horizontal drilling and hydraulic fracturing from traditional vertical drilling, the number of economically productive development units has increased. This has resulted in increased drilling, causing an increase in total truck numbers required to service oil development. A 2006 study report published by the North Dakota Department of Transportation (NDDOT) compared the loaded truck volumes associated with each type of well technology. In

the report, a vertical well was estimated to generate a total of 395 loaded truck trips: 264 inbound trips and 164 outbound trips. Drilling a horizontal well was estimated to generate a total of 606 loaded truck trips: 402 inbound trips and 280 outbound trips (North Dakota Department of Transportation 2006). In 2006, the majority of Bakken formation development was located in the Elm Coulee oilfield in Montana, and the impacts to North Dakota state highways were primarily due to development outside of the state. Connecting highways specified in the report included ND highway 1804 between Williston and the Montana border, US highway 85 from Williston to Alexander, ND, and ND highway 68 between US 85 and the Montana border. Each of these highways provided a direct connection between the Williston area and the Elm Coulee oil field.

Beginning in 2007, oil development increased in North Dakota, near the Mountrail and Williams County border. With the change in geographic location of drilling activity came changes to the drilling processes, resulting in additional truck trips generated. Recent estimates by NDDOT show approximately 400 inbound truck trips associated with the drilling of a traditional vertical well, consistent with the 2006 estimates. Movements associated with horizontal drilling have increased significantly since the 2006 study, primarily due to increases in the number of hydraulic fractures as well as enhancements to the horizontal drilling processes. A 2010 study estimates a total of 1,100 inbound loaded truck trips for an average horizontal well in North Dakota (Upper Great Plains Transportation Institute 2010). A 2012 study has increased this number to 1,150 inbound loaded truck trips (Upper Great Plains Transportation Institute 2012). Individual truck movements for a typical Bakken horizontal well including hydraulic fracturing are shown in Table 1.

Table 1. Drilling related movements per typical Bakken well (Upper Great Plains Transportation Institute 2012)

Item	Number of Loaded Trucks
Sand	100
Freshwater	450
Wastewater	225
Frac Tanks	115
Rig Equipment	65
Drilling Mud	50
Chemical	5
Cement	20
Pipe	15
Gravel and Scoria	80
Fuel Trucks	7
Frac Pumper Trucks	15
Workover Rigs	3
Total	1,150

Locations for inputs are widespread throughout the study region. Sand for use in hydraulic fracturing is obtained at sand transload facilities, as the bulk of the material is shipped in from out of the region by rail. Fresh water is sourced from local groundwater, municipal water sources, and surface water from rivers. Frac tanks move from site to site to provide temporary storage capacity during the fracturing process. Rig equipment moves from site to site, and includes the heavy equipment associated with the initial drilling process. Drilling mud, chemicals, and fuel are generally sourced from larger cities within the areas where well service companies are located. Pipe, like sand, is obtained from rail transload facilities.

Crude oil and saltwater comprise the main outputs from oil production. Currently, for every three barrels of crude oil produced, one barrel of saltwater is produced. Saltwater is disposed to injection wells, which are located throughout the study area. Crude oil is transported to a transload facility or refinery for export out of the state. There is only one refinery in North Dakota, located in Mandan, which consumes a small portion of the oil patch's production. The

remainder is transported by truck or small diameter pipe to transload facilities for further transportation by pipeline or rail.

Of note are the number of truck trips associated with sand and water. A typical Bakken horizontal well in 2012 utilized 3 million gallons of water, and 4 million pounds of sand during the fracturing process, representing a total of 550 inbound loaded truck movements. Once production begins, the produced water is then transported to saltwater disposal wells (SWD) for injection and disposal. The number of trucks associated with outbound oil and saltwater varies based upon the location of wells and the initial production (IP) rate (Helms, Director, Oil and Gas Division 2011).

## 1.2. Statement of the Problem

NDDOT utilizes a 20-year design standard for all highways in the state. In planning terms, this is defined as the design life. The design life is the desired life of a highway based upon an expected number of equivalent single axle loads (ESALs). An ESAL is a standardized measure of the impact that an 18,000-pound four-tire axle would have on either a flexible or rigid pavement. Based on that estimate, the highway structure is designed to last 20 years. Pavement design begins with the estimation of the total ESALs over a segment of highway over the 20-year design life of the pavement. The pavement life is further defined in terms of the service life of the pavement. The service life is the actual life of a highway. The service life of a highway may be different than the design life if the number of ESALs is different than anticipated when designing the highway. If the ESAL levels increase beyond the levels used in the pavement design, the service life of the pavement would be decreased.

As an example, a sample pavement section may be designed for 100 ESALs per day. For flexible pavements, the design life is consistently 20 years. Converting the daily ESALs to

annual ESALs yields 36,500 ESALs per year. Over 20 years, this represents a total of 730,000 ESALs. If the ESAL levels would conform to the 100 ESAL per day forecasts, the service life of this example highway segment would be equal to the design life.

However, in western North Dakota, anecdotal evidence has provided examples of highways that are receiving ESAL factors that are higher than the design ESALs by a factor of 10. In the example above, this would reflect a highway segment which is receiving 1,000 ESALs per day. The design life would still be 20 years under this case, but the service life would be reduced to two years, due to the highway segment receiving 20 years of ESAL impacts within a two-year timeframe.

The goal of pavement design and traffic forecasting is for the service life to equal the design life. “That is to say that when properties and structural conditions of the existing pavement, base and subgrade materials are known, the existing traffic and loads are known and an accurate estimate of future traffic and load growth are known; the pavement design process will result in a design life and service life which will be equal to 20 years” (North Dakota Department of Transportation 2006). The first components of the conditional statement, structure, and existing traffic can be readily observed through field study and traffic count collections. Accurate estimates of future traffic and load growth require forecasting models and knowledge of trends in equipment usage over time. This study attempts to improve the MDT and NDDOT design processes for highways by improving the accuracy of traffic forecasts in the area impacted by increased oil extraction.

Trend analysis is currently used to forecast traffic levels on state highways within the study region (Levi 2012). Periodic traffic counts are conducted to assess existing traffic levels. These are compared against similar counts in previous years, and a growth rate is calculated

based upon the change in traffic volume over time. In the absence of a new major traffic generator(s), this approach provides reasonable results. For example, in a rural area not impacted by oil development, the primary freight generators would be through traffic and agricultural movements. Normal growth factors may include increasing population in the larger cities, which the through movements serve, and increased agricultural tonnage as a result of changes in crop mix and yield rates by year. Trend analysis may sufficiently reflect expected traffic growth under these conditions.

However, when a major traffic generator such as a grain shuttle elevator or processing facility is introduced, trend analysis is insufficient to predict future flows, as it is heavily influenced by historical data, which were collected prior to the new traffic, and does not predict the new generators themselves. Once sufficient historical data are available following the inclusion of the major generator, trend analysis may be sufficient to predict future rural traffic flows as the network becomes consistent again.

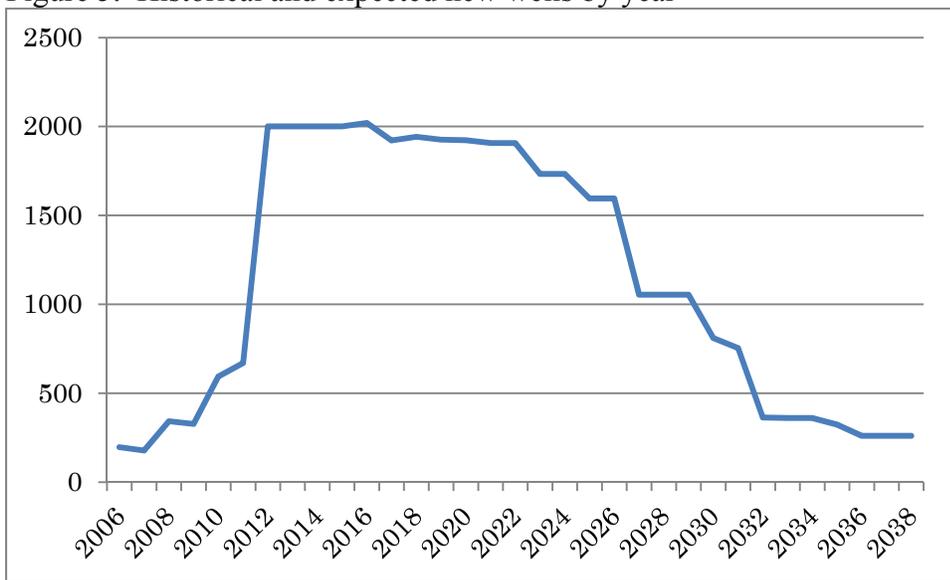
In oil development areas, many major traffic generators are added each year, and a consistent network of origins, destinations, and volumes do not exist and will not until development has ceased. Under these circumstances, trend analysis is not sufficient to estimate future traffic and ESAL levels.

Recent oil development has introduced many significant traffic generators throughout a 22- county region in North Dakota and Montana. In 2012, it was forecasted that 2,000 new wells will be drilled (Helms, Director, Oil and Gas Division 2011). At 2,300 truck trips per well, this represents a total of 4.6 million truck trips annually, related to drilling activities. In addition, average annual well production of 23,291 BBLS per well adds roughly 500,000 truck trips. In total, this represents of 5.1 million one-way, or 10.2 million truck trips when the empty backhaul

is considered. The addition of these truck trips has placed considerable stress on the existing highway system.

Recent forecasts estimate that the level of drilling will peak at 2,000 new wells per year in 2012 and continue at that level through 2016 (Figure 5). At this point, total annual new wells will decrease slightly each year until 2023, when a more significant decrease will occur.

Figure 5. Historical and expected new wells by year



From 2006 to 2011, there was a significant increase in the number of wells drilled, and a corresponding increase in truck trips generated from oil activity. Under traditional trend analysis, traffic growth is significantly underestimated over this time period. As traffic count data is collected, the trend analysis may be updated but still produce significant errors due to the scope and duration of oil development.

Due to the importance of ESAL estimates for use in pavement design to meet the 20-year design life standard, traditional forecasting methods cannot be used. Traditional forecasting would result in significant over-building or under-building of highways to meet the expected ESAL loads. In the case where the trend included historical traffic data before significant oil development alongside current traffic data that show significant three- or four-fold increases in

traffic, the ESAL forecast at the end of the design life would far exceed expected actual ESAL figures. This would result in a highway segment that is built to specifications to handle traffic far above actual traffic values, consuming excessive highway funds. Similarly, if the trend analysis does not include current counts reflecting the additional ESAL factors as a result of increased oil development, excessive highway fund expenditures may arise as the service life would be shorter than the design life, necessitating multiple improvements to meet the design life. Moreover, as pavement condition deteriorates, lower cost improvements such as thin-lift or structural overlays may no longer be feasible, and more costly improvements such as reconstruction become necessary.

### 1.3. Objective of Research

The objective of this research is to develop a traffic model to estimate truck volumes generated by oil development in eastern Montana and western North Dakota for specific highway segments for the next 20 years. Results of this model will provide improved forecasts of truck volumes and ESALs, which will provide improved information to pavement design and planning officials for use in corridor planning and pavement design.

### 1.4. Importance of the Study

This study will follow the four-step approach to traffic modeling, with two specific sub-models designed to improve the accuracy of the models. The components of the four step model are 1) trip generation, 2) trip distribution, 3) mode split, and 4) traffic assignment. Both gravity models and optimization models rely on a unit of impedance between origins and destinations. Often this is a function of time, distance, or cost. One may assume that time is an accurate representation of driver behavior, particularly with passenger travel. Trucking companies often quote prices on a per-mile basis, so distance should be minimized in this case. This study

considers cost associated with distance and time. Variable costs such as fuel consumption, tire wear, maintenance, and repairs are primarily a function of distance, although travel speed is large component of fuel consumption. Variable labor costs are a function of time, based upon trip distance and travel speed. Moreover, the study will utilize a segment-specific cost model, which is unique in the fact that it directly considers travel speed, surface type (and the impacts of roadway condition on trucking cost) as well as distance and wait time at facilities. Previous optimization studies utilized distance as a proxy for cost or per-mile cost derived from a survey, rather than actual roadway characteristics.

The proposed optimization model is similar to methods used to estimate flows of agricultural production from fields to grain elevators, fields to processors, between elevators, and to final destinations. A key portion of this model is the selection of origin destination pairs. Previous studies have assigned pairs based upon geographic proximity, and selected least cost routes to connect them. This study approaches the problem first from the route perspective by connecting all possible origins and destinations using a least cost algorithm. The cost of each route is used as an arc cost in the optimization model, which selects the set of routes to minimize the total system cost.

This study will also utilize a new method of forecasting future well locations. Previous studies have randomly distributed wells, or located them based upon proximity to existing wells. Multiple methods of well location will be examined and tested for the level of improvement relative to previous methods. This study will utilize the Susceptible, Infected, and Recovered (SIR) method, which is used for modeling the spread of disease epidemics.

Finally, previous studies of truck transportation in the Bakken formation have focused on individual states and not the entire region. A study currently underway includes the Montana

portion of the Bakken, along with the border counties, and this study will expand further to include the entire U.S. side of the formation. Ideally, the study would contain the entire formation extending into Saskatchewan and Manitoba, but initial contacts have added uncertainty to data availability from those provinces.

This study utilizes five individual models. The GIS network model provides information on the speed, surface type, and connectivity of the road network over which shipments are routed. The truck cost model estimates the cost of operating over these segments based upon roadway characteristics and wait times. The forecasting model estimates future locations of wells based upon historical data. The network routing algorithm provides the least cost paths from all origins to all potential destinations, providing a route optimized set of transportation options. The trip distribution model utilizes a mathematical programming model to choose the routes that result in the minimum distribution cost for the entire system.

#### 1.5. Organization of the Study

The remainder of this dissertation is organized by chapter. Previous studies are reviewed in Chapter 2 with a focus on the traffic modeling processes, impedance factors, and forecast well distribution. Methodology is discussed in Chapter 3, beginning with the tasks required to locate, route, and optimize oil-related movements within the study area. In addition, data sources are discussed, including types of data, sources, and data quality. Chapter 4 presents the results of the analysis including sensitivity analysis, and comparison of selected methodologies against traditional methodologies. Chapter 5 discusses the impact of the results and uses the results to draw conclusions and offer suggestions for future improvements.

## CHAPTER 2. LITERATURE REVIEW

As discussed in Chapter 1, the objective of this study is to develop a freight traffic model to assign and estimate the impacts of oil development in eastern Montana and western North Dakota on the highway systems in these areas. In the practical sense, this study utilizes a mathematical optimization model with inputs generated by a GIS network model, a truck cost model, and an oil production location forecasting model to predict truck trips on highway segments.

Traffic models often follow the Four Step Model (FSM) approach. Although this study uses a modified version of the FSM, the FSM serves as an organizational tool for the beginning of this chapter. Following discussion of the FSM, relevant truck cost modeling literature is presented, as cost minimization is the basis of the traffic assignment component of this study. Spatial modeling of epidemics is discussed next, and parallels to expansion of oil exploration are drawn. The chapter closes with a brief review of optimization models and a summary of conclusions comparing this study to existing research.

### 2.1. Four-Step Models

Conventional transportation modeling utilizes the FSM. The components of the FSM are 1) trip generation, 2) trip distribution, 3) mode split, and 4) traffic assignment. Significant quantities of research have applied the FSM for use in urban area vehicle routing. This section will review literature relevant to each of these FSM sub-models and describe improvements on these models that will be addressed in this research.

#### 2.1.1. Trip Generation

The first step in the development of a transportation model is identification of the origins and destinations of the trips to be modeled. Trip generation forecasting identifies the type and

scope of movements between traffic analysis zones (TAZ). TAZ are defined as “Geographic areas dividing the planning region into relatively similar land use and land activity. Zones represent the origins and destinations of travel activity within the region...every household, place of employment, shopping center, and other activity...are first aggregated into zones and then further simplified into a single node called a centroid” (Barton-Aschman Associates, Inc. 1998). The ideal size of the TAZ depends on the use of the model: “large-sized zones for system or statewide planning...medium-sized zones for arterial planning...small-sized zones for corridor analysis” (Cambridge Systematics 2007). In passenger trip generation models, these zones are generally defined using population or geographic area, though population is favored. In freight models, the TAZ can range from a geographic area to a single point.

Trip generation begins with activities and the type and number of trips generated by each activity. The end result is that trip generation, “translates the FSM from activity-based to trip-based, and simultaneously severs each trip into a production and an attraction, effectively preventing network performance measures from influencing the frequency of travel” (McNally 2007). This should not be taken to mean that network factors such as highway condition would not impact the trips, rather the trips are as a result of activities (i.e., the demand for trips is a derived demand). In reality, a significant change in network performance would influence the activities, thereby impacting trip generation. From the outset, definition of the TAZ themselves and activities occurring within the TAZ is the focus. Trip generation studies generally focus on one of two methods: category-analysis or regression analysis. Category-analysis or cross-classification analysis assumes that similar activities such as businesses generate similar trips within the same category. For example, a hardware store of a given size is expected to generate the same number of trips as a similar hardware store of comparable size. The number of trips

generated is estimated based on previous observation in other geographic areas. A drawback of category analysis is the assumption that trip generation for a particular category is the same across different geographic areas. As mentioned above, the size of the TAZ should be determined based upon the use of the model. The size of the TAZ also determines the level of aggregation of activities. This document describes a study that will examine trips at the highway segment level, which is even further disaggregated than a corridor study to assess impacts on particular highway segments. As the number of TAZ increase, so does the computational burden.

There is extensive literature on the generation of passenger trips in urban areas, with frequent use of the category-analysis model utilizing frequency and intensity of activities within the TAZ. Passenger trip generation rates by activity may be estimated based upon primary or secondary data or gleaned from previous research. The Institute of Transportation Engineers published trip generation rates by land uses ranging from residential to large-scale retail (Institute of Transportation Engineers 2008). Trip generation rates in this publication are estimated from a number of previous studies, and are the “standard by which local traffic impacts are typically estimated” (Cervero and Arrington 2008). A 2002 review of freight trip generation studies shows frequent usage of linear regression analysis to estimate freight trips generated by firms as a function of land use and vehicle types (Iding, Meester, and Tavasszy 2002).

While no trip generation rates from oil and gas development are presented in the ITE publication, specific information regarding the number, type, and truck configurations are available through previous studies and state transportation departments (Mitra, Tolliver, and Dybing 2012) (Colorado Department of Transportation 2010).

### 2.1.2. Land Use Forecasting

Existing land use is a key input to the trip generation component of the FSM. Since planning horizons for roadway networks are long term in nature, the expected changes in land use throughout the study area must be forecasted. Significant research has been undertaken to forecast urban and suburban land use changes. However, as the topic of this study is primarily rural agricultural areas, a review of urban literature was not conducted. Distribution of new wells is a key component to assessing traffic impacts of oil development, and a review of potential methods is included.

The area of oil development in the Bakken formation is primarily agricultural, ranch, or park lands. It is unlikely that other industrial uses of the land will occur. It is not expected that significant changes in land use from existing use will change, only the addition of oil activity. For example, oil development on agricultural land will not contribute a land-use footprint large enough to displace future agricultural activity.

Two primary methods of distributing new well locations are discussed in the methodology section of this proposal. A review of literature indicated that these methods have not been used in published works to date. Previous studies have used ad hoc location of new wells based upon existing well locations and permit applications within geographic boundaries (Upper Great Plains Transportation Institute 2010). In addition, maximum likelihood distribution of future wells was tested, but predicted the spread of new wells near Lake Sakakawea, and did not reflect oil development on the opposite side of the lake, where significant development is currently underway (Upper Great Plains Transportation Institute 2012). As described in Chapter 3, this study utilizes a spatial technique to distribute new well locations. The technique has previously been used to model the spread of disease epidemics. It

is primarily based upon exposure of a portion of a population to infected individuals in this study, the technique is used to describe the extent, spread, and duration of oil development.

### 2.1.3. Trip Distribution and Traffic Assignment

Trip generation focuses on trips originating as a result of activities present within some zones, and trips attracted by activities present within other zones. Once the origins, potential destinations, and number of trips have been identified, movements between production (origins), and (attractions) destinations are estimated. Distribution refers to the selection of flows between origins and destinations, and is generally made using a gravity model or linear programming model. Traffic assignment occurs once movements between origins and destinations have been selected, and the minimum cost route between them is selected. The distinction between distribution and assignment is that distribution selects the origin and destination for individual trips generated, and assignment selects the method of connecting them. This is generally the final step in the FSM, but in the case of optimization models, traffic assignment for all possible destinations from origins is completed to generate arc cost data for the model.

The gravity model for trip distribution contains three primary components: zones where trips originate, zones where trips terminate, and a measure of separation between the zones. The measure of separation between the zones is a key factor, as it represents the level of attraction between the zones or repulsion between zones. In many cases, a generalized cost of traveling between the zones, often a combination of travel time, distance travelled, and actual costs is used (S. P. Evans 1972). “It is assumed that the number of trips per unit time between pairs of zones for a particular purpose is proportional to a decreasing cost function of the cost of traveling between them” (E. Evans 1970). The use of the gravity model for trip distribution is widespread.

The end result of this type of analysis is the number of trips between each origin and each destination (trip assignment).

Optimization is another method of distributing trips between origins and destinations. An example from the Eastern Washington Intermodal Transportation Study utilized a mathematical programming model using GAMS to distribute grain flows from fields to elevators in Washington State (Jessup and Ellis 1997). The optimization seeks the minimum cost of distributing grain subject to cost associated with trip distance. Given known grain production and known grain demand at elevators, assignment of trips between townships and elevators was made by estimating the least cost set of shipping routes. Transport costs were estimated using a regression equation estimated from elevator survey responses concerning truck costs per bushel/mile (Jessup and Ellis 1997).

A more recent study utilizes similar methods to develop a traffic model for grain transportation in North Dakota from township to elevator or processor, and transshipments between elevators. In this study, the objective function minimizes the distance of travel, as grain trucking rates are quoted on a per-mile basis, and distance is used as a proxy for transportation cost (Tolliver, et al. 2011).

#### 2.1.4. Mode Split

This study focuses only on truck transportation generated by oil development in the study region. For these movements, there are no alternative modes.

## 2.2. Truck Cost Modeling

As mentioned above, trip distribution and assignment seeks to select routes and assign traffic subject to a measure of impedance. This impedance may be defined as time, distance, cost, or a combination of the three. This study utilizes a cost-minimization approach based upon

route- specific truck costs that depend on characteristics of individual segments of roadway. Due to the importance of the truck cost model component to this study, a review of previous research is presented.

### 2.2.1. Approximating Truck Rates with Truck Costs

Truck cost may be described in two different ways. To the firm operating a private fleet, this may be long-run marginal cost of the trip, including operating cost and the opportunity cost of capital. To the firm utilizing for-hire trucking firms, this is the price paid for shipping cargo from an origin to a destination. The former is the trucking cost, and the latter is the truck rate. This distinction is important, as this study utilizes an economic-engineering truck cost model to estimate trip costs, and assumes that the truck cost is representative of the truck rate paid for these shipments. For this assumption to be acceptable, a number of economic factors must be discussed.

Truck movements modeled in this study are all truckload movements. That is, the shipper provides sufficient quantities of cargo that the cubic capacity or the weight capacity is reached, and there is a single shipper for each movement. The truckload trucking industry is comparable to a perfectly competitive industry. Characteristics of a perfectly competitive industry include a large number of firms, freedom of entry and exit, no control over prices, and all firms producing a homogenous product (McCarthy 2001). Entry and exit to the industry is relatively easy, as the only resources needed are capital to purchase a truck and trailer and a qualified driver to drive the truck. As it is a truckload industry, consolidation terminals are not needed as would be the case in less-than-truckload firms. Services provided by truckload firms are homogenous within trailer types. For all types of industries, the profit maximizing level of output is the level of output where marginal revenue is equal to marginal cost. Since firms in a

perfectly competitive industry have no control over prices, price is constant over all levels of output, therefore marginal revenue is equal to price, and the profit maximizing level of output occurs where price is equal to marginal cost.

In this study, the economic cost of trucking is used rather than accounting cost. Thus explicit and implicit costs are included. Explicit costs of providing truckload service are those costs mentioned above that are directly related to the operation and ownership of the trucking equipment. Implicit costs include the opportunity costs of operating a trucking firm, which are the foregone returns on their capital investment that may have been realized if the investment was not made in trucking.. Accounting profit is equal to the total revenue minus the total explicit costs. Economic profit is equal to the total revenue minus the explicit and implicit costs, and therefore considers opportunity cost. In the long run, in a perfectly competitive industry, economic profits are equal to zero (McCarthy 2001).

In the short run, only variable inputs are easily changed. In the truckload industry, variable inputs would be fuel, labor, tires, maintenance, and repairs. In the long run, all inputs are variable, including the number and type of trucks. While a trucking firm could charge a price that did not recover fixed costs in the SR, if it does not charge a price high enough to cover fixed costs, eventually it will have to exit the industry. Thus, it is reasonable to assume trucking firms charge a price high enough to recover all of their costs.

As mentioned above, the profit maximizing level of output for a perfectly competitive firm occurs where price is equal to marginal cost. In the short run, this would represent the marginal costs of providing truckload service given current capital investment (i.e., number of trucks). In the long run, firms adjust all inputs (including capital) to minimize costs. If a firm experiences excess capacity in the short run, they will reduce their capital; while if they

experience overuse of capital, they will employ the optimal amount of capital for the output they provide, they are in long-run equilibrium, and their long-run marginal cost is equal to short-run marginal cost.

In a perfectly competitive industry, firms are forced by the marketplace to achieve long-run equilibrium. Firms that operate at excess capacity or not enough capacity will be forced to adjust capacity or be forced out of the market by more efficient firms. Moreover, entry and exit will occur until firms in the industry achieve zero economic profit. This is where price equals long-run marginal cost equals average cost, and where average cost is at a minimum. Because of this feature of perfectly competitive markets, if the assumption is made that firms are in long-run equilibrium, price can be approximated by the total average costs that they experience.

Economies of scale occur when average total cost decreases as additional units of output are produced. “For motor carriers most evidence seems to point to constant returns to scale...Most cost studies of the trucking industry therefore reflect a technological structure that is conducive to an industry that would be (and is) highly competitive without regulation of prices and entry” (Gomez-Ibanez, Tye, and Winston 1999). The lack of scale economies in the motor carrier industry indicates that the costs of firms providing truckload services face similar costs for providing services, regardless of firm size.

Specification of the marginal cost of a truck movement requires consideration of joint costs associated with fronthaul and backhaul movements. “Joint costs exist when the provision of a specific service necessarily entails the output of some other service...Return trips (or ‘back-hauls’), where the supply of transport services in one direction automatically implies the provision of a return service, are the classic examples in transportation economics” (Button 2010). To accurately reflect the marginal cost of a shipment, changes in total cost as a result of

the shipment must be considered. If there is a loaded fronthaul, and an empty backhaul, the marginal cost of the truck trip is the cost of the round-trip, as the purpose of the trip is specifically for the loaded inbound movement, and therefore all costs of the trip may be attributed to the loaded portion. If there is both a loaded fronthaul and backhaul, there are dual purposes to the trip, and the marginal cost of the trip in each direction should be considered. In this study, the vast majority of the truck movements have an empty backhaul, so the round trip cost represents the marginal cost of the trip. A subset of trips involving movements of rig equipment are loaded both inbound and outbound, and the cargo is the same in both directions. For these trips, the marginal cost is the cost of the shipment in each direction.

If the marginal cost of the truck trip is equal to the price of the movement, then truck costs may be used to approximate truck rates. As described below, the explicit and implicit costs of providing truckload service are considered. This includes an opportunity cost of capital. The opportunity cost of capital should represent the value of foregone earnings in an equally risky alternative. The finance literature provides guidance for obtaining an opportunity cost of funds provided by all investors. The weighted average cost of capital is a weighted average cost of debt and equity (weighted by the share of each in the firm's capital structure), where the cost of equity is obtained from the capital asset pricing model.

### 2.2.2. Truck Cost Components

Truck costs of individual movements are a function of trip distance, operating characteristics, vehicle characteristics, input prices and equipment prices. As outlined in this section, estimates of these costs are obtained through a variety of methods, including surveys of trucking firms, experimentation, and economic-engineering models that utilize operating

characteristics from observation of operating factors. Often, estimating truck costs is made difficult by a lack of publicly available data.

