AN AGENT-BASED SIMULATION MODEL TO INVESTIGATE THE PRICING OF RURAL ROADS IN SASKATCHEWAN

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ABSTRACT

Industry in Saskatchewan, including natural resource, manufacturing and agriculture, is dependent on road infrastructure to reach suppliers and markets. The 296 Rural Municipalities (RMs) in Saskatchewan are responsible for the construction and provision of the extensive rural road network consisting of mostly gravel roads, which can be costly to maintain under heavy vehicle traffic. In general, road users do not directly pay the road provider for their road use; however, the decisions of road users can affect the costs incurred by road providers and vice versa.

The goal of this research was to determine the feasibility of applying an agent-based model (ABM) to represent and compare the road use and road provision of a rural road network in Saskatchewan. The main objective was to develop an ABM to determine whether pricing a rural road network on an incremental cost basis would result in a net benefit when considering combined road use and road provision costs.

The developed ABM included: road segments, nodes (intersections), road users, and a road provider. Simple heuristics were used to represent road use and road provision decision making, including least cost routing and traffic-based prioritization for road upgrade decisions. Vehicle traffic in the model was generated based on exogenous origin-destination (OD) inputs. The ABM was developed using a hypothetical road network and was applied to a case study rural road network.

The permit fees considered in this research essentially shifted the incremental costs for road provision under traffic loading from the road provider to the road users. The purpose of this type of permit fee structure was to investigate road management policies that may be more cost effective when considering combined costs (road use and road provision costs). This type of permitting could provide a more direct linkage between road use and payment to fund road provision, which may be more equitable than current road funding mechanisms (e.g., gas tax, property tax).

Model runs showed that the inclusion of permit fees incentivized road users for some OD pairs to change their routing and drive longer distances in order to drive larger percentages of their routes on upgraded road segments. This change in routing caused road user costs to

increase with longer distances driven, and road provision costs to decrease due to lower traffic on gravel road segments. The shift in traffic routing due to the inclusion of permit fees was also found to change the road segments selected for upgrade, based on the simple traffic count prioritization upgrade criteria.

While each considered scenario resulted in a net benefit (reduction in road provision and road use costs), the magnitude of the net benefit was consistently marginal in relation to the base case (without permit fees). Since permit fees were based on the incremental road provision cost, and, generally, road provision costs were small relative to road use costs, the magnitude of the permit fee does not impose strong incentives for altering road user behavior. Permit fees only altered road user route choice if there were alternative routes in which the road users did not have to significantly increase their trip distance (and costs) to find routes with upgraded road segments. Given the relatively low impact of permit fees on resulting combined costs found in the scenarios considered, the associated administrative costs may not be worthwhile for a road provider to implement such a permit fee structure.

A sensitivity analysis was completed for select parameters of the model. The analysis provided insights into the selection of road provision parameters resulting in the lowest road provision and road use costs such as: minimum traffic levels used for road upgrade criteria, annual budget levels, and the impact of shifting traffic patterns.

The model developed in this research illustrates the feasibility of using an ABM to support decision making involving road use and road provision policies. The complexities involved in road use, road provision and road performance required several simplifying assumptions to complete the model. Nonetheless, the results produced with the model illustrate the potential implications of various road use and road provision decisions.

Further work to expand simplifying assumptions and refine model inputs may allow the model to become useful for road providers in understanding the impacts of alternative road provision policies for real world road networks.

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LIST OF ABBREVIATIONS

ABM:	Agent-based Model
ADT:	Average Daily Traffic
EUAC:	Equivalent Uniform Annual Cost
GIS:	Geographic Information System
GVW:	Gross Vehicle Weight
KM:	Kilometer
LCC:	Life Cycle Cost
OD:	Origin-Destination
ODD Protocol:	Overview, Design concepts and Details Protocol
POM:	Pattern-Oriented Modeling
RM:	Rural Municipality
VEH:	Vehicle

CHAPTER 1 INTRODUCTION

1.1. Background

1.1.1. Rural Saskatchewan Road Transportation

Industry in Saskatchewan, including natural resource, manufacturing and agriculture, is dependent on road infrastructure to reach suppliers and markets (The Saskatchewan Association of Rural Municipalities, 2014). The value of Saskatchewan's exports has almost doubled over the last decade to reach 32.6 billion dollars in 2015, the second highest they have ever been (Government of Canada, 2016). The industry growth in Saskatchewan is expected to continue: Saskatchewan's plan for growth suggests a doubling of the value of Saskatchewan’s 2012 exports and increase in the 2012 total crop production of 10 million tonnes by 2020. (Government of Saskatchewan, 2012).

Industry transportation requirements in rural Saskatchewan have undergone significant changes in recent decades. Grain rationalization beginning in the late 1980's resulted in larger, heavier trucks hauling grain over longer distances on roads that were not built to accommodate high traffic and heavy loads (Christensen, Nolan, & Sparks, 2001). The oil and gas industry in Saskatchewan has been variable with rapid growth in past years to a recent decline due to global economic factors. The criticality of roads to support the oil and gas industry is particularly apparent for the heavy oil industry in northwest Saskatchewan where industry is dependent on rural roads to transport oil by truck due to the high viscosity of the raw material that makes transporting by pipeline difficult. (Saskatchewan Government Relations, 2003).

While the Saskatchewan Ministry of Highways and Infrastructure (SMHI) is responsible for highways throughout the province, much of the road network falls under municipal jurisdiction (Government of Saskatchewan, c2013). The 296 Rural Municipalities (RMs) in Saskatchewan are responsible for the construction and provision of the extensive rural road network consisting of approximately 134,000 kilometers of roads, most of which are unpaved (Government of Saskatchewan, 2016; Transport Canada, 2011). Providing an acceptable level of service on rural roads is important for supporting industry and not imposing transportation constraints that may impede industry growth. While the link between providing adequate level of service for transportation infrastructure and industry prosperity is intuitive, this general linkage is supported by a report based on over 200 infrastructure related studies found that “there is a positive correlation between infrastructure, productivity and economic growth, evident across the entire spectrum of economic models and other approaches used to test for that relationship” (Ploeg & Holden, 2013).

Typically, RMs fund the construction, maintenance and repair of the road network through various taxes such as property tax and gas tax. Currently, for most road users, there is no cost to use the road network directly related to road use: roads may be travelled on essentially "for free".[1] Although there are existing tools for RMs to recover some costs due to heavy vehicle consumption of rural roads (e.g., Road Maintenance Agreements for concentrated hauling, and permits for over dimensional non-divisible loads), for the most part, vehicles may use the road network without compensating the RM for direct road use. With no cost to individual road users for incremental road use, there is little incentive for the road user to consider how their actions may affect road consumption or road damage. The RM (as the road provider) and road users are essentially acting independently.

However, the actions of both road users and road providers can affect each other through their impact on the road network. RMs may influence road users through road maintenance, repair and capital upgrade activity (e.g., vehicle operating costs can change depending on road type and road condition) or through road use policy (e.g., the RM may impose restrictions on vehicle weight and speed). Road users can cause damage to roads (e.g., heavy vehicles traveling on roads particularly when roads are vulnerable to damage in the Spring or during wet periods) and thereby influence the required efforts and associated costs for the RM to repair the road.

This feature of road users and road providers acting independently while their decisions affect one another was a primary motivation for the question underlying this research: are there potential benefits from coordinating road provider and road user actions? To investigate this question and model road provider and road user decisions and costs, an agent-based modeling approach was taken which, as described in the following section, is well suited to this type of problem.

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[1] Of course the road user has internal costs to use the road network (e.g., fuel costs, time costs etc.).

1.1.2. Agent-Based Models:

The use of Agent-based Models (ABMs) has gained popularity in the past 20 years for providing insights into complex systems across varying disciplines (Niazi & Hussain, 2011). While there are several notions of how best to describe a software agent, a useful description is given by (Jenning & Wooldridge, 1996): “A self-contained program capable of controlling its own decision making and acting, based on its perception of its environment, in pursuit of one or more objectives.” ABMs are designed in terms of autonomous software entities (agents) that attempt to achieve their objective through interactions with other agents in terms of high-level protocols and languages (Zambonelli, Jennings, & Wooldridge, 2003).

ABMs are ideal for representing complex systems that are difficult to fully and accurately describe: "Complex systems exhibit a rich variety of behaviors, including many that are counterintuitive. To capture these effects, complex systems must be analyzed from a holistic rather than a reductionist point of view" (Barton & Stamber, 2000). In other words, the main distinguishing feature of ABMs is that the macro (or system) level properties of the system under consideration emerge from the behavioral rules that are assigned to agents at the micro level (Ormerod & Rosewell, 2009). This style of developing models by creating individual agents is commonly described as “bottom-up” since the higher level properties of the system are generated based on lower level details of agents within the model. A benefit of ABMs is that they can provide insights into the considered system from the patterns that may emerge that are not obvious from the agents' simple, local decision frameworks.

As will be discussed in Chapter 2, ABMs have been used in the transportation field to provide valuable insights into various transportation problems. There are several attributes of road provision and road use in rural Saskatchewan that suggest an ABM approach may provide valuable insight. A study by (Burmeister, Doormann, & Matylis, 1997) suggests that ABMs are useful to describe a complex system under three conditions: (1) the problem domain is spatially distributed, (2) the subsystems exist in a dynamic environment, and (3) the subsystems need to interact in a flexible manner.

Road use and road provision in rural Saskatchewan fits the criteria identified by (Burmeister et al., 1997) in that: (1) a road network and road users are spatially distributed, (2) road segments are dynamic (over time and space) in that they may change condition or may be upgraded to have different properties, and the number and type of road users (traffic) will change over time and over space (different traffic characteristics on different road segments), and (3) the interactions between road users, road providers and the road network requires flexibility (e.g., road providers imposing weight restrictions or permit fees on road users, which may change over time and depend on individual road user properties). Another motivation for the ABM approach is the capability to model decentralized systems that are owned by different stakeholders (Parunak, 1997). This is precisely the situation for rural roads in Saskatchewan: RMs own and maintain the roads, while road users own and maintain their vehicles, yet the decisions by road users and road providers can affect one another.

Given the nature of road provision and road use, the bottom-up style of ABMs was deemed to be a good fit for modeling and gaining insight into the decisions and costs for road provision and road use under various policies.

1.2. Research Goal

Given the independent decision making of road providers and road users and the interconnectedness of their actions, an ABM appears to be a suitable tool for modeling and understanding the system of road provision and road use.

The goal of this research was to determine the feasibility of applying an ABM to represent and compare the road use and road provision of a rural road network in Saskatchewan. Of interest was investigating various scenarios involving road users and road providers to determine if implementing road permit fees may help to align incentives and result in net benefits for the Province.

1.3. Research Objectives

The main objective of this research was to develop an ABM to determine whether pricing a rural road network on an incremental cost basis would result in a net benefit when considering combined road use and road provision costs.

1.4. Scope

Given the bottom-up nature of ABMs, several assumptions were required at the road segment level and the individual vehicle level in order to gain insights at the system level. The fields of road use and road network management have high complexity and uncertainty with a significant amount of detailed work completed on various aspects considered in the model developed in this research. In order to develop a reasonably simple model, several concessions and simplifying assumptions were required for normally complex areas such as road performance, road network management, and road user decision making.

This research is focused on rural roads in Saskatchewan that are under RM jurisdiction. Road upgrade was considered (e.g., upgrading a gravel road to a paved road), but neither road reversion to gravel nor road abandonment were considered. Road types considered in the model were gravel and paved roads.[2] The model was developed such that additional road types could be considered in the model.

Rural road networks are generally large relative to traffic volumes. As such, for the purposes of this research, traffic effects were not of particular interest; road users do not directly interact with each other (neither traffic nor congestion effects were modeled).

Road performance modeling for the condition of roads was not included in this model.[3] It was assumed that roads have an average condition based on the maintenance and rehabilitation activity schedule of the RM represented in the model. The relationship between road use and associated road provision costs is taken as exogenous inputs to the model. While this relationship between road performance and road use is difficult to quantify and depends on a number of factors for any given road segment, it was assumed that given the system level

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[2] While there are several possible types of gravel and paved roads, for this version of the model, generic gravel and paved roads typical of rural Saskatchewan were assumed. Additional types of gravel and paved roads could easily be incorporated into the model so long as information was known regarding their LCCs of provision, user operating costs and their general performance under vehicle loading.

[3] As will be discussed in Chapter 3, the performance of gravel roads in particular is complex and difficult to predict (performance is influenced by soil moisture, weather, traffic loading etc.). If a relationship were known for predicting gravel (and paved) road condition given various inputs such as traffic loading characteristics and season, then it could certainly be incorporated into the model. Given the uncertain nature of gravel road performance and lack of available predictive condition modeling, road condition was scoped out of this version of the model.

insights of interest in this research, the variability in road performance would average out when considering a large network.

Costs considered in the model include road provision costs (life cycle costs on a road segment basis) and road use costs (operating costs, time costs and permit fees). All unit costs in the model are taken as exogenous inputs (e.g., unit cost per length for road upgrade, vehicle operating cost per unit distance driven, etc.).

While road pricing was investigated, the logistics and implementation details to develop a permitting system were not considered.

The nature of ABMs allow for a significant amount of detail to be included in the model. The scoping assumptions above were made in order to complete the model within reasonable development timelines. There is potential to expand the simplifying assumptions in several areas as is discussed in Chapter 7.

1.5. Methodology

This research began with a literature review focused first on existing rural road network models in order to provide context of existing approaches to the road management problem. The literature review then considered ABMs with a focus on ABMs in transportation to review existing approaches for techniques and findings of modeling transportation networks.

Since agent-based modeling is a relatively new field, there does not exist well-established best practices for the development and validation of ABMs. One of the accepted methods of developing ABMs, and the method used in this research, is pattern-oriented modeling (POM) developed by (Grimm et al., 2005). POM was developed to make "bottom-up" modeling (that is, defining agents in terms of objectives and rules, then observing interaction between agents and emergent patterns at a system level) more rigorous and comprehensive. The steps in the POM process are:

1. Defining Model Purpose
2. Identifying Performance Criteria

3. Programming Model Structure

4. Model Testing

5. Sensitivity Analysis

6. Model Documentation

The first four steps in the POM method are repeated as required until the modeler is satisfied with model development. The ABM described herein was first developed for a hypothetical road network for simplicity in inputs and producing outputs. The ABM was then applied to a real world RM case study using actual road network properties and traffic loading. The software used to develop the model was AnyLogic 6.0, a java based simulation software platform that supports agent-based modeling.

1.6. Significance of Research

The results of this research may support consideration of treating rural roads as “consumables” subject to pricing as opposed to roads being treated as a “free good”. A key measure of interest in this research was the net benefit of scenarios (considering combined costs of road provision and road use), which may help to understand the potential social benefit and implications of implementing a user-pay system for rural roads. Results would be anticipated to be of assistance to RMs in considering the impacts of various policies including road pricing, road upgrade and road weight restrictions. The permitting considered in this research may help to provide a more direct linkage between road use and payment to fund road provision, which may be more equitable than the current road funding mechanisms.

The results documented herein provide insights into the feasibility and potential benefits of using ABMs to model rural road networks and the potential implications of using a road pricing system.

1.7. Layout of Thesis

This document consists of seven chapters. Chapter 2 presents a review of the pertinent literature including a review of existing modeling approaches to road use and road management, as well as ABMs in general and ABMs applied to transportation.

Chapter 3 describes the underlying principles of road use and road provision, which guide the model structure. Key variables are presented and governing equations for use in the model are developed.

Chapter 4 describes the ABM developed in this research. Chapter 4 follows the ODD (Overview, Design Concepts and Details) protocol developed by (Grimm et al., 2006; Grimm et al., 2010) with some modification to include descriptions of human decision making based on the work by (Muller et al., 2013). As such, Chapter 4 can be read independently as an overview of the entire model. However, given the complexities of this research area, it is recommended this document be read in the order it is presented with Chapter 3 introducing and developing important principles and equations that are leveraged in Chapter 4.

Chapter 5 describes the results of model runs using a hypothetical road network and default model inputs including a sensitivity analysis.

Chapter 6 describes implementation of the developed ABM to an RM case study.

Chapter 7 provides the findings and conclusions of this research as well as suggested areas for future research.

CHAPTER 2 LITERATURE REVIEW

2.1. Introduction

This chapter provides a review of the pertinent literature for this research, which is grouped into two categories:

(1) rural road network models;

(2) agent-based models.

A review of relevant road network models is presented first to illustrate existing approaches for both identifying potential shortcomings in existing models where ABMs may be beneficial, as well as highlighting insights from previous modeling efforts that aided in the development of certain aspects of the model developed in this research.

2.2. Rural Road Network Models

Numerous approaches to modeling road networks have been developed. Of interest in this research were rural road network models that included both the road provision costs and road use costs. As road type and road condition can affect both road provider and road user costs, it is generally recommended that life cycle cost (LCC) analysis include both road provision and road use costs (Berthelot, Sparks, Blomme, Kajner, & Nickeson, 1996; Delwar & Papagiannakis, 2001). Of particular interest were models including LCC considerations, cost benefit analysis for some type of network policy or alternative, and some consideration of road user routing through the network.

A relevant model using a LCC framework is the Roads Economic Decision Model (RED), which was developed to improve the decision making process for low-volume rural roads (Archonda-Callao, 2004). The model (based in Microsoft Excel) allows users to enter in specific characteristics of roads such as: traffic, vehicle speed, road type and geometry and road condition. The model outputs both agency costs to maintain the road as well as the predicted user costs for vehicles using the road. Economic analysis is performed on the road segments and outputs are calculated for alternative upgrade strategies that may reduce user and/or agency costs.

While RED provides a useful framework for modeling the predicted road costs and alternative road upgrade strategies, the model does not predict the impact that road upgrade will have on traffic patterns. The RED model allows for the effects of traffic diversion to be accounted for, but the user must enter in the number of diverted vehicles and their new routes. This limitation is an area where the model developed herein may be used to better understand the effects that road upgrade (and road use restrictions) will have on vehicle route choice and the resulting user and agency costs.

Other notable models with similar frameworks discussed in (Archonda-Callao, 2004) include the World Bank's Highway Design and Maintenance Standards Model (HDM-III), and the Highway Development and Management Model (HDM-4). However, these models do not capture all benefits associated with low-volume unpaved roads and inputs to these models are impractical to collect in the context of rural road networks in Saskatchewan.

A study was completed by (Baumel, Miller, Pautsch, & Hamlett, 1989) that considered alternate investment strategies for a rural road network with an emphasis on the effects on both the agency and user costs. Three case studies were completed in Iowa, USA including survey questionnaires related to origin and destination patterns. The study found net benefits arising from scenarios involving road betterment, road abandonments and conversion of roads to lower maintenance standards. The greatest benefits depended on the properties of the existing road network road, but, generally, the conversion of roads to lower maintenance standards appeared to result in the highest net benefit. The study included user and agency costs in the cost benefit analysis of each policy alternative, which is consistent with the style of analysis for alternatives considered in this research. A limitation pointed out by (Baumel et al., 1989) was that the extensive computational requirements restricted their analysis to groups of roads, rather than consideration on a segment-by-segment basis. A strength of the model developed herein is the ability to analyze outputs on a segment-by-segment basis.

A mathematical model was developed by (Christensen, Nolan, & Sparks, 2001) to consider rationalization of a rural road network in Saskatchewan including road investment and abandonment of road segments. The study incorporated maintenance and upgrade costs, traffic flows and routing decisions. The study describes the model as a constrained optimization problem and finds optimal solutions for minimizing total costs (user plus agency costs). As noted by (Christensen et al., 2001), most road network design problems focus on capacity issues related to congested road segments. The study, similar to the model developed in this research, did not include congestion effects. The study found that the scenario with unconstrained capital budget resulted in the most convenient network configuration for users.

A benefit cost analysis of rural road closure was completed by (Babcock & Alakshendra, 2011) using three Kansas case studies. The study included agency and user costs and found that rural counties could save money by closing some relatively low-volume roads. The study uses the network model TransCAD, which allows for calculation of shortest path routing through the network. This allowed the impacts of road closure to be modeled and the alternative routing and resulting costs could be considered. This study by (Babcock & Alakshendra, 2011) is similar to the model developed in this research with some key differences in that the model developed herein: used an ABM, considered road upgrade and not road abandonment, considered shortest path routing based on road weight restrictions as well as user costs.

A model developed by (Tolliver, Dybing, Lu, & Lee, 2011) considered investments in county and local roads in North Dakota based on flows from crop producing zones to elevators and plants. The study found that the average farm-to-market trip distance has approximately doubled from 1980 as have the costs for maintaining acceptable levels of service on county and local roads. The model is GIS based, which allows for traffic to be driven by known crop producing zones. The model is similar to that in this research in that a GIS environment is used, the road network is represented by nodes and links where nodes can represent origin or destinations for vehicles, and Dijkstra's algorithm is used to find the shortest path for vehicles to travel to their destinations. Another important aspect that the model has in common with the model developed in this research is that the road provider costs for unpaved roads, while in reality are subject to several external factors such as weather and traffic speed, were assumed to be solely a function of traffic. Differences to this research are that the model developed herein considered weight restrictions on road segments, which can affect vehicle routing as vehicles alter the weight hauled per trip, and permit fees were considered.

Research completed by (Athanasenas, 1997) developed deterministic and probabilistic traffic simulation models to support a cost benefit analysis of alternative rural road investment strategies in the USA (Minnesota, Polk County). The model optimizes for minimum total cost (agency LCC plus user costs) given an exogenous origin-destination (OD) traffic demand matrix. The study identifies a set of selected cost-efficient rural road management strategies and identifies the strategy with highest benefit-cost ratio, which involves selected investments of upgrading gravel segments to paved segments combined with abandonment of select roads and bridges. A similar approach to handling the exogenous OD matrix was used in the model developed in this research.

A decision support system called RoadOpt was used by (Karlsson, Ronnqvist, & Frisk, 2006) to plan forest road upgrading to avoid road blocking due to thawing or heavy rains. The model uses a GIS environment to generate traffic flows (based on shortest path) and describes the problem as a mixed integer linear programming problem and optimizes for minimum total cost for transportation and upgrading under various constraints such as weight restrictions on road segments. The model has several common elements to this research. The primary unique aspects of interest relevant to this research and not found in many other road network modeling approaches are the consideration of weight restrictions for road users and road upgrades to prevent impassable roads. These are similar aspects to considerations in this research regarding how road weight restrictions and road upgrades can affect route choice and, in turn, total user and agency costs. The model was able to use a case study and identify delivery points to which it would be favorable to concentrate traffic during periods of low accessibility.

Before moving on to consider the ABM specific literature, an observation from (Magnanti & Wong, 1984) may be appropriate: “Although discrete choice integer programming models are generally ideal for addressing the type of combinatorial complexities and interaction effects that arise in network planning, they are generally not well suited for dealing with the risk and uncertainties that are inherent in many strategic decision-making situations. In these instances, other planning tools, such as simulation, decision analysis, or multiattribute utility theory, are attractive alternatives to integer programming analysis.” This feature of simulation being suitable to incorporate risk and uncertainties in a decision-making context (involved in road provision and road use decisions) is an underlying motivation for the style of ABM chosen in this research.[1]

2.3. Agent-Based Models

Agent-based modeling has become increasingly popular in the last 20 years (Niazi & Hussain, 2011). In 2005, a survey was completed on existing research using ABM approaches to transportation and traffic management (Davidsson, Henesey, Ramstedt, Tornquist, & Wernstedt, 2005). The survey found that, generally, ABMs were very suitable for the domain of transport logistics. Of the 56 papers reviewed, 11 of them were focused on road transportation. The majority of the road transportation papers were focused on some variation of real-time cooperative traffic management and route guidance (e.g., avoiding congested road segments). The reviewed papers differ from the model developed in this research in that agency costs were typically not considered and the environment of the surveyed models was typically an urban environment where traffic congestion effects are significant.

Another survey of ABMs was completed by (Health, Hill, & Ciarallo, 2009). The survey included 279 articles and identified several areas of improvement required to advance ABMs as an analysis tool. The suggested areas for improvement included ABM tools independent of software, a common ABM language extending across domains, standard expectations of ABMs, standard requirements for complete model descriptions for independent replication of models, and specific validation techniques for ABMs that would be expected for all models. The study found that 65% of the ABMs included in the survey were incompletely validated. Model validation is currently a major challenge for ABMs due to the generally complex nature of the models and lack of existing standards.

While ABMs have been increasing in popularity, it remains a relatively new field. As such, there are not well-established, widely accepted standards for model development and model documentation. There have been recent efforts to develop standards to enable ABMs to be compared in a consistent framework called the ODD (Overview, Design Concepts and Details) protocol developed by (Grimm et al., 2006; Grimm et al., 2010). The ODD protocol

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[1] Risk and uncertainty were not included in this version of the model. Potential areas for including uncertainty are highlighted in Chapter 4.

was modified by (Muller et al., 2013) to allow for ABMs that include human agents and decision making, known as "ODD+D". The ODD methods have been used by several researchers with success and has been generally well received and has been found as helpful for comparing models as well as helpful to follow in developing ABMs.

The applicability of ABMs to modeling transportation phenomena were studied by (Kikuchi, Rhee, & Teodorovic, 2002). They explain that current transportation problems generally involve complex systems and the traditional approach to analysing transportation systems has been a top-down approach to achieve overall objectives. To more appropriately represent the complex transportation systems of today, ABMs have begun to be used in order to employ a bottom-up approach. Individual agents do not make globally optimal decisions, which is a limitation of ABMs. However, this noted limitation can become a strength for gaining an understanding of system dynamics in order to understand the implications of alternate policies or external influences.

The high degree of freedom in developing ABMs leads to a low probability that models will have many overlapping features. While no models were found that had similar scope and focus to the model developed in this research, the models discussed in this section typically have at least one overlapping feature with the current research. Although there are a number of existing ABMs focused on traffic logistics (queuing, real-time route choice, congestion etc.), there has been limited work done with ABMs considering both road users and road providers and their interactions. Notable examples of ABMs related to civil infrastructure management that do consider both road provision and road usage are discussed below.

An ABM was completed for urban infrastructure management (Osman, 2012). This work presented the case for adopting a bottom-up approach for modeling the complexities of infrastructure asset management using an ABM. The agents used in the model were: infrastructure users, infrastructure assets, infrastructure operators and politicians/decision makers. The model focused on the infrastructure service quality delivered to users in an urban environment. The modeling efforts demonstrated that ABMs may be used to represent the complex relationships between users, politicians and asset managers.

Although the model developed herein not focused as heavily on the user-perceived, subjective service quality, and was based on a rural environment rather than urban, the work by (Osman, 2012) remains relevant. The general model structure presented in (Osman, 2012) is similar to that of the model developed in this research in terms of similar agents used (infrastructure user, infrastructure asset, infrastructure operator, political/decision-maker); however, the politician agent was not used in the model developed in this research. Also, AnyLogic was the software used to develop the model, which is the same software used for the model developed in this research. The study evaluates the model by contrasting it with a Markov Decision Process framework using a road network for a small Canadian city.

Another ABM was developed to model an urban pavement management system (Sanford Bernhardt & McNeil, 2004). This work considered a 1,000 segment pavement network and modeled the pavement condition index (PCI) over time. The model included decision makers and infrastructure users as agents in order to represent the complexities of infrastructure management and use. Various scenarios were investigated such as reductions in financing and varying infrastructure deterioration rates. Results were quantified in terms of overall network condition, user costs and agency costs. The results demonstrate that an agent-based approach to modeling infrastructure management is an appropriate method of representing the complex system. The findings indicate that geography is an important detail; network connectivity means that connecting road segments share the same (or at least similar) traffic. This element of road segment connectivity and importance of road location within the network is a feature that was identified in the model developed in this research.

A relevant ABM in transportation asset management that included a cost benefit of road repair was developed by (Moore, Tijoe, Manzella, Sanford Bernhardt, & McNeil, 2008). The study developed an ABM using two separate modeling environments: MATLAB and Repast. The agents used in the MATLAB prototype were: pavement segments, users, work crews, engineers, and politicians. The model included deterioration, user costs and road repair costs based on exogenous inputs from a separate model. Project selection for road repair was based on two methods: the first was a worst first algorithm, in which segments in the worst condition were repaired first, the second was a Benefit-Cost Analysis (BCA) on the project so that the projects with highest benefit (in terms of user costs) were done first. It was determined that the BCA method resulted in a higher overall pavement system condition at a lower cost. One of the limitations identified by the authors was not representing the rerouting of traffic to avoid poor quality roads.

An ABM developed to represent the impacts of climate-change adaptation on transportation infrastructure was developed by (Bhamidipati, 2015). The model included similar agents to the model developed in this research including: assets, asset owners, and asset users. The model used the GAMA modeling platform, and used a random OD matrix based on a simple gravity model to generate agent trips. Asset users were assumed to take the shortest path, avoid congestion, follow speed limits and cause damage to assets. Assets deteriorated using a simple linear profile from good to bad condition. The asset owner had the choice to either fix the worst condition asset segment first, wait and repair assets at a predefined maintenance schedule, or repair assets when they dropped below an acceptable threshold condition value. The model was then expanded to incorporate a climate event. During the simulation, climate events could occur (e.g., flood, rain, snow) and cause areas of roads to become impassable, causing some asset users to be diverted and have to find a new shortest path to their destination. The results of scenarios included the additional time due to diversion of asset users as the total system delay time caused by the climate event. The model was able to determine which OD pairs were most affected by climate events. While the model developed in this research does not incorporate climate events, there are similarities in how road policy restrictions can affect road users in terms of diversions from the shortest path. For instance, in the model developed in this research, when heavy vehicles are over the weight restriction of a road segment or group of road segments, they become impassible for the vehicle at those weights essentially in the same way as a climate event causing roads to become impassable.

An ABM developed by (Kolck, 2010) focused on insights into an urban distribution center (UDC) and included similar aspects to the current research including: tolls (pricing roads), decision making by road users including shortest path determination, and calculating results in terms of financial impacts. The agents in the model included: freight carriers, UDC, trucks, retailers, and roads. The road network representation in this model is quite similar to that used in this research in that the road network is represented by two types of agents: streets (or segments) and nodes. Freight carriers were driven by demand for goods by retailers and perform routing to find the best routes to minimize their expenses. The model uses a genetic algorithm for solving truck routing and variable demand location. Key differences between this study and the current research were that the study did not include agency decision making for road maintenance nor upgrade, was in an urban environment with congestion effects, and required a genetic algorithm for vehicle routing based on daily delivery schedules.