Automobile cost estimates and resale values are widely available from multiple sources such as manufacturers, dealers, and resellers, and serve primarily as a marketing tool for consumers. Similar data are not readily available for trucks. “This is probably because buyers of trucks are more knowledgeable about their purchases, and hence have less use for such services” (Barnes and Langworthy 2003). In addition, trucking firms as a business are required to keep detailed records for fuel tax, registration, and accounting purposes, and have greater amounts of data upon which to estimate individual cost components. A typical automobile owner would not have similar incentives to collect detailed data, thereby creating an opportunity for third parties to present these data as an educational and marketing tool.

In a 2003 research report, the Minnesota Department of Transportation (MNDOT) conducted a review of prior truck cost studies and models, with a focus on conventional semi-truck cost components for data collection purposes to develop a spreadsheet-based truck costing model (Barnes and Langworthy 2003). The MNDOT study review focused on the data used to obtain cost estimates as well as the distribution of the individual component costs.

A distinction should be drawn between linehaul and terminal truck costs. Most truck cost models consider the linehaul components of truck costs, such as fuel, labor, mileage-related maintenance, tire wear, and mileage-related depreciation. Terminal costs such as loading, unloading, and fuel consumption due to idling and queuing times are often not considered and distributed over trip mileages. Moreover, in some cases, terminal costs may be wrongly attributed to linehaul operations. For example, if the annual opportunity cost of truck ownership is divided by the annual miles, some costs that are really incurred while waiting at terminals are

attributed to linehaul operations. When using a per-mile cost to estimate truck cost for individual shipments, this could result in an overstatement of long-haul movement costs relative to short-haul movement costs. As presented in Chapter 3, this study will incorporate estimates of terminal costs for different facility types to reflect the entire trip cost for use in the optimization model.

Linehaul cost components may be classified as vehicle-based and driver-based. Vehicle-based cost components include fuel, truck and trailer depreciation and opportunity costs, repair and maintenance, fuel taxes, truck insurance premiums, tires, licensing, permits and tolls. Driver-based cost components are divided among wages, benefits and bonuses (Trego and Murray 2010). Although specified separately in Trego and Murray (2010), fuel taxes are included in fuel price, and will not be addressed separately in this model. These costs may also be classified as fixed or variable in the short run. Fixed costs include truck and trailer depreciation and opportunity cost, insurance premiums, licensing, and permits. Variable cost components include all driver-related costs, fuel and oil, tires, fuel taxes, and tolls. Economic theory states that in the short run, only variable costs may be easily changed, and vary with differing levels of output, or in the case of truck costing models, miles driven. For the variable cost components, there may be a linear or non-linear relationship between trip distance and variable costs. Fixed costs do not change with output and cannot be changed in the short run, and the per-mile impact of fixed costs is dependent on annual truck utilization.

In the long run, both variable and fixed costs are variable. Due to the longer planning horizon, changes to the amount and type of capital investment is possible; therefore considering fixed inputs variable in this context is appropriate. In the case of firms providing truckload services, this would primarily be changes in the size of the fleet. It also needs to be considered

because the other possible decision is exit. If firms don't earn fixed costs, they will sell their trucks and exit the industry. Since the capital requirements for equipment are relatively small compared with other industries, entry and exit to the industry would also be easy.

### 2.2.3. Variable Costs

As outlined above, variable costs vary with changes in output in the short run. That is, as the number of miles driven increases, the variable costs associated with the trip increase. The five major variable cost components are fuel consumption, oil consumption, tire wear, maintenance and repair, and labor. Fuel consumption models are based upon experimental tests of different vehicle types on differing terrain at a range of travel speeds. Oil consumption is often estimated as a function of distance as it is "a relatively unimportant component of vehicle operating cost," and estimates are obtained through a survey instrument rather than experimentation (US Department of Transportation 1982).

Because estimates of tire wear costs are rare, much of the truck cost literature cite the U.S. Forest Service tire wear models, which were developed as a part of an overall vehicle costing system (Della-Moretta and Sullivan 1976). Of note in this research is the importance given to tire wear due to roadway conditions traveled by forest service vehicles. The model presented in Della-Moretta and Sullivan (1976) was designed to consider the impacts of low standard roads traveled by logging vehicles. In recent models, fuel consumption and labor costs account for higher proportions of truck costs due to the relative consistency in highway conditions. Tire wear costs are estimated through consideration of tire wear estimates, total miles driven, and tire costs (Berwick and Dooley, Truck Costs for Owner/Operators 1997).

Labor costs are estimated through calculation of the total labor hours driving and waiting at origin and destination. Some models include wage variations between driving and waiting

times to account for compensation practices within the industry (Berwick and Farooq, Truck Costing Model for Transportation Managers 2003). Utilizing such a model for a route-specific costing function must consider the application of per-mile terminal costs over differing trip lengths. Per-mile cost estimates derived, including terminal costs, must not be applied generally throughout an entire network, as the proportion of terminal costs per mile would certainly vary based upon the length of the trip. For example, consider a 50-mile and 100-mile truck trip which includes linehaul costs of \$2.50 per mile and terminal costs of \$40. The cost of the 50-mile trip would be \$165 and the cost of the 100-mile trip would be \$290. This equals \$3.30 per mile or \$2.90 per mile for the 50- and 100-mile trips respectively. Each per-mile cost estimate is only applicable for trips that have the distance specified in the model, and cannot be used as a network-wide per-mile cost. This study separates linehaul and terminal costs, as linehaul costs are consistent over all roadway miles within roadway categories. Terminal costs are added after the route selection process has been completed.

As mentioned above, roadway condition may have a significant impact on variable truck costs, particularly with tire wear. Adjustment factors for tire wear, maintenance, and repair based upon present serviceability ratings (PSR) have been estimated separately using the U.S. Forest Service slip-energy model. (US Department of Transportation 1982) Building upon these assumptions, adjustment factors for tire wear, maintenance, and repair based upon roadway PSR were estimated (Barnes and Langworthy 2003).

In the review of literature, Barnes and Langworthy (2003) provided comparisons of variable cost estimates for fuel, tires, and maintenance and repair from previous studies.

Table 2. Truck literature short run variable cost summary (cents per mile) (Barnes and Langworthy 2003)

Source	Total Costs	Fuel	Maint./Repair	Tires
Roth, 1992	121	17.3	12.0	2.5
Faucett, 1988	109	21.6	10.9	3.5
Berwick, 1996	104	19.0	10.0	4.0
USDA, 1995	108	19.1	15.5	2.8
Trimac, 2001	174	24.4	10.5	3.5
Volvo, 2000	64	6 mpg	7.1	2.1

#### 2.2.4. Fixed Costs

Variable costs are one component of truck costs. This study utilizes a total cost per mile for providing truck transportation, and therefore must consider fixed costs in conjunction with variable costs. Fixed-cost components do not change with varying levels of output. Data items considered in truck costing models are purchase price, salvage price, useful life, depreciation, insurance, and opportunity cost (Berwick and Dooley, Truck Costs for Owner/Operators 1997). Purchase price, salvage price, and interest estimates are typically obtained through surveys of truck manufacturers and trucking firms and used to calculate depreciation cost. Depreciation expenditures are divided into two categories: use-related (miles) and time-related (years). Often, the two are mixed as is the case in Berwick and Dooley (1997), as the useful life is specified in years, and the depreciation cost is converted to per-mile costs by dividing annual depreciation by annual mileage.

“Depreciation expense is one of the most difficult of all non-fuel running costs to estimate correctly. The major area of contention in the debate concerning depreciation is what, if any, portion of the expense should be assigned to operation of the road” (US Department of Transportation 1982). Whether time-based or use-based depreciation is considered, the estimation principles are the same. Time-related depreciation is approximated by the reciprocal of the maximum useful life of semi tractors and trailers in years. Use-related depreciation is

approximated by the reciprocal of the maximum useful life of semi tractors and trailers in miles. The primary difference between these two measures is annual truck utilization, measured in miles traveled per year.

While depreciation considers the per-unit application of fixed costs, it does not directly consider the opportunity cost of the capital invested in truck equipment. The weighted average cost of capital is a representation of the minimum return on capital investment that a firm must earn or the capital will be invested elsewhere. The cost of capital is the “weighted average of the cost of equity and after-tax cost of debt, weighted by market values of equity and debt” (Damodaran 2012). For the purposes of this study, the weighted average cost of capital is adjusted to reflect pre-tax cost of capital. The rationale for this is that the post-tax cost of capital in marginal cost calculation would result in a price that is below the level necessary to meet the necessary return plus the tax burden.

### 2.3. Contribution of the Research

This study follows the four-step approach to traffic modeling, with a truck cost and spatial distribution model designed to improve the accuracy of the forecasts. The truck cost model offers an improvement over previous studies in that the impedance used in the routing and optimization models expressly considers surface condition and travel speeds in calculating trucking costs. As mentioned in the trip distribution section, both gravity models and optimization models rely on a unit of impedance between origin and destination sets. Often, this is a function of time, distance, or cost. One may assume that time is an accurate representation of driver behavior, particularly with passenger travel. Trucking companies often quote prices on a per-mile basis, so distance should be minimized in this case. This study considers cost associated with distance and time. Moreover, the study will utilize a segment-specific cost

model, which is unique in the fact that it directly considers travel speed, surface type (and the impacts of roadway condition on trucking cost) as well as distance and wait time at facilities. The optimization studies mentioned above utilize distance as a proxy for cost or per-mile cost derived from a survey, rather than actual roadway characteristics.

This study also makes an improvement over previous studies in the optimization method used. The optimization model utilized in this study is similar to methods used to estimate flows of agricultural production from fields to elevators, fields to processors, between elevators, and to final destinations. Previous studies have assigned origin-destination pairs based upon geographic proximity, and selected least cost routes to connect them. This study approaches the problem first from the route perspective by connecting all possible origins and destinations using a least cost algorithm. The cost of each route is used as an arc cost in the optimization model, which selects the set of routes to minimize the total system cost. This allows for a more accurate assignment of traffic flows that may not necessarily be limited to flows of points in close proximity.

A third improvement this study makes is in forecasting locations of traffic generators. This study utilizes new methods of forecasting future well locations. Previous studies have randomly distributed wells, or located them based upon proximity to existing wells. Multiple methods of well location are examined and tested for the level of improvement relative to previous methods. Methods include: maximum likelihood algorithms and the Susceptible, Infected, and Recovered method, which is used for modeling spread of disease epidemics.

Finally, previous studies of truck transportation in the Bakken formation have focused on individual states and not the entire region. This study will expand further to include the entire

U.S. side of the Bakken formation. Ideally, the study would contain the entire formation extending into Saskatchewan and Manitoba, but is unavailable from those provinces.

This study utilizes five individual models. The GIS network model provides information on the speed, surface type, and connectivity of the road network over which shipments are routed. The truck cost model estimates the cost of operating over these segments based upon roadway characteristics and wait times. The forecasting model estimates future locations of wells based upon historical data. The network routing algorithm provides the least cost paths from all origins to all potential destinations, providing a route optimized set of transportation options. The trip distribution model utilizes a mathematical programming model to choose the routes that result in the minimum distribution cost for the entire system.

## CHAPTER 3. DATA AND METHODS

This chapter outlines the methodology used to develop a freight traffic model to estimate impacts of oil development and exploration in eastern Montana and western North Dakota. This chapter is organized into six major sections, based upon individual models utilized in the analysis: 1. GIS network modeling, 2. Truck cost model, 3. Network routing algorithm, 4. Future well distribution, 5. Route assignment/trip distribution, and 6. Summary of methods. Within each section, the data requirements necessary for each step in the analysis are discussed.

### 3.1. GIS Network Model

The GIS network model used in this study consists of shapefiles containing line and point features. The line features are the highway networks themselves. Point features represent potential origins and destinations within the study area.

Roadway shapefiles have been obtained from the North Dakota GIS Hub and the Montana Department of Transportation. Each of these data sources are maintained by the respective departments, and include information on roadway surface type, jurisdiction, and location. The roadway networks include all roadway types: trails, township, county, county major collectors, forest service, tribal, state, and federal. Within the state and federal roadway types, functional classes are included to designate interstate, US, and ND highways.

The primary limitation of the roadway networks in the GIS shapefiles is identification of roadway segments below state and federal jurisdictions. Often, the Emergency 911 (E911) roadway address is included, but identification is not included on the entire network population. This study disaggregates the network to the segment level for cost calculations, and combines individual segments into routes. Next, traffic volumes are assigned to these routes. Finally, the routes are disaggregated to the component segments to summarize traffic volumes from multiple

sources to individual segments. Due to the data handling techniques involved, a unique identifier for each road segment is required. Since the identifiers on the existing datasets do not meet this standard, a unique identifier is generated for each segment, with logic that will allow it to be cross referenced to the original dataset for visualization purposes.

A secondary limitation of the roadway network is speed limit data. The speed limit is a critical data component for use in cost calculations. Expected truck route selection would involve traveling to a higher jurisdiction of road wherever possible due to faster travel speeds and improved roadway condition. For example, if an oil well is being drilled in a rural area that is serviced by a township road, it is expected that the driver will use this road to travel to the nearest county or state highway for the longer portion of the trip.

For state and federal roadways, speed data are obtained from the Highway Performance Monitoring System (HPMS) datasets provided by each department of transportation. The HPMS data contain detailed information about roadway geometry, condition, and traffic volumes. However, these data do not exist for every segment within the study area as the HPMS is a representative sample of the highway system. This sample is expanded to represent the overall highway network conditions. General speed limit rules by state are shown in Table 3 and Table 4. Since the study area primarily consists of rural roads with minimal changes in speed limits, it is assumed that the speed limits assigned to the samples are representative of the non-sample segments as well. One possible violation of this assumption would occur when a state highway goes through a small town where speed limits typically decrease to 45 or 25 mph. For local and county roads, a database of speed limits is not available. General rules are established for each surface type and jurisdiction to approximate travel speeds on these segments.

Table 3. North Dakota standard speed limit guidelines (North Dakota Department of Transportation 2011)

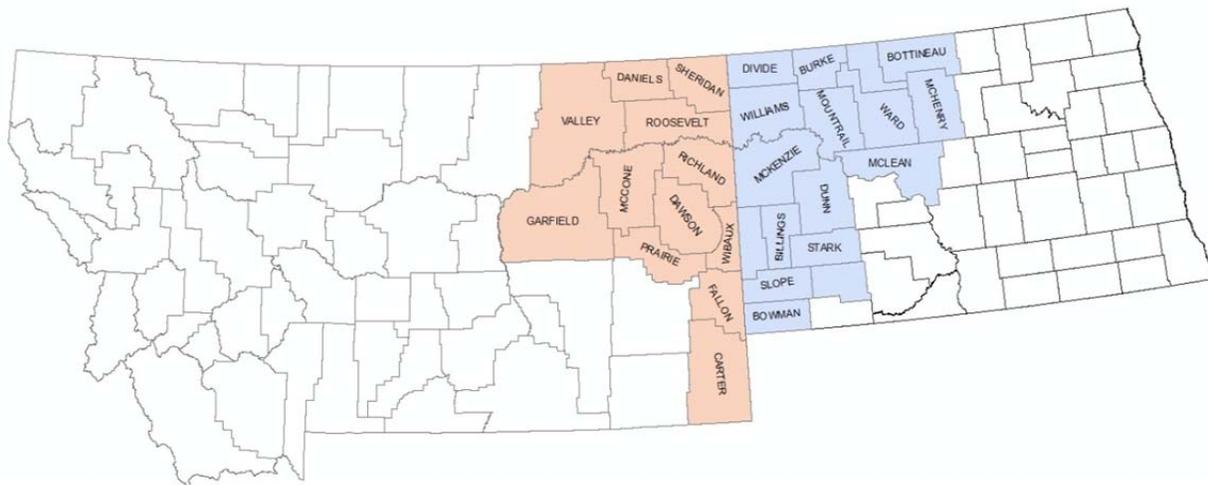
Speed Limit	Criteria
20 mph	School zones, when view is obstructed
25 mph	Business districts, residential areas, parks
55 mph	Gravel, dirt, or loose surface
65 mph	Paved two-lane highways
70 mph	Paved and divided multilane highways
75 mph	Access controlled, paved and divided, multilane interstate highways

Table 4. Montana truck speed limit laws (Montana Department of Transportation 2010)

Speed Limit	Criteria
	Daytime
65 mph	Interstate
60 mph	Primary and Secondary
	Nighttime
65 mph	Interstate
55 mph	Primary and Secondary

The geographic scope of the study is presented in Figure 6.

Figure 6. Study area



The network comprises connected, individual segments with the attributes describing the travel speed, surface type, jurisdiction, and functional classification. The next step in the analysis is to identify the locations that will be connected via the GIS network.

### 3.1.1. Locations

A transportation analysis zone describes the geographic unit and the level of disaggregation within the study network. In urban traffic models, this is typically defined by census characteristics such as population. The focus of this study is freight rather than passenger traffic, so boundaries will be set based upon geography rather than population.

The base geographic area in oil development is the spacing unit. In North Dakota, this is typically a 1,280-acre tract, one mile by two miles in dimension. Ideally this would be the unit of analysis for this study. However, computational limitations necessitate that a larger unit of development be used in this analysis. In this study, the total number of spacing units would exceed 10,000, exceeding the software's capabilities.

This study will use the township as the traffic analysis zone. A six mile by six mile township represents 18 1,280-acre spacing units. Aggregating oil development at this level will introduce a degree of error, as forecasted wells will be assigned to the centroid of the township. The error arises from the point at which the truck movements will enter or leave the township. Because the location of the new wells is at the centroid, the maximum possible error is 3 miles in any direction. In comparison, the maximum error of using the centroid of a spacing unit is one mile in any direction.

The U.S. Bureau of Transportation Statistics National Transportation Atlas Data (NTAD) shapefiles of county subdivisions provide township boundaries, as well as township centroids. Many counties in western North Dakota and eastern Montana have unorganized townships, and there is no legal distinction for township boundaries within these counties. However, this study utilizes township as the transportation analysis zone for boundary purposes rather than organizational purposes. The township centroids serve as the destination for inbound

movements and the origin for outbound movements. Locations of the input locations and outbound destinations are discussed below.

#### 3.1.1.1. Freshwater

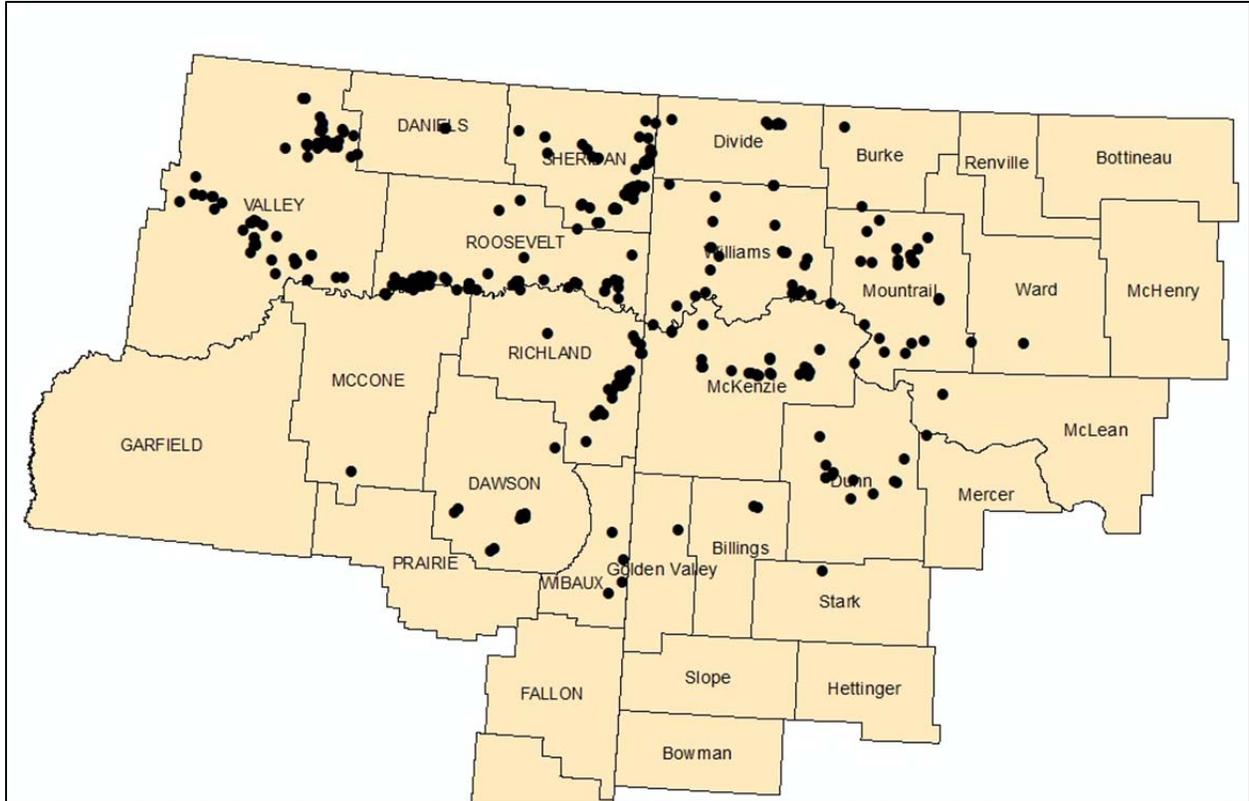
Freshwater is the largest generator of truck trips in the hydraulic fracturing process, comprising more than one-third of the total truck trips. Freshwater sources include groundwater, municipal water systems, rivers, and surface water. Due to the high demand for water at each well site, it is expected that freshwater will be a constraining factor for the distribution model. Both Montana and North Dakota have regulatory bodies that govern the total output and quantity of the water available for sale to secondary parties for each water source.

Montana freshwater sources are obtained from the Montana Department of Natural Resources and Conservation database. Specific output volumes and use classifications are used to define the subset of existing water resources available for use in oil development. North Dakota fresh water sources are obtained from the North Dakota State Water Commission, which maintains a shapefile of all permitted and water permit applications, along with associated annual capacities.

In the 2011 North Dakota Legislative Session, House Measure 1206 addressed the development of the Western Area Water Supply Project, which involves the construction of a pipeline system designed to connect municipalities, rural water users, and water sources (Chapter 61-40 Western Area Water Supply Authority 2011). With the expanded population growth in western North Dakota, this is expected to provide sufficient water resources to support future population levels. In addition to human consumption, a portion of the water will be available for use by the oil industry. Shapefiles of the water depot locations have been obtained from the

Western Area Water Supply Authority management, along with expected completion dates and expected capacity available for oil development use.

Figure 7. Freshwater locations

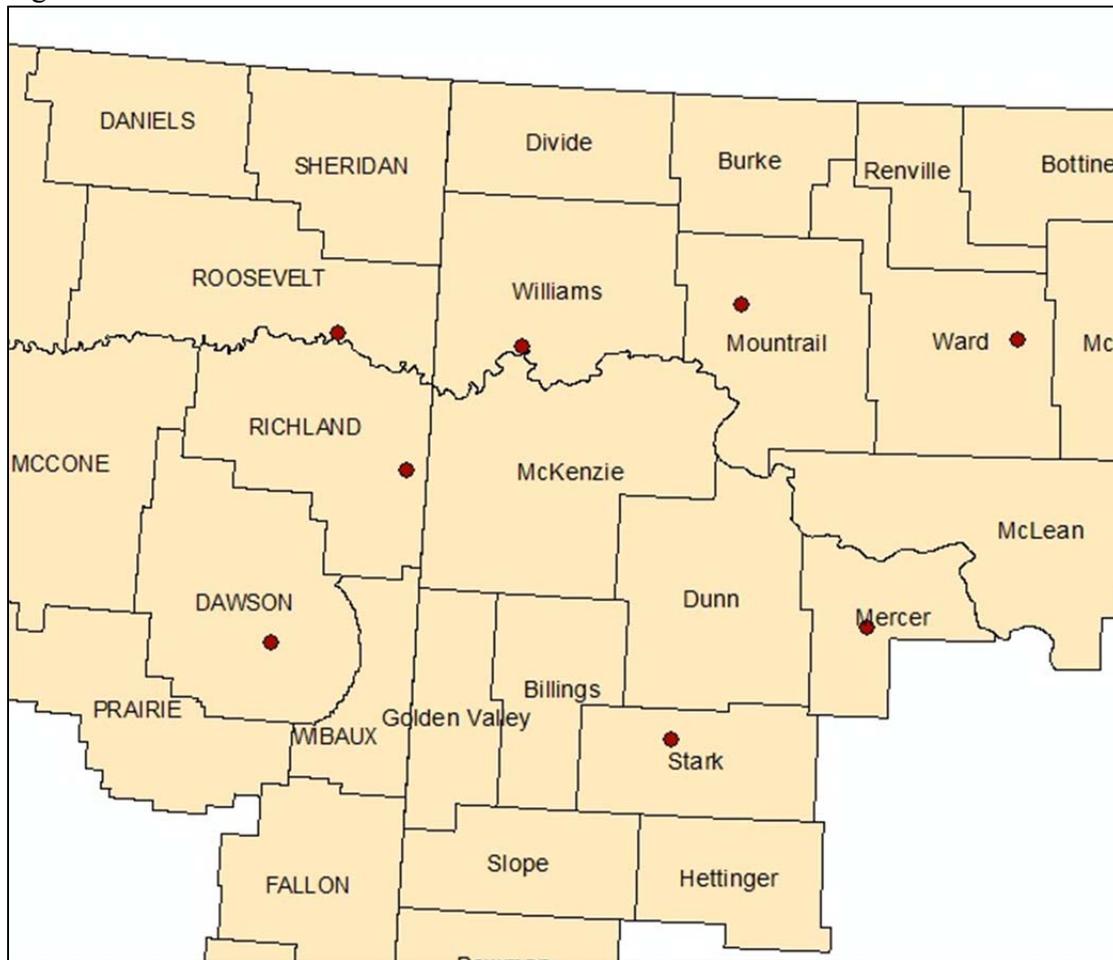


### 3.1.1.2. Sand

Sand is used in the hydraulic fracturing process to prop open cracks in the oil bearing shale following the detonation of explosive charges. By maintaining these gaps within the shale, additional oil may be extracted from the well. The type of sand used as proppant in the Bakken development has very specific characteristics and is not found in North Dakota or Montana. All sand used in the fracturing process is brought into the region via rail.

There are currently five locations in the study area that are sand transload facilities, all of which are located in North Dakota. They are located near the cities of Beulah, Dickinson, Minot, Ross and Williston. These facilities serve all sand demands within the model and are currently not limited by capacities.

Figure 8. Sand transload locations



### 3.1.1.3. Oil Transload

Outbound oil from producing wells is moved by truck or pipeline to oil collection facilities. Oil collection facilities include rail transload facilities and pipe transload facilities. The mode which is used to transport crude oil to collection facilities depends on terrain, pipeline connectivity, age of the development area, and production rate. Individual wells are often connected to a small diameter pipeline that runs on the surface. The incidence of this connection is dependent on the terrain and distance to the nearest collection facility. Recent history has indicated that within three years after drilling, a portion of new wells will be connected to this type of pipeline system, thereby reducing the number of trucks moving over the highway system

(Helms, Director, Oil and Gas Division 2011). Mode data for existing wells are maintained by the state of North Dakota, but not the state of Montana. Interviews with the Montana Oil and Gas Board have indicated that transportation practices in Montana are similar to North Dakota (Halvorson 2012). Whether or not an individual well is connected to the pipeline system is dependent on terrain, production rate, and proximity to other connected wells or oil fields (production density). North Dakota collects monthly mode choice information for existing wells for crude oil outputs, but does not maintain a historical database upon which statistical analysis could be conducted.

Oil transload facilities represent the second major constraint in the distribution model. Table 5 shows that additional oil handling capacity has been added in recent years, and is expected to continue into the near future, based upon permit applications and company press releases. The primary mode used is pipeline, and additional pipeline capacity is expected to be brought on line by 2013. However, additional capacity shown in 2012 and 2013 is not currently available, and may not be constructed for numerous reasons including environmental, economic, or funding considerations. Rail transload facilities are currently expanding, and are expected to expand throughout the near term, as indicated by railroad press releases.