There have been several ABMs developed to study commodity transport chains. These models typically focus on the logistics and interactions between buyers and sellers, shippers and carriers and various transport modes to move goods. While the focus of these types of models is not closely aligned with the model developed in this research, there are transportation related aspects in the models that are relevant to this research such as: transport cost, route choice and the impacts that various policies may have on user behaviors and costs.

An ABM called TAPAS was used by (Holmgren, Davidsson, Persson, & Ramstedt, 2012), to consider various scenarios that explicitly modeled production and customer demand as well as interactions between individual transport chain actors. Various transport mode choices (road, rail, and sea) were included in the model and scenarios were run to consider implementing road tolls, which caused a shift in routes involving more rail transports and less road transports.

A prototype called INTERLOG was used by (Liedtke, 2009) to model shippers and carriers interacting through simulated auctions of transport contracts resulting in generated tours. Of particular relevance in (Liedtke, 2009) was the behavior experiments conducted with motorway tolls to understand the feedback effects and adaptive reactions to policy measure. The model results showed that after tolls were imposed, trucks would take shorter but more time consuming routes, and there was a trend towards full truckloads.

An ABM for freight transport was developed by (Schroeder, Zilske, Liedtke, & Nagel, 2012) with an emphasis on transport service providers and carriers, leveraging the MATSim traffic simulation. Similar to (Holmgren et al., 2012) and (Liedtke, 2009), (Schroeder et al., 2012) considered scenarios with tolls for vehicles as well as considering scenarios where heavy vehicles were prohibited within cities and model various tour-planning algorithms. The results, summarized in terms of total distance travelled by the carrier, show that the framework can be used with behavior models and suggest the framework can serve as a link between existing specialized transport chain building and vehicle routing models.

2.4. Chapter Summary

In summary, ABMs have gained popularity in the past 20 years. Since the ABM field is relatively new and still developing, there is a need for a more standard approach for model development, documentation and validation. ABMs appear to be well suited to transportation related features and several models have been developed investigating a range of aspects of transportation problems, including traffic considerations, asset management, logistics and supply chain analysis, among others. Also, there are several "non-agent-based-models" (e.g., integer optimization and other network models) that share commonalities with aspects of the ABM developed in this research and proved useful for developing the model employed herein.

CHAPTER 3 RURAL ROAD NETWORK PRINCIPLES AND EQUATIONS

3.1. Introduction

This chapter covers the principles of road use and road provision considered in this research and develops key equations. The principles and equations described in this chapter are used to support the model developed in this research. A detailed description of the actual agents, processes and parameters used in the developed model is provided in Chapter 4.

As will be outlined in Chapter 4, the developed model includes representations of a road network, road users, and a road provider. This chapter is organized to be consistent with the structure of the developed model in that the principles and costing are presented separately for road network, road users and road provider, with key parameters and decisions outlined in Figure 3.1.

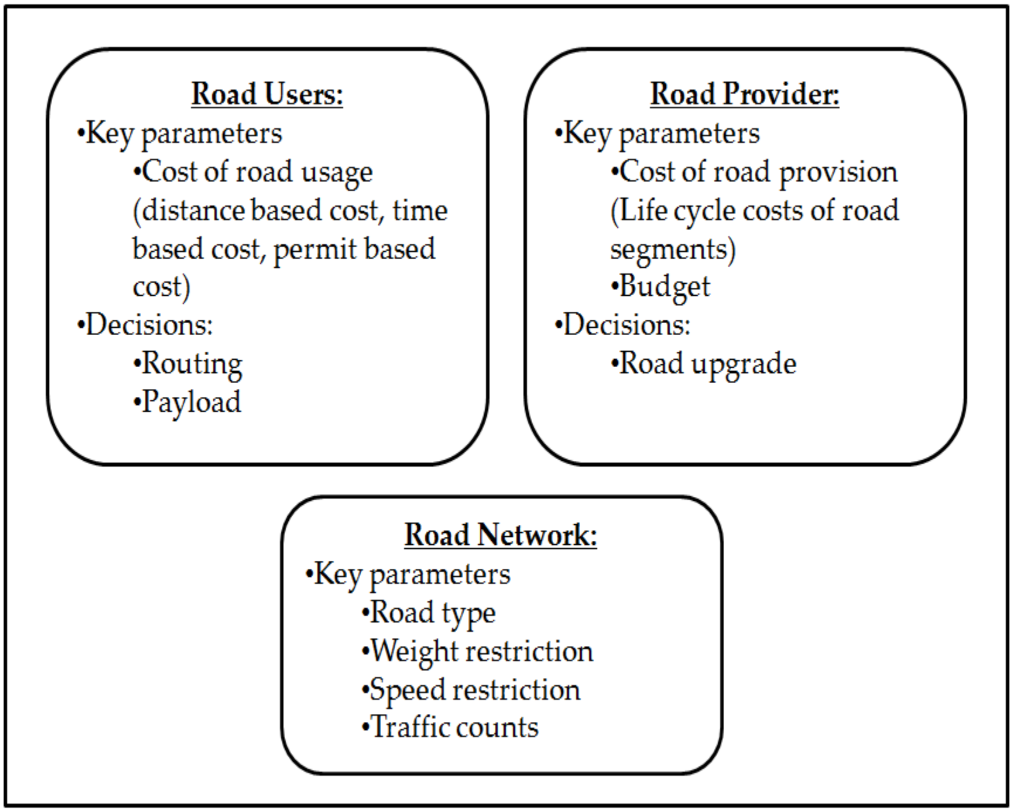

Figure 3.1 Organization of Key Parameters and Decisions.

3.2. Road Network Representation

To support the equations for road users and the road provider, the road network representation is introduced first. The road network in this research is represented as an undirected, weighted graph. This style of representation for the road network is typical for research related to road use and road network management. The representation of the road network as a graph is convenient for considering network properties such as: shortest path routing and tracking properties on a segment-by-segment basis (user cost, provider cost, road upgrade etc.). The nodes of the graph represent intersections and the segments (edges) of the graph represent road segments. To support the descriptions of principles and equations, a simple, illustrative road network is used as the basis for this chapter as shown in Figure 3.2.

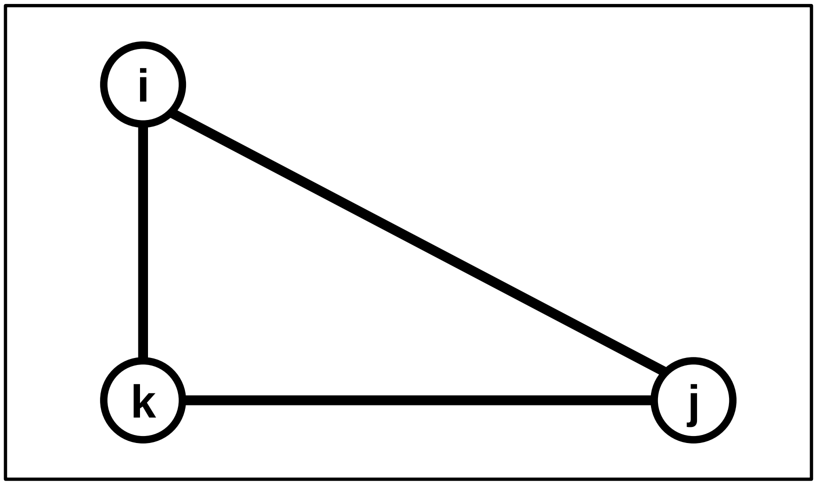

Figure 3.2 Simple Illustrative Road Network.

Segments shown in Figure 3.2 are referred to by indicating the nodes on either end of the segment. For example, the segments making up the network shown in Figure 3.2 are: <i,j>, <i,k>, and <j,k>. This method of representing the road network requires that each road segment necessarily begins and ends at a node.

The road network is a common element with which both road providers and road users interact. The remainder of this chapter covers the underlying principles and equations for how road providers and road users interact with the road network.

3.3. Road Users

The road use principles of interest in this research included user costs, route choice and payload hauled. Since road use has an impact on costs incurred by the road provider (in terms of incremental road consumption and damage), it was of interest to understand the incentives and decision making of road users in order to consider road network provision policies. The equations governing user costs, which are used in supporting user decision making processes in the model, are developed in the following section.

3.3.1. Road User Costing

Road user costs are broken into three components: a distance based cost, a time based cost, and a permit fee cost. Total user costs were required both as a measure of interest for the results of model runs and to allow road users to find the shortest path (in terms of user cost) to their destination. For road users to find the least cost route, the total user costs had to be calculated for each road segment (edge) within the road network (graph). The equations in this section outline how the user costs were calculated for a given road segment.

First, consider the distance based cost for a road user. This represents the operating cost to the user for travelling over a road segment, which includes components such as: fuel, oil, tires, maintenance and repair, ownership and licensing and insurance (Berthelot, Sparks, Blomme, Kajner, & Nickeson, 1996). There may be several other cost categories such as safety, collisions, comfort and convenience or environmental impacts, but for the purposes of this research, the distance based costs were assumed to include only the vehicle operating costs indicated above. If additional user costs were of interest, it would be possible to modify the model to include them. While there are many factors that can impact vehicle operating costs (e.g., vehicle speed, vehicle weight, etc.), for the purposes of this research, the main parameter of interest that affects vehicle operating cost was assumed to be road type.[1] As such, it was assumed that vehicle operating costs were a function of road type and vehicle type. The distance based user cost for travelling across road segment, <i,j>, is given by Equation 3.1.

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[1] Additional factors on user costs such as speed and weight could potentially be included in the model, but were scoped out for simplicity in required model inputs. As will be outlined in Chapter 4, unit rates for vehicle operating cost were based on an assumed vehicle speed and weight.

$$[UC_{Distance}]_{<i,j>} = OC_{v,r_{<i,j>}} * L_{<i,j>} \tag{3.1}$$

where:

$OC_{v,r_{<i,j>}}$ = the unit operating cost of a vehicle of type, v, for a road of type, r ($/km);

$L_{<i,j>}$ = the length of road segment, <i,j> (km).

The time based user cost reflects the vehicle operator's wages and labor costs. It was assumed that time costs were a solely a function of vehicle type (passenger or heavy truck). While operator wages can vary depending on a variety of socio-economic factors, default values for unit time based costs for passenger vehicles and trucks were based on (Apex Engineering Limited, 2012), as described in more detail in Chapter 4. Time costs were included in the model to allow for cost considerations when the time for road users to reach their destination is changed due to alternate routing patterns. Since congestion and traffic effects were not considered in the model, the time required for a road user to travel across a road segment is based on road length and speed limit of the road segment. The time based user cost for travelling across road segment, <i,j>, is given by Equation 3.2.

$$[UC_{Time}]_{<i,j>} = TC_v * \frac{L_{<i,j>}}{SL_{<i,j>}} \tag{3.2}$$

where:

TC_v = the unit time based cost for operator of vehicle type, v ($/hour);

$L_{<i,j>}$ = the length of road segment, <i,j> (km);

$SL_{<i,j>}$ = the speed limit of road segment, <i,j> (km/hour).

The permit based cost represents any permit fees that the road provider has imposed on vehicles for travelling on a road segment. Permit fees set by the road provider may vary by road segment (depending on road type), vehicle type, vehicle weight, and season. The details of how permit fees are established are discussed in Section 3.4. The permit based user cost for travelling across road segment, <i,j>, is given by Equation 3.3.

$$[UC_{Permit}]_{<i,j>} = PC_{r_{<i,j>},v,l,s} * L_{<i,j>} \tag{3.3}$$

where:

$PC_{r_{<i,j>},v,l,s}$ = the unit permit cost for road type, r, vehicle type, v, whether the vehicle is loaded, l, and season, s ($/tonne-km);

$L_{<i,j>}$ = the length of road segment, <i,j> (km).

Now the total user cost to travel across any given road segment can be calculated by combining the costs from Equation 3.1, Equation 3.2, and Equation 3.3. The total user costs for travelling across road segment, <i,j>, is given by Equation 3.4.

$$[UC_{Total}]_{<i,j>} = [UC_{Distance}]_{<i,j>} + [UC_{Time}]_{<i,j>} + [UC_{Permit}]_{<i,j>} \tag{3.4}$$

The total user cost per segment, $[UC_{Total}]_{<i,j>}$, is a key variable for model functionality as it is the measure used by road users in determining the least cost route to their destination, which is discussed in more detail in the next section.

The total user costs for a given route through the network travelling on multiple segments beginning at origin node, O, and ending at destination node, D, is given by Equation 3.5.

$$[UC_{Total}]_{O-D} = \sum_{n=1}^{N_{O-D}} [UC_{Total}]_{<i,j>_n} \tag{3.5}$$

where:

$< i,j >_n$ = the n^th road segment in the route from node, O, to node, D;

N_{O-D} = the number of road segments within the chosen route from node, O to node, D.

An important measure of cost from a material hauler's perspective is the cost per payload-distance (e.g., dollars per tonne-kilometer). For a given OD trip, the total user cost per payload-distance is given by Equation 3.6.

$$[UC_{tonne-km}]_{O-D} = \frac{[UC_{Total}]_{O-D}}{P_{O-D} * \sum_{n=1}^{N_{O-D}} L_{<i,j>_n}} \tag{3.6}$$

where:

N_{O-D} = the number of road segments within the chosen route from node, O to node, D;

P_{O-D} = the payload of the vehicle for the O-D trip (tonne);

$L_{<i,j>_n}$= the length of the nth road segment in the route from node, O, to node, D (km).

When haulers perform multiple trips, which include empty return trips, Equation 3.6 must be modified slightly, as is described in the model description in Chapter 4.

3.3.2. Road User Routing and Payload

As outlined in the previous section, road users incur costs for travelling across road segments, which may vary depending on vehicle and road properties. To model routing through the road network, it was assumed that road users calculate and travel along the least cost route (in terms of their own total user costs) from their origin to their destination.

The notion that road users behave rationally has been challenged by several transportation researchers, and rational decision making in general has been questioned by behavioural researchers (Xu, Zhou, & Xu, 2011). For simplicity in model design and inputs, it was assumed that road users were rational in choosing the least cost route to their destination. It is acknowledged that this is a potential area for refinement for future versions of the model to incorporate alternate decision making heuristics for road user trip timing and route choice.

In a road network with uniform road type, the least cost route would be equal to the shortest path in terms of distance, but when road networks have different road types with different associated unit costs, the least cost route is not necessarily the shortest distance path. This method of routing can be described as a shortest path problem, which can be solved from any origin node to every other node in the network with Dijkstra's Algorithm, with the weighting of edges (road segments) in the network as user costs, which are dependent on road type and vehicle type.[2] Since road type can change over time, the least cost route for an origin destination pair may change over time and it may be different for different vehicle types.

Road users hauling bulk material have the option to vary the weight of material hauled on any given trip. Typically, bulk material hauling is most cost effective for the hauler if they haul the maximum allowable payload for each trip. While a heavier payload can increase the operating costs of the vehicle (due to increased rolling resistance, for example), the increase in operating costs is typically small compared to the costs of completing additional trips at lower payloads. For the model developed in this research, it was assumed that haul weight did not affect user costs.

In Winter months in Saskatchewan, haulers are typically allowed to haul at Primary weights (or sometimes above Primary weights) as there is often minimal consumption or damage to roads in cold weather. In the non-Winter months, there may be weight restrictions imposed on select segments in order to protect vulnerable roads from damage due to heavy vehicles. When there are weight restrictions in place on select roads, the haul weight decision becomes relevant for the road user. Depending on road network characteristics, the road user may have an option to haul at heavy weights over a long distance, or to haul at lighter weights over a shorter distance dictated by weight restrictions on select road segments.

To determine the lowest cost weight and route combination for a given trip, the following approach is used. To reduce the number of possibilities, haul weight possibilities were grouped into typical weight restriction categories used in Saskatchewan (Primary, Secondary (85%

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[2] Dijkstra's Algorithm is a well-established algorithm for finding the shortest paths between nodes in a graph (Dijkstra, 1959).

Primary), 75% Primary, 50% Primary, and 5,500kg).[3] To represent the additional trips required by hauling at reduced weights, a cost factor is calculated and applied to user costs when finding the least cost route. This method of using a cost factor to represent multiple trips assumes that the road user is engaged in hauling material over multiple trips and is interested in minimizing the cost for the total material haul (not just the cost for a single trip). The user cost weight factor for a vehicle type, v, is given by Equation 3.7.

$$UC_{WF,v} = \frac{P_{MAX,v}}{P_{REDUCED,v}} \tag{3.7}$$

where:

$P_{MAX,v}$ = the maximum payload that vehicle type, v, can haul (tonne);

$P_{REDUCED,v}$ = the payload that vehicle type, v, can haul under the reduced weight category being considered (tonne).

To clarify how the user cost weight factor is used, consider a simple example of a vehicle engaged in hauling material over multiple trips from the same origin to the same destination. If a vehicle is hauling at the maximum payload capacity, then $P_{REDUCED,v}$ = $P_{MAX,v}$ and $UC_{WF,v}$ = 1. If the vehicle is hauling at half the maximum payload capacity, then $P_{REDUCED,v} = \frac{1}{2} P_{MAX,v}$ and $UC_{WF,v}$ = 2. Under this half maximum payload haul weight, the user cost weight factor of 2 suggests that the user has to make two trips to haul the same amount of material as one trip at maximum payload and so the user costs are doubled under this reduced haul weight.[4]

The least cost routing algorithm (based on Dijkstra's Algorithm) assigns road segments a very large value (representing infinity) if the gross vehicle weight (GVW) of a vehicle is greater than the weight restriction imposed on that road segment. This prevents road users from

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[3] Weight categories used in the model are set based on GVW. In Saskatchewan, weight restrictions are generally imposed per vehicle axle, but for simplicity in model inputs, weight restrictions were approximated to a percentage GVW of Primary weight allowance (e.g., Secondary weight assumed to be 85% of Primary weight allowance). Primary weights for vehicle types considered in this research are outlined in Appendix A.

[4] This style of choosing haul weights assumes that the same truck configuration would be used. In reality, industry related road users hauling bulk material may chose alternative vehicle configurations that may change the allowable material hauled per trip since weight restrictions are typically based on axle weight. This consideration of alternate vehicle type is not considered in the model, but it could potentially be included if information was known regarding the decision making process of selecting a vehicle type for a given trip.

travelling over any road segment if the chosen haul weight exceeds the segment-specific weight restriction. Using the total user costs for a route given by Equation 3.5, and the user cost weight factor given by Equation 3.7, the objective of the least cost routing algorithm to find the least cost combination of haul weight and route choice is given by Equation 3.8.

$$Minimize\left([UC_{Total}]_{O-D} * UC_{WF,v} \right) \tag{3.8}$$

where:

$[UC_{Total}]_{O-D}$ = the total user costs for a given route beginning at origin, O and ending at destination, D ($);

$UC_{WF,v}$ = the user cost weight factor;

subject to:

$GVW_v < WL_{<i,j>}$

where:

GVW_v = the gross vehicle weight of vehicle, v (tonne);

$WL_{<i,j>}$ = the weight limit restriction imposed on road segment, <i,j> (tonne).

Essentially, haulers consider the least cost route to their destination under each weight category and choose the least cost combination of haul weight and route before beginning their trip, as is described in more detail in Chapter 4.

3.4. Road Provision

As outlined in *The Municipalities Act*, one of the responsibilities of a municipality in Saskatchewan is “to provide services, facilities and other things that, in the opinion of council, are necessary and desirable for all or part of the municipality” (The Municipalities Act, 2005). The focus of this research is on the transportation service that an RM provides through the management of the rural road network.

To cost effectively provide transportation services, RMs can make a number of decisions relating to the road network. The primary RM decisions of interest in this research are concerning: (1) road treatment strategy, and (2) road use management strategy.[5] This section begins with a discussion of road performance and treatment strategy to explain how RM decisions and related costs for road operation, maintenance, rehabilitation and upgrade are handled. This section concludes with consideration of the road use management strategy including how weight and speed restrictions and permit fees are handled.

3.4.1. Road Performance and Treatment Strategy

Road performance is inherently uncertain and dependant on a number of factors including road type, soil type, soil moisture, seasonality effects, traffic volumes, traffic characteristics, etc. There has been extensive work done on modeling road performance, but for this research, road performance was assumed to be fairly simplistic. The focus of this research is on understanding the combined impacts of various road network decisions and not on the detailed performance of the roads. It was assumed that the performance and costs of roads were known for different roads types.

RMs make decisions regarding the timing and type of maintenance, repair and rehabilitation activities to road segments. Road treatment strategies can vary widely by RM. Even within an RM, treatment strategies can vary by road segment, depending on a number of local factors mentioned above. Typically, RM road networks are largely gravel roads with some dirt roads and some types of surfaced roads including paved roads. Gravel road treatment strategies typically consist of routine blading, spot gravel addition, dust proofing, shoulder pulling and periodic gravel addition.

Generally, the type of treatments are fairly consistent for a given type of road (e.g., gravel road segments tend to have the same required maintenance activities, and paved road segments tend to have the same required maintenance activities, although the timing and frequency of activities can vary by segment). RMs typically make decisions for a group or “class” of roads

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[5] As will be discussed later, RM decision making may vary spatially and temporally. That is, road treatment strategies and road use management strategies may vary by road segment and may vary over time (e.g., seasonal weight restrictions on select road segments).

based on those roads having similar properties (width, road structure, surface type, soil type, etc.). Typically, there is some set schedule of routine maintenance and periodic treatments for each road type (frequency of road blading, frequency and amount of gravel addition etc.).

For gravel roads within an RM, assuming a relatively constant soil type, the predominant factor influencing the extent of required maintenance has been found to be traffic (Zimmerman & Wolters, 2004). In general, when traffic increases on a gravel road, the frequency of road blading increases as does the amount of gravel addition for spot repairs and regraveling. The relationship between traffic levels and maintenance activities is difficult to define because of a number of uncertain, variable factors mentioned previously. Particularly when soil moisture is high, gravel roads are highly susceptible to heavy vehicles, which can cause failures as heavy loads cause high stresses to penetrate greater depths within the subgrade (Barton, Wilson, Churko, & Hopkin, 1989).

While researchers have identified various factors that influence unpaved road costing, there does not appear to be an existing model that includes these factors to predict road performance and costs. Even if such a model existed, for the purposes of this research, obtaining the data necessary to accurately predict road costs was unfeasible and out of scope. In order to estimate road costs with information that is more readily available, traffic was used as the predictor of road costs based on road costing functions. This relationship between traffic and road provision costs is discussed further in the following section.

Each maintenance or upgrade activity that the RM undertakes has some associated cost. The costs incurred by the road provider in completing activities in their road treatment strategy are described in the following section.

3.4.2. Road Provision Costing

To maintain the road network, RMs may take a number of actions such as: routine maintenance activities, repair activities and capital upgrade activities. The combined costs of all activities on a given road segment, on a long-term basis, are known as the LCCs of the road segment. While predicting future maintenance costs for specific road segments is very difficult due to the numerous uncertainties in road performance (as outlined in the previous section), developing cost estimation for average costs over a road network is more feasible (Schuler, 2007). This research uses cost estimates that are representative of average road costs over the network.

The LCC of a road segment includes: initial construction costs, annual maintenance costs, and periodic repairs and rehabilitations (if applicable) throughout the lifespan of the road. An illustrative LCC profile is shown in Figure 3.3.

In order to compare the LCC for different road segments, it is convenient to express the LCC as the Equivalent Uniform Annual Cost (EUAC), which uses a discount rate to translate all costs over the life cycle of a road segment into a single value stated in dollars per year.

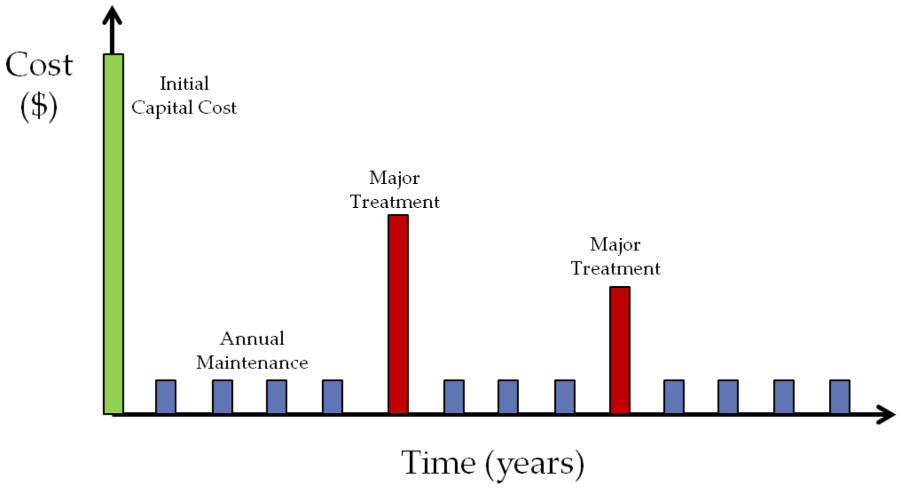

Figure 3.3 Illustrative Life Cycle Cost Profile for a Road Segment.

The initial capital cost to construct a road segment is translated to an EUAC by using Equation 3.9.[6]

$$EUAC\ of\ Present\ Cost = P * \frac{d(1+d)^N}{(1+d)^N - 1} \quad \textbf{3.9}$$

where:

P = the cost of a present activity in today's dollars ($);

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[6] The LCC equations used in this section are standard equations for translating LCCs and can be found in general engineering or economics texts.

d = the discount rate (%);

N = the useful life of the road (years).

The initial capital cost is included in the LCC discussion in this chapter for comparing total costs between various road types under various traffic levels. In model runs, for extant road segments, the initial cost to construct the road segment is considered as a sunk cost and is not included in the cost calculations. In the model, the capital costs included are for the upgrade of extant road segments. When capital costs are incurred for road upgrade, Equation 3.9 is used to translate the upgrade capital cost to an EUAC.

Road maintenance and repair activities may be broken out into annual activities that are completed each year, and periodic activities that are not completed every year. To calculate the total EUAC of any given road segment, the inclusion of the cost of annual activities is a trivial sum over all annual costs, as they are already in the required dollars per year unit of measure by definition. Any periodic future maintenance or rehabilitation activities (i.e., activities not completed each year) for a given road segment are translated to an EUAC by using Equation 3.10.

$$EUAC\ of\ Future\ Cost = F * \frac{d}{(1+d)^N - 1} \tag{3.10}$$

where:

F = the cost of a future activity in today's dollars ($);

d = the discount rate (%);

N = the number of years in the future that the cost is incurred (years).

Using Equation 3.10 for each type of periodic activity, the EUAC for a road segment may be stated as in Equation 3.11.

$$EUAC = EUAC\ of\ Initial\ Costs + Annual\ Costs + EUAC\ of\ Future\ Costs \tag{3.11}$$

where:

$EUAC\ of\ Initial\ Costs$ = the EUAC of the initial capital construction cost for the road segment ($/year);

$Annual\ Costs$ = the sum of the cost of all the activities performed each year on a road segment ($/year);

$EUAC\ of\ Future\ Costs$ = the sum of the EUAC of all future periodic activities (activities not conducted each year) on a road segment ($/year).

As discussed previously in this chapter, the LCCs for unpaved roads can vary across an RM and are highly sensitive to local conditions. The focus of this research is on the effects of road pricing (i.e., managing road usage through permit fees) on costs incurred on a network level; the focus is not on developing a predictive road costing model. Therefore, the road treatment strategy, based on simplified road performance models, and associated costs are exogenous to the model developed in this research.[7]

In the literature, it has been found that while there are several factors impacting road performance and costing, average daily traffic (ADT) is a statistically significant factor in calculating agency costs (Babcock & Alakshendra, 2011). Based on these findings, some researchers have developed models that predict agency costs using ADT as the independent variable. These types of models were leveraged for this research, because agency costs as a function of ADT were required as an exogenous input for the model developed in this research.[8]

A particularly useful effort, which produced plots for various road types similar to Figure 3.4, was completed by (Zimmerman & Wolters, 2004). The study, completed in South Dakota, produced a model that supports the road upgrade decision based primarily on traffic counts. The study will be considered in more detail in Chapter 4 for road costing functions that support the upgrade decision. The general approach for leveraging findings from the study is outlined as follows.

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[7] As will be described in Chapter 4, the model was designed such that if a predictive road costing model is known, it may be input into the model with relatively little model manipulation required.

[8] Unfortunately, the cost functions leveraged for this research did not include sufficient details for the dependence of agency costs on vehicle types making up the road traffic. As such, the impact of vehicle type (e.g., truck vs. passenger vehicle) had to be estimated for model inputs, as will be described in Chapter 4.

For road segments of a given type (e.g., gravel road, sealed road, paved road), determine the life cycle profile of treatments under various traffic levels. Then assign unit rates to the various treatments to produce the LCC profile (as Figure 3.3 introduced previously). The LCC profile is then translated into an EUAC using Equation 3.9, Equation 3.10 and Equation 3.11. Once this is done, the EUAC for various traffic levels for a road type can be fit with a best fit line. Typically a linear function is the most appropriate. The EUAC of a road segment is calculated for various traffic levels for each road type as in Equation 3.12.

$$\begin{aligned}[EUAC]_{r,t} \;=\; & [\text{EUAC of Initial Costs}]_{\mathrm{r}} + [A\mathit{nnual\ Costs}]_{\mathrm{r,t}} \\ & + [\mathit{EUAC\ of\ Periodic\ Costs}]_{\mathrm{r,t}}\end{aligned} \tag{3.12}$$

where:

r = the type of road segment;

t = the traffic level for the segment (ADT).

Ideally, Equation 3.12 would be known for every possible traffic level for each road type. In practice, the approach is typically to use Equation 3.12 (or some variation) to determine costs for ranges of traffic, e.g., ADT of 0-50, 50-100, 100-150, etc.

Plotting the values from Equation 3.12 allows the relationship between EUAC and traffic count to be determined. Assuming the relationship is indeed linear, an illustrative plot of the best fit lines is shown in Figure 3.4.

As shown in Figure 3.4, there are two road types represented. Road Type 1 (green line) with the higher slope is more sensitive to traffic than Road Type 2 (blue line) with lower slope as is typically the case with gravel and paved roads, respectively. When traffic volumes are less than the point at which the lines cross, ADT_1, Road Type 1 would be preferable for the road provider with the lower LCC. When traffic is higher than ADT_1, Road Type 2 would be preferable with lower LCC and better suited to accommodate higher traffic volumes.[9] The point

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[9] This assumes that traffic volumes are roughly consistent over the service life of the given road type. In reality, this may not be the case.

at which the linear functions cross is an important "trigger point" used in the road upgrade decision discussed in the next section.