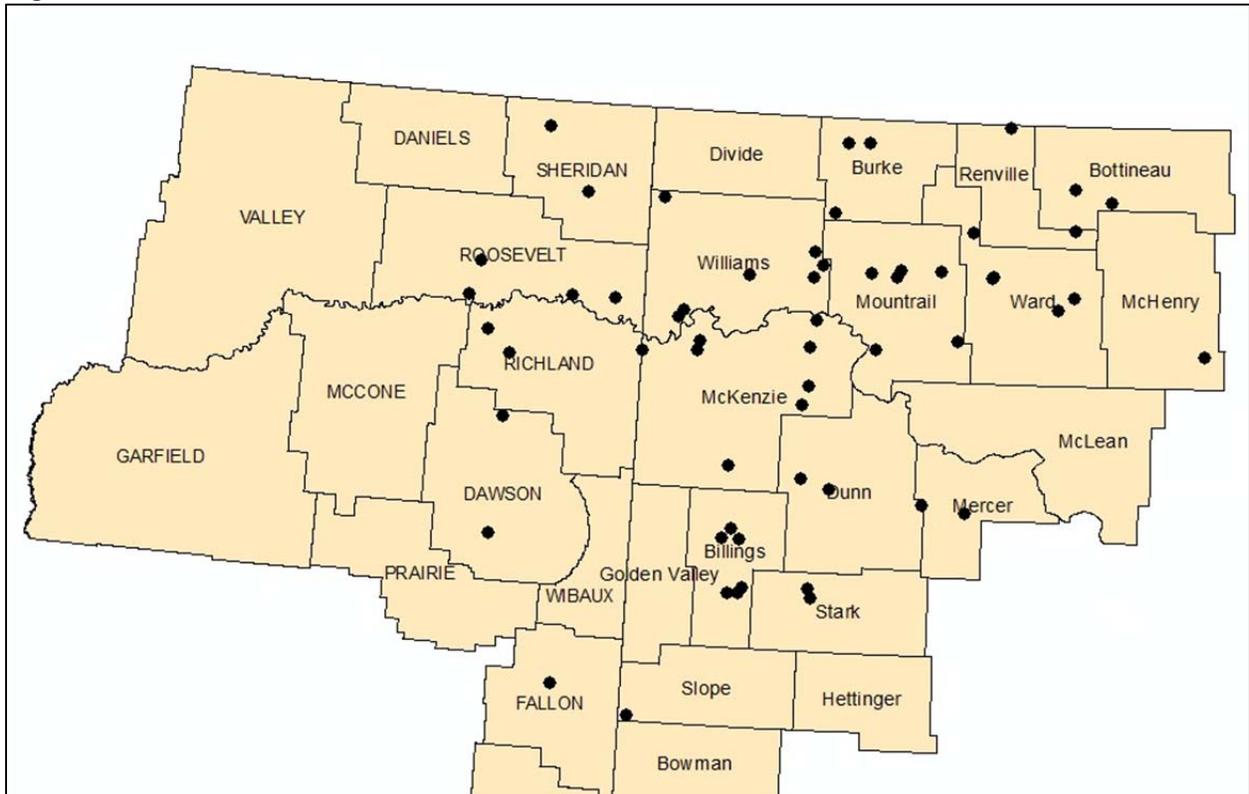
Within the model, only the oil collection facilities that are in existence during the year of analysis will be considered. In future years, only facilities that are currently under construction, or have existing dedicated funding sources will be included.

Table 5. Historical and forecasted outbound oil transportation capacity (Kringstad 2010)

Transportation System Capacity, Barrels Per Day	2007	2008	2009	2010	2011	2012	2013
Pipeline Transportation							
Butte Pipeline	92,000	104,000	118,000	118,000	118,000	118,000	118,000
Enbridge ND	80,000	110,000	110,000	161,500	161,500	161,500	161,500
Tesoro Mandan Refinery	58,000	58,000	58,000	58,000	58,000	58,000	58,000
Enbridge Sweet Only	-	-	-	-	23,500	23,500	23,500
Enbridge Bakken Expansion	-	-	-	-	25,000	25,000	145,000
Butte Pipeline Expansion*	-	-	-	-	32,000	32,000	32,000
Butte Loop*	-	-	-	-	-	50,000	50,000
Plains Bakken North*	-	-	-	-	-	50,000	50,000
Keystone XL Interconnect *	-	-	-	-	-	-	100,000
Pipeline Only Total	230,000	272,000	286,000	337,500	418,000	518,000	738,000
Rail Transportation							
Various sites	-	30,000	30,000	30,000	30,000	30,000	30,000
EOG Rail	-	-	65,000	65,000	65,000	65,000	65,000
Dakota Transport Solutions	-	-	-	20,000	40,000	40,000	40,000
Hess Rail	-	-	-	-	-	60,000	60,000
Rangeland COLT Hub	-	-	-	-	-	27,000	27,000
Rail only Total	-	30,000	95,000	115,000	135,000	222,000	222,000
Total	230,000	302,000	381,000	452,500	553,000	740,000	960,000

The typical capacity of a crude truck shipment is 220 barrels of oil. Considering this, the total outbound crude oil capacity in 2012 represents 3,363 loaded truck trips and 3,363 empty backhaul trips daily.

Figure 9. Oil transload locations



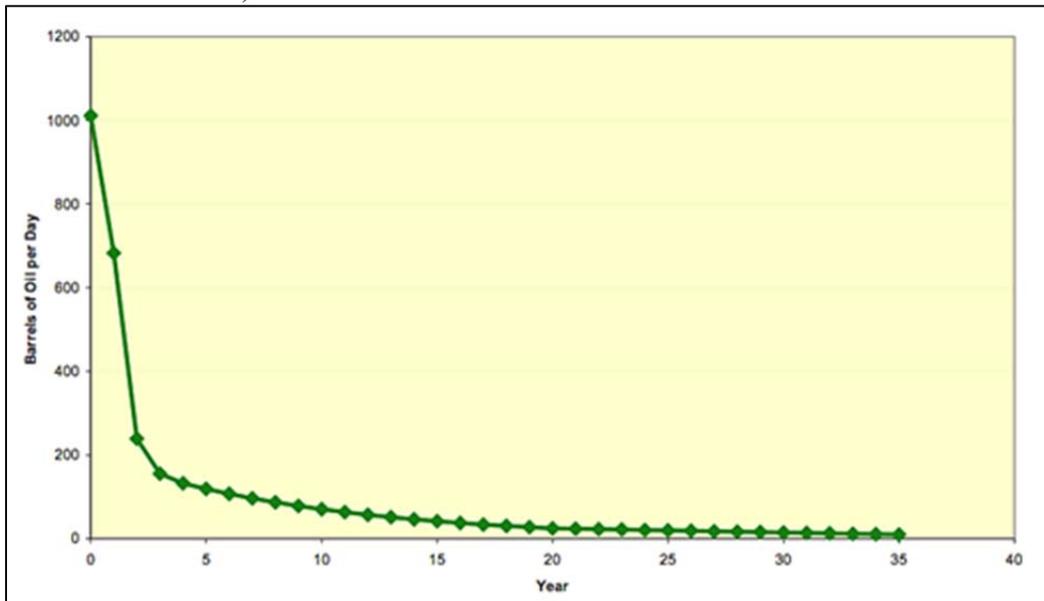
#### 3.1.1.4. Existing Wells

Shapefiles of existing well locations have been obtained from the Montana Oil and Gas Board and the North Dakota Oil & Gas Division. Data for existing wells in Montana include monthly production reports, gas flaring statistics, as well as saltwater-oil ratios for individual wells. North Dakota data include the location of each individual well, but not historical production data. Monthly data have been requested from the Oil & Gas Division, but will only serve as a snapshot of production, as confidentiality requirements prevent the full release of data.

Outbound crude oil moves by either truck or gathering pipeline to transload facilities. Gathering pipelines are typically small diameter pipes laid on the ground surface. Multiple wells connected to this system feed into a tank battery and are fed to a crude oil pipeline.

Figure 10 shows the production curve of a typical Bakken well. The initial production rate is shown as the intercept of the Y axis. Following the initial production of the well, there is a sharp decline in the first four years, followed by a more gradual decline. From interpretation of the data underlying this chart, it shows that 64.7% of a well's production occurs within the first three years, with the remaining 35.3% in years 4 through 35.

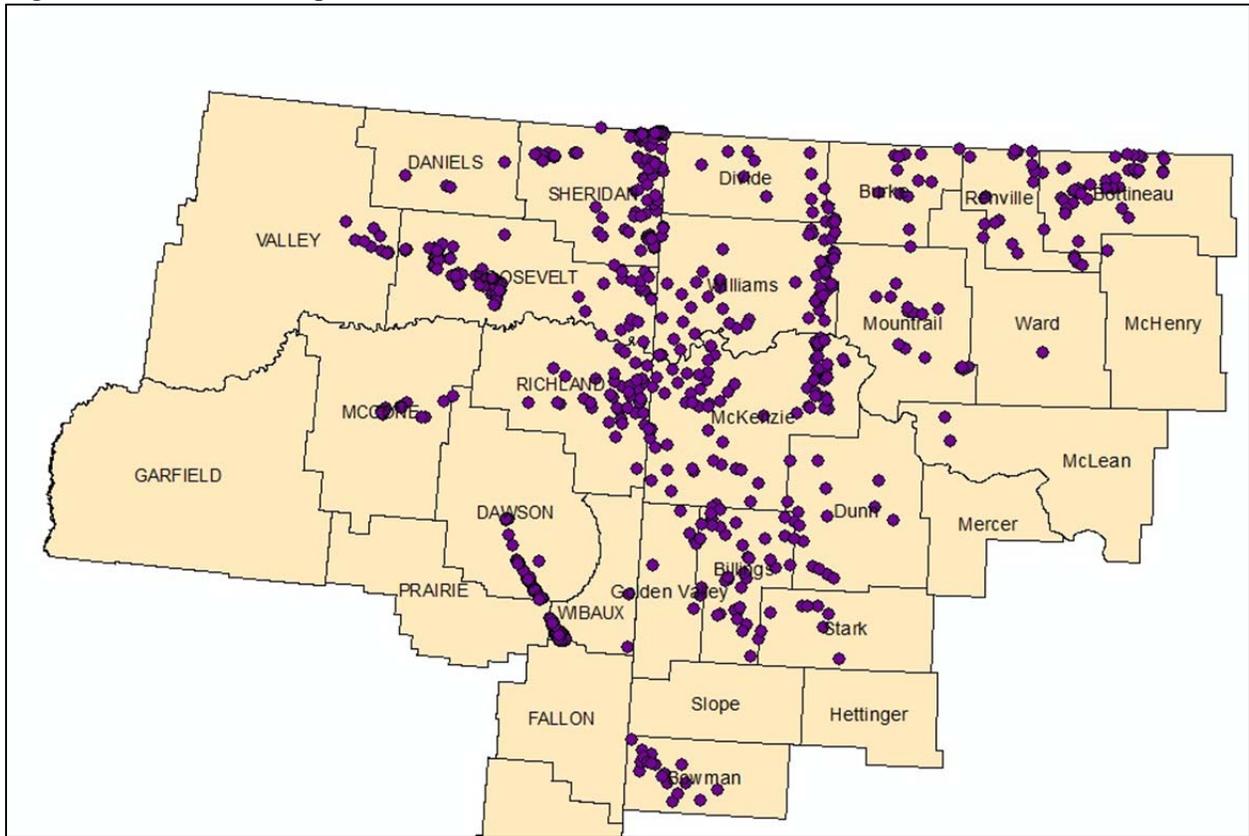
Figure 10. Typical Bakken well production curve (North Dakota Industrial Commission, Oil and Gas Division 2012)



#### 3.1.1.5. Saltwater Disposal

Saltwater disposal (SWD) well locations are obtained from shapefiles from the Montana and North Dakota regulatory authorities and are shown in Figure 11. As mentioned above, North Dakota data include volumes and mode used for delivery to injection wells. While Montana data include monthly saltwater production, North Dakota data do not. However, the ND Oil & Gas Division provides a Barrels of Oil/Barrels of Saltwater (2:1 BO:BSW) ratio which will be used to estimate the saltwater production in relation to known oil production. The locations of SWD disposal wells are shown in Figure 11 below.

Figure 11. Saltwater disposal locations



### 3.2. Truck Cost Model

A major distinction between this study and previous studies integrating GIS and mathematical programming models is the estimation of arc costs. The cost associated with the selection of a route between origin and destination is a sum of the costs of each segment along the route. Due to the rural area in which oil development is occurring, very few origins or destinations will be located directly on a state highway. In fact, many truck trips will be generated on township or county roadways, which have differing surface types and travel speeds.

This study utilizes economic engineering methods to estimate truck costs. Truck movements modeled in this study are bulk truckload movements with the exception of overweight non-divisible equipment movements. It is likely that the incidence of economies of scale are limited, if present at all. If this assumption is correct, the economic-engineering

approach to estimating truck costs is sufficient. Moreover, the truckload market is highly competitive, due to the ease of entry and low fixed costs, as the network and facilities are provided by government or other private entities. The estimated long-run marginal cost will be used to approximate the truck rate for individual shipments. This study assumes that motor carrier firms are in long-run equilibrium. Therefore, since this implies that long run marginal cost is equal to long-run average cost, the study calculates long run marginal cost of individual shipments by using average cost per mile estimates that are based on annual miles driven by trucking firms.

According to the FHWA, eight primary factors contribute to variable truck costs: fuel consumption, oil consumption, tire wear, maintenance and repair, use-related depreciation, accidents, emissions, and running speeds. Since this study approximates truck rates with long-run marginal cost, costs that are fixed in the short run are considered as well (including opportunity cost of capital). As the focus of this study is exclusively on route selection and optimization, costs associated with externalities such as accidents and emissions will not be taken into consideration (US Department of Transportation 1982). Moreover, accident rates are influenced by traffic levels and other factors. There is an obvious connection between running speed and fuel consumption, and a connection between labor costs and running speed. The tradeoff between fuel cost and labor cost depends highly on the input prices for each. In addition to linehaul costs associated with the transportation of oil inputs or outputs, consideration will be given to the terminal costs that arise from the transportation process.

### 3.2.1. Variable Costs

The short-run variable cost components considered in this study are fuel, labor, tires, maintenance, and repair. This section outlines how each of these cost components is calculated.

#### 3.2.1.1. Fuel Consumption

Fuel consumption is estimated using the procedures outlined in Berwick and Dooley (1997). The equation for fuel costs is based upon truck fuel efficiency at 55 miles per hour. Fuel consumption is a function of weight and speed and varies between loaded and unloaded movements as well as truck type and configuration (Berwick and Dooley, Truck Costs for Owner/Operators 1997). The fuel cost equation is based upon previous research, and costs are estimated for level terrain (Knapton 1981). This equation is further modified to reflect fuel efficiency decreases as speed increases above 55 miles per hour. For each 1 mile per hour above 55 miles per hour, fuel economy drops an estimated 2% (Ryder 1994). A more recent report by Bridgestone Truck Tire Company estimates the fuel economy drop at 1.6% per mile per hour over 55 miles per hour (Bridgestone Firestone North American Tire, LLC 2008). The difference between the two estimates is probably a result of improved truck engine and drivetrain technology. Thus, the more recent estimate of the fuel economy change from speed is used.

The modified fuel consumption equation for speeds greater than 55 is:

$$(1) \text{ Miles per Gallon} = \left[ \frac{1}{(VC) * \left( \frac{GVW}{1000} \right) + FC} \right] * [(1 - (0.016 * (MPH - 55)))]$$

Where:

FC = fixed coefficient (varies by truck type)

GVW = gross vehicle weight

VC = variable coefficient (varies by truck type)

MPH = miles per hour

The first term of the equation represents the fuel consumption at a constant speed of 55 miles per hour. The second term represents the reduction in fuel efficiency for each mile per hour above 55 miles per hour, adjusted to reflect current estimates from Bridgestone Firestone North American Tire, LLC. Fixed fuel consumption coefficients are presented in Table 6 and variable fuel consumption coefficients are presented in Table 7. These coefficients refer to the fixed and variable components to fuel consumption estimated at a 55 mph running speed.

Table 6. Fuel consumption fixed coefficient, by trailer type  
(Berwick and Farooq, Truck Costing Model for Transportation Managers 2003)

Configuration	RMD	Conventional	Spread Tandem	Tridem
Van	0.0008	0.0008	0.0008	0.0008
Flatbed	0.0009	0.0009	0.0009	0.0009
Hopper	0.0008	0.0008	0.0008	0.0008
Tanker	0.0009	0.0009	0.0009	0.0009
Reefer	0.0008	0.0008	0.0008	0.0008
53' Dry Van		0.0008		

Table 7. Fuel consumption variable coefficient, by trailer type  
(Berwick and Farooq, Truck Costing Model for Transportation Managers 2003)

Configuration	RMD	Conventional	Spread Tandem	Tridem
Van	0.1203	0.11068	0.11068	0.1155
Flatbed	0.113592	0.1045	0.1045	0.1090
Hopper	0.1203	0.11068	0.11068	0.1155
Tanker	0.113592	0.1045	0.1045	0.1090
Reefer	0.1203	0.11068	0.11068	0.1155
53' Dry Van		0.11068		

The results of equation 1 represent fuel consumption in miles per gallon. The reciprocal of this estimate is the gallons of fuel consumed per mile. This is multiplied by the fuel cost per mile to estimate the fuel consumed per mile traveled, and is calculated for each road segment within the study area based upon roadway travel speed. The fuel price in Williston, ND, at the

time of this study was \$4.24 per gallon for #2 diesel, including state and federal fuel taxes (North Dakota Gas Prices 2012).

The fuel consumption equation for speeds 55 or less is:

$$(2) \text{ Miles per Gallon} = \left[ \frac{1}{(VC) * \left( \frac{GVW}{1000} \right) + FC} \right]$$

### 3.2.1.2. Maintenance and Repair

Maintenance and repair costs are estimated with the methodology outlined in Berwick and Dooley (1997). Baseline estimates of maintenance and repair for trucks is estimated to be \$0.09 per mile at the base gross vehicle weight. This estimate is adjusted using a formula that is a function of gross vehicle weight and percent time loaded or empty (Faucett & Associates 1991). The base gross vehicle weight is 58,000 pounds and maintenance and repair costs are adjusted by 0.00097 cents per 1,000 pounds above or below the base weight.

$$(3) \text{ Loaded Truck Adjustment} = ((GVW-58,000)/1000)*0.00097*\text{Percent time loaded}$$

$$(4) \text{ Empty Truck Adjustment} = -((58,000-GVW)/1000)*0.00097*\text{Percent time empty}$$

These estimates are based upon costs from Berwick and Dooley (1997), and it is highly likely that costs have increased in the 15-year interim. Maintenance and repair cost estimates derived from these equations are adjusted for inflation using the “Motor vehicle repair and maintenance” producer price index from the Bureau of Labor Statistics (U.S. Bureau of Labor Statistics 2012).

### 3.2.1.3. Tire Wear

Tire wear costs are estimated using the methodology presented in Berwick and Dooley (1997), and are a function of weight, distance, and tire cost. Below weights of 3,500 pounds per tire, it is assumed that tire cost is independent of weight. Base tire costs are estimated by dividing the tire cost by the useful life of the tire. This estimate is adjusted by weight of the

truck. Tire weights greater than 3,500 pounds are increased by 0.7% for each 1% increase in tire weight, this adjustment is added to the base tire cost. For tire weights less than 3,500 pounds, the base tire cost is utilized. The base tire cost per mile is adjusted using the following formula:

$$(5) \text{ Tire cost/mile adjustment} = (\text{GVW}/\text{tire} - 3500) / 3500 * 100 * 0.007 * \text{Tire Cost/miles}$$

Where:

GVW=Gross Vehicle Weight

Tire Cost=Cost of trailer or tractor tire

Miles=Expected tire wear life in miles

In addition, tire costs per mile vary based upon the surface condition of the roadway over which the miles are traveled.

#### 3.2.1.4. Surface Condition

Roadway surface condition has an impact on maintenance, tire costs and repair. It is evident that the rougher the roadway surface, the greater the tire wear, as well as greater wear and tear on the vehicle represented by increased maintenance, repair and tire costs. Surface condition also affects fuel consumption. If the roadway surface has deteriorated to the point at which the travel speed has decreased, it is likely that the fuel efficiency of the vehicle has increased due to slower travel speeds. Since this study utilizes lower travel speeds on lower class roads, which typically have poorer surface conditions, it is assumed that the relationship between fuel consumption and surface type has been considered indirectly in the fuel consumption equation of the truck costing model.

A common measure of the condition of a roadway surface is the Present Serviceability Rating (PSR). Primary factors in the calculation of this number are travel speed, cracking, and pavement distress. Guidelines for PSR ranges are presented in Table 8.

Table 8. Present serviceability rating (Federal Highway Administration 2003)

PSR	DESCRIPTION
4.0- 5.0	Only new (or nearly new) superior pavements are likely to be smooth enough and distress free (sufficiently free of cracks and patches) to qualify for this category. Most pavements constructed or resurfaced during the data year would normally be rated in this category.
3.0 - 4.0	Pavements in this category, although not quite as smooth as those described above, give a first-class ride and exhibit few, if any, visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracking and spalls.
2.0 - 3.0	The riding qualities of pavements in this category are noticeably inferior to those of the new pavements and may be barely tolerable for high-speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements may have a few joint fractures, faulting and/or cracking and some pumping.
1.0 - 2.0	Pavements have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes raveling, cracking, and rutting and occurs over 50% or more of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, and scaling and may include pumping and faulting.
0.0 - 1.0	Pavements are in extremely deteriorated conditions. The facility is passable only at reduced speed and considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75% or more of the surface.

Table 9 presents adjustment multipliers to represent increased costs due to surface condition. A surface with a pavement serviceability rating greater than 3.5 (PSR), analogous to an international roughness index (IRI) of less than 80 represents baseline cost conditions. For this study, it is assumed that state highways within the study region fit within this category due to the funding and maintenance levels. As the roadway condition deteriorates, the adjustment multiplier increases. A recent study in western North Dakota surveyed road conditions of paved county major collector (CMC) routes. The average PSR weighted by mileage is 3.088, which would result in a multiplier of 1.05, or a 5% increase in cost above the baseline (Upper Great Plains Transportation Institute 2012). PSR values for gravel roads have been estimated at 1.5 and

1.8, which would utilize the adjustment multiplier of 1.25, representing a 25% increase in cost above the baseline (Hough, Smadi, and Schulz 1996). The multipliers presented in Table 9 are used to adjust the tire and maintenance and repair costs to reflect the impact of roadway condition.

Table 9. Truck cost adjustment factors due to surface condition (Barnes and Langworthy 2003)

PSR	IRI (inches/mile)	Adjustment Multiplier
< 2.0	170	1.25
2.5	140	1.15
3.0	105	1.05
>3.5	80	1.00

The pavement condition adjustment multiplier is only applied to the costs that are directly impacted by pavement roughness, and not reflected by changes in speed. These costs include maintenance, repair, and tire costs. As discussed above, pavement roughness impacts travel speed and therefore fuel costs are approximated by speed limit differences by pavement class and surface type.

#### 3.2.1.5. Driver Wages

One significant attractor of labor to the Bakken region has been high wages during a time of economic downturn in other parts of the country. Due to the higher hourly rate, travel time and queuing costs contribute significantly to total truck costs. Assuming fuel consumption of 5 miles per gallon, an average speed of 55 miles per hour, and a fuel price of \$4.00 per gallon, the hourly fuel consumption cost equals \$44.00 per hour. Recent job advertisements posted on the North Dakota Job Service website indicate that truck driver wages in the oil patch range from \$60,000-\$100,000 per year, or roughly \$28-\$48 per hour (North Dakota Job Service 2012). As wages approach the upper end of the range, the impact of travel speed and queuing become more

significant. It should be noted that this is labor cost attributed to linehaul activities. The labor component of terminal costs is discussed later.

$$(6) \text{ Labor Cost} = (\text{Length}/\text{MPH}) * \text{WR}$$

Where :

Length = segment length

MPH = speed in miles per hour

WR = hourly wage rate for truck drivers

The driver cost equation divides the length of the segment by the speed to obtain the number of hours that it will take a driver to travel the segment. This is multiplied by the wage rate per hour to calculate the labor cost per mile traveled.

#### 3.2.1.6. Running Speeds

Each segment is assigned a speed limit based upon known posted limits, surface type, and road condition. It is assumed that drivers will drive within the legal speed limit, unless bound by condition and surface type factors or congestion. Speed limits were presented earlier in Table 3 and Table 4. However, the impacts of road conditions on tire wear and maintenance are not reflected by the running speed over the roadway segments. Therefore an alternate method to relate roadway conditions is needed to reflect these increased costs.

#### 3.2.2. Fixed Costs

The fixed cost components considered in this study are depreciation, insurance, sales tax on the tractor and trailer purchase, license fees, and opportunity cost. This section outlines how each of these cost components is calculated.

### 3.2.2.1. Depreciation and Opportunity Costs

Depreciation is the cost attributable to reduction in the value of an asset due to use and time. The useful life of tractors is assumed to be five years, and 10 years for trailers (Berwick and Dooley, Truck Costs for Owner/Operators 1997). Annual depreciation for tractor and trailer equipment is calculated using equations 6 and 7 below:

$$(7) \text{ Tractor Depreciation} = (\text{Purchase price} - \text{Salvage price}) / \text{Useful-life} / \text{Annual miles}$$

$$(8) \text{ Trailer Depreciation} = (\text{Purchase price} - \text{Salvage price}) / \text{Useful-life} / \text{Annual miles}$$

Dividing these estimates by the annual truck utilization yields the per-mile depreciation cost for tractors and trailers. Annual utilization estimates for for-hire trucking firms was obtained from the 2002 vehicle use and inventory survey, and was estimated to be 68,200 miles per year (US Census Bureau 2004). Estimates for individual truck types were provided in the inventory and use survey, but it likely that utilization of tank trucks in particular within the state of North Dakota has significantly changed since 2002.

Depreciation considers only the proportional equipment costs per mile and does not account for the opportunity cost of the capital invested in trucking equipment. The total cost of equipment is the summation of the depreciation and opportunity cost. To represent the opportunity cost of capital invested in trucking equipment, the before-tax weighted average cost of capital is used. The weighted average cost of capital estimate is obtained from Damodaran Online, and is adjusted to represent the pre-tax cost of capital. Consideration of the post-tax cost of capital in marginal cost calculation would result in a price that is below the level needed to meet the necessary return plus the tax burden. The pre-tax weighted average cost of capital is calculated as:

$$(9) \left( \frac{E}{D+E} \right) \frac{C_E}{1-T} + \left( \frac{D}{D+E} \right) C_D$$

Where:

E=Equity

D=Debt

C<sub>D</sub>=Cost of Debt

C<sub>E</sub>=Cost of Equity

T=Tax Rate

For the trucking industry, the ratio of equity to debt and equity is 70.35%, the cost of equity is 8.97%, the ratio of debt to debt and equity is 29.65% the tax rate is 25.48% and the cost of debt is 5.29% (Damodaran 2012). Entering these numbers into the above equation, the before-tax weighted average cost of capital for the trucking industry is 10.04%

To estimate the opportunity cost, the following formula is used:

$$(10) \quad \text{Opportunity Cost} = (\text{Purchase price} + \text{Salvage price} / 2) * \text{Cost of Capital}$$

#### 3.2.2.2. Insurance

Insurance premiums are paid on an annual basis. To convert the annual premiums to a per-mile cost, the following formula is used:

$$(11) \quad \text{Insurance Cost} = \text{Insurance premium} / \text{Annual Miles}$$

#### 3.2.2.3. Sales Tax

The motor vehicle excise tax is 5% of the purchase price (the sales price less any trade-in amount) or, if the vehicle is acquired by means other than purchase, the tax is 5% of the fair market value (Office of State Tax Commissioner 2012). The sales tax is incurred only at the

time of purchase. To convert the sales tax to an annual per-mile cost estimate, the following equation is applied:

$$(12) \quad \text{Sales Taxes} = (\text{Purchase price} / \text{Useful Life}) * \text{Sales tax rate}$$

### 3.2.3. Terminal Costs

As mentioned above, wait times at loading or unloading facilities can contribute significantly to the trip cost due to labor prices. It is unclear whether route selection will be influenced by wait times, except where there are significant differences in wait times between facilities. For example, a truck delivering sand to a rig site would likely not be impacted by wait times, because the expected wait time is similar for all sand transload facilities. Anecdotal evidence has suggested that there is wide variability in the wait time for freshwater sources. Depending on the loading equipment and demand, wait can range from minutes to hours. Data on wait times and loading/unloading times at origins and destinations were obtained from telephone surveys of transportation companies providing well service in western North Dakota and are shown in Table 10.