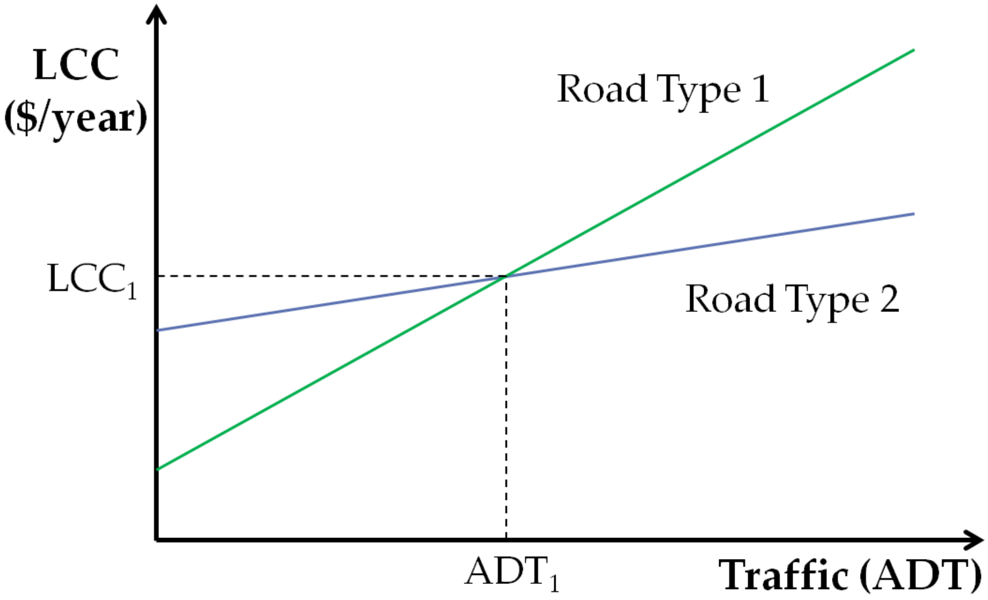

Figure 3.4 Illustration of Life Cycle Cost vs. Traffic Volume.

The linear functions developed by the process outlined above give the EUAC per unit length as a function of traffic for each road type, r, as given in Equation 3.13.

$$[EUAC\ /\ \mathrm{km}]_r = \mathrm{m_r} * \mathrm{ADT} + \mathrm{b_r} \tag{3.13}$$

where:

m_r = the slope of the line of annualized agency LCC versus traffic levels for road type, r ($/ADT);

ADT = the average daily traffic (number of vehicle passes);

b_r = the y-intercept of the line of annualized agency costs versus traffic levels for road type, r ($).

Once Equation 3.13 is established for each road type, the EUAC for any given road segment, <i,j>, which is of road type, r, may be calculated with Equation 3.14.

$$[EUAC]_{<i,j>} = [EUAC \text{ / km}]_{r_{<i,j>}} * \mathrm{L}_{<i,j>} \tag{3.14}$$

where:

$[EUAC \text{ / km}]_{r_{<i,j>}}$ = the unit EUAC per km of the road type, r, of segment, <i,j> ($/km/year);

$L_{<i,j>}$ = the length of the road segment, <i,j> (km).

As mentioned earlier, any upgrades completed to extant road segments during model runs are tracked separately and translated to EUAC using Equation 3.9. The EUAC for the entire network is calculated by summing the EUAC for each road segment and EUAC of the amount spent on capital upgrades, as given by Equation 3.15.

$$[EUAC_{Network}] = \sum_{n=1}^{N} \left\{ [EUAC]_{<i,j>_n} + [EUAC\ of\ Upgrade\ Cost]_{<i,j>_n} \right\} \tag{3.15}$$

where:

$[EUAC\ of\ Upgrade\ Cost]_{<i,j>_n}$ = the EUAC of the upgrade costs for the nth road segment, $< i,j >_n$ ($/year);

$[EUAC]_{<i,j>_n}$ = the EUAC of the nth road segment, $< i,j >_n$, for the past year based on traffic counts input into the function for its road type ($/year);

N = the number of road segments within the network.

3.4.3. Road Upgrade Decision

There have been several efforts towards determining when a gravel road should be upgraded. The report by (Jahren et al., 2005) indicates that despite high initial costs, there may be potential benefits of paving a road such as: a change in required maintenance activities, reduction in dust, smoother and safer surface, improved vehicle and driver efficiency, lower vehicle user costs, and redistribution of traffic. Another potential benefit mentioned by (Jahren et al., 2005) is that the upgrade may draw traffic off of gravel roads and on to the paved roads, which may reduce required maintenance activities on gravel roads. These potential benefits are in line with the features of interest in this research: understanding the impacts that road upgrades may have on user route choice and resulting agency and user costs.

An economic analysis that includes costs over the life of the roads considered is generally recommended for a road upgrade decision (i.e., consideration of LCCs). While various other aspects such as dust reduction, safety considerations, and public opinion should be considered, for the purposes of this research, the road upgrade decision was based solely on an economic analysis of the user and agency costs directly related to the road segment use and provision. The report by (Schuler, 2007) found that while there are multiple factors that affect the road upgrade decision, the simplest was the traffic volume.[10] Similar to the approach for LCC functions, for the purposes of this research, a simplified decision process for road upgrade was used, which was solely based on ADT of the road segment and subject to budget constraints.

As mentioned in the previous section, the point at which the linear costing functions of road types cross in Figure 3.4 - the trigger point - is an important point for the road upgrade decision used in the model developed in this research. The full road upgrade decision making process represented in the model is presented with more detail in Chapter 4. Essentially, the decision is a simple prioritization based on traffic counts where road segments are considered for upgrade if they are above the trigger point where the traffic levels indicate that upgrading would result in lower total life cycle costs. The upgrade decision is based on combined agency and user costs as illustrated in Figure 3.5. The trigger point (the point at which the lines cross in Figure 3.5) occurs at a lower traffic volume when considering network costs (agency plus user costs) than the trigger point when considering only agency costs.

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[10] Traffic volume is not necessarily the most significant/important factor in the road upgrade decision; traffic volume was chosen as the primary factor because of the availability of traffic count data produced by the model. If other factors were to be included in the model (e.g., public opinion, improvements required for road base and drainage, etc.), then they could be included in the road upgrade decision as well.

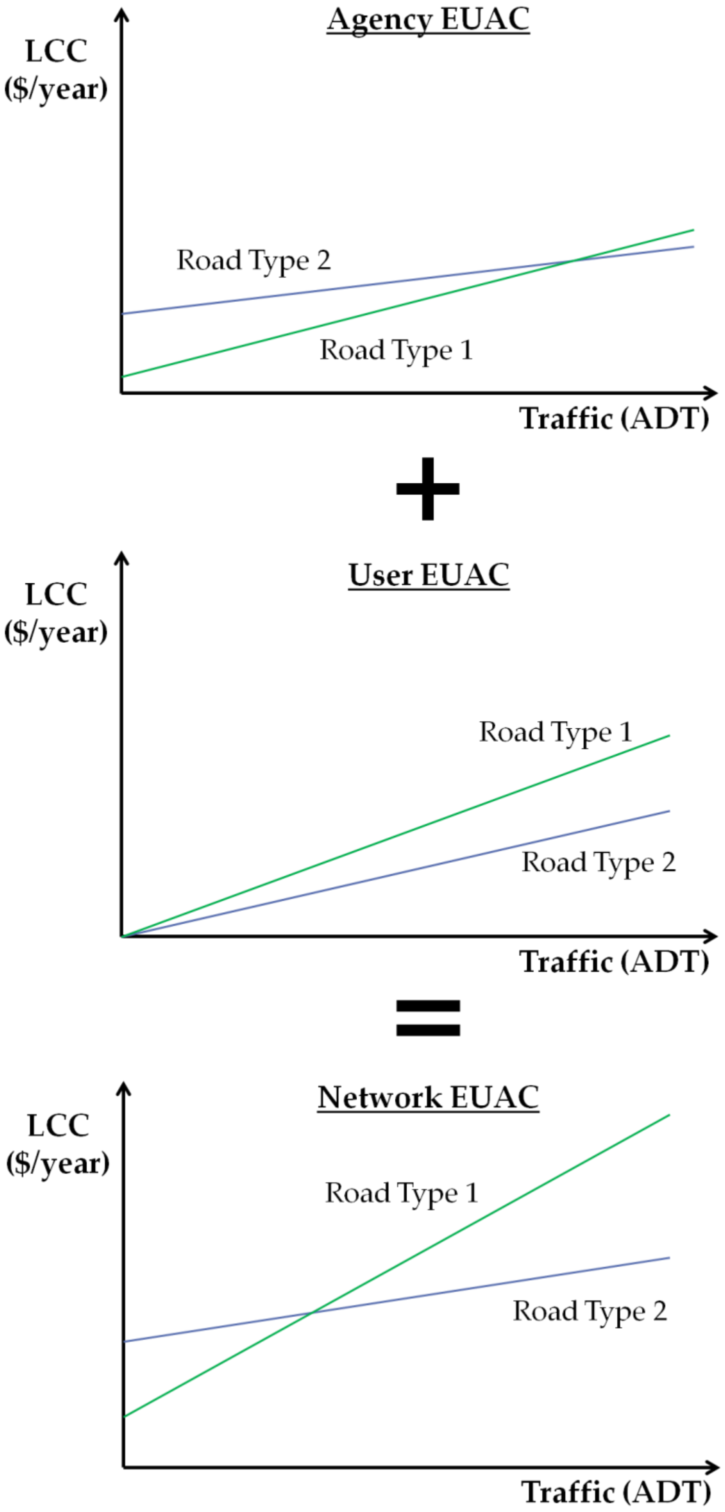

Figure 3.5 Combined User and Agency Costs by Traffic Count.

Road upgrade costing and budget constraints are handled as follows. The capital upgrade decision and associated costs in a given year are represented in Equation 3.16 using a binary (yes or no) variable.

$$Annual\ Agency\ Capital\ Cost = \sum_{n=1}^{N} \left(y_{<i,j>_n} * Unit\ Upgrade\ Cost * L_{<i,j>_n} \right) \qquad \mathbf{3.16}$$

where:

$y_{<i,j>_n}$ = 1 or 0 (1 = upgrade, 0 = no upgrade for the nth road segment in the network, $<i,j>_n$);

$Unit\ Upgrade\ Cost$ = Cost per kilometer for an upgrade ($/km);

$L_{<i,j>_n}$ = the length of the nth road segment in the network, $<i,j>_n$ (km);

N = the number of road segments in the network.

The RM is constrained by annual budget levels, which are used towards capital upgrades of the road network. This constraint each year may be described as in Equation 3.17.

$$Annual\ Agency\ Capital\ Cost \leq Annual\ Agency\ Capital\ Budget \qquad \mathbf{3.17}$$

where:

$Annual\ Agency\ Capital\ Budget$ = the funding available to the RM for capital upgrades (does not include the costs of maintenance, repair and periodic renewals of existing roads) ($).

The decision making process for RMs in considering road upgrades is covered in Chapter 4.

3.4.4. Road Use Management Strategy

The previous section outlined how an RM can manage the road network through a road treatment strategy. This section discusses how an RM can manage the road network by managing the road users. Given the impact that road use has on road performance, discussed in Section 3.4.1, there are potential benefits to be had by managing road usage. Further, if road usage can be coordinated with appropriate road treatment strategies, more significant benefits may be had. Potential methods of managing road use that were of interest in this research included managing: vehicle weight, vehicle speed, and vehicle permit fees.

Currently in Saskatchewan, RMs may restrict the allowable vehicle weight on road segments to various weight classifications (e.g., Primary weight, Secondary weight). The weight allowances are often guided by the time of year, but may be adjusted based on subgrade soil moisture or other properties as the RM sees fit. For example, in the Spring, when roads are thawing and are particularly vulnerable to damage from heavy vehicles, fairly significant weight restrictions may be imposed on select segments in an attempt to prevent extensive road damage due to heavy vehicles, which may require costly repairs. In the Winter, roads are less susceptible to damage, so weight allowances are often less restrictive.

The type of road can influence the weight restrictions that the road provider chooses to implement. Upgrading a gravel road to a paved road, for example, may result in less restrictive weight restrictions, as paved roads are less susceptible to environmental impacts and better suited to accommodate heavier loads. The weight limit decision is not modeled in this research: the weight limits are exogenous inputs to the model and are based on season, as is typical in Saskatchewan, and are input based on existing weight limits in place for the case study being considered in the model.

Speed limits may also be imposed on road segments. While varying speed can influence both user costs and the impact of vehicles on road performance (speed can affect the amount of consumption/damage that the road user imposes on the road segment), the variance of speed limits on road segments was not of particular interest in this research. Speed limits were necessary to include in the model in order to calculate the time required for vehicles to travel across road segments. Speed limits are exogenous inputs to the model and are input based on the existing speed limits in place for the case study being considered in the model.

The RM may also impose a price for certain vehicles to use the network. Currently, RMs in Saskatchewan are able to issue permits for non-divisible, overweight vehicles. This research considered the impacts of imposing permit fees on trucks hauling bulk material (divisible loads). While this style of permitting may not be currently legal for RMs to implement, there are other jurisdictions that have implemented similar types of permitting (Newbery, 1988).

The concept of road pricing has been investigated internationally and there are many toll systems and road permitting systems in place. The majority of permitting systems relate to congestion costs for highly congested urban roadways. This research was scoped to rural road networks where the large spatial layout of road segments and relatively low traffic levels generally result in negligible congestion effects.

Understanding the full implications of using a permitting system is a complex, difficult task. A review of road pricing literature by (Levinson, 2010) found that while there are potential issues with equity associated with road pricing, those issues can be addressed with the appropriate mechanisms (e.g., reducing other taxes and investing in infrastructure and services) to provide the correct incentives to road users to reach equitable ends. With the complexity of features in the model developed in this research, the full details of road pricing and usage of revenues was not considered in detail.

There are several methods of pricing roads. (Litman, 1999) points out that a mileage charging system is suitable for charging near marginal costs of vehicle use (which may include vehicle axle weight, accident risk, and pollution emissions). A study by (Forkenbrock, 2005) discusses the benefits of implementing a per-mile user charge for different standards of roads, such as charging a higher per-mile charge for heavy vehicles travelling on lower standard roads than higher standard roads can encourage heavy vehicles to travel on higher standard roads that are better suited to accommodate heavy vehicles. These studies and the desire to use a simple pricing system lead to the scope of road pricing used in this research to be a simple, weight-distance based fee with a transfer of funds from road users to the road provider.

Permit fees considered in this research were based on the principle of marginal cost of road usage. Road users impose four main costs to society: accident externalities, environmental pollution, road damage, and congestion (Newbery, 1988). For simplicity, costs imposed by road users in this research were scoped to include incremental road damage only. Determining the exact relationship between road use and marginal cost for road provision is difficult in practice.

The values used for incremental road cost per vehicle pass were based on existing literature and are outlined in Chapter 4.

Road users in the model were assumed to always pay the appropriate permit fee. In reality, under a permitting system, there is potential for road users to cheat by either not obtaining/paying the imposed permit fee or to operate outside the constraints of the permit fee. This type of cheating was not considered in the model; however, there is potential to include considerations for this type of cheating by incorporating some probability of being caught and severity of consequences for road users operating without a permit, as discussed in Chapter 4.

3.5. Net Benefit (Combining Costs)

To this point, this chapter has outlined the decision making and costs for the road provider and road user separately. This section outlines how the road provider and road user costs are combined. The variables and equations in this section are used to compare the results of model runs.

The main measure of comparison between model runs was the total combined cost, which included the total road provider cost as well as the total cost for all road users in a model run, given in Equation 3.18.

$$Total\ Cost = \sum_{t=0}^{T}([EUAC_{Network}]_t) + \sum_{u=0}^{U}([UC_{Total}]_{O-D})_u \qquad \textbf{3.18}$$

where:

T = the total number of years in the model run;

U = the total number of OD trips completed in model run.

It may be that some model runs result in a reduction in costs for the road provider but increase total costs to road users and vice versa, so it is useful to track each of them separately as well as combined to better understand the results for road users and the road provider in the model run. So long as the decrease in one of either road provider or road user costs is greater than the increase in costs for the other, then that suggests the model run offers a net benefit and is worth exploring.

3.6. Chapter Summary

This chapter covered several key principles and equations related to road provision and road use that were used in the model. Key principles included: road network representation, road user costing and decision making regarding routing and haul weights, road provider costing and decision making regarding road upgrade and road use management such as weight restrictions, speed restrictions and permit fees.

This chapter laid the groundwork for a detailed description of the ABM developed in this research, which is covered in Chapter 4. A detailed description of the actual agents, processes and parameters used in the developed model is provided in Chapter 4. The discussion of the complexities and scoping of relevant principles in this chapter allows for those principles to be discussed more concisely in Chapter 4 to help give a more succinct outline of the developed model.

CHAPTER 4 AGENT-BASED MODEL DESCRIPTION

4.1. Introduction

This chapter describes the ABM developed in this research. The model is described for a hypothetical road network using hypothetical default values to illustrate model design and functionality. The results generated from the model using inputs described in this chapter are given in Chapter 5. Source code for the developed model is available upon request.

As the field of ABM is relatively new, there is not a standard, accepted protocol for documenting models. One method of documenting ABMs, which has been used by several researchers with success, is the Overview, Design concepts and Details (ODD) protocol developed by (Grimm et al., 2006; Grimm et al., 2010). The ODD protocol was modified by (Muller et al., 2013) to allow for ABMs that include human agents and decision making, known as "ODD+D". The documentation in this chapter follows the ODD protocol with some minor modification to include human decision making based on insights from the work done by (Muller et al., 2013) on the ODD+D protocol. The organization of this chapter is outlined in Table 4.1.

Table 4.1 Overview, Design Concepts and Details Overview (Adapted from (Grimm et al., 2010)).

Overview	1. Purpose
	2. Entities, state variables, and scales
	3. Process overview and scheduling
Design Concepts	4. Design concepts
	• Basic principles
	• Emergence
	• Individual Decision Making
	• Sensing
	• Interaction
	• Stochasticity
	• Collectives
	• Observation
Details	5. Initialization
	6. Input data
	7. Submodels

4.2. Purpose

The purpose of the model was to determine the feasibility of applying an ABM to represent the road use and road provision of a rural road network in Saskatchewan. Of interest was investigating various scenarios involving road users and road providers to determine if implementing road permit fees may help to align incentives and result in net benefits. Specifically, road upgrade and road pricing were considered and the resulting road user and road provider costs were the key outputs of interest.

4.3. Entities, state variables, and scales

This section outlines the four types of agents within the model: *Road Node*, *Road Segment*, *Vehicle*, and *RM*.

Road Nodes and *Road Segment*s do not have decision making ability; they are reactive agents. These two agent types were chosen to support a graph style network to be used in the model so that calculations could be done for network routing and so that properties of road segments could be changed and monitored on a segment-by-segment basis (costs of road provision and road use, road upgrade etc.).

Road Nodes exist at each end of every *Road Segment*. *Road Nodes* represent either intersections, the end of a "dead-end" road, or a point along a road segment if traffic is generated by or destined for some point along the road segment. The location of each *Road Node* must be input by the user before the model run and does not change during a model run. *Road Nodes* function as points for alternative routing as well as origin and destination points for *Vehicles*.

Road Segments require input of the starting and ending *Road Node* before initiating a model run.[1] When a *Road Segment* is created, it connects the specified starting and ending *Road Nodes* (in effect, creating the road network). *Road Segments* have a road type property (e.g., gravel road) that has an associated cost function used by the *RM* and is used by *Vehicles* to determine their unit operating cost. The *Road Segment* tracks traffic counts (for each *Vehicle* type) each time a *Vehicle* passes over it.

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[1] It does not matter which node is identified as starting or ending node (no one-way roads are considered).

Vehicles are generated by *Road Nodes* based on input vehicle generation rates, which may change over the model run. *Vehicles* spawn at the location of the *Road Node* that creates them (*Vehicle* origin) and travel the least cost route (in terms of their own user costs incurred) to another *Road Node* (*Vehicle* destination). Key properties of the *Vehicle* agent include: vehicle configuration, weight category, unit time related costs, and unit distance related operating costs for each different road type. The total *Vehicle* user cost includes the time based unit costs, distance based unit costs, and distance based permit fee costs (if a permit fee is issued for a particular *Road Segment* by the *RM*). *Vehicles* travel at exactly the speed limit of the *Road Segment* they are on and they cannot travel on *Road Segments* if they are heavier than the weight restriction.

Once *Vehicles* are created in the model, they calculate the least cost route to travel from their current origin to their desired destination. Finding the least cost route involves using a shortest path algorithm using their own costs on each *Road Segment* as the weighting function. The least cost routing algorithm is considered for various payload amounts, as there may be weight restrictions on *Road Segments* that may prevent *Vehicles* from travelling across them at heavy weights. Once the least cost combination of payload amount and route is determined, the *Vehicle* proceeds to travel the across *Road Segments* within the route to arrive at the desired destination *Road Node*. *Vehicles* are assumed to make round trips. For *Vehicles* that are trucks: they begin loaded with payload, travel to their destination, become empty, and then return to their origin.[2]

The *RM* is the only agent type that is not replicated (only one instance of this agent type), and does not have a spatial representation in the model. The *RM* has an annual capital budget for the upgrade of *Road Segments*. The *RM* can directly influence *Road Segments* and change any *Road Segment*'s weight limit and road type.[3] These changes can then influence *Vehicles* when they travel over the *Road Segments* (potentially affecting the routing and costs of *Vehicles*). The

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[2] The route for a loaded *Vehicle* is not necessarily the same route for an empty *Vehicle*, as road weight restrictions may alter least cost routing given the current GVW of the *Vehicle*. If it were desirable to model trucks being loaded while traveling in both directions, minor modifications to the model could be completed to accommodate such a hauling scenario.

[3] The *RM* can only upgrade a road type (e.g., from gravel to paved). Reversion of paved roads to gravel roads was not considered, although this type of road change could be relatively easily incorporated into the model if a decision making framework for such considerations was known.

RM incurs costs based on exogenous cost functions for road type based on traffic counts. The *RM*'s decision to upgrade a *Road Segment* occurs annually and is based on a simple heuristic of prioritization of traffic counts and life cycle cost comparison under budget constraints.

The time step of the model is one hour. This time step allowed for analysis of individual trips as well as summary analysis over multiple years in a relatively short model run time. The model uses a calendar date as the time format and model runs begin and end at input calendar dates. The calendar date time format is convenient for handling *RM* decision making, which tends to be based on monthly, seasonal or annual cycles (e.g., seasonal weight restrictions on road segments and annual budgeting practices). Model time is continuous to allow *Vehicles* to move continuously throughout the model environment. Discrete events are triggered at various points throughout the model for decision making and updating and summarizing variables (e.g., hourly, monthly, seasonally, and annually).

Space is represented in the model using a Geographic Information Systems (GIS) environment.[4] The use of a GIS environment was motivated by two factors. First, a GIS environment allows for relatively straight-forward importing of *Road Nodes* and *Road Segments* into the model when a case study has GIS based data for their road network. Second, a GIS environment allows straight-forward calculations of true distance (i.e., real world case study distance) between locations. Since *Road Nodes* exist at each end of every *Road Segment*, finding the true distance of *Road Segments* is straight-forward. Similarly, handling the true speed of *Vehicles* is more convenient with the true distances known (with some required conversions of the model time representation of real time).[5]

The state variables of the model and agents are shown in Table 4.2. There are additional variables in the model, but if they are not listed in Table 4.2, they may be calculated or inferred

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[4] Note that the model functionality does not require a GIS environment; the road network could be represented in a simple two-dimensional environment without loss of functionality. The conversion between GIS coordinates and two-dimensional coordinates would require relatively minor changes to preserve model functionality.

[5] The GIS environment also lends itself well to the inclusion of additional agents in the model (such as oil industry companies or farmer agents) that may have associated location data for generation of vehicles, as discussed in the future work section in Chapter 7.

from some combination of state variables (for example, *Season* is not a state variable because it may be inferred from the current date of the model).[6]

Table 4.2 State Variables in Model.

Agent	State Variable	Description	Unit
Road Node			
	nodeVPD	Number of vehicles generated by the node per day.	vpd
Road Segment			
	roadType	Type of road (paved or gravel).	-
	weightLimit	Weight allowance category for vehicles.	-
	trafficCountPassenger	Passenger vehicle count to date.	#
	trafficCountTruckLoaded	Loaded Truck vehicle count to date.	#
	trafficCountTruckEmpty	Empty Truck vehicle count to date.	#
	rmCostMonthly	Monthly RM road provision cost due to traffic.	$
Vehicle			
	returnTrip	Indicates if vehicle is heading to initial destination or returning to initial origin (boolean).	-
	vehWeightCat	Current weight category of vehicle (e.g., Primary, Secondary weight) (also indicates if loaded or empty).	kg
	curNextNode	Current next node in the network the vehicle plans to drive.	-
	curRoad	Current road segment the vehicle is on.	-
	totalDist	Total distance travelled for vehicle.	km
	totalTonneKm	Total tonne-km hauled for vehicle.	tonne*km
	totalDistBasedCost	Total distance based cost for vehicle.	$
	totalTimeBasedCost	Total time based cost for vehicle.	$
	totalPermitFeeCost	Total permit based cost for vehicle.	$
RM			
	totalLccNoCap	Total LCCs without including capital upgrade cost.	$
	totalEuacCap	Total annualized capital upgrade costs.	$
	totalPermitFeeRev	Total permit fees collected from vehicles.	$

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[6] Note that generally "Parameters" refer to values that are input and do not change throughout model runs. "Variables" may or may not be input by the model user, but they generally change during model runs.

While many variables are defined locally for agents within the model, there are also global variables that exist "outside" of specific agents: these global variables are referred to as belonging to the *Main Model*. While not state variables, the *Main Model* contains variables that track various properties over all created *Vehicles* such as: total *Vehicles* created, total distance travelled, total costs, etc.

The agents that make up the model along with state variables and interactions between agents are shown in Figure 4.1. The properties, interactions and decision making of the agents in Figure 4.1 are described in more detail in the remainder of this chapter.

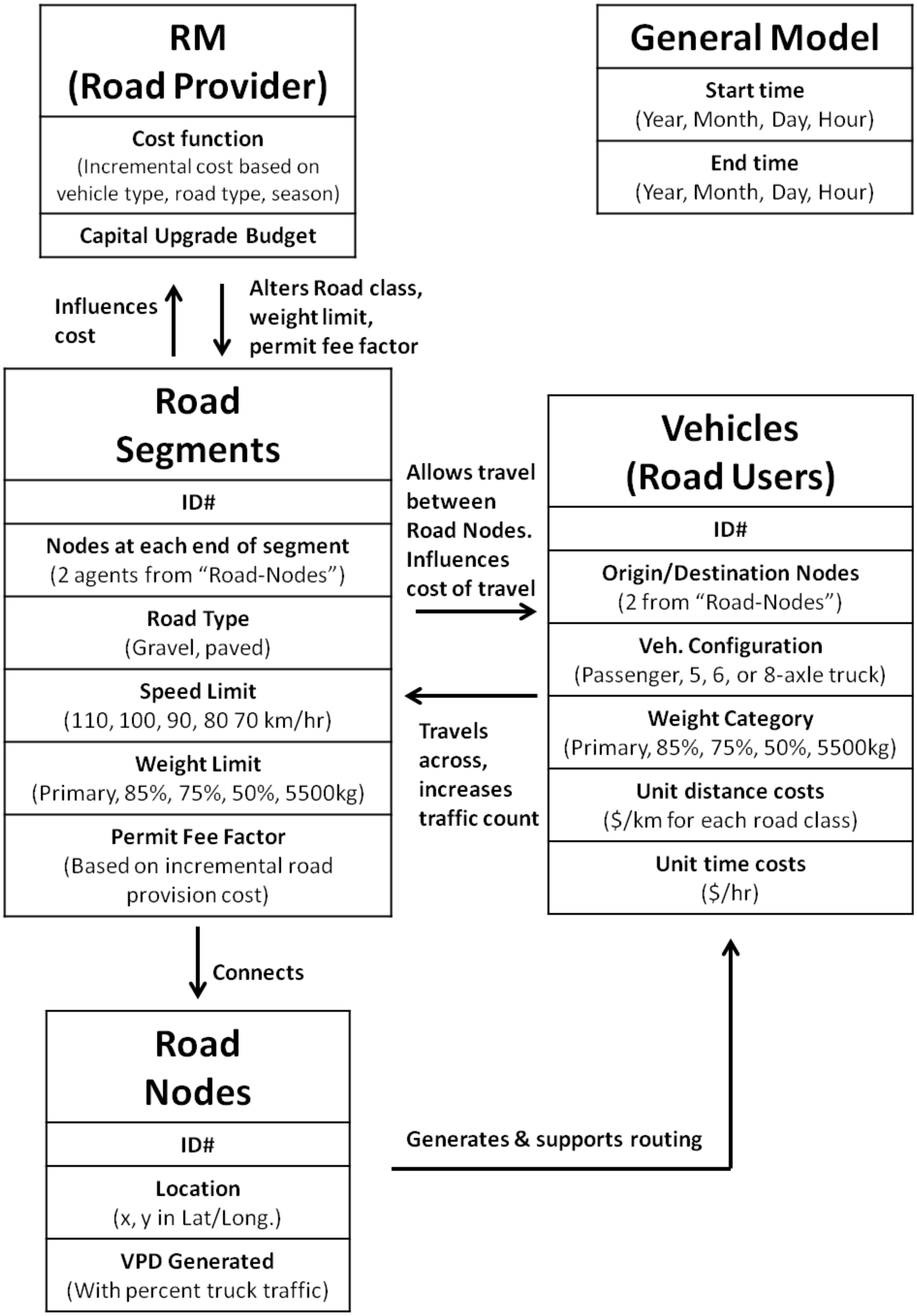

Figure 4.1 Overview of Agents and Interactions.

4.4. Process overview and scheduling

Due to the segregated nature of ABMs, the chronological flow of model activity can be difficult to follow. As agents are created, they will have their own internal processes that may run in parallel to other agents and processes in the model. To describe the scheduling of key events in the model, process charts are developed for each of the four model agents as well as a process flow chart for the *Main Model*. The *Main Model* process flow chart is considered first, as it is where the model environment and model agents are created (model agents exist within the environment in the model). An overview of the process flow of the *Main Model* is given in Figure 4.2.

As shown in Figure 4.2, the *Main Model* process is broken into "initiation" and "operational" components. The initiation component initiates various model timers and then loads the initial agents into the model environment. User input required for initialization values is outlined later in Section 4.6. The operational component essentially consists of timers that trigger actions of various agents; much of the model functionality is contained within the functionality of agents (described in subsequent process flow charts). For all agents except *Vehicles*, the process flows shown in this section continue until the *Main Model* timer indicates that the model run end date has been reached and the model run is terminated.