Table 10. Reported wait and loading times at oil-related facilities

	Wait time at Origin	Loading time at Origin	Wait time at Destination	Unload time at Destination
Freshwater	90-150 minutes	30 minutes	Minimal	45 minutes
Sand	15 minutes	30 minutes	75 minutes	45 minutes
Pipe	Minimal	45 minutes	30 minutes	45 minutes
Oil	Minimal	60 minutes	10 minutes	60 minutes
SWD	10 minutes	45 minutes	75 minutes	60 minutes

The labor rate of \$40 per hour is applied to the wait and loading time at origins and destinations. Fuel consumption during idling averages one gallon of diesel per hour of idling time (Oregon Department of Environmental Quality 2010). Total terminal hours are equal to the

total wait and loading/unloading time at the origin or destination. Terminal costs are equal to the total terminal hours multiplied by the summation of driver wages and idling costs.

$$(13) \quad \text{Terminal Cost at Origin} = (WT_O + LT_O) * [W + (FC_I * FP)]$$

$$(14) \quad \text{Terminal Cost at Destination} = (WT_D + LT_D) * [W + (FC_I * FP)]$$

Where:

$WT_O$  = Wait time at Origin

$WT_D$  = Wait time at Destination

$LT_O$  = Loading time at Origin

$LT_D$  = Unloading time at Origin

$W$  = Hourly driver wage rate

$FC_I$  = Hourly fuel consumption while idling (gallons/hour)

$FP$  = Fuel price per gallon

Within the framework of the analysis, it is expected that the inclusion of terminal costs will not likely impact the route selection, as the trip must necessarily include the dummy link to connect to the facilities. Even in cases of freshwater movements, where total terminal time varies significantly, least cost route selection will not be impacted. However, the optimization model will seek to minimize the total distribution cost of freshwater within the study area, and the optimal origin-destination assignment will likely be impacted by differences in terminal costs.

For all locations other than freshwater, a constant terminal cost is applied. For freshwater locations, the estimated wait time is based upon the expected throughput capacity. It is assumed that the loadings of freshwater are consistent throughout the year. If this assumption is correct, the average loading time can be inferred from annual capacity as well as flow rates at the sites.

Since the freshwater data sources originate from two different governmental sources, data elements are not consistent across all facilities. In the North Dakota water data provided by the State Water Commission, total annual capacity is measured in acre-feet. Montana's Division of Natural Resources provides annual capacity in million gallons. Conversion of acre-feet to gallons provides a common measure of capacity. As mentioned above, it is assumed that the loadings are consistent throughout the year and flow rates can be calculated by dividing annual capacities by the number of working hours during the year. This estimate approximates the wait time at the facility. Wait times are calculated for each water facility in the analysis area.

#### 3.2.4. Total Trucking Costs

Total trucking costs are calculated for each segment of road based upon jurisdiction, surface type, and average surface condition. In addition to road segments, terminal costs are applied to dummy segments that connect the highway network to the origin and destination facilities. The summation of the linehaul (road segment) and terminal (dummy segment) costs on an individual route represents the total long range marginal cost associated with the origin and destination movement.

#### 3.3. Network Routing Algorithm

Once the network has been established, and connectivity ensured, route generation occurs between possible origins and possible destinations. Each township is connected to each of the origin and destination locations for future use in the network optimization models. Connection of each potential origin and destination is done for two reasons. The first is to avoid arbitrarily designating the maximum distance which shipments may travel. Second, due to the capacity limitations placed on freshwater and oil collection facilities in the optimization models, complete connectivity of origins and destinations are critical.

To generate the optimal route between origins and potential destinations, ESRI ArcMap Network Analyst is used. Network Analyst utilizes Dijkstra's algorithm to select the least cost path between an origin and multiple destinations. "The shortest path problem with nonnegative arc lengths is one of the most natural network optimization problems and occurs widely in practice. Dijkstra's algorithm is the best known algorithm for the problem in theory and the most robust in practice" (Review of Dijkstra's Algorithm).

Link costs are estimated using the truck cost methodology for individual segments based upon speed and surface factors. The purpose of routing in this study is to identify the least cost routes between origins and destinations for use as arc costs in a distribution optimization model. Dijkstra's algorithm is a search algorithm that computes the shortest paths among non-negative edges with assigned costs to all destinations from a source, instead of selected origin-destination pairs (Medhi 2007). "It starts from the source node and iteratively expands a tree that ultimately spans all nodes reachable from that source" (Misra 2009). The algorithm output is the set of least cost routes between the source node and all destination nodes. The aggregation of each link cost represents the minimum truck cost between origins and destinations. The selected route cost does not change as traffic is assigned; therefore, congestion costs are not expressly considered. This study will explore an iterative process to recalculate route costs post traffic assignment to generate new link costs for use in route selection.

Routing in Network Analyst first begins with network construction. The roadway shapefiles from Montana and North Dakota are merged using the merge utility under the geoprocessing menu. This merge combines two independent network shapefiles into a new, single output dataset. As the two original files have differing attributes, prior to the merge, the number of attributes were minimized to common attributes to streamline the merge and minimize

merge errors. After the completed merge, the attribute database file was imported into SAS in order to repopulate the attribute table and perform conversions to add consistency between the files. This network is then used to create a routable network for use in routing.

Creation of the network dataset involves multiple steps. The first of which is to ensure network connectivity. ArcMap has two methods of accomplishing this: connectivity by end point and connectivity by any vertex. For this study, connectivity by any vertex was selected, as it not only connects end points between segments but also any intersection between segments. Once connectivity is ensured, attribute variables for use as costs for minimization in the routing algorithm are selected. As described earlier, segment cost representing the truck cost of traversing an individual segment is selected. In addition to the objective attribute, time and distance are selected. In the Network Analyst routing options, these attributes may be accumulated in the same manner as cost, although not selected as the minimization objective. This provides additional data for sensitivity analysis.

Once the routable network has been completed, the next step is to specify the problem type. Since this study utilizes the cost between origin and destination facilities, the closest facility problem is selected. The closest facility problem selects the minimum cost route between an incident (origin) and facility (destination). For example, in the sand routing problem, there are a total of 1,582 township incidents, and nine sand facilities.

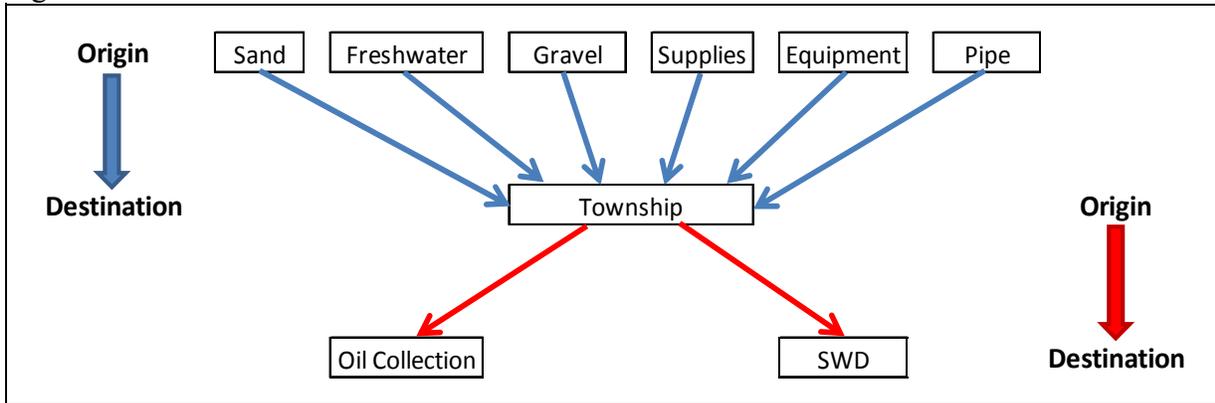
Prior to network routing, analysis properties are adjusted on a case-by-case basis to ensure the correct analysis scope and type. First, the analysis settings are modified to specify that the model impedance is defined as cost. The number of facilities to find is set at the total number of facilities in the routing problem, for reasons previously described. Accumulation

settings are specified to include accumulation of route cost, time, and distance, although the closest facility problem minimizes route cost only. Following these steps, route selection begins. The duration of the routing process depends on the total number of origins and destinations. For all outbound routes, there are a total of 1,582 origins and varying numbers of destinations, depending on output type. For each destination, 1,582 routes will be selected. Once the total number of routes exceeds 250,000-300,000, Network Analyst automatically halts the process and produces an error message citing memory limitations. The number of potential routes in each iteration depends on the number of facilities as well as the distance, as longer routes would be composed of additional segments, thereby adding to the total memory load. Experimentation resulted in an upper limit of 150 destinations from each township per routing session. For this reason, where the number of locations exceeds 150, multiple runs were conducted and the resulting route costs were aggregated to a single file.

Using this method, each origin is connected to each potential destination. The set of origins and destinations are not fixed throughout the entire analysis, as drilling locations will change from year to year, and additional locations will be added to the network as time progresses. For example, the base set of oil collection facilities is expected to expand between 2012 and 2015 as additional capacity is introduced, as shown in Table 5.

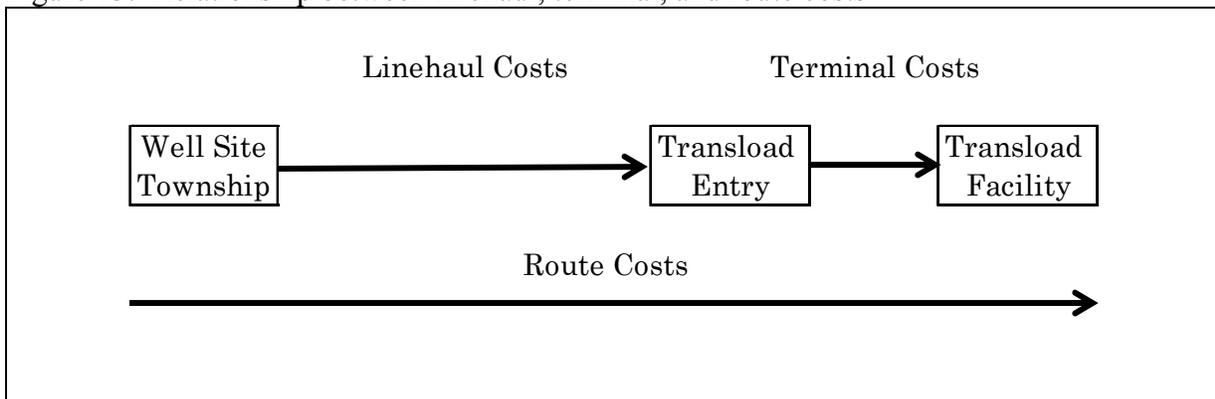
The existing route sets are first used to connect sources of existing oil and saltwater production to oil collection facilities and saltwater disposal wells. As shown in Figure 12, inbound inputs to drilling are routed to the township TAZ and represented by the top set of arrows. Outbound movements of crude oil to collection facilities and saltwater to SWD facilities are represented by the lower set of arrows.

Figure 12. Movement classes



Through these steps, the cost of the route between each origin and destination is calculated. However, terminal costs are also included to reflect the true cost of the truck trip. As mentioned previously, terminal costs reflect the cost of loading and unloading and wait times at well sites or transload facilities, including associated labor and fuel costs due to idling in a queue. For each of the origin and destination locations, a dummy link is constructed and is assigned a cost based upon the terminal costs consisting of wait, loading, and unloading times. The sum of the linehaul costs estimated from the truck cost model and the terminal costs at the dummy link represent the total cost of the route, as shown in Figure 13.

Figure 13. Relationship between linehaul, terminal, and route costs



### 3.4. Future Well Location Distribution

Forecasting future traffic volumes over highway segments due to oil development requires forecasts of new wells by year, and the expected duration of production. Forecasts

provided by the North Dakota Oil & Gas Division contain the expected number of new wells by year and county. Since the level of this analysis is below the county level, a method to further disaggregate the forecasts to the township level is required.

### 3.4.1. Oil Production Forecasts

#### 3.4.1.1. Oil Exploration and Drilling Phases

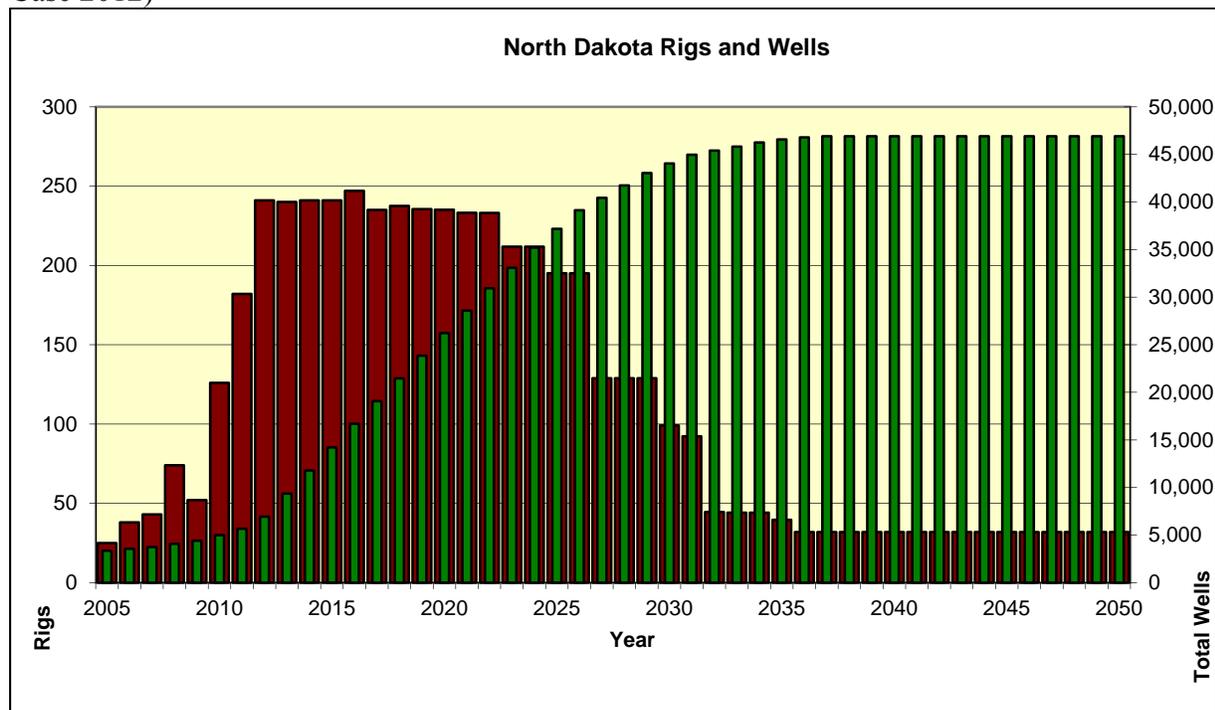
Recent Bakken development has followed two primary drilling phases. The first phase involves drilling a single well to secure a lease on a spacing unit. Spacing units are 640- or 1,280-acre land units and the base unit of development. Most Bakken spacing units are 1,280 acres. Prior to initial exploration, oil companies negotiate a drilling lease with landowners for a specified dollar amount per acre. Once the lease goes into effect, the oil company must drill at least one well within five years, or forfeit their lease in the absence of a lease extension. Many existing leases have been in effect since the beginning of the newest Bakken boom in 2006-2008, and renegotiation of leases would result in significantly higher lease rates, hence the motivation to secure the leases wherever possible.

The second phase is also known as the “fill-in” phase. As mentioned in the introduction, a typical Bakken spacing unit will have a total of seven wells drilled. The fill-in phase may occur at any time following securement of the lease. Since there is a higher penalty in the form of higher lease rates with not completing a Phase I well within a specified time, there is a greater incentive for Phase I completion. The incentive, according to regulatory representatives, drives the number of drilling rigs within the development area.

The North Dakota Oil and Gas Division produces forecasts of oil development on a periodic basis. Forecasted oil development is disaggregated to the county level. The method of forecasting the number of wells to be drilled in each county is a function of the number of

undeveloped spacing units, units under development, completed units, and rig numbers. The number of rigs by county each year is forecasted by the Oil & Gas Division and is the primary driver of oil development. Statewide estimates are shown in Table 8. The left vertical axis represents the number of rigs estimated by year. The right vertical axis shows the total number of wells drilled by year. Note that as the number of rigs decreases starting in 2023, so does the rate of new wells added, as the new wells are a function of the number of rigs operating in the state.

Figure 14. Historical and forecasted rig and well numbers (Helms, Jobs Projection Expected Case 2012)



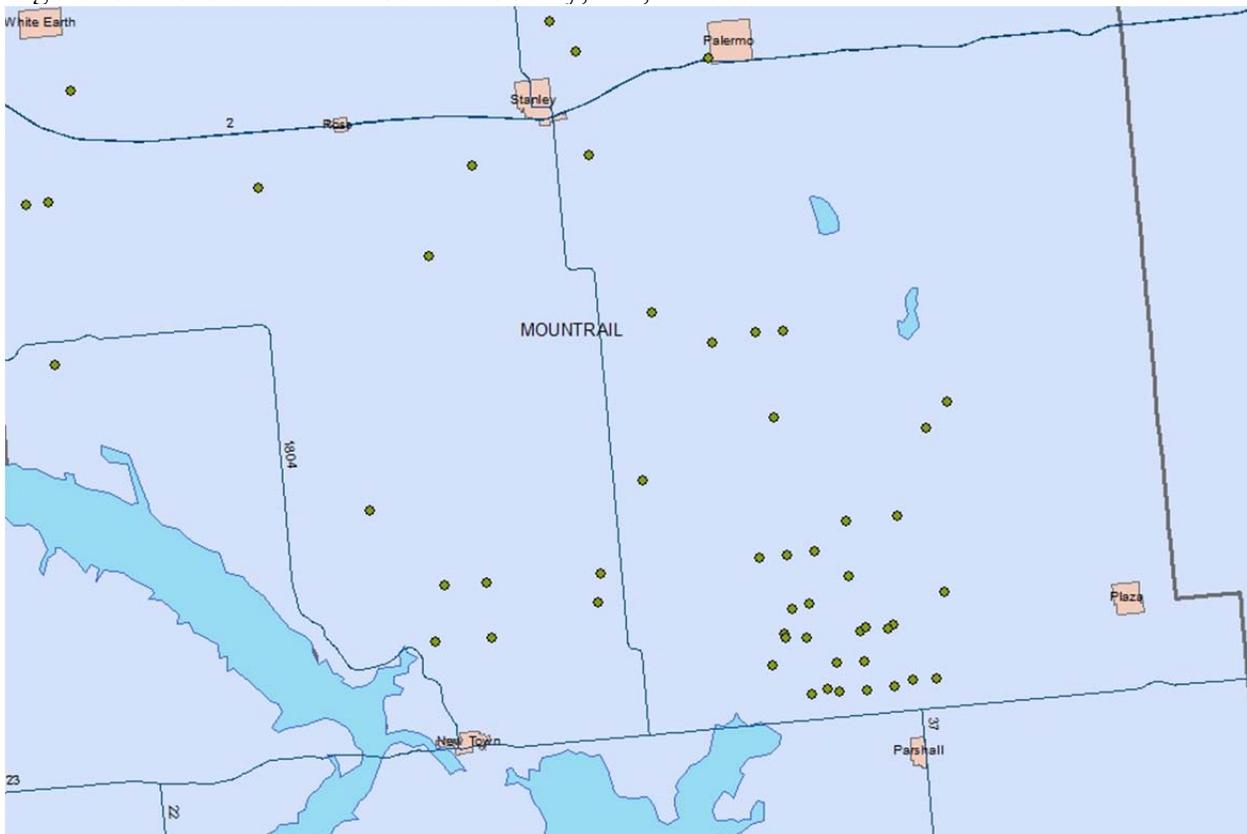
The scope of oil development in North Dakota is 17 counties: Billings, Bowman, Burke, Divide, Dunn, Golden Valley, Hettinger, McHenry, McKenzie, McLean, Mercer, Mountrail, Renville, Slope, Stark, Ward, and Williams.

The Montana Oil and Gas Board do not provide formal public forecasts. Discussions with OGB representatives, however, indicate that future development will occur within three

counties in Montana: Sheridan, Roosevelt, and Richland. However, due to input source and output destination locations being outside of the primary development area, the geographic scope has been increased to 11 counties in Montana. There is significant cross border traffic resulting from inputs such as gravel sourced in Montana for use in North Dakota wells, and outputs of crude oil produced in North Dakota, but shipped to a transload facility in Montana.

Oil exploration and extraction in the Bakken formation has occurred and is continuing to occur in two phases. The first phase involves drilling of a single well to secure spacing units on an oil lease. The second phase includes the drilling and fracturing of additional wells to complete the spacing unit development. Initial development of the Bakken formation in North Dakota using horizontal drilling occurred in 2006-2007. As shown in Figure 15, the initial phase of this round of development occurred in south central Mountrail County.

Figure 15. Wells drilled in Mountrail County, ND, in 2007



Each dot on the map represents a single well. Note that early development is distributed throughout the area, with single wells at most locations. This distribution represents a combination of exploration and lease securement, as single wells within spacing units are shown. Figure 16 includes all wells drilled from 2007-2009. The distribution of wells has expanded outside the initial area of development, but the spacing between the wells still signals that Phase I development is still underway. This is indicated by single points spaced roughly one mile apart, representing a single well on a one-mile by two-mile spacing unit, with infrequent multiple locations within the spacing unit proximity. When Phase II drilling occurs, multiple wells are located directly adjacent to existing wells, often within distances of 100 yards or less. Note that Phase I and Phase II drilling may occur simultaneously within a geographic area.

Figure 16. Wells drilled in Mountrail County, ND, 2007-2009

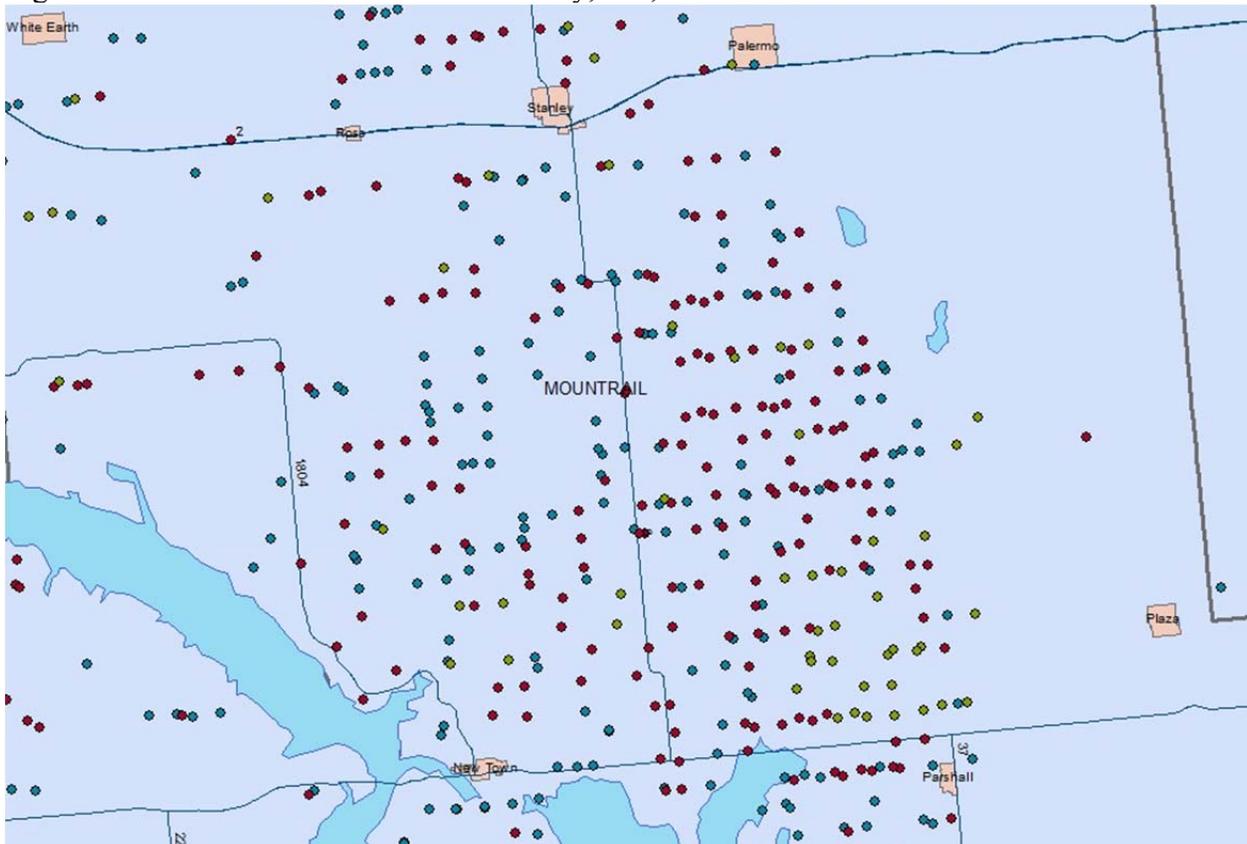
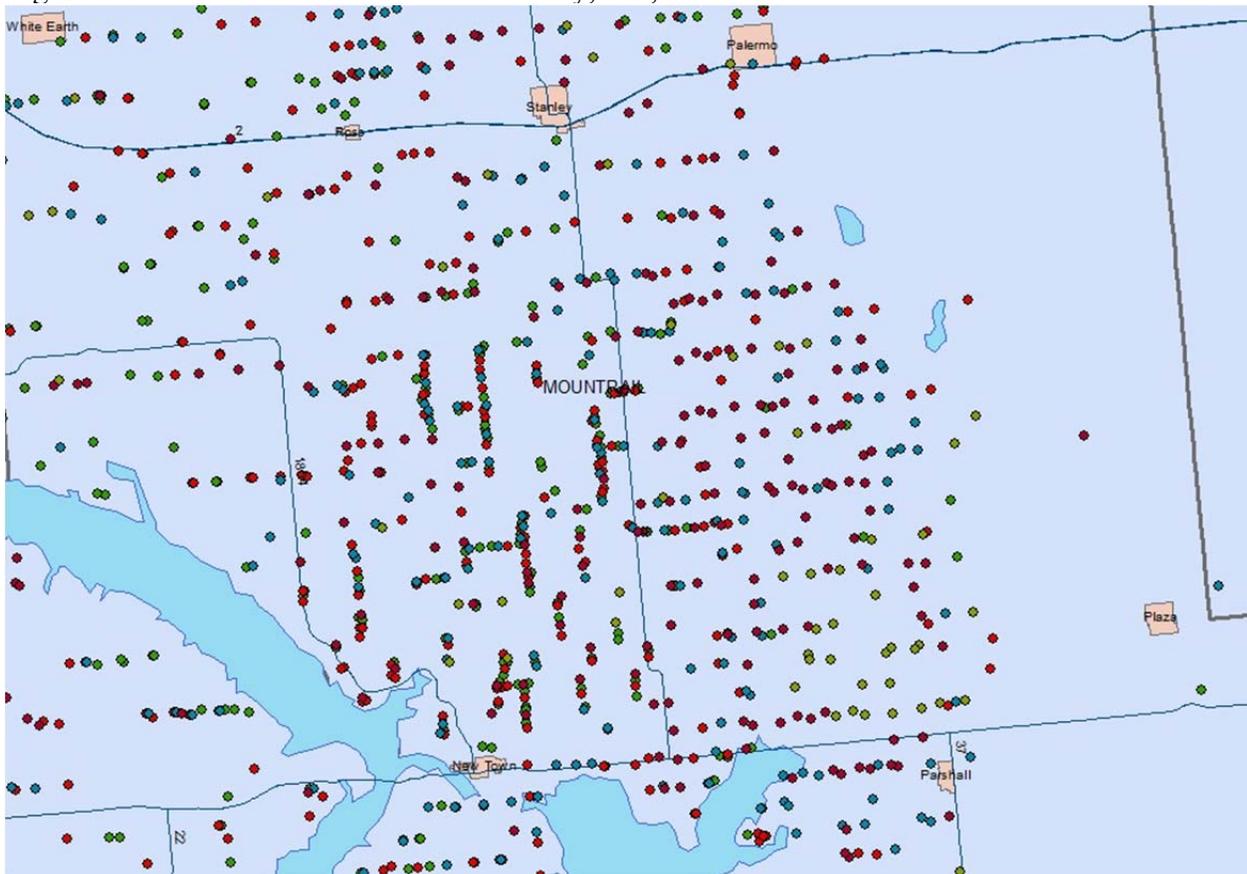


Figure 17 shows the locations of all wells drilled in southern Mountrail County between 2007 and 2011. The rows of oil wells located north of New Town, ND, represents areas where Phase II or fill-in drilling has occurred. Many of the spacing units in this area are fully developed, and drilling will cease. This Phase II activity can be seen directly north of New Town in the lower center of the figure. The lines of adjacent wells represent spacing units that have completed Phase II of exploration.