The process flow chart for the *RM* agent is shown in Figure 4.3. The *RM* begins by initiating parameters and then setting permit fees on *Road Segments* (if permit fees are considered in the scenario, as specified before model start by the user). The remainder of the *RM* functionality is triggered by timers. A change in season triggers a change in road weight restrictions for *Road Segments* (based on inputs). A change in month triggers a summary of the costs incurred by the *RM* in the previous month. A change in year initiates the road upgrade decision process. The trigger point for road upgrade is input as a parameter for the *RM*, and the actual ADT for the previous year is tracked within each *Road Segment* as described later in this chapter.

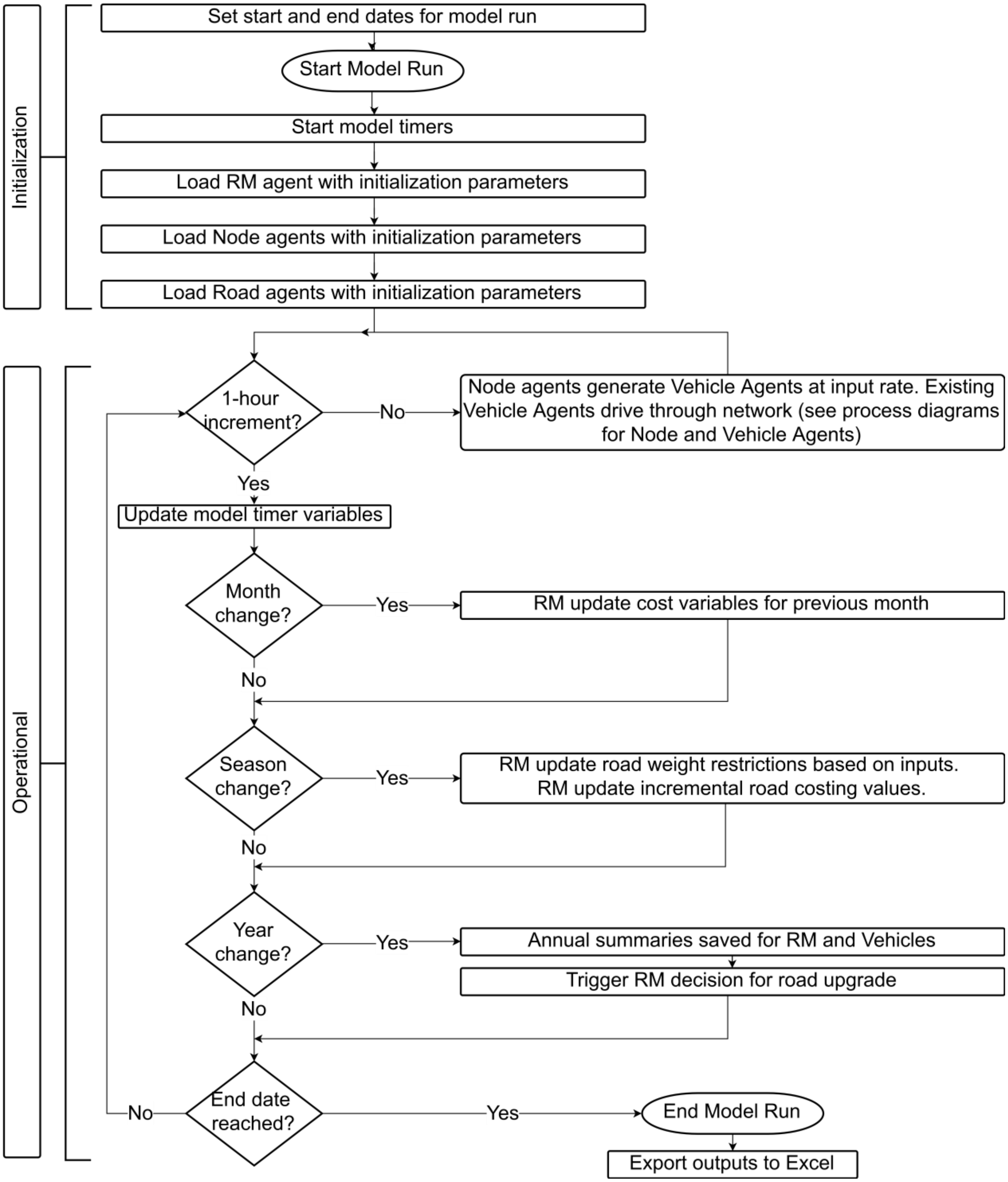

Figure 4.2 Overview of the Main Model Process.

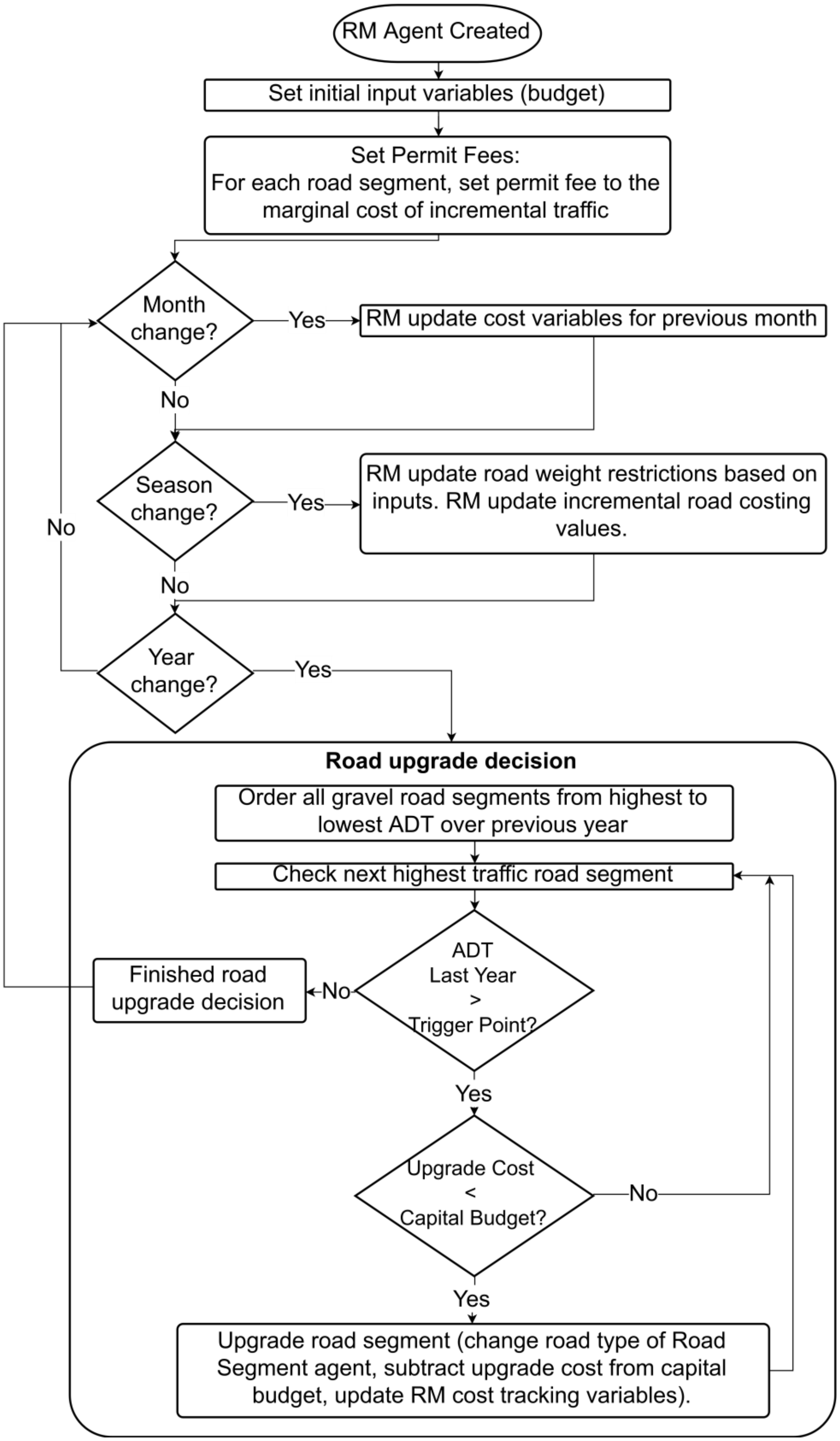

Figure 4.3 Overview of the Rural Municipality (RM) Agent Process.

The process flow chart for the *Road Node* agent is shown in Figure 4.4.

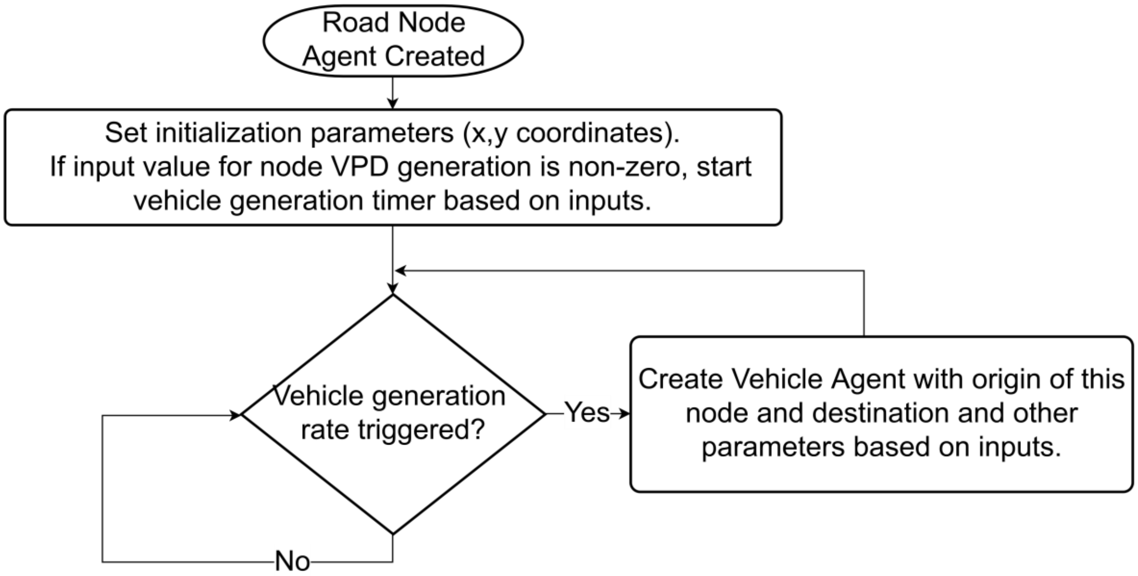

Figure 4.4 Overview of the Road Node Agent Process.

As shown in Figure 4.4, *Road Nodes* begin by initializing parameters and setting their location and then proceed to generate *Vehicles* at an input rate. The vehicle generation rate is driven by an input OD matrix with inputs for number of *Vehicles* generated as well as the percent of the *Vehicles* that are trucks and percent passenger vehicles.

The process flow chart for the *Road Segment* agent is shown in Figure 4.5.

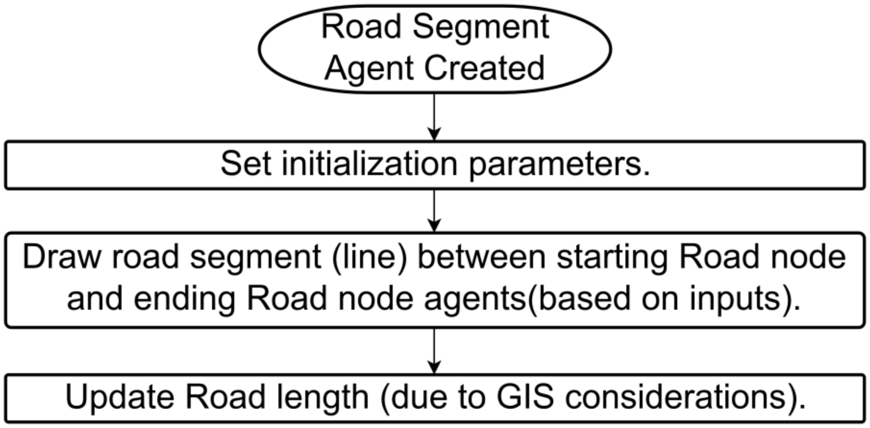

Figure 4.5 Overview of the Road Segment Agent Process.

As shown in Figure 4.5, the *Road Segment* has a very simple, limited process flow chart. Essentially, *Road Segments* initialize parameters and are drawn between starting and ending *Road Nodes*. Any further updating of *Road Segment* properties is done by other agents (e.g., *Vehicles* incrementing traffic count of *Road Segment* when passing over it). Once all *Road Segments* are created, the road network is complete and *Vehicles* may begin to be created within the road network.

The process flow chart for the *Vehicle* agent is shown in Figure 4.6. When *Vehicles* are created in the model, they initialize timers and begin at the location of the *Road Node* that generated the *Vehicle* (the origin).[7] The *Vehicle* then moves through three states: "at-origin", "driving", and "at-destination". The *Vehicle* begins in the "at-origin" state where the simple decision heuristic determines the least cost combination of payload weight and route choice to the *Vehicle*'s desired destination. The process flow in Figure 4.6 is for a truck *Vehicle*; passenger *Vehicles* follow the same process flow, but the considerations for payload are skipped. The *Vehicle* then moves to the "driving" state where it follows the ordered list of *Road Nodes* determined in the least cost route, hauling the payload amount determined in the "at-origin" state.

On arrival at each *Road Node*, the *Vehicle* updates various cost tracking variables and increments the traffic count of any *Road Segments* travelled on. Once the *Vehicle* arrives at the final *Road Node* in the route (the destination), it moves to the "at-destination" state. The *Vehicle* then switches its origin and destination nodes (current origin node becomes new destination node), becomes empty (zero payload) and repeats the process to complete the round-trip. Note that the returning path chosen by the *Vehicle* may be different that the initial path, depending on road restrictions and permit fees in place. Once the *Vehicle* returns to the initial origin node, the *Vehicle* is destroyed. *Main Model* variables track various totals for *Vehicle* costs before the *Vehicle* is destroyed.[8]

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[7] The spatial representation of *Vehicles* exist only within the road network; that is, *Vehicles* are always either following along a *Road Segment* or else at a *Road Node* agent, they are never "lost in space" outside of the road network agents.

[8] If more details were desired for certain *Vehicles* or groups of *Vehicles* (e.g., fleets) over time, then it may be desirable to allow *Vehicles* to complete multiple trips, rather than destroying them after each round trip. This would require some model modification, which would be anticipated to be fairly straightforward.