Figure 17. Wells drilled in Mountrail County, ND, 2007-2011

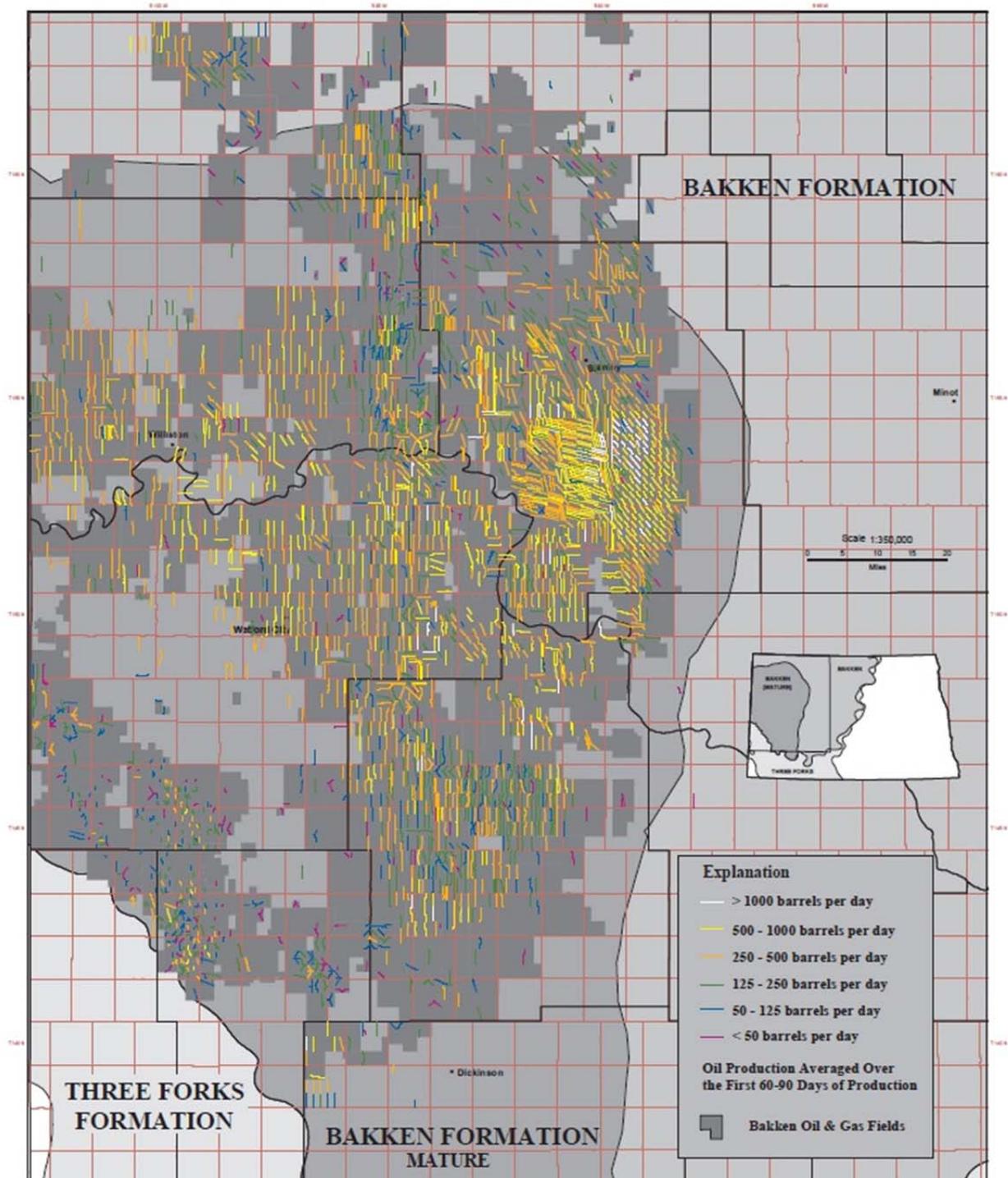


As Figures 15-17 show, there is significant variation in distribution of these wells at the sub-county level. However, forecasts of future oil development in North Dakota are at the county level. One method used in a previous study to disaggregate the county forecasts was to randomly distribute future wells throughout the county. In certain counties this is representative of observed development. However, the Mountrail County example provides evidence that this

method is not acceptable overall. The maps show a clear eastern boundary of oil development within Mountrail County, running north and south of Parshall, ND. This represents the “economic boundary” of oil development within Mountrail County under current market and regulatory conditions.

The locations of future wells and potential economic boundaries are dependent on the level of production that can be obtained at new well sites. The North Dakota Geological Survey outlines the thermally mature areas of the Bakken formation. The majority of existing development has occurred within these thermally mature areas, and represents the potential outer economic boundaries of Bakken development. Figure 18 shows the location of the boundaries of the thermally mature area of the Bakken formation overlaid with existing oil wells categorized by initial production rates. Historically, the development of horizontal wells in the North Dakota Bakken centered in southern Mountrail County, and has expanded to the south, west and northwest.

Figure 18. Existing oil wells in relation to thermal maturity (Nordeng 2010)



### 3.4.1.2. Factors Influencing the Likelihood of Development

A prerequisite for well drilling is location within the economically viable portion of the Bakken formation. The primary definition of the economically viable portion of the Bakken can be taken to coincide with the mature area of the formation. The vast majority of existing Bakken wells is located within the thermally mature area boundaries. However, there have been successful wells drilled in northeastern Divide County and southern Burke County, which are outside of this boundary. An alternative definition would be within demarcated Bakken Oil & Gas fields as outlined in Figure 18. Similar to the boundaries of the thermally mature areas, there are exceptions to the use of these boundaries, and it is expected that additional oil fields will be defined as oil development progresses.

Historical data have shown that new wells are generally drilled within close proximity to existing wells. In the initial development timeframe, this was not necessarily the case as a base set had not yet been established. Recent development has shown considerable clustering within sub regions.

The spacing unit is the base unit of development. Using the assumption of a maximum of five to seven wells per spacing unit based upon historical practices, the existing number of wells in any given spacing unit may prove to be a useful predictor of future development. Upon completion of Phase 1 drilling activities, it is assumed that Phase 2 drilling will occur at a later period. Once the total of five to seven wells is drilled, the spacing unit will not receive additional wells, and the unit is considered fully developed. However, not all spacing units receive five to seven wells, as productivity and economic considerations may limit the development. Additionally, the timeframe between completion of Phase 1 and Phase 2 drilling is not known, and may range from months to years.

It is unclear whether there are dependencies between locations aside from proximity. The ownership of specific leases is unknown outside of state trust land leases. If one oil exploration firm were to secure leases over a large continuous geographic area, advance planning with respect to gathering pipelines could be completed and development could operate in an efficient least-cost manner, as the location of future wells would be determined by connectivity to the firm's existing network. However, as evidenced by trust land leases ownership, it appears that no one firm demonstrates widespread continuous ownership. While it is certain that clustering of new wells is occurring, the rationale is assumed to be that the wells are simply located in highly productive and economically viable oil fields. It is certain, either way, that the spatial location of new wells will be correlated to the location of existing wells, which is consistent with Tobler's First Law of Geography, which states "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). In the case of oil development, there are highly, moderately, and marginally productive oil development areas. The closer the proximity of a location to higher production areas, the greater is the expected density of exploration.

#### 3.4.1.3. Spatial Data Analysis

In this study, the Susceptible, Infected and Recovered model is used as a method of modeling future oil development. This model was initially designed for use in modeling the spread of disease epidemics (Shulgin, Stone, and Agur 1998). The organization of the model is as follows:

$N$ =population

$S_t$ =segment of the population who have not encountered the disease at time  $t$

$I_t$ =segment of the population who are infected with the disease at time  $t$

$R_t$ =segment of the population who have previously been infected but are now recovered at time  $t$

The three groups can further be described as fractions of the total population N

$$s_t = S_t/N$$

$$i_t = I_t/N$$

$$r_t = R_t/N$$

Where:  $S_t + I_t + R_t = N$  and  $s_t + i_t + r_t = 1$

The model assumes that one can only move from S to I to R, and not in the opposite direction. That is, once infected with a disease such as chicken pox, upon recovery the infected develops an immunity that prevents them from future infections. A fully developed spacing unit will have five to seven wells upon completion. For the purposes of this study, the midpoint of six wells is used. In the situation of oil development, one could group spacing units in similar categories: Susceptible (undrilled), Infected (at least one well drilled but less than or equal to five), and Recovered (six wells drilled, exploration complete) (Shulgin, Stone and Agur 1998). In the SIR epidemic model, there are two potential movements, between S and I and between I and R. The rate at which population moves from S to I is represented by  $\beta$ , which represents the contact rate. The infection is spread from I to S. The rate at which population moves from I to R is represented by  $\gamma$ , which represents the rate of recovery. Equation 1 shows that the number of susceptible persons in time period t+1 is equal to the starting population of S minus the proportion of susceptible population multiplied by the Infected population and the contact rate. The recovered population is equal to the starting recovered population plus the infected population multiplied by the recovery rate. Finally, the number of infected persons is equal to starting infected plus the portion of susceptible now infected minus the number of infected now recovered.

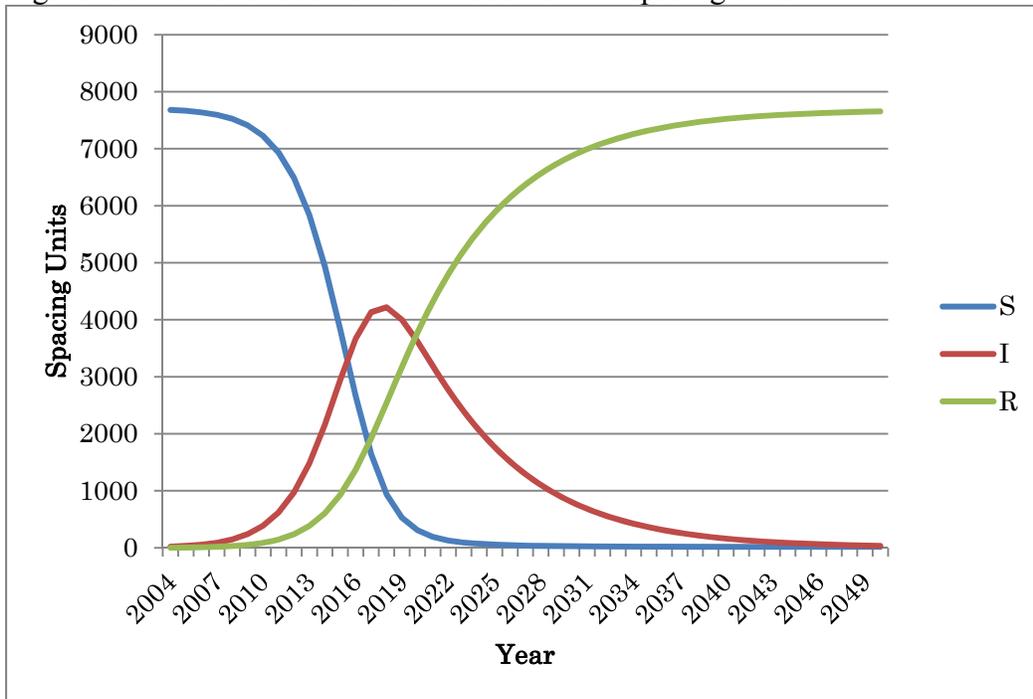
$$(15) \quad S_{t+1} = S_t - \beta s_t I_t$$

$$(16) \quad R_{t+1} = R_t + \gamma I_t$$

$$(17) \quad I_{t+1} = I_t + \beta s_t I_t - \gamma I_t = I_t(1 + \beta s_t - \gamma)$$

In the oil forecasting usage,  $\beta$  represents the spread of Phase I development, which historically is based upon geographic location and proximity to existing wells and  $\Delta t$  represents the time period corresponding with Phase II or fill-in drilling. In forecasts of oil development in the Bakken, the total number of wells drilled during time period  $t$  is a function of the number of drilling rigs in time  $t$ . Full forecasts are presented later in this document and show that there is an increased number of drilling rigs during the Phase I stage of oil exploration and a decrease at a later date, which will be represented by differing contact and recovery rates. Once a spacing unit has been fully “infected” with seven wells, it is deemed recovered. In the SIR model, exposure and recovery are typically measured in days, where well development would instead be measured in years. Figure 19 illustrates the model results of North Dakota spacing units under test contract and recovery rates using formulas 1-3 above. Contract and recovery rates will be calibrated based upon known well location data from 2005-2011 and new wells forecasted by the North Dakota Oil & Gas Division. Roughly 7,700 spacing units have been defined in North Dakota, and the figure illustrates the number of spacing units in each category over time.

Figure 19. Demonstration of SIR model for ND spacing units



Spatial distribution of the susceptible, infected, and recovered spacing units by time first begins with the definition of a two-dimensional lattice so geographic location between spacing units may be quantified. The level of aggregation in this study is the township level, which represents a geographic area of 36 square miles, which consists of 18 1,280-acre spacing units. Since a typical 1,280-acre spacing unit will have five to seven wells before it is complete, we may use the midpoint of six as a representative total. As a township consists of 18 1,280-acre spacing units, complete exploration would represent 108 wells. A subset of the existing township boundary shapefile is selected, with outer boundaries being the thermally mature area of the Bakken formation, and designated as the two-dimensional lattice for use in the spatial SIR model. Within the lattice, each cell will have four neighbors: one to the north, one to the south, one to the east, and one to the west, which share a boundary with the central cell. Each cell will be given an initial state of S, I or R, based upon known observations.

Using methodology outlined in Tome and Ziff (2010), a stochastic lattice model with asynchronous dynamics with corresponding distribution algorithm will be developed. As above, each cell can be occupied by only one state: S, I, or R. “At each time step, a site is randomly chosen and the following rules are applied: (i) if the chosen site is in state S or R, it remains unchanged, (ii) If the chosen site is in state I then (a) with the probability  $c$  the chosen site becomes R and (b) with the complementary probability  $b=1-c$  a neighboring site is chosen at random...if...in state S it becomes I; otherwise it remains unchanged” (Tome and Ziff 2010). Probabilities are based upon rate of contact and recovery.

$$(18) \quad b = \beta/(\beta + \gamma)$$

$$(19) \quad c = \gamma/(\beta + \gamma)$$

The SIR model will be simulated using a dynamic Monte Carlo method. The procedure begins with random selection of an I site randomly from the available list of I sites. Next, a random number  $x$  in  $(0,1)$  is generated. If  $x \leq c$  then I is now R. If  $x \geq c$ , one of the four nearest neighbors of the I site is randomly selected. If the neighbor is S, then it is now I, and added to the list of I sites. This procedure is repeated as long as I sites remain (Tome and Ziff 2010). Thus the distribution of I and R is made throughout the lattice. The movement between S and I, and I and R are limited by the number of forecasted new wells by county in a given time period, with the movement between S and I representing one new well, and the movement between I and R representing five new wells.

The SIR model considers clustering and proximity in addition to rate of spread and recovery to model the spread of epidemics. Oil development, like epidemics, occurs in clusters in areas of close proximity. This is as a result of location of economically viable drilling locations due to the underlying geology and the resulting productivity of oil wells. By directly

considering existing economically viable production areas, the SIR model estimates the spatial development of oil development and accounts for clustering. This method is likely superior to random distribution of future wells within the study area, as development firms seek to minimize the costly movement of oversize and overweight rig equipment while seeking to maximize return by focusing on areas that have proven economic viability.

As described earlier, public land lease locations are available from the North Dakota State Land Department, which provides data on the year of lease origination as well as the lease termination year. Historical data have shown that leases are often drilled in the last year of the lease, thereby preventing renegotiation of the lease terms. This study did consider the use of these lease locations as representative new “infections.” However, assumptions would have to be made as to the development timeframe of surrounding private lands, as private land leases are confidential. Due to the nature of these assumptions and the limited timeframe for public land data, public land leases were not utilized for modeling the future spread of development. Moreover, a lease represents the timing of exploration on a single spacing unit. This study aggregates development to the township level, and utilizing lease expiration data would necessitate assumption that a single spacing unit is representative of the entire township.

### 3.5. Mode Choice

In North Dakota and Montana, once an oil well has reached completion and begins producing crude oil, the outbound oil may be transported to a collection facility by truck or pipe. Construction of collector pipelines represents a significant investment with per-inch per-mile costs ranging from \$50,000 to \$75,000 (Kringstad, 2012). For 3-inch pipe, this represents a cost of \$150,000 per mile. Factors influencing the likelihood of investing in pipe infrastructure include ownership, productivity, and density. The first factor refers to the percentage of the draw

area in which a single firm has ownership. The rationale is that if a firm had a significant lease investment in an area, the more likely they are to invest in pipelines. Productivity refers the initial production rate of wells drilled in an area, and varies significantly throughout the study area. For example, in 2012, new wells in Mountrail County had an average initial production rate of 803 barrels of oil per day. In McKenzie County, average initial production exceeded 1,300 barrels of oil per day. As production increases, the number of daily trucks required to transport crude oil to collection facilities increases, as does the trucking cost. The terminal and linehaul costs of pipeline transportation are significantly different than those of truck transportation, and there is certainly a threshold where pipe transportation becomes the least cost option. Finally, production density is a combination of ownership and productivity. Historical data reflect that as portions of the oil patch become more mature, pipeline transportation increases. This is analogous to the recovery stage in the SIR model, wherein oil development would cease as the density of wells has reached a maximum. For the purpose of this analysis, once a township reaches maturity, it is assumed that outbound oil is transported by pipeline.

### 3.6. Route Assignment/Distribution Model

Assignment of routes for individual truck movements will be done through a constrained optimization model. Each township has multiple origins from which inputs may be sourced, yet only one will be chosen. Assignment of origin-destination pairs assumes that the source movement is an all-or-nothing assignment, as the route costs of alternative sources will remain the same for all truck trips. It should be noted that within the optimization framework, the township represents both an origin and a destination. For inbound drilling-related movements, the origins are the sources of the inputs, and the destination is the township well site. For

outbound production-related movements, the origin is the township, and the destinations are collection facilities or disposal wells.

The objective of the oil development distribution model is to minimize the total cost of moving six inputs and two outputs from input origins and to output destinations (Equation 20), subject to the following constraints: the demands at the township well sites (Equation 21), the supply capacities at input origin locations (Equation 22), handling capacities at destination locations (Equation 23), and the number of trucks on a route must be greater than or equal to zero (Equation 24).

$$(20) \quad \text{Min} \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^o c_{ijk} * x_{ijk} + \sum_{j=1}^m \sum_{l=1}^p \sum_{k=1}^o c_{jlk} * x_{jlk}$$

$$(21) \quad \sum_{i=1}^n x_{ijk} = D_{jk} \quad \forall jk$$

$$(22) \quad \sum_{j=1}^m x_{ijk} \leq S_{ik} \quad \forall ik$$

$$(23) \quad \sum_{j=1}^m x_{jlk} \leq U_{lk} \quad \forall lk$$

$$(24) \quad x_{ijk} \text{ are non – negative integers for all } i, j, k$$

Where:

i=Index for input origin

j=Index for township

k=Index for freight class

l=Index for outbound destination

$c_{ijk}$ =Cost of carrying freight k between i and j

$x_{ijk}$ =Truckloads of freight k between i and j

$c_{jlk}$ =Cost of carrying freight k between j and l

$x_{jlk}$ =Truckloads of freight k between j and l

$D_j$ =Demand at township j

$S_i$ =Supply at origin  $i$

$U_j$ =Capacity at destination  $l$

This study does not expressly consider the impact of congestion on the state highway system. It is possible that as additional trucks are assigned to a highway segment, the cost of traveling that segment may rise due to decreased travel speed resulting from congestion. Theoretically, this could redirect background traffic to other highway routes. Due to the connectivity of the state highway system in western North Dakota, it is assumed that the impacts of congestion would be minimal on route selection. This assumption does not ignore the reality that congestion is occurring, but that the impacts are limited due to the lack of alternative routes crossing the Missouri River and Lake Sakakawea.

### 3.7. Route Disaggregation and Segment Assignment

The distribution model assigns truck movements to individual routes. An individual segment of the state highway system may theoretically be included in each route that was chosen. For this reason, the selected routes must be disaggregated to component highway segments in order to assign the traffic flows to individual segments.

### 3.8. Model Calibration

Forecasted truck traffic due to oil production represents a portion of total truck traffic over roadway segments. Total traffic is a combination of oil movements modeled in this study, secondary traffic, and local and through traffic. Secondary traffic is generated as a result of oil development. Examples would include construction, retail, and fuel movements generated by population increases within the study area. Local traffic includes movements that would likely be generated whether or not oil development occurred, and would include agricultural and

manufacturing movements. Through traffic includes movements that do not originate or terminate within the study region, including long haul movements.

Each of these traffic classes lend themselves to distinct roadway functional classes. For example, long-haul through movements would be more likely to use routes including interregional corridors or interstate highways due to travel speed, connectivity, and access control. Secondary movements are often long-haul movements that terminate within the study area, and also would utilize interregional corridors and interstate highways. Local movements, including modeled oil movements, would use all functional classes of highway, as the generation and termination points are located in rural areas, often not directly connected to interregional or interstate highways.

Pavement designers consider the total traffic over a highway segment. While the incremental oil traffic would be useful to a planning official, the total traffic is what drives design. There is not a linear relationship between truck AADT and improvement cost, although there is assuredly a positive correlation.

Traffic model calibration requires inclusion of external traffic variables to estimate the total traffic over a highway segment. “Calibration in the traditional four-step modeling process was accomplished by modifying model parameters until the models replicated the travel patterns exhibited by the O-D survey” (Federal Highway Administration 1990). In this study, the calibration effort focuses primarily on non-modeled traffic components. Traffic count classification data are collected from MDT and NDDOT, and is either in point or line shapefiles. For point shapefiles, the nearest traffic observation on a route is used to represent traffic at the segment level. Line shapefiles are preloaded with segment level traffic data. The difference between observed and modeled traffic is the focus of the calibration effort.

For all levels of traffic, it is expected that increases will occur over the analysis period whether or not oil development occurs. To account for future non-modeled traffic, growth factors must be applied to the base year traffic. Two previous studies are used to generate traffic growth factors to apply to non-modeled traffic. The first study is the Freight Analysis Framework (FAF). FAF “estimates commodity movements by truck and weight for truck-only, long distance moves over specific highways. Models used to disaggregate flows are based on geographic distributions of economic activity rather than a detailed understanding of local conditions and the resulting network flows should not be used as a substitute for local data to support local planning and project development” (Federal Highway Administration 2010). The second is a more recent draft traffic forecast report in the Williston, ND area. Different growth rates are estimated for background (non-oil related) and oil related (activity based) traffic (SRF Consulting 2012).

Growth estimates from these two studies vary greatly, primarily due to the underlying methodology and timeliness of data. FAF utilizes 2007 traffic data, which are prior to widespread increases in oil development within the study region. Growth factors from FAF may prove useful for modeling the through traffic component, and background traffic in the lesser impacted oil counties. SRF background traffic growth factors are based upon trip generation estimates tied to population growth within the Williams, McKenzie, and Mountrail County areas, which represent the most significantly impacted oil counties in the study. Due to the differences in assumptions, a single set of growth factors was not applied to the entire study area. In higher development counties, the SRF growth factors are used, and in the fringe counties, the FAF growth factors are used.

## CHAPTER 4. RESULTS

This chapter is organized into three main sections that correspond to the three major models used to develop truck traffic forecasts. The first outlines the truck cost model results, which are presented for four different truck configurations across a number of travel speeds. The next section presents the results of the SIR model to predict oil development and discusses measures of accuracy in predictions of development timeframes and spatial distribution of wells. The third section presents the results of the traffic model, first visually for the entire study region, and then route-specific forecasts for a number of the high impact highways. Within each section, comparisons to existing methods are presented and conclusions are drawn on the effectiveness of the methods used in this study.

### 4.1. Truck Cost Model

Truck cost estimates were calculated for use in approximating truck rates charged to travel over individual roadway segments in the model. Truck cost serves as the primary form of impedance in the routing model, and the optimization model objective is to minimize transportation cost. This section outlines individual estimates of truck cost measures used in the routing analysis.

#### 4.1.1. Model Parameters

Cost factors used in the truck cost model are presented in Table 11. Parameters are grouped by variable and truck configuration. With the exception of trailer price, all variables are consistent across truck configurations.

Table 11. Truck cost model parameters by truck configuration

Variable	Conventional Flatbed	Conventional Tanker	Conventional Dump	RMD Tanker
Tractor – Useful Life	5 years	5 years	5 years	5 years
Trailer – Useful Life	10 years	10 years	10 years	10 years
Salvage Value	30%	30%	30%	30%
Annual Mileage	68,200 miles	68,200 miles	68,200 miles	68,200 miles
Purchase Tax Rate	5%	5%	5%	5%
Cost of Capital	7.88%	7.88%	7.88%	7.88%
Trailer Price	\$39,450	\$37,500	\$43,295	\$75,000
Tractor Price	\$111,000	\$111,000	\$111,000	\$111,000
Labor Rate	\$40/hour	\$40/hour	\$40/hour	\$40/hour

#### 4.1.2. Truck Cost Model Estimates

This section presents the cost estimates generated by the truck cost model. Variable and fixed cost components are discussed individually, and a brief description of model outputs are presented.

##### 4.1.2.1. Variable Costs

Fuel consumption estimates for different truck configurations are presented in Table 12 below. All estimates are presented in miles per gallon. As speed of travel increases, the fuel economy decreases across all truck configurations.

Table 12. Fuel economy by truck configuration and travel speed

Truck	Trailer	40	45	50	55	60	65	70
Conventional	Flatbed	5.39	5.39	5.39	5.39	4.84	4.31	3.77
Conventional	Tanker	5.39	5.39	5.39	5.39	4.84	4.31	3.77
Conventional	Hopper	5.72	5.72	5.72	5.72	5.15	4.57	4.00
RMD	Tanker	5.20	5.20	5.20	5.20	4.60	4.16	3.60

Conversion of fuel economy resulted in the per mile variable cost for fuel. As specified in Chapter 3, the fuel cost used was \$4.24 per gallon. Estimates of fuel cost per mile are shown in Table 13. Per-mile fuel cost at 70 miles per hour is roughly double per-mile costs at 40 miles per hour.

Table 13. Fuel cost per mile by truck configuration and travel speed

Truck Type	Trailer	40	45	50	55	60	65	70
Conventional	Flatbed	\$0.79	\$0.79	\$0.79	\$0.79	\$0.88	\$0.98	\$1.12
Conventional	Tanker	\$0.79	\$0.79	\$0.79	\$0.79	\$0.88	\$0.98	\$1.12
Conventional	Hopper	\$0.74	\$0.74	\$0.74	\$0.74	\$0.82	\$0.93	\$1.06
RMD	Tanker	\$0.82	\$0.82	\$0.82	\$0.82	\$0.92	\$1.02	\$1.18

Labor cost is primarily a function of travel speed and wage rate per hour. As speed increases, the labor cost per mile decreases. Labor costs are consistent across all truck configurations. However, in reality there may be higher wages for drivers of longer rocky mountain double rigs due to the requisite skill and experience. Additionally, truck driver wages used are representative of oil trucking only, and would not be directly transferrable to other commodity movement. Labor cost estimates are shown in Table 14. The tradeoff between fuel and labor costs is evident as travel speed increases. As mentioned above, as speed increases from 40 miles per hour to 70 miles per hour, the per-mile fuel cost roughly doubles. As speed increases from 40 miles per hour to 70 miles per hour, labor costs decrease by roughly half.

Table 14. Labor cost per mile by truck configuration and travel speed

Truck Type	Trailer	40	45	50	55	60	65	70
Conventional	Flatbed	\$1.00	\$0.89	\$0.80	\$0.73	\$0.67	\$0.62	\$0.57
Conventional	Tanker	\$1.00	\$0.89	\$0.80	\$0.73	\$0.67	\$0.62	\$0.57
Conventional	Hopper	\$1.00	\$0.89	\$0.80	\$0.73	\$0.67	\$0.62	\$0.57
RMD	Tanker	\$1.00	\$0.89	\$0.80	\$0.73	\$0.67	\$0.62	\$0.57

Maintenance and repair costs estimates are relatively consistent over all single trailer configurations. Baseline estimates of maintenance and repair for trucks is estimated to be \$0.09 per mile at the base gross vehicle weight. This estimate is adjusted using a formula that considers the gross vehicle weight and percent time loaded or empty (Faucett & Associates 1991). The base gross vehicle weight is 58,000 pounds, and maintenance and repair costs are adjusted by 0.00097 cents per 1,000 pounds above or below the base weight. As shown in Table

15, loaded truck maintenance and repair costs are 12.6 cents per mile for all conventional configurations, with an increase to 13.1 cents for the rocky mountain double configuration. A similar relationship occurs with empty maintenance and repair costs per mile.

Table 15. Maintenance and repair cost per mile by truck type

Truck Type	Trailer	Loaded	Empty
Conventional	Flatbed	\$ 0.126	\$ 0.077
Conventional	Tanker	\$ 0.126	\$ 0.076
Conventional	Hopper	\$ 0.126	\$ 0.076
RMD	Tanker	\$ 0.131	\$ 0.080

Tire wear costs are estimated using the methodology presented in Berwick and Dooley (1997), and are a function of weight, distance, and tire cost. Below weights of 3,500 pounds per tire, it is assumed that tire cost is independent of weight. Base tire costs are estimated by dividing the tire cost by the useful life of the tire. This estimate is adjusted by weight of the truck. Tire weights greater than 3,500 pounds are increased by 0.7% for each 1% increase in tire weight, this adjustment is added to the base tire cost. For tire weights less than 3,500 pounds, the base tire cost is utilized. Per mile estimates of tire costs are presented in Table 16. For all conventional truck configurations, the tire costs for trucks and trailers are consistent, as the legally loaded weight and number of tires are consistent. Truck tire costs for rocky mountain double configurations decreases as the increase in tires is not proportional to the increase in weight. However, trailer tire costs double as the number of trailer tires also double.

Table 16. Per mile tire cost by truck type

Truck Type	Trailer	Truck	Trailer	Total
Conventional	Flatbed	\$0.02325	\$0.0210	\$0.0443
Conventional	Tanker	\$0.02325	\$0.0210	\$0.0443
Conventional	Hopper	\$0.02325	\$0.0210	\$0.0443
RMD	Tanker	\$0.01956	\$0.0420	\$0.0616

Adjustment factors based upon roadway surface condition are presented in Table 17. As described in Chapter 3, these adjustment factors are used to reflect increases in tire, maintenance, and repair costs due to pavement roughness measures.

Table 17. Surface condition adjustment factors

Truck Type	Trailer	State Paved Adjustment	County Paved Adjustment	Gravel Adjustment
Conventional	Flatbed	1.00	1.15	1.25
Conventional	Tanker	1.00	1.15	1.25
Conventional	Hopper	1.00	1.15	1.25
RMD	Tanker	1.00	1.15	1.25

Total variable costs are presented in Table 18. The cost estimates vary by speed, with the least cost travel speed consistently in the 55 to 60 miles per hour range. This is as a combination of the decreasing labor costs as travel speed increases versus the increasing fuel costs as travel speed increases, and demonstrates the tradeoff between the two.

Table 18. Total per mile variable costs by truck configuration and travel speed

Truck Type	Trailer	40	45	50	55	60	65	70
Conventional	Flatbed	\$1.99	\$1.88	\$1.79	\$1.70	\$1.71	\$1.77	\$1.87
Conventional	Tanker	\$1.99	\$1.88	\$1.79	\$1.70	\$1.71	\$1.77	\$1.87
Conventional	Hopper	\$1.94	\$1.83	\$1.83	\$1.66	\$1.66	\$1.71	\$1.80
RMD	Tanker	\$2.04	\$1.93	\$1.93	\$1.76	\$1.78	\$1.83	\$1.94

#### 4.1.2.2. Fixed Costs

The salvage value of the truck and trailer are calculated at 30% of the purchase price. Depreciation estimates are shown in Table 19 below. Annual depreciation is equal to the difference between purchase price and salvage value divided by the useful life. Annual depreciation divided by the annual utilization results in the per mile depreciation cost. The opportunity cost of truck and trailer ownership is calculated at the midpoint of the ownership cost and equally distributed over the useful life of the truck. Per-mile opportunity cost is calculated by dividing annual opportunity cost by annual utilization.

Table 19. Depreciation and opportunity cost by truck type: annual and per mile

Truck Type	Depreciation		Opportunity Cost	
	Annual	Per Mile	Annual	Per Mile
Conventional Flatbed	\$18,301	\$0.2684	\$7,314	\$0.1072
Conventional Tanker	\$18,165	\$0.2663	\$7,220	\$0.1059
Conventional Dump	\$18,570	\$0.2723	\$7,501	\$0.1099
RMD Tanker	\$20,790	\$0.3048	\$9,043	\$0.1326

Per mile estimates of insurance, license fees, sales taxes, and firm overhead are presented in Table 20. Insurance and license fees are a flat annual rate and division by annual utilization results in a per-mile cost. Sales taxes are incurred during the first year of ownership, and converted to a per-mile estimate by dividing total taxes paid by useful life and annual utilization.

Table 20. Per mile insurance, license, sales tax and overhead by truck type

Truck Type	Insurance	License Fees	Sales Taxes	Overhead
Conventional Flatbed	\$0.1053	\$0.0219	\$0.0191	\$0.1070
Conventional Tanker	\$0.1053	\$0.0219	\$0.0190	\$0.1070
Conventional Dump	\$0.1053	\$0.0219	\$0.0195	\$0.1070
RMD Tanker	\$0.1053	\$0.0219	\$0.0218	\$0.1070

The summation of variable, fixed, and opportunity costs are presented in Table 21. Travel speeds of 55-60 miles per hour produce the lowest total per-mile truck cost, which is primarily due to the tradeoff between fuel costs and labor costs as travel speed increases.

Table 21. Total per mile linehaul truck costs by truck configuration and travel speed

Truck	Trailer	40	45	50	55	60	65	70
Conventional	Flatbed	\$2.89	\$2.78	\$2.69	\$2.60	\$2.61	\$2.67	\$2.77
Conventional	Tanker	\$2.88	\$2.77	\$2.68	\$2.60	\$2.61	\$2.66	\$2.76
Conventional	Hopper	\$2.85	\$2.74	\$2.65	\$2.57	\$2.57	\$2.62	\$2.71
RMD	Tanker	\$3.04	\$2.93	\$2.84	\$2.76	\$2.78	\$2.83	\$2.94

This study utilizes a segment-based truck rate approximated by truck costs that vary by travel speed, roadway condition, and truck configuration. In addition, terminal costs associated with each individual movement class are included to reflect the true cost of the trip, which is used to approximate truck rates. Table 22 presents a sample movement of sand from a transload

facility to a township. The round trip distance of this trip is 50 miles, and there is an empty backhaul. For comparative purposes, two roadway types are shown: gravel and paved state highway. In reality, movements will likely travel over a combination of gravel, county paved, and state paved segments to complete a trip, but this illustration assumes the entire trip occurs within these two categories of roads.

Table 22. Comparison of truck costs by roadway type and condition

	Gravel	State Highway
PSR	2.0	3.5
Linehaul Cost per Mile	\$2.74	\$2.57
Miles	50	50
Total Linehaul Cost	\$137.00	\$128.50
Total Terminal Cost	\$121.66	\$121.66
Terminal Cost per Mile	\$2.43	\$2.43
Total Cost per Mile	\$5.17	\$5.00

The PSR for gravel roads is assumed to be 2.0, and 3.5 for state highways. In reality, the PSR for gravel may be lower, but tire and repair and maintenance cost adjustment factors consider all PSR values below 2.0 to be equal. On gravel roads, the linehaul cost per mile is higher than state highways due to surface condition and travel speed. For both shipments, the trip distance in miles is equal. The total linehaul cost is calculated by multiplying the linehaul cost per mile by the trip distance. Total terminal cost assumes a 15-minute wait and 30-minute loading time at the origin and a 75 minute wait and 45-minute unloading time at the destination. Dividing the total terminal cost by the trip distance results in the terminal cost per mile, which are equal for both movements. The total cost per mile is the summation of linehaul cost per mile and terminal cost per mile.

The literature review cited a number of studies that used a per-mile truck cost which was constant across all roadway segments. Route selection and optimization using these cost estimates effectively minimizes the distance between origins and destinations, as each mile of

road is assigned the same cost. As an example, assume that the per-mile cost used to select routes is equal to the state highway total cost per mile, \$5.00, as specified in Table 22. If this cost is used for all segments considered in the routing process, individual roadway characteristics and travel speed would not be considered, and the cost for gravel segments would be underestimated by \$0.17 per mile. By directly considering roadway condition and travel speed, the true cost for a trucking firm to provide services more closely approximates truck rates. Moreover, routes selected using a segment specific truck cost would not over or underestimate the actual cost of traveling over those segments.

In addition to consideration of segment specific characteristics, if terminal costs are included in a given constant per-mile truck cost estimate, the portion of terminal costs attributed to long trips may be overstated in comparison with shorter trips. Table 23 presents two trips that are equal in every way except the length of the trip. As before, this trip represents a sand movement from a transload facility to a township well site with empty backhaul. For each trip, the linehaul cost per mile is equal, but the total linehaul cost for the 25-mile trip is one half that of the 50-mile trip. Total terminal costs are equal for each trip, but the per mile cost of the 25 mile trip is greater than the per-mile terminal cost of the 50-mile trip, as there are fewer miles to which to attribute the terminal costs.

Table 23. Comparison of truck costs by trip distance

	50 Mile Trip	25 Mile Trip
PSR	3.5	3.5
Linehaul Cost per Mile	\$2.57	\$2.57
Miles	50	25
Total Linehaul Cost	\$128.50	\$64.25
Total Terminal Cost	\$121.66	\$121.66
Terminal Cost per Mile	\$2.43	\$4.87
Total Cost per Mile	\$5.00	\$7.44

In this scenario, the terminal cost component of total cost is directly attributed to the trip itself. Thus, the terminal costs per mile vary with trip length. Studies that utilize a constant per-mile truck rate for all trip distances and include a terminal cost component may incorrectly attribute terminal costs per mile as the length of the trip varies. For example, if the cost estimates for the 50-mile trip presented in Table 23 would be used to represent the per-mile cost for every roadway segment in the study area, it would attribute a \$2.43 per mile terminal cost to each mile traveled. This would be appropriate if every trip was 50 miles in length. However, as the trip distance decreases from 50 miles, the impact of terminal costs would be understated, since the trip basis is 50 miles. Moreover, as trip distance exceeds 50 miles, the terminal costs per mile would be overstated, as the total terminal cost would be spread over additional miles, thereby reducing the per-mile terminal costs. Direct consideration of the terminal costs at the destinations ensures that the per-mile terminal costs are correctly attributed based upon trip distance.

#### 4.2. Truck Routing

One of the improvements that this study makes with respect to route selection is using segment specific-truck cost estimates rather than using a standard per-mile cost of travel for all segments and routes. Use of a constant per-mile cost for all segments and routes effectively selects routes based upon distance, rather than true truck costs, and does not approximate the rate that trucking firms charge for their services. Additionally, this method does not consider roadway characteristics such as surface condition and travel speed, as a constant per-mile cost is applied to all roadway segments.

To represent differences in route selection based upon distance and truck cost, routes connecting sand transload facilities and townships were generated using both distance and truck

cost. Differences are categorized by distances and costs. Comparison of differences in total distance under both distance-optimized and cost-optimized routes for sand movements are shown in Table 24 below. Statistical measures are shown in the first column. The second column presents these measures under the distance-optimized routing. The third column presents the statistical measures under cost-optimized routing. It should be noted that for all comparisons, the numbers and route locations are equal. Under both distance- and cost-optimized routes, the minimum distance is equal. The maximum distance under cost-optimized routing is greater than the maximum distance under distance-optimized routing, which indicates that route selection differs under each optimization method. As would be expected the sum of all route distances under distance-optimized routing is less than the sum of distances under cost-optimized routing.

Table 24. Comparison of distance statistics under distance- and cost-optimized routing

	Distance Optimized	Cost Optimized
Number of Routes	14,148	14,148
Minimum Distance	1.23	1.23
Maximum Distance	342.43	401.21
Sum of Distances	1,784,704.95	1,882,544.63
Mean Distance	126.15	133.06
Standard Deviation	67.11	67.26

As this study utilizes minimum cost as the method of routing, comparison of the costs under minimum distance and minimum cost is required. Table 25 presents a comparison of cost outputs under each routing method. As before, the number of routes under each routing method is equal, as is the minimum cost route. The maximum route cost under distance optimization is greater than the maximum cost under cost optimized routes. Of particular note is the difference between the sum of costs under distance-optimized routes and cost-optimized routes.

Table 25. Comparison of cost statistics under distance- and cost-optimized routing

	Distance Optimized	Cost Optimized
Number of Routes	14,148	14,148
Minimum Cost	\$2.98	\$2.98
Maximum Cost	\$1,155.45	\$948.77
Sum of Costs	\$5,199,441.72	\$4,303,950.72
Mean Cost	\$367.50	\$304.20
Standard Deviation	\$186.46	\$150.39

From the results presented in Table 24 and Table 25, it is clear that the routes selected under minimum cost criteria are different than those under minimum distance criteria.

Consideration of segment-specific cost factors necessitates that each segment, or categories of segments, be given specific costs as a result of roadway condition and travel speed.

#### 4.3. SIR Model

A SIR model was developed to model the spread of oil development throughout the study area. The SIR model was developed to model the spread of epidemics, thereby classifying portions of a population as susceptible, infected, or recovered at different time periods. The total population is equal to S+I+R. A person may move from S to I and I to R, but not from R to I or I to S. For the purposes of this study, the susceptible group represents townships in which oil development has not yet occurred, or is in the early stages of development. The infected group represents townships that have completed Phase I drilling. Phase I drilling refers to drilling at least one well per spacing unit to secure leases. The recovered group represents townships that have completed Phase II drilling. Each spacing unit, when fully developed, will receive five to seven wells, with a midpoint of six. Since a township consists of 18 individual 1,280-acre spacing units, Phase I completion represents 18 wells within a township, and Phase II completion represents a total of 108 wells within a township. Movements from S to I represent a township

moving from zero wells drilled to 18 wells drilled, equaling 18 new wells. Movements from I to R represent a township moving from 18 wells drilled to 108 wells drilled, equaling 90 new wells. The rate of infection, which represents the movement from the undeveloped to the Phase I completion, is represented by parameter  $\beta$ . The rate of recovery, which represents the movement from Phase I to Phase II completion, is represented by parameter  $\gamma$ . The starting values of these parameters are unknown. Historical data are limited to four years of exploration in the Bakken formation. Forecasts of future development provided by the Oil & Gas Division include the number of new wells per year through 2035. In the absence of significant historical data, the SIR model parameters were used to fit the model to the forecasts provided by the Oil & Gas Division through the least squares procedure. The selected parameters were:  $\beta=0.7547$ ,  $\gamma=0.1183$ . The number of predicted wells per year under the forecast given by the ND Oil & Gas Commission and the SIR model are presented in Table 26. It should be noted that the given forecast is itself a forecast, and its accuracy is based upon the best information available to the Oil & Gas Commission. Of note is that the initial year forecasts of new wells under the SIR methodology reflect new wells, additional wells will be drilled as a result of existing drilling activity in the region, either Phase I or Phase II activities.

Table 26. Comparison of given forecasts and SIR forecast annual new wells per year

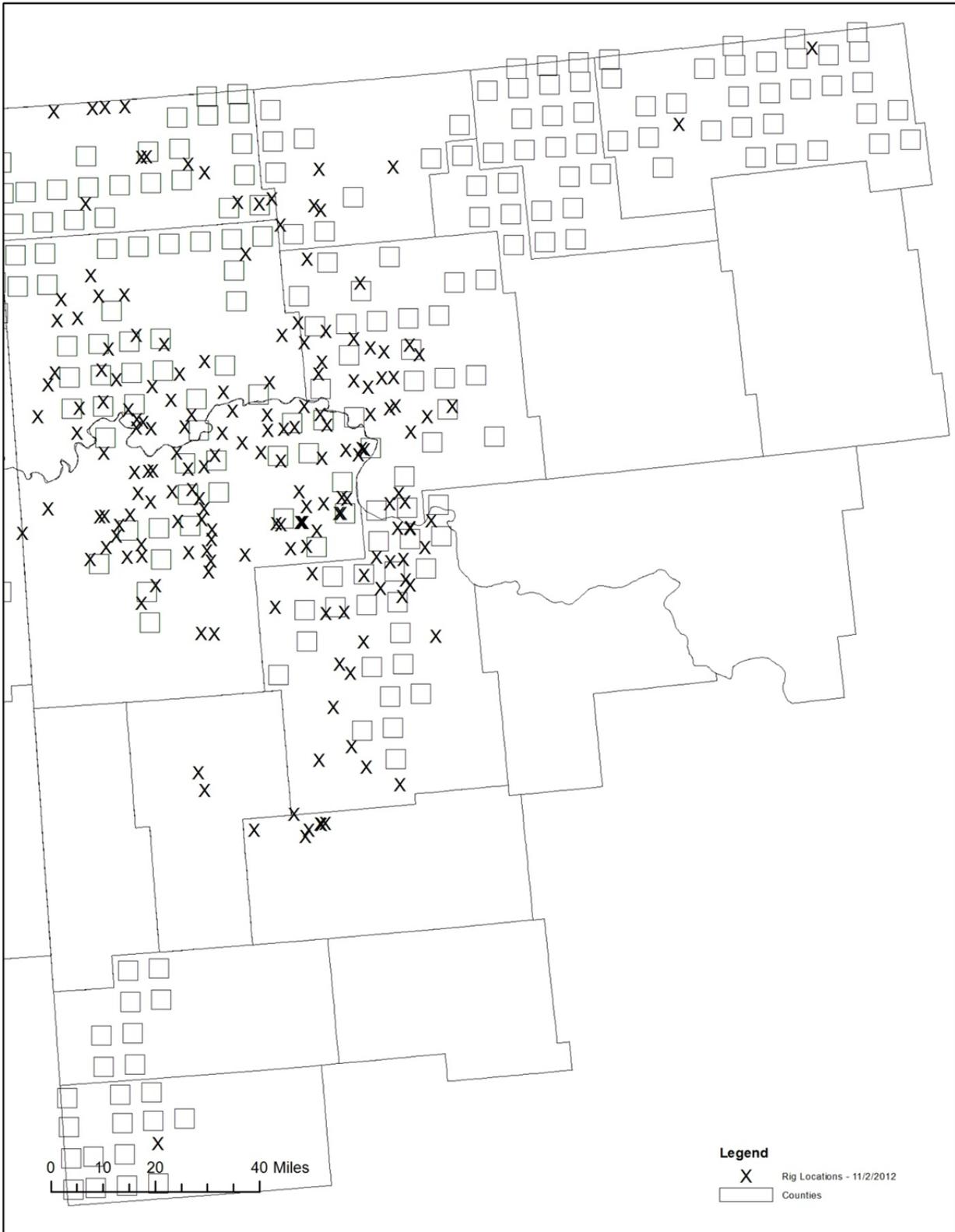
Year	Given Forecast	SIR Forecast
2012	1,271	809
2013	2,410	1,244
2014	2,430	1,843
2015	2,430	2,577
2016	2,490	3,316
2017	2,370	3,814
2018	2,395	3,854
2019	2,379	3,469
2020	2,377	2,933
2021	2,358	2,462
2022	2,354	2,099
2023	2,138	1,818
2024	2,134	1,589
2025	1,966	1,395
2026	1,966	1,228
2027	1,304	1,082
2028	1,304	954
2029	1,300	842
2030	1,002	743
2031	912	655
2032	434	578
Total	39,720	39,303
$\beta=0.7548, \gamma=0.1183, \text{MAPE}=0.34, \text{RMSE}=644.52$		

As described in Chapter 3, the model uses existing locations as seed points from which “infection” may spread. In terms of oil development, this represents the expansion from drilled areas into undrilled areas. The SIR model predicts the spread from one area to another, but does not return the expected annual number of wells directly. Once the township moves from S to I, it is assumed that 18 wells are drilled during the year that the infection occurs. For movements from I to R, the duration of drilling was calculated by subtracting the year of infection from the year of recovery. This represents the duration of Phase II drilling within the selected township. The annual number of wells for Phase II drilling is equal to 90 wells divided by the duration. Due to potential rig availability issues, it is assumed that drilling occurs at a consistent pace

within the years between infection and recovery, and not all at once during the year of recovery. The mean duration of drilling in townships was 7.12 years, with a minimum duration of 3 years and a maximum duration of 17 years. Once Phase I is completed, the mean number of wells in a township drilled per year is 12, with a minimum of 4 and a maximum of 24. The SIR model varies from the given forecast in that the number of expected wells beginning in 2015 exceeds the given forecast until 2023, at which point the given forecast exceeds the SIR forecast.

To evaluate the usefulness of the SIR model to model oil development spatially, the forecast drilling locations were compared against drilling rig locations at the time of the analysis. Drilling rig locations are only available for North Dakota wells at the time of the analysis, so the Montana counties and forecasts are not included in the visualization. Figure 20 shows the forecasted drilling locations represented by hollow squares, and the actual rig locations on November 2, 2012, with an X.

Figure 20. Existing rig locations and SIR model forecasted locations: 2012



In 2012, the SIR model estimates 288 drilling locations in North Dakota, based upon currently infected townships that are in the process of recovery (Phase II drilling) and newly infected townships (Phase I drilling). The SIR model predicts the location of new infections which represents a movement from state S to state I, with each location representing 18 new Phase I wells. In addition, the SIR model predicts Phase II drilling (state I to R) based upon the township recovery year and the existing number of wells. Of these 288 locations, 17 are Phase I infections, and 271 are Phase II wells. Thus, a total of 306 Phase I wells and 503 Phase II wells for a total of 809 wells are predicted to be drilled in 2012 by the SIR model. Since a comparison of forecasted locations to actual drilling locations is required to assess location accuracy, only the drilling locations selected by the SIR model will be compared to the actual drilling locations as of November 2, 2012 based on rig locations.

To compare the model's effectiveness to random selection of drilling locations, 288 drilling locations, the same number as predicted to be drilling in 2012 by the SIR model, were selected at random. Model accuracy was calculated by calculating the distance from each selected drilling location to actual rig locations. These distances were calculated for the 288 SIR selected locations as well as the 288 randomly selected locations. A comparison of the two distance calculations is shown in Table 27.

Table 27. Comparison of SIR to random location

	SIR Forecast	Random Selection
Count	288	288
Minimum Distance	0.25	1.62
Maximum Distance	45.14	151.22
Sum of Distance	2,848	10,859
Mean Distance	9.89	37.70
Standard Deviation	8.83	39.76

The distances shown in Table 27 represent the distance between predicted and actual locations and are used to measure location error. The minimum location error for the SIR model is 0.25 miles as compared with 1.62 miles for random selection. The maximum location error for the SIR model is 45.14 miles as compared with 151.22 miles for random selection. The average location error of the SIR model is 9.89 miles, while the average location error for random selection is 37.70 miles. From these statistics, it appears that the SIR model more accurately predicts well drilling locations than a random selection of drilling locations. However, because several predicted locations may use the same existing location to assess proximity, this is not a perfect measure of spatial forecast accuracy. To supplement this spatial measure of forecast accuracy a comparison is made between the predicted number of wells at the township level from the SIR model (wells existing prior to 2012 plus new wells) and currently existing wells at the township level. In the 288 townships the SIR model lists as drilling in 2012, the actual minimum number of wells is 1 and the maximum number of wells is 67. The average number of existing wells in those townships was 10.67 with a standard deviation of 11.04 wells. This compares to an SIR prediction of 26.27 wells, on average, for these townships. In the 288 townships selected at random, the actual minimum number of wells is zero and the actual maximum is 48. The average number of existing wells in these townships is 3.87. Under random prediction, the number of wells in each township could be anywhere between 0 and 108. Thus, a random number is generated for each. The average number of wells predicted in the randomly selected townships is 54. This average is different than the actual average of 3.87 that exists in these randomly selected townships.

While these data provide comparisons between SIR and randomly selected drilling locations and existing number of wells, it does not specify the degree of error. To assess the

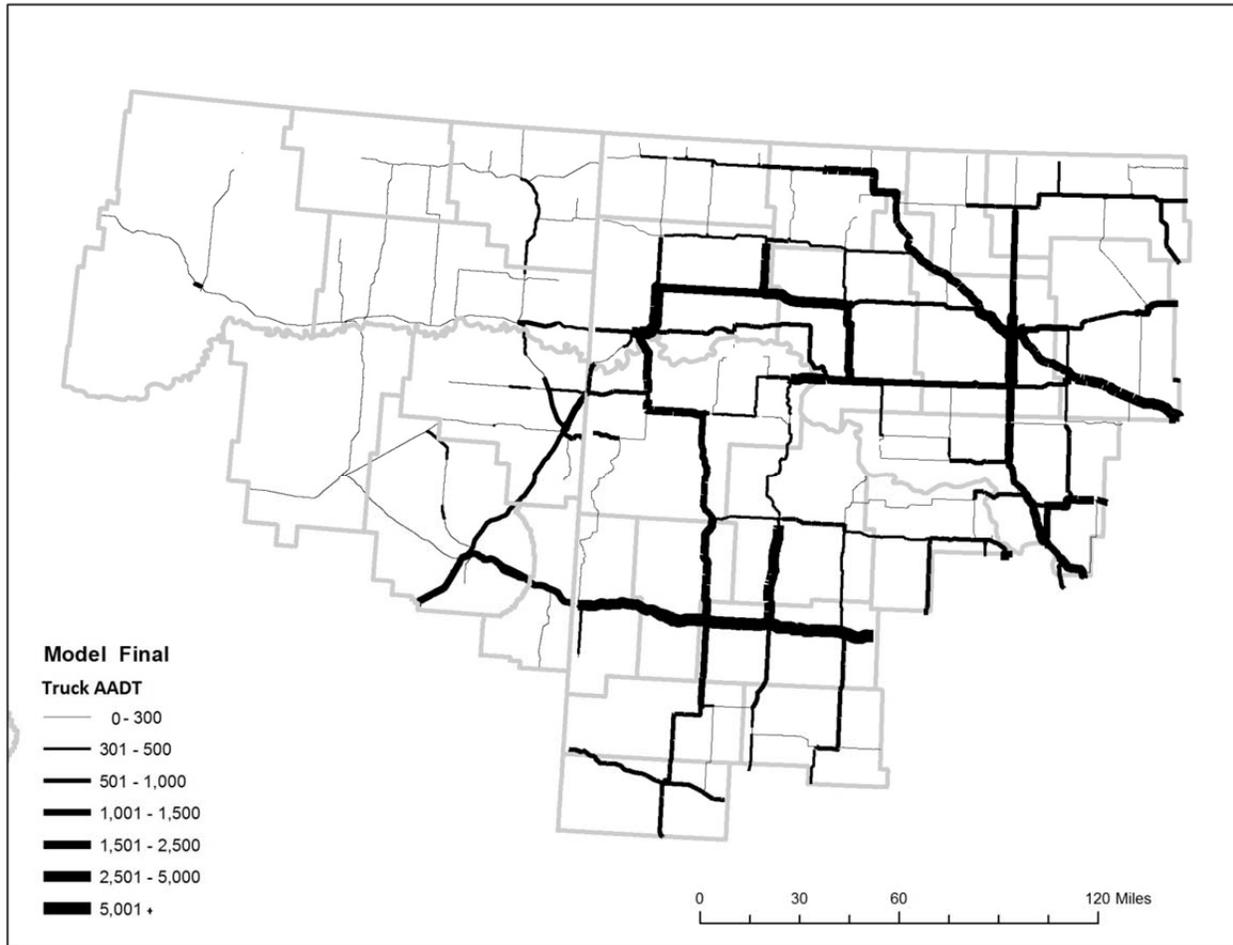
degree of error in the predicted number of wells against random selection of locations, the mean absolute percentage error is calculated. For SIR selected locations, the MAPE of existing versus predicted wells is 156.88. For randomly selected locations, the MAPE of existing versus randomly selected wells is 322.52. While the SIR has a high degree of error, it is important to clarify that this is not only a measure of the number of existing wells, but rather is a combination of location error and prediction error. When compared with random selection error in location and number of wells, the SIR predicted well numbers is a superior prediction method.