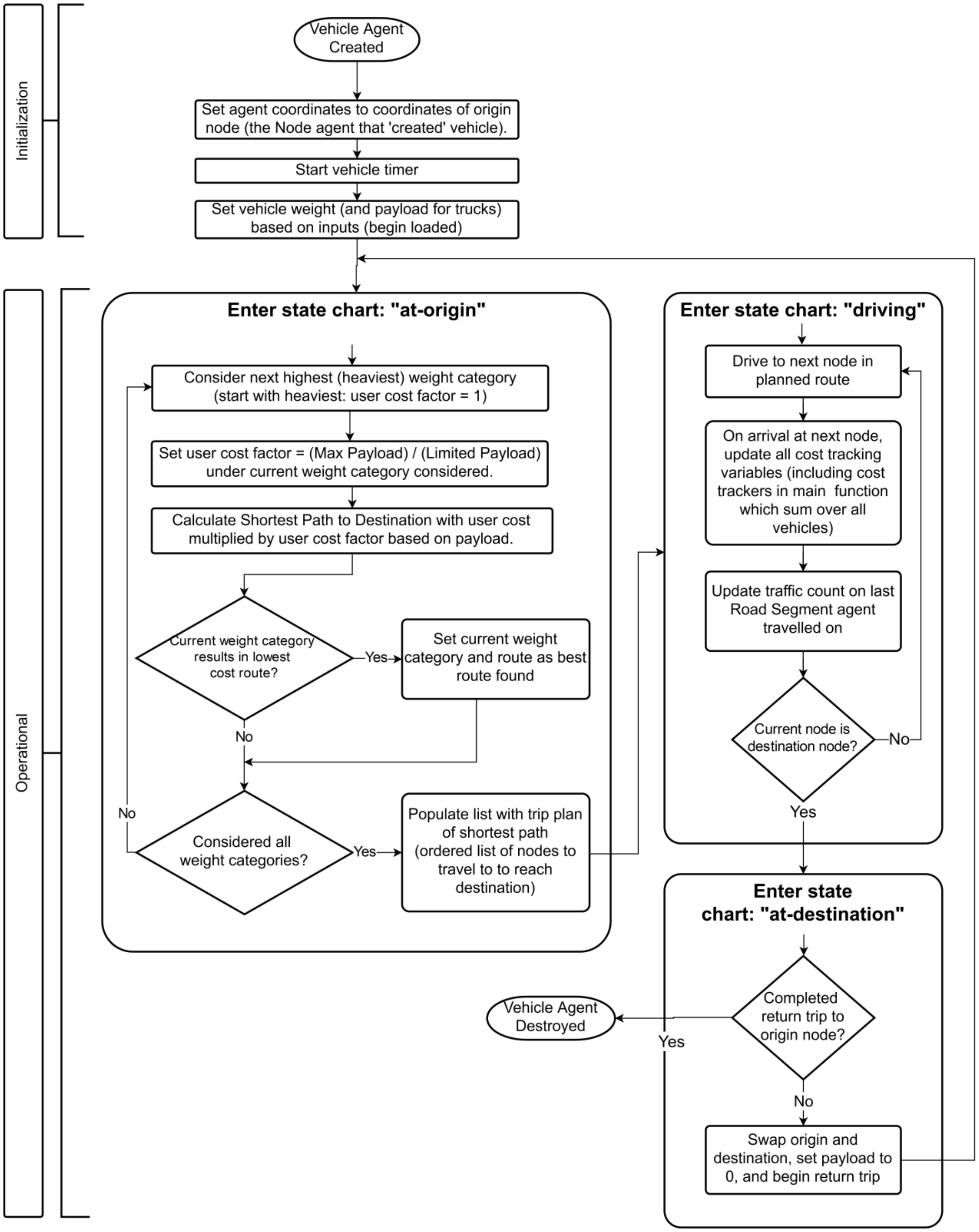


Figure 4.6 Overview of the Vehicle Agent Process.

4.5. Design concepts

There are eleven design concepts in the ODD protocol, but not all design concepts are relevant for the model; non-relevant design concepts were omitted from this chapter. Some additional concepts from the ODD+D framework related to human decision making were added to this section.

4.5.1. Basic Principles

This section outlines the basic parameters used for each agent in the model. The basic principles used in the model are as follows:

Road Nodes and *Road Segments* are created and combined to represent an undirected, weighted graph. This style of representing a road network allowed for various network theory applications (shortest path) as well as allowed for tracking properties of each road segment individually and allowed *Vehicles* to be generated at various points throughout the network (at *Road Nodes*).

Vehicles follow least cost routing using Dijkstra's Algorithm, a shortest path algorithm for networks, with road weighting based on user costs. *Vehicles* incur user costs, which are based on exogenous unit cost inputs based on road type and vehicle type.

The *RM* costing uses a LCC framework to calculate road provision costs, as is generally recommended for understanding total asset costs. The road upgrade decision hinges on prioritization based on traffic counts subject to budget constraints.

The key output from the model used to compare scenarios was net benefit. Under the scope of the model, net benefit was defined as the reduction in the combined road provider and road user costs over a model run compared to a defined base case model run.

Rather than providing insights into any basic principles, the aim of the model is to provide insights into impacts of applying policies to a road network in terms of road provider and road user behaviour and costs.

4.5.2. Emergence

Road upgrade selection and the resulting road provider and road user costs and *Vehicle* routing are emergent from road provider and road user decision making. Traffic counts influence the road upgrade decision, while road upgrade influences routing and traffic counts. Distance based permit fees and road weight restrictions can influence routing patterns, which can then influence *Road Segments* selected for upgrade. The emergent road provider and road user decisions and associated costs were investigated under various scenarios.

4.5.3. Individual Decision Making

Annually, the *RM* decides which (if any) *Road Segments* to upgrade. As discussed in Chapter 3, there are several aspects of the road upgrade decision that should be included. The road upgrade decision in the model is a very simplified version of the actual road upgrade decision process and is based on an LCC comparison: when traffic counts are high enough that the calculated LCC of the upgraded *Road Segment* are less than the non-upgraded *Road Segment* based on the previous year's traffic counts, then the *Road Segment* is considered. Of these considered *Road Segments*, the one with highest traffic count is considered first and is upgraded if the cost is less than the remaining annual capital upgrade budget. Then subsequent *Road Segments* are considered by decreasing traffic counts until no further *Road Segments* can be upgraded within the remaining budget.

A *Vehicle*'s objective is to minimize their own user costs while completing return trips in the road network. The decisions of *Vehicles* are haul weight and routing. *Vehicles* have a set destination and must decide the least cost combination of haul weight and route to reach their destination and return to their origin. User costs include the distance based cost of operating the vehicle, time-related costs and any distance based permit fees that must be paid during transport. *Vehicles* calculate the least cost route to their destination while obeying the weight and speed restrictions for each *Road Segment* using Dijkstra's Algorithm. To represent additional trips required at lower haul weights to haul the same amount of material, a user cost factor based on the current haul weight considered is applied to user costs when finding the least cost route.

4.5.4. Sensing

All agents have perfect, global knowledge of all relevant variables. *Vehicles* have perfect knowledge of the current road network (e.g., weight allowance, road type etc.) and can perfectly calculate the costs of alternate routing paths to their destination. The *RM* has perfect knowledge of traffic counts on every *Road Segment*.

4.5.5. Interaction

The *RM* and *Vehicles* interact directly with *Road Segments*: the *RM* may impose constraints or modify the type of *Road Segments*, and *Vehicles* affect the traffic count property of *Road Segments*. The *Road Segment* can passively interact with both the *RM* and *Vehicles*: the properties of the *Road Segments* impact the costs incurred by both the *RM* and *Vehicle*. *Vehicles* do not interact with each other (no traffic effects considered).

4.5.6. Stochasticity

There are no stochastic processes in the model.

It is acknowledged that the model may be improved by incorporating stochasticity into various areas such as: route choice (users do not always chose the least cost route), traffic generation rates, randomly shifting OD patterns, road performance and associated costs,

Road users in the model were assumed to always pay the appropriate permit fee and follow weight and speed restrictions. In reality there is potential for road users to disobey road restrictions or to not obtain/pay the imposed permit fee. This type of cheating was not considered in the model; however, there is potential to include considerations for this type of cheating by incorporating some probability of being caught and severity of consequences for road users.

4.5.7. Collectives

Collectives are not modeled explicitly. However, the collection of all *Road Nodes* and *Road Segments* may be thought of as a Network collective. In that sense, both *Vehicles* and the *RM* do consider the Network collective: *Vehicles* consider all agents within the Network collective when finding their desired route, and the *RM* costs are summed over all agents within the Network collective. Again, the Network collective is not defined in the model to have any state variables or traits; it is mentioned here only to illustrate the principle of a collective Network represented by the sum of all *Road Nodes* and *Road Segments*, which is used in some outputs for model runs.

4.5.8. Observation

The following data are collected from the model for analysing mode runs. Data collected from the *RM*: total road provision costs by segment and for total network (monthly), total capital costs (annually), total number and length of *Road Segments* upgraded (annually), total permit fee revenue (monthly), net costs (monthly). Data collected from *Vehicles* after each completed trip: distance travelled, distance based operating cost, time based cost, permit based cost, total user cost, total weight hauled, total weight-distance (i.e., tonne-km). Also, traffic count data are recorded for *Road Segments* (monthly). All data are available from the model to be tested (no data hidden from modeller).

4.6. Initialization

The complete set of initialization and input values are given in Appendix A. This section provides a qualitative summary. Note that "initialization" in this section refers to values that must be specified prior to starting model runs, and "input" is data that is input throughout model runs as described in the following section.

At the beginning of a model run, there exists only a (empty) GIS environment, and an *RM* agent. The *RM* is created on start-up with annual budget set from initialization data. Immediately after startup, *Road Nodes* are created, followed by *Road Segments*, which connect *Road Nodes*. The initialization values (most importantly, location) for all *Road Nodes* and *Road Segments* are input (with an Excel spreadsheet) before the model has started. There is no randomness in the initialization; each run begins the same unless input data are changed. No *Vehicles* exist at the start of model runs; *Vehicles* are generated by *Road Nodes* after all of the *Road Nodes* and *Road Segments* have been created.

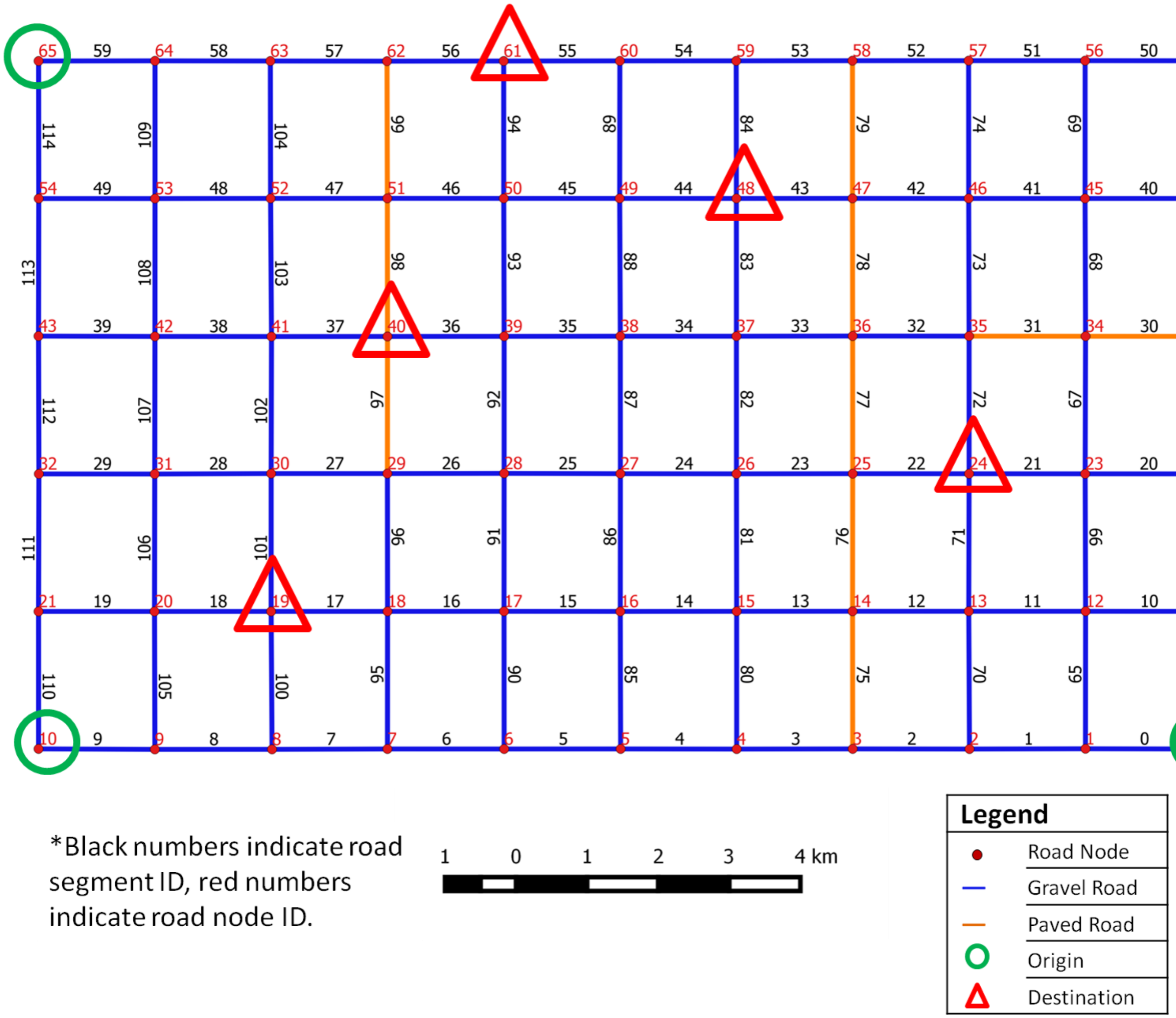
In the *Main Model*, the start and end dates for the model run must be entered prior to the model run. The default is a start date of January 1, 2013, and an end date of January 1, 2018 (giving a five year model run). The start and end date may be adjusted based on the scenario under consideration. However, some model outputs are calculated on an annual basis, so for the current version of the model, the time period should be at least one calendar year and the model should end on the same day of the year as the start date (i.e., model runs should use an integer number of years for proper reporting of results).

The *Road Nodes* and *Road Segments* are obviously dependent on the specific road network under consideration. The defaults in the model are for a hypothetical road network. For each *Road Node*: ID, y, and x location (GIS latitude/longitude) must be specified prior to the model run. For each *Road Segment*: ID, starting and ending node (the unique ID of the *Road Node* at each end of the *Road Segment*), road type, and speed limit must be specified prior to the model run.

The default road network and other default values are intentionally chosen to represent a typical RM in Saskatchewan. The hypothetical network was modeled after a RM road network where, typically, north-south roads are one mile apart, and west-east roads are two miles apart, as shown in Figure 4.7.

For the default hypothetical road network in Figure 4.7, there were a total of 66 *Road Nodes* and 115 *Road Segments*. The majority of *Road Segments* were gravel with select *Road Segments* being paved. In Figure 4.7, green circles indicate origins and red triangles indicate destination nodes used in the OD vehicle generation discussed in the next section (with some green circles also used as destinations).

For *Vehicles*, two types were considered: light passenger vehicles and 6-axle heavy vehicles. For each *Vehicle* type: configuration (for heavy vehicles), unit distance based costs for each road type, and unit time based costs of operating must be specified prior to the model run. The values used for these parameters are given at the end of this chapter in Table 4.6. *Vehicles* are generated by *Road Nodes* based on the OD tables outlined in the following section.



*Black numbers indicate road segment ID, red numbers indicate road node ID.

Figure 4.7 Hypothetical Road Network with Origins and Destinations.

4.7. Input data

The input data that is used throughout model runs is outlined in this section. The full summary of input data is given in Appendix A. "Input" data are different from "initialization" in that input data are used throughout the model run, not necessarily at model start-up.

For *Road Nodes*, during the course of a model run, the state variable, "