#### 4.4. Traffic Model Forecasts

Following the completion of optimization models for each of the movement classes for each year in the analysis period, route segments were collected. The aggregation of the traffic flow over each segment represents the total direct impact of oil development within the study region, which is the sum of individual movements.

Presentation of traffic forecast results are difficult, as there are 4,034 individual highway segments with 20 years each of truck traffic, flexible ESAL and rigid ESAL forecasts. Due to the volume of data, results are presented visually in maps with variations in map symbology representing different traffic volumes. The results are presented annually for the first five years of the analysis, and in five-year increments following 2017. Where major changes in traffic volumes occur, highway segments and rationale for the traffic volume changes are provided. The first year of the analysis was 2012. Traffic forecasts for 2012 are shown in Figure 21. As was expected, significant traffic can be found near the dense development areas in Dunn, McKenzie, Mountrail, and Williams Counties in North Dakota. In particular US 85, US 2, ND 22, ND 23, and MT 16 have significant forecasted impacts.

Figure 21. Truck traffic forecast 2012



Truck traffic forecast estimates in 2013 are presented in Figure 22. While visually, the results appear similar to 2012, there are significant increases along US 85 and ND 23, primarily driven by production and exploration in the areas surrounding Lake Sakakawea.

Figure 22. Truck traffic forecast 2013

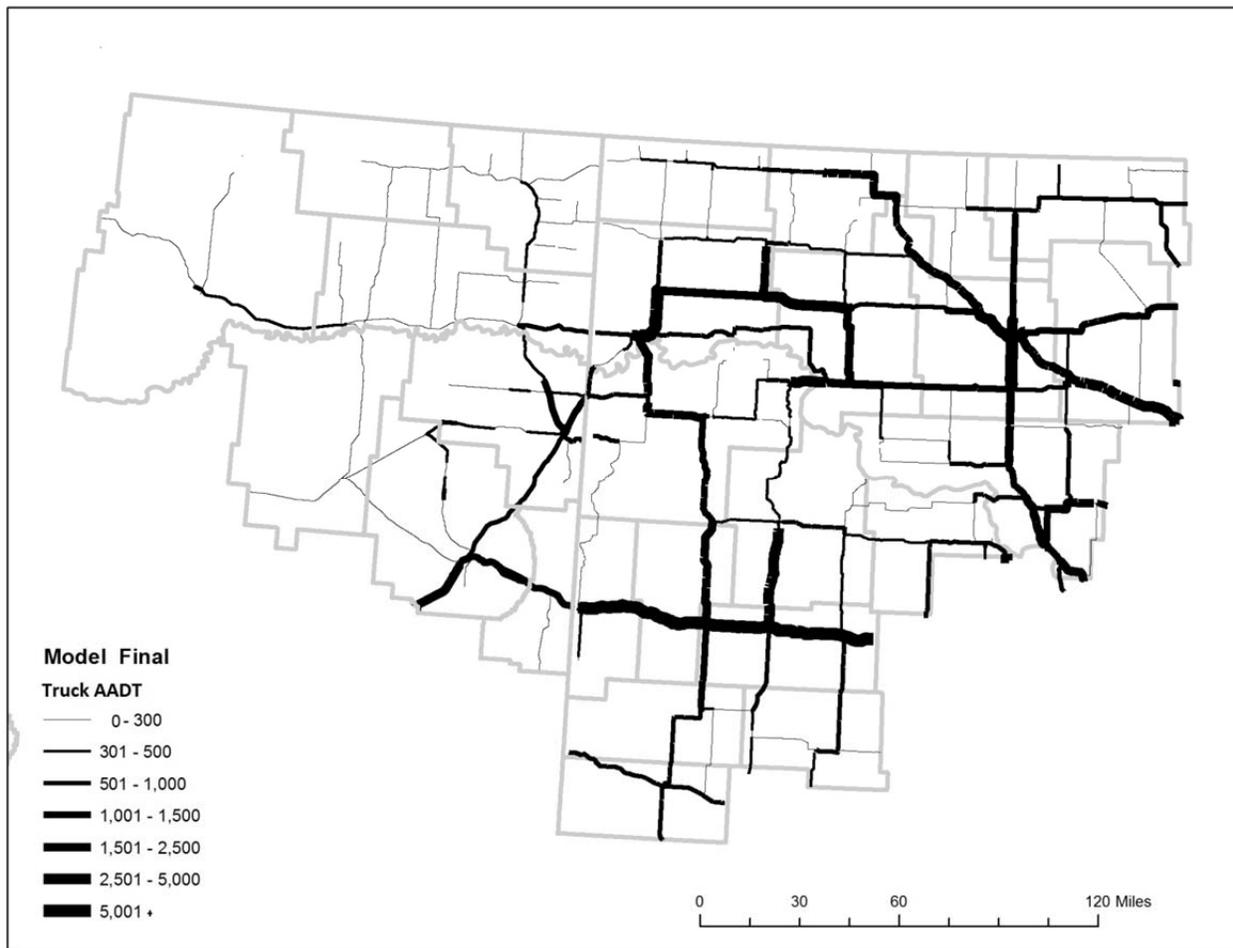
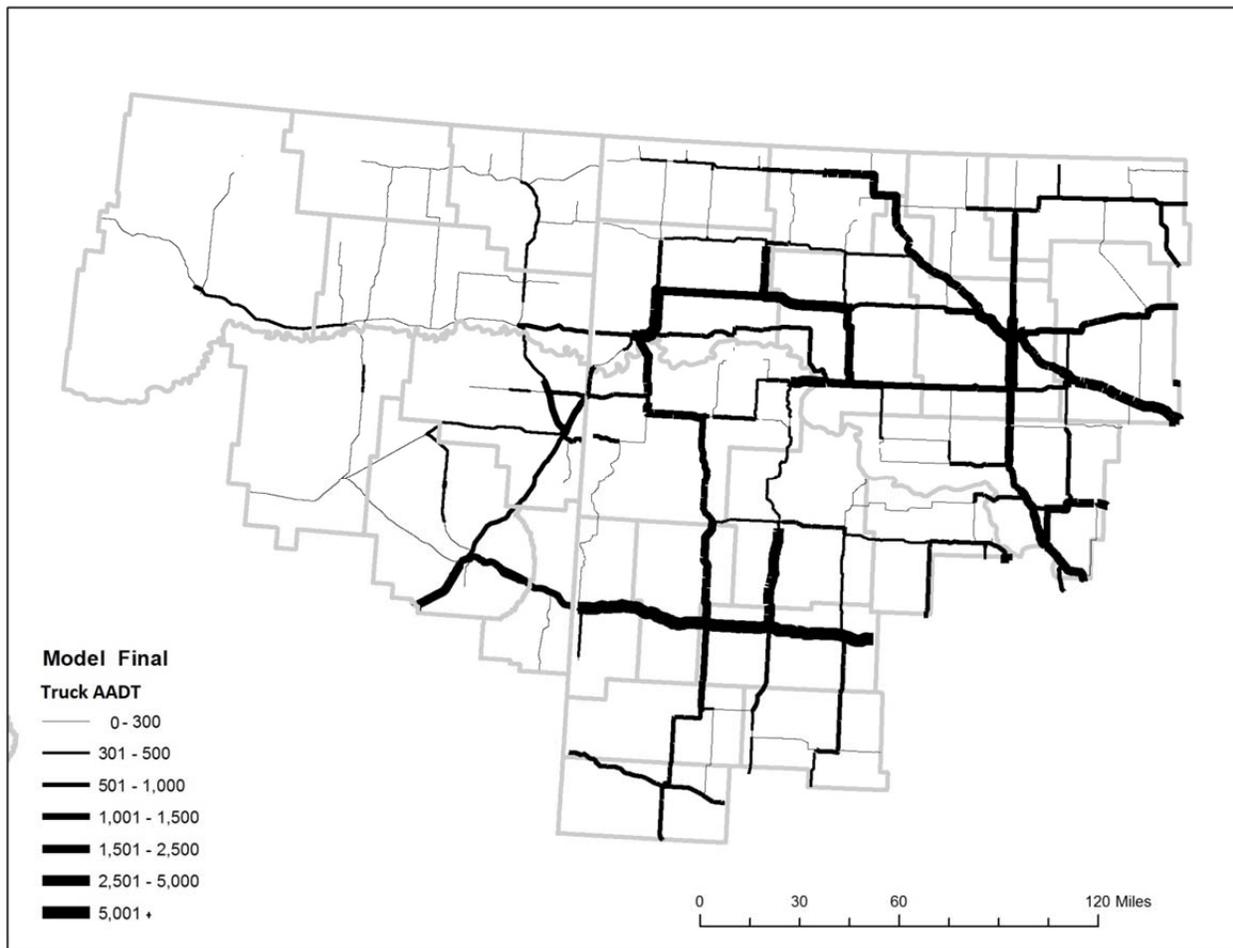


Figure 23 presents the traffic forecasts for 2014. During this year, significant increases occur along US 2 between Williston and Minot, as well as ND 23 near Newtown and ND 200 east of Killdeer. The latter of these increases is due to frac sand movements originating in Beulah, ND.

Figure 23. Truck traffic forecast 2014



Truck forecasts for 2015 are presented in Figure 24. Areas of increase from 2014 include those mentioned above, as well as additional increases on US 85 from Watford City to Williston, ND. Similar increases occur through 2017 as shown in Figure 25 and Figure 26.

Figure 24. Truck traffic forecast 2015

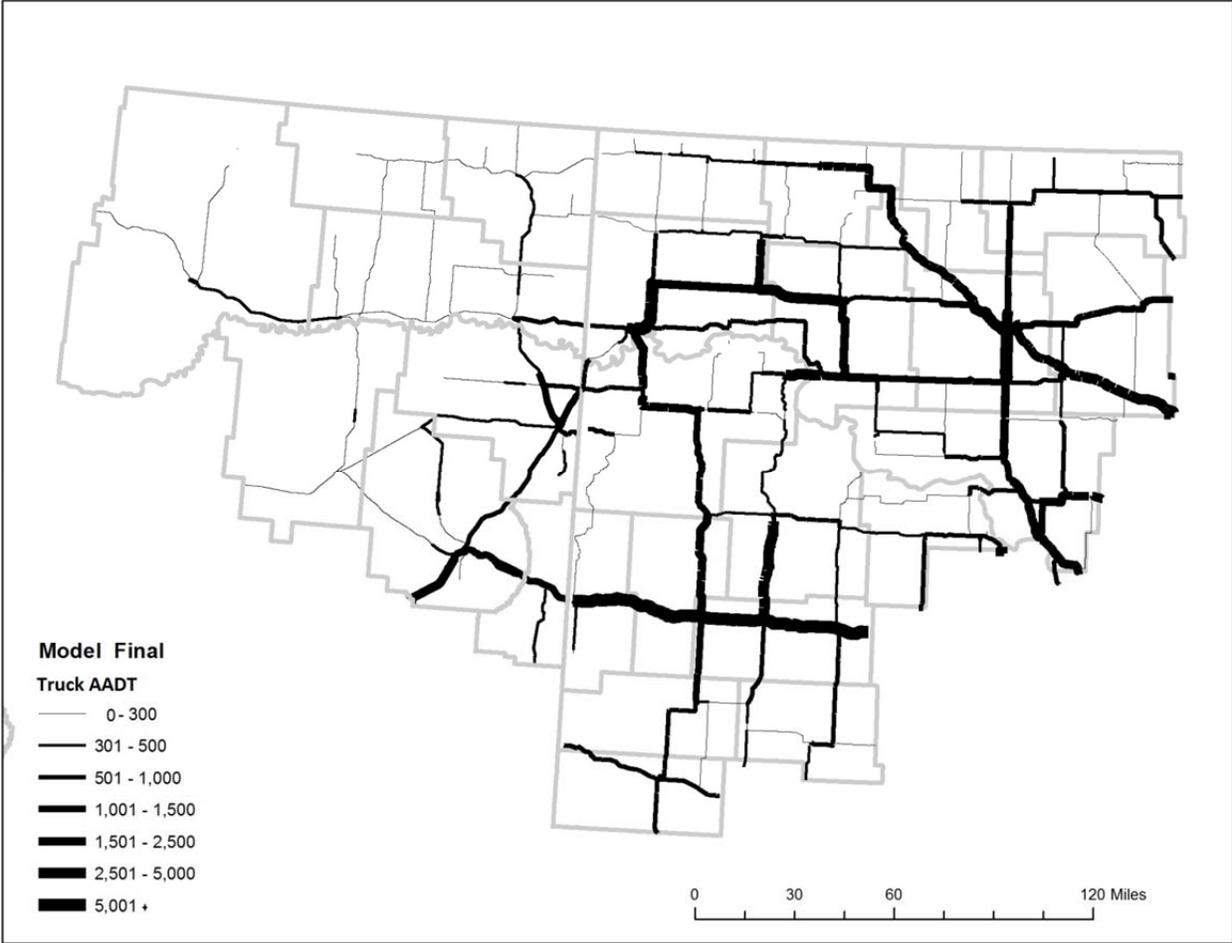


Figure 25. Truck traffic forecast 2016

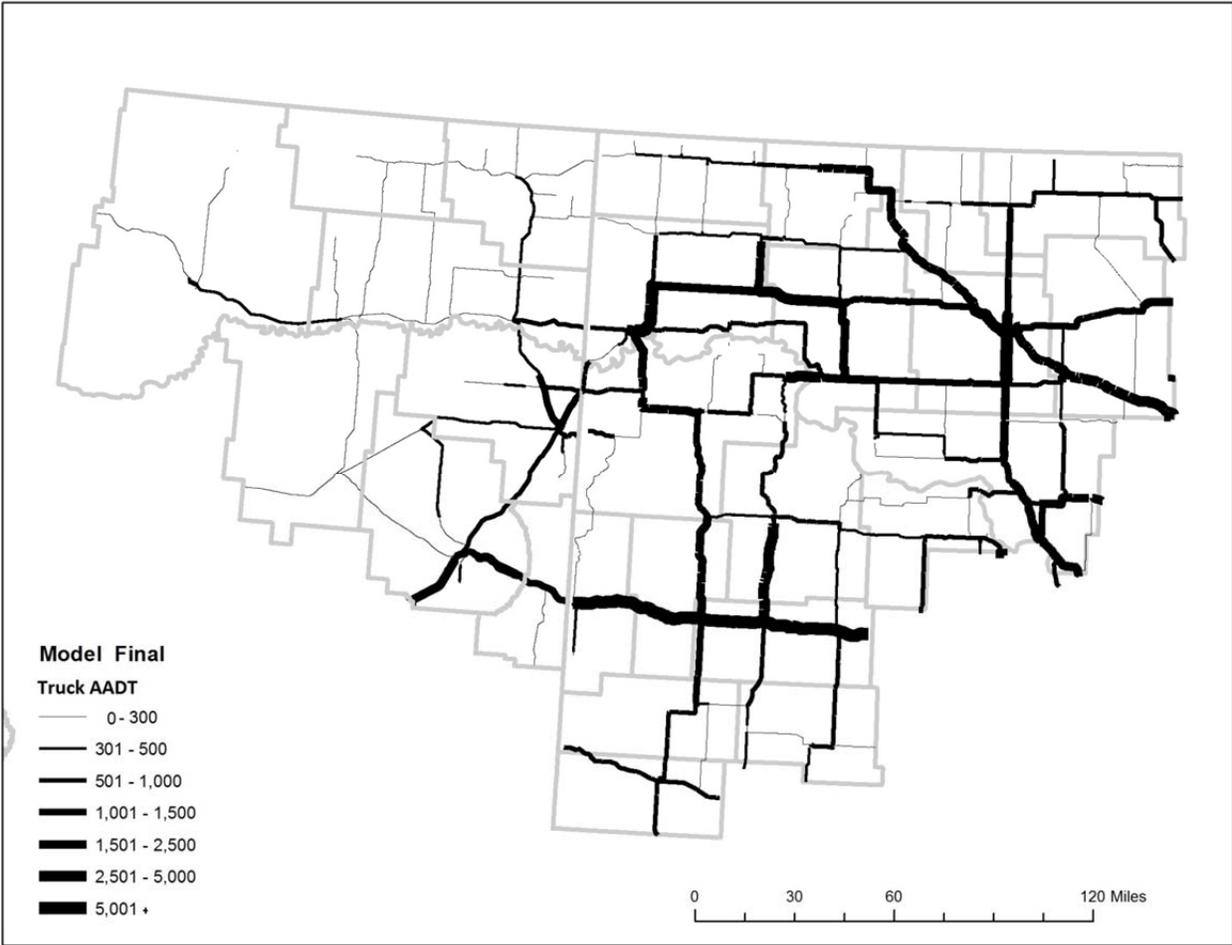
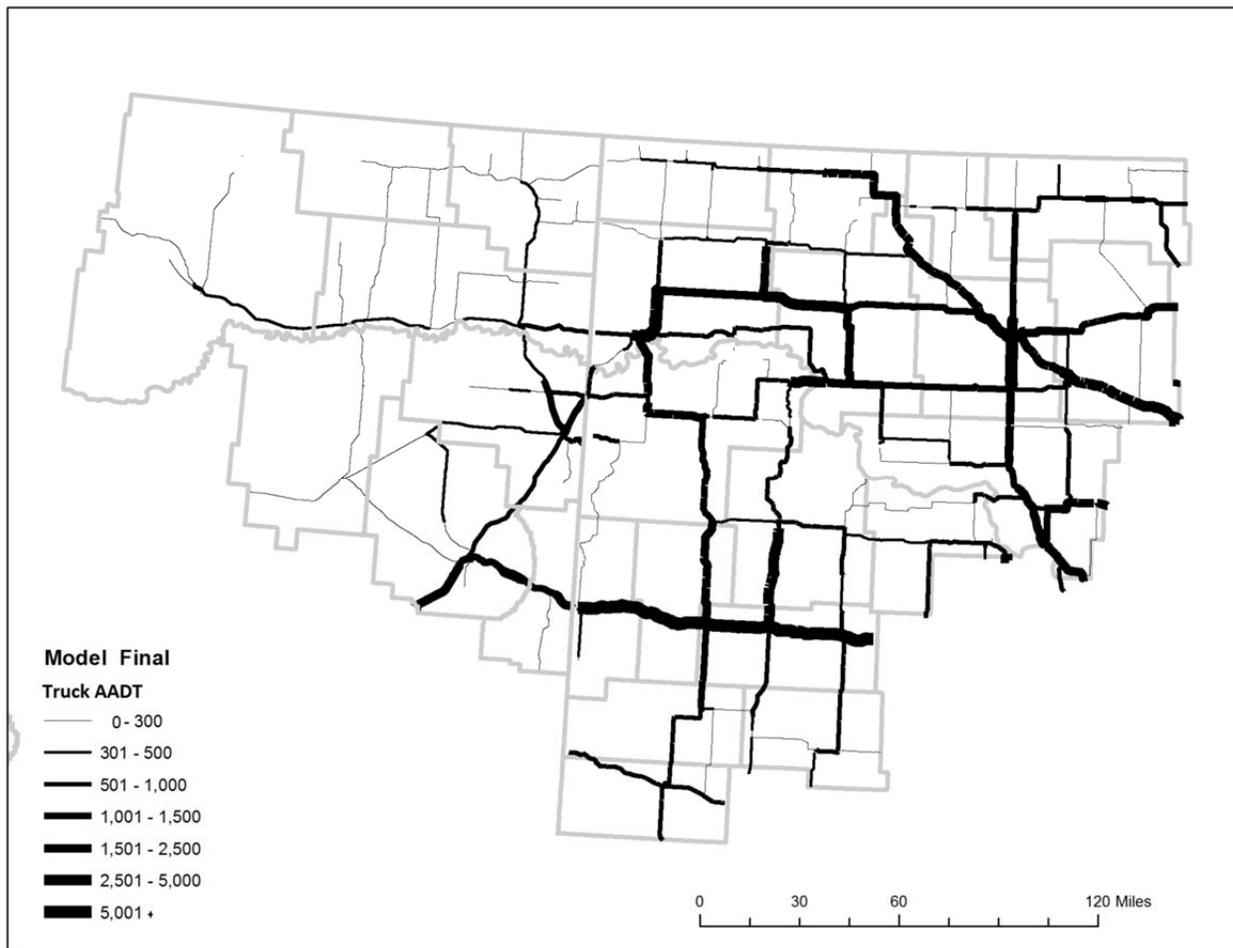
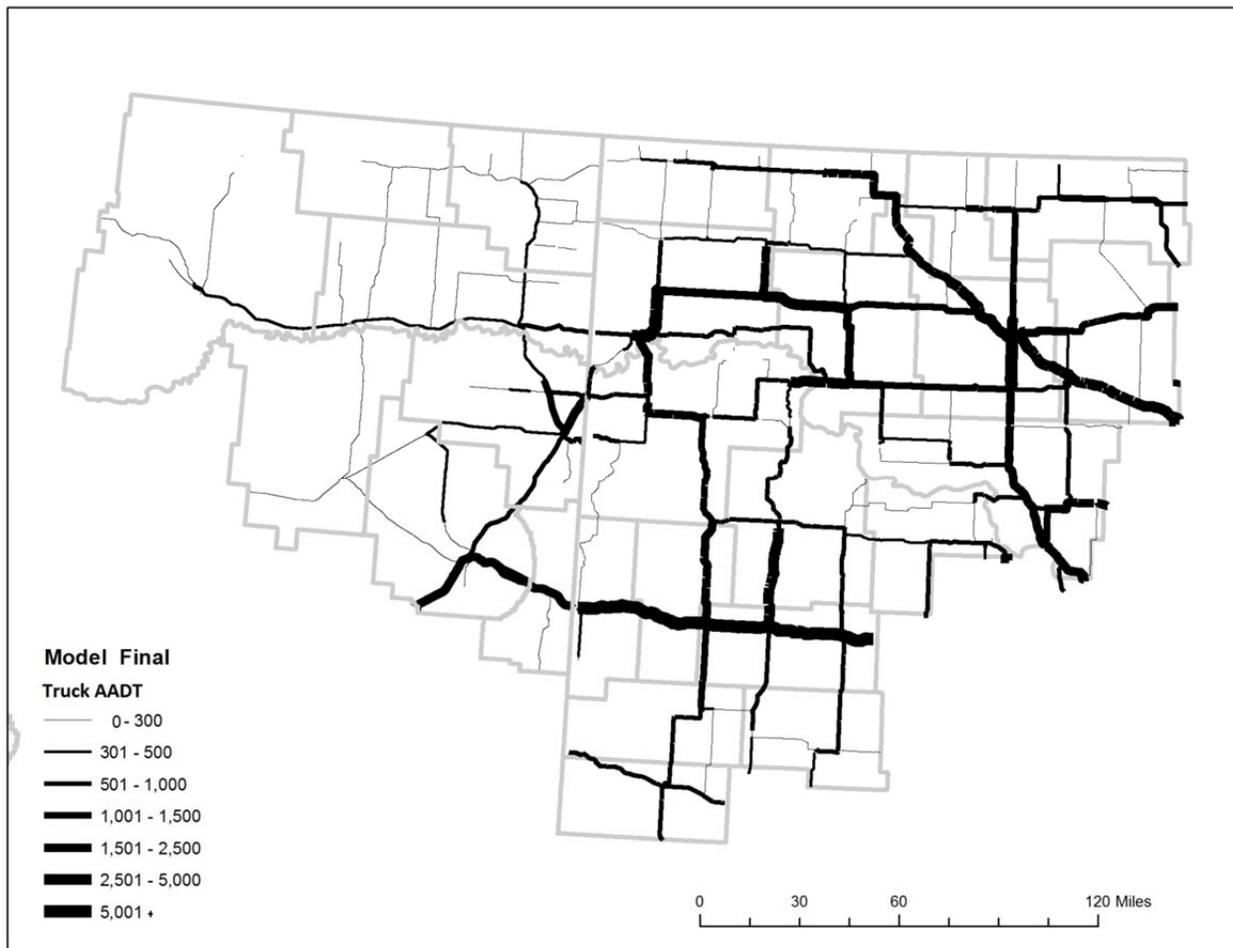


Figure 26. Truck traffic forecast 2017



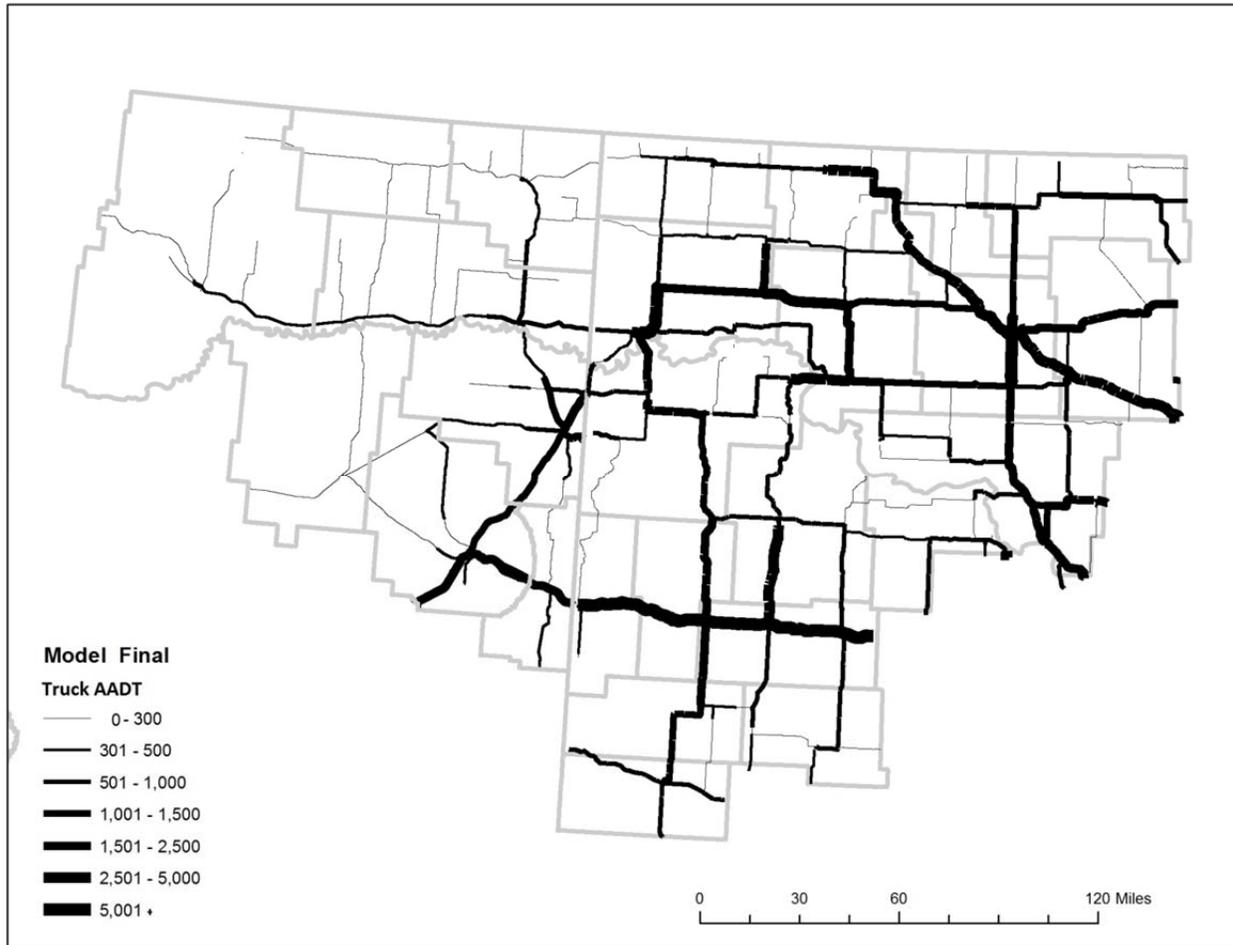
As time progresses in the traffic forecasts, the impact of additional producing wells becomes evident in traffic growth throughout the entire study area. All primary corridors in North Dakota see growth, but the impact of oil development near Sidney, MT, along with cross-border movements of inputs and outbound oil lead to growth on MT 200 from the North Dakota line to Sidney. Additionally, traffic increases on MT 16 from Culbertson to Sidney, MT.

Figure 27. Truck traffic forecast 2022



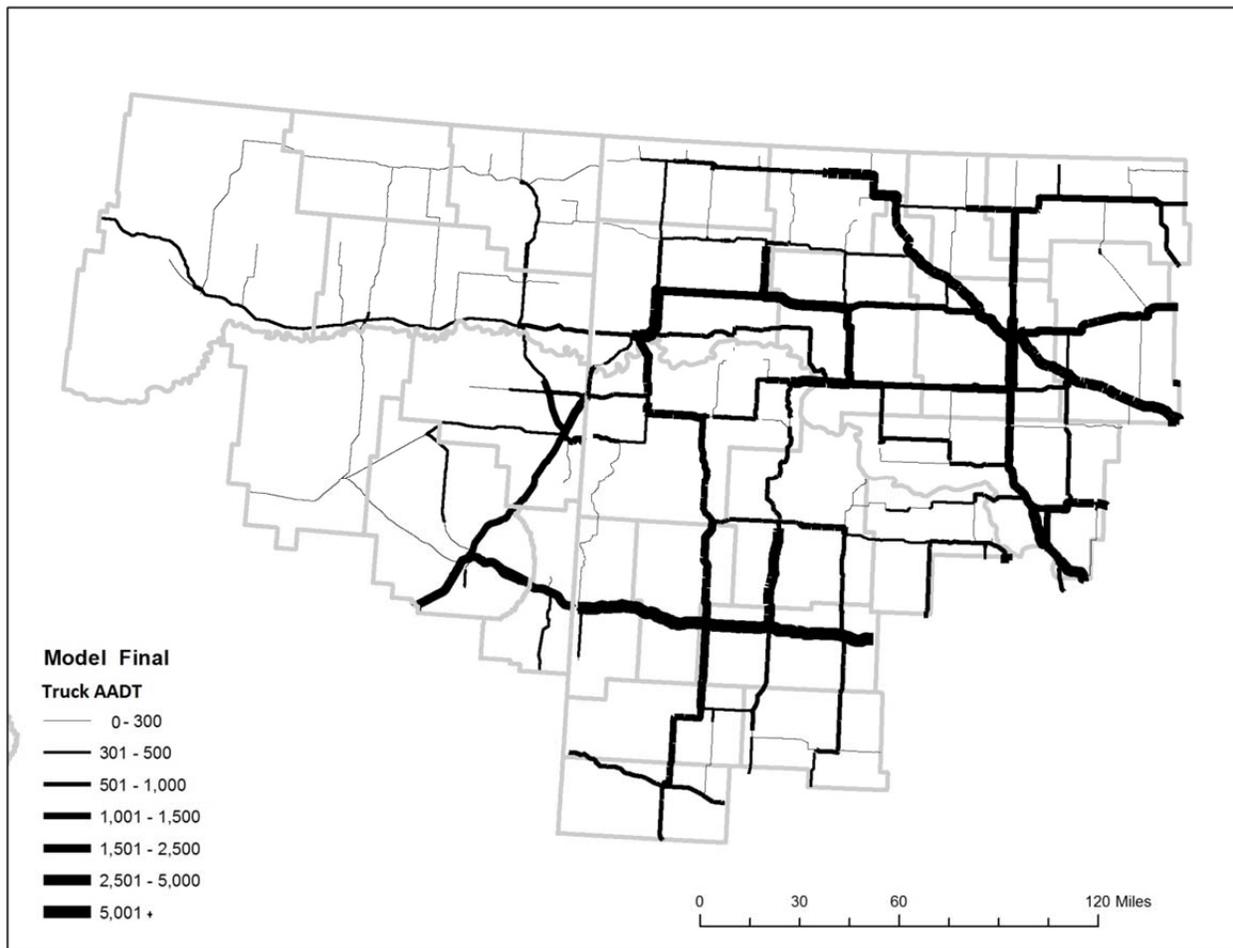
From 2022-2027, growth is consistent throughout the study area, as the number of new wells begins to decrease as shown in Figure 28. Both the SIR model and forecasts from the North Dakota Oil & Gas Division show that at this period in time, the rig numbers in the area will have already begun to decrease. As rig numbers decrease, the number of new wells will also decrease. As a result of the steep production decline curve seen in Bakken wells described in Chapter 1, this will also result in a decrease of oil production throughout the entire region.

Figure 28. Truck traffic forecast 2027



Growth from 2027-2032 still occurs even as forecasted oil development and production decline, primarily as a result of the annual growth in background traffic, which comprises through movements, local movements, and population-related movements. Figure 29 presents the traffic forecasts in 2032.

Figure 29. Truck traffic forecast 2032



As discussed earlier, it is expected that freshwater availability would be the limiting factor in the optimization problems. To assess the impact of the capacity limitations for freshwater inputs on the solution, shadow prices were collected from the output data. As there are many individual freshwater sources, all shadow prices are not presented. Rather, discussion on the changes in shadow prices based upon locations is included. Shadow prices represent the change in the objective value if a constraint is relaxed. In this case, the constraints under consideration are the output capacities at freshwater locations. As a reference point, the optimization results from 2022 are selected, as this is this final year of peak drilling according to the North Dakota Oil & Gas Division. For the freshwater optimization problem, all shadow

prices are negative, as an increase in the constrained capacity results in a decrease in the objective function which minimizes total distribution costs.

Shadow prices for freshwater capacities range from -42.92 to -271.34 in the 2022 optimization run. This means that adding one additional truckload of freshwater capacity at various facilities decreased trucking costs by \$43 to \$271. This suggests that oil developers may be willing to pay large amounts to expand water capacity in some areas. Of note is that the largest shadow prices (in absolute value) occur within the primary oil development area, as this is the primary area of demand for freshwater. Also of note is that shadow prices in Montana are larger in later years, as is reflected in the sourcing of freshwater from the western area of the study region, thereby necessitating longer distance trips.

The traffic model estimates generated by this study reflect the impact of oil development within the study area. Individual movements include inbound inputs to well locations and outbound crude oil and saltwater to collection facilities. Growth in background traffic is considered through the model calibration. Model calibration involves the comparison of observed traffic counts to predicted oil movements. Since oil traffic is only a portion of the total traffic observed, consideration of the background traffic is necessary to forecast total truck traffic for planning and design uses. A lower annual growth factor is used for modeling the through traffic component, and background traffic in the lesser impacted oil counties, and is arrived at through examination of pre-oil development traffic. Impacted traffic growth factors are based upon trip generation estimates tied to population growth within the Williams, McKenzie, and Mountrail County areas, which represent the most significantly impacted oil counties in the study. Due to the differences in assumptions, a single set of growth factors was not applied to

the entire study area. In higher development counties, the impact area growth factors were used, and in the fringe counties, the baseline growth factors were used.

This study expressly considered oil traffic movements in conjunction with oil development throughout the study area. This contrasts with traditional “look back” methods or trend analysis. Traditional trend analysis involves the calculation of a traffic growth rate based upon a number of previous traffic observations. Often, the three previous traffic counts are used to develop a growth rate, which is then applied to the 20-year traffic forecast. Due to variations in the frequency of traffic counts, this could equal a time period from three to 12 years. Frequency of traffic counts depend on expected changes in traffic over the short term. Prior to oil development, traffic counts were conducted in one-third of North Dakota each year. This means that every three years, a count is conducted, and a trend would be developed from changes in traffic over nine years. Recently in western North Dakota, due to increases in traffic, this interval has decreased to one year, and data are collected annually.

Pavements are designed to withstand a cumulative number of ESALs over the design life of the pavement. Typically for flexible pavements, this is a 20-year design life. The service life of the pavement is the actual life of the pavement, and reflects differences in ESALs from the design. If the forecast number of ESALs is equal to the number of design ESALs, the service life is equal to the design life. If the actual number of ESALs exceeds the design ESALs, the service life of the pavement is less than the design life of the pavement.

The objective of this study was to develop a traffic model that improves truck and ESAL forecasts above traditional traffic forecasting techniques. To assess whether this objective has been met, comparison of traditional forecasts and this study’s forecasts is required. The Highway Performance Monitoring System provides NDDOT traffic forecasts reported to the

U.S. Department of Transportation. “The HPMS is a national level highway information system that includes data on the extent, condition, performance, use and operating characteristics of the nation's highways” (Federal Highway Administration 2012). Of these data, existing AADT, future year AADT, and percent trucks are used to calculate the existing and future year truck numbers. The most recent data available are the 2010 HPMS dataset, reported to FHWA in 2011.

Two highways in North Dakota that have been significantly impacted by oil traffic are US 85 from Watford City, ND, to US 2 west of Williston, ND, and ND 23 from Watford City to New Town, ND. As these segments are significantly impacted, they will be used to illustrate the differences between forecasting methods. HPMS traffic data and future year traffic data for these segments are presented in Table 28.

Table 28. Traditional truck traffic forecast results: US 85 and ND 23

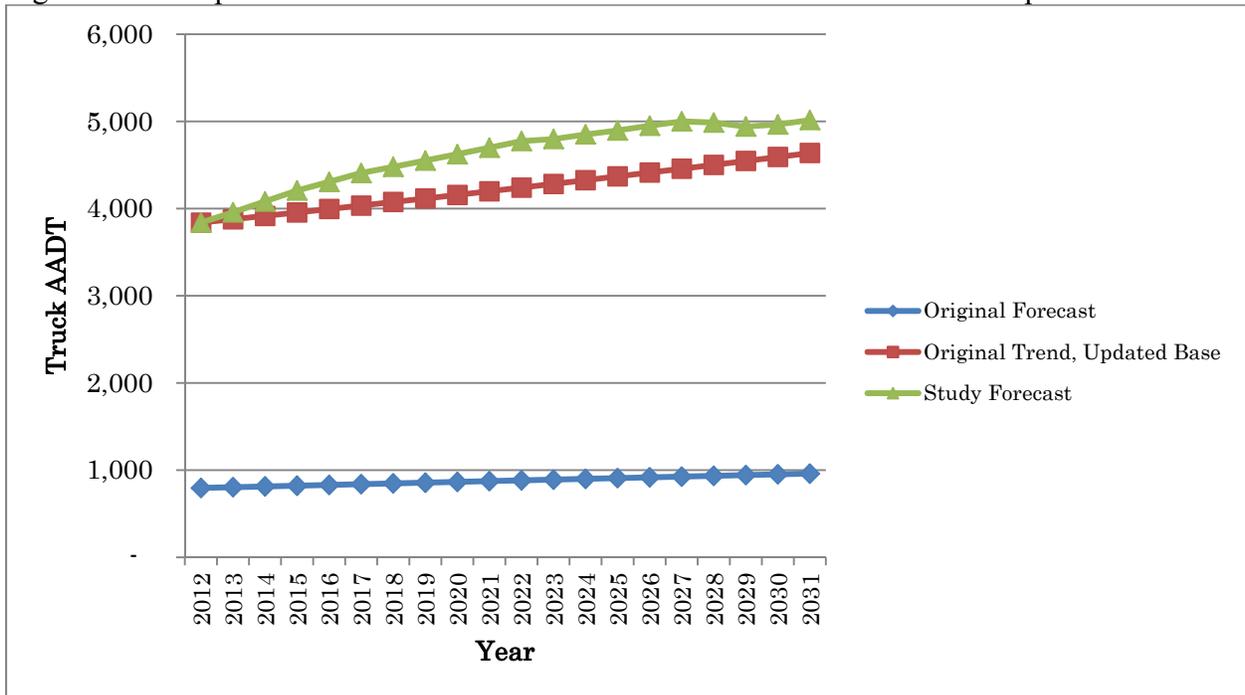
	Reference Point	2010 Trucks	2031 Trucks	Annual Growth Rate
US 85	152	778	960	1.1114%
ND 23	42	1,252	1,704	1.7172%

For comparative purposes, the traffic forecasts presented in Table 28 will be used against model traffic forecasts in two ways. The 2010 traffic forecast will be compared directly against model forecasts. Next, the growth rate from the 2010 forecast will be used to forecast traffic from the base 2012 truck count numbers. The comparison for US 85 at milepost 152 is shown in Figure 30. The top line represents the study forecasts, the middle the original trend line applied to 2012 base traffic counts, and the lower line represents the original forecast.

It is clear that if the original forecast were used for pavement design purposes that the pavement would be substantially under-built, and the service life would be far below the design life of the pavement. However, it is unlikely that pavement designers would directly use the

2010 forecasts without consideration of current traffic. For this reason, application of the growth rate from the 2010 forecast to current traffic levels is a more appropriate comparison. For all years during the analysis period, the study forecast exceeds the traditional forecast. It should be also noted that the model forecast does not grow in a simple linear manner, rather it represents increases and decreases in oil growth throughout the analysis period. For this segment of highway, if the model forecast is accurate, the service life of this segment of highway would be less than the design life, and additional improvements and maintenance would be required during the 20-year period.

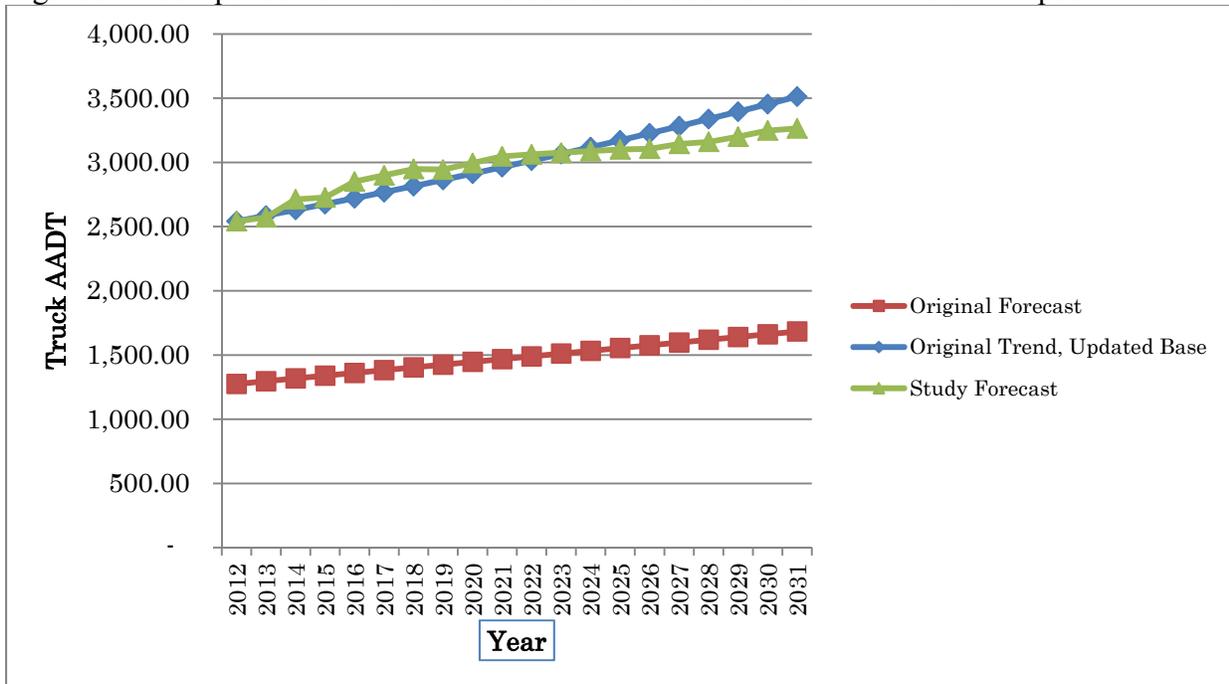
Figure 30. Comparison of traditional forecasts to model forecast: US 85 at milepost 152



A similar comparison for ND 23 at milepost 42 is shown in Figure 31. Again, the original forecast would result in significant under-building of this roadway, which would result in multiple improvements over the analysis period. But, as mentioned above, it is unlikely that a pavement designer would utilize this forecast without consideration of current traffic levels. This section of pavement differs from the US 85 example in that the study forecast initially

exceeds the updated trend line, but in the latter years of the analysis, the trend line exceeds the study forecast. As previously discussed, the spread and duration of oil development in North Dakota is expected to reach a peak in the mid-2020s, and decrease from that point into the future. The study forecast shows this mid-range peak in traffic before it plateaus from 2024 to 2026. If the pavement were designed using the original trend with the updated base, the pavement would be over-built for the cumulative 20-year traffic levels, if the study forecast is accurate, as the cumulative study ESALs are less than the updated trend line cumulative ESALs.

Figure 31. Comparison of traditional forecasts to model forecast: ND 23 at milepost 42



It is expected that highway planning officials would use these traffic forecasts in conjunction with existing traffic forecasting methods for use in planning decisions and pavement design. The model presented in this document is based upon assumptions and traffic data provided in 2012. As time progresses, current traffic data should be considered when making comparisons between model results and existing traffic forecasting methods.

## 4.5. Study Contribution and Research Application

### 4.5.1. Study Contribution

This study utilized an optimization model which has been utilized in numerous previous studies, to select least cost set of routes between origin and destination pairs. However, this study used optimization to select the origin-destination pairs themselves in addition to the least cost set of routes. This contrasts with previous studies that selected origin-destination pairs based upon geographic proximity.

This study presents an application of the SIR model to spatial distribution of freight generators, specifically future well drilling locations. As historical data are limited, it may be of use to further validate this model in the future when additional data become available. The use of this type of model may be transferrable to other freight generation modeling, particularly if the locations of the activities are bound by nature and significant clustering can be found. In this study, geology was the deciding location factor rather than economic activity.

The truck cost model outlined in this study improves on truck costs used in previous network analysis studies. This study considers a truck type specific cost, which varies by the individual roadway segment. As segment condition, surface type, and travel speed vary, costs are also likely to vary. Use of a network-wide constant per-mile truck cost would not directly consider segment conditions, and therefore produce results that are not representative of actual travel costs. This means that the optimization model will choose routes that are not representative of those actually chosen. In contrast, by considering segment characteristics, this study more accurately predicts routes where traffic travels, and improves on segment specific forecasts.

Traffic forecasting techniques used in this study serve to improve upon existing rural road traffic forecasting methods. One specific contribution is to include explicit consideration of major traffic generators. In comparison to traditional trend analysis, which derives traffic growth factors based upon previous observations, the timing of the observations is critical to assessing the potential impacts of new freight generators. As this study considers freight generators directly, the forecasts produced reflect the timing of the traffic generated, and reduces the potential for error as seen in trend analysis.

The timing of the traffic impacts is important, because pavements do not deteriorate in a linear manner as additional ESALs are introduced. Pavement preservation analysis considers the impact of timely maintenance and improvements and compares the costs of each. Application of these maintenance and improvement activities prior to significant pavement deterioration results in a significantly lower cost improvement type (e.g. asphalt overlay instead of reconstruction). Knowledge of when the pavement will experience ESAL loads allows planners and pavement designers to time improvements more appropriately, thereby minimizing improvement costs. Rural states essentially compete with urban states for highway funding. This requires rural states to justify the benefits and costs of scarce funds spent on rural road improvement. Urban road improvements have significant benefits; these improvements impact large numbers of travelers and economic activities. However, these benefits come at a significant cost due to the type of infrastructure being improved and the impact of construction on economic activities and land use. Rural roads, in comparison, have relatively low traffic volume, and therefore lower benefits. However, these benefits come at a significantly lower cost due to the type of improvement implemented.

States have limited highway funding from which to improve their roads. As funding is scarce, the focus for state planning officials should be on the most efficient and productive uses of existing funds. Traffic forecasting is important to proper pavement design, and therefore to the allocation of these scarce funds among the roadways in the state. The cost of enhanced forecasting methods as presented in this study is very small in comparison with the benefits of avoiding poor forecasts that result in incorrect allocation of scarce funds.

State and federal highways are funded through the Highway Trust Fund, which is composed of revenues collected from federal fuel taxes. These funds are then redistributed to states based upon a funding allocation formula. Currently, North Dakota and Montana receive more revenue from the Highway Trust Fund than is generated in the respective states. Due to increased fuel efficiency in recent years coupled with higher vehicle miles of travel, the revenue generated by the Highway Trust Fund has decreased while miles traveled have increased. In addition, inflation in highway construction costs in recent years has placed constraints on the number and type of improvements that are funded by the Highway Trust Fund appropriations. These trends may result in lawmakers revisiting the allocation of funds through the funding allocation formula, which may result in a decrease of funds for use in rural road maintenance and improvement. If highway funds to rural states were decreased through changes in the allocation formula, the importance of forecast accuracy would certainly increase.

#### 4.5.2. Research Application

This study focused on modeling traffic generated due to oil development and production within eastern Montana and western North Dakota. Methods presented in this study are readily transferable to other geographic regions and trip generation activities. The existing study would

be further improved through inclusion of additional traffic generation activities such as explicit consideration of agricultural movements.

The models presented in this study are directly applicable for assessing the impacts of infrastructure development. Since the truck costs used as impedance factors in the routing algorithm are segment specific, any changes in surface condition or type will change the cost of traveling over those segments. This may be particularly useful for benefit-cost analysis of potential improvements, as changing the cost through roadway improvement will likely change the distribution of traffic. In addition to roadway-specific analysis, investment in other infrastructure may increase or decrease traffic on certain segments. The tools in this study will allow researchers to consider impacts of the location of new facilities such as shuttle elevators and water depots, or state investment in railroads and pipelines. Depending on the location and type of infrastructure being considered, there may be an increase or decrease in traffic. Since this study explicitly considers traffic generators, build and no-build scenarios would show the impacts of location of these types of facilities.

Scenario analysis is another use for the methods presented in this study. For example, if the oil producing region were to experience drought conditions within the next 20 years, it is likely that the water locations would have reduced capacities due to changes in water permitting. The result of these capacity changes may result in exploration companies traveling out of the direct oil producing region to source freshwater, thereby increasing the geographic scope of highway impacts due to oil development.

Environmental impacts may be assessed through these models as well. Dust generation on unpaved roads has become a concern for residents, farmers and ranchers. As the number of trucks traveling over an unpaved road increases, so does the dust that is generated. This study

could further be adapted to consider county roads, and environmental impacts of truck generated dust could be considered.

Finally, a variation in the use of this model would be to assess benefits and costs of various potential highway improvements when funding levels change. The model could be used to assess the traffic impacts of changes in pavement condition. In the short run, this would consist of comparing the impacts of various alternative improvements. However, in the long run, this type of analysis could be used to study the impacts of decreased funding levels or the impacts of increased highway construction costs, or a combination of the two. Since funding is scarce, if costs continue to increase, the number of miles that may be improved per year will decrease, thereby resulting in overall system deterioration.

#### 4.6. Summary

This chapter presented the results of the truck cost, SIR, and traffic forecasting model. Truck costs were estimated for different truck configurations over a range of travel speeds. Comparisons of segment-based truck cost estimates to constant per-mile truck cost estimates were presented. In addition, comparison of terminal cost per-mile attribution demonstrated the importance of cost specification at the segment level. SIR forecast results were presented, and comparison of SIR forecasts to actual forecasts were provided. In addition, the spatial distribution of wells using the SIR model was compared against random assignment of wells. Traffic forecasts by year were presented along with discussion of significantly impacted roads and likely causes. Comparison of model forecasts against trend line analysis showed the implications of using traditional forecasting techniques in the environment of changing traffic levels. The following chapter will provide a summary of the study, and identify study limitations

and future areas of research to increase understanding of highway impacts of oil development in eastern Montana and western North Dakota.

## CHAPTER 5. CONCLUSIONS AND FUTURE RESEARCH

### 5.1. Conclusions

A truck traffic model was developed to estimate traffic levels under widespread and high-volume oil development in eastern Montana and western North Dakota. Development of the model required estimation of multiple models to estimate truck cost, development timeframes, development locations, selected truck routes, and optimization.

Truck costs were estimated using an economic engineering model, which included individual calculations for fuel consumption, maintenance and repair, tire costs, fixed costs, and opportunity costs. Each cost was converted to per-mile costs and applied to individual roadway segments based upon surface type, roadway condition, posted speed limits, and jurisdiction. These costs represented impedance factors for use in selecting segments to connect origins and destinations by routes using a route selection algorithm.

Routes were generated for each possible origin and destination within the study region, and costs were accumulated. For origins and destinations, terminal costs due to loading and wait times were estimated using throughput, loading, and wait time estimates. Terminal costs were applied to each origin and destination. These terminal costs were added to the linehaul segment of the trip representing the total terminal and linehaul costs for an individual truck movement. Future well development was estimated using an SIR model, which estimated the timing and distribution of new wells within the study area. Results indicate that the SIR may be useful in predicting the number and spread of new oil wells within the Bakken formation. However, due to limited historical data in the formation, future assessment of the accuracy of this forecasting model should be completed. Moreover, as the assessment of the temporal distribution of new wells was compared to another forecast, the importance of comparison with historical data is

imperative. As discussed throughout this document, oil development within the region is very dynamic, and many exogenous factors may positively or negatively impact the extent and duration of oil exploration within the Bakken region.

A series of optimization models were developed to select the set of least cost routes between each origin and destination with the objective of minimizing the total distribution cost for each commodity movement class. Individual segments were collected for each route included in the least cost set, and traffic volume estimates were aggregated at the segment level. The traffic model was calibrated using observed traffic volumes through traffic classification counts obtained from MDT and NDDOT.

It is expected that the traffic model estimates will be used in conjunction with traditional traffic forecasting methods, and routinely examined as historical traffic data become available.

However, the model developed in this study expressly models oil-related movements, which is a significant improvement over traditional trend analyses, and the direct impacts of oil development on state highways may be directly assessed through interpretation of model results.

## 5.2. Limitations of the Study

While this study is a comprehensive analysis of inbound and outbound oil-related movements in Montana and North Dakota, it is necessary to acknowledge the study limitations in relation to assumptions and data availability. The township centroid is the representative destination for inbound movements and origin for outbound movements. While each township may contain many miles of road, only one road segment is chosen to connect the centroid to the state highway system. This level of aggregation introduces a level of error in the routing, which is deemed acceptable to the author.

With the origin destination pairing, it was assumed that any well site may source inputs or ship outputs to any possible destination. This may not be entirely consistent with real-world practice, as some facilities may be owned and maintained solely for the transportation of one firm's commodities, thereby excluding competitors. This assumption was made due to lack of data on precise ownership of existing and future oil well locations.

### 5.3. Future Research

Oil development and exploration in the Bakken region is very dynamic, and this study utilized assumptions and forecasts based upon the best information available at the time. Several issues should be considered for future research topics, based upon the study assumptions. First, this study focuses only on the truck movements generated by oil development and exploration, as the purpose of the study is to assess the resulting highway impacts. Oil exploration, development, and distribution in the Bakken are a multimodal venture which includes truck, rail, and pipeline movements. Future research considering the entire oil distribution system from inputs to crude oil at refineries and export locations would greatly develop the understanding of the transportation impacts of oil development in the region. While additional trucks traveling the roadways in the area add significantly to the infrastructure needs, consideration of capacity limitations of rail and pipeline for transportation of outbound crude oil to destinations is important, as these capacity limitations may have an impact on the modal share into the future. Of all the movements considered in this study, freshwater sourcing for use in hydraulic fracturing appeared to be the limiting factor. Recent construction of the Western Area Water Authority pipeline has added to the total capacity of the region for freshwater, and it is expected that similar projects will continue into the future. However, as local freshwater capacity reaches upper limitations, exploration firms will need to travel further to source the freshwater needed

for the hydraulic fracturing process. This effectively expands the study area far beyond the oil development areas, and the corresponding highway impacts will follow. Throughout the study period, capacities were held constant. In reality, changing weather patterns may increase or decrease the permitted capacities over the study period.

This study presented the use of the SIR model to estimate new well numbers and locations. However, at the time of the study, roughly 8,000 wells were active in the study region, with 38,000 new wells expected throughout the entire period. As additional historical data become available, it would be useful to further validate the SIR model parameters and reassess the model utility, as well as exploration of other spatial distribution models to improve forecast accuracy.

Finally, traffic congestion is not directly considered in this study. As the optimization model assigns traffic volumes to routes based upon truck costs, travel time costs may impact route selection under situations where roadway congestion becomes an issue. Future research, including dynamic assignment, may prove useful in considering the impacts of roadway congestion on route selection and assignment of O-D pairs.

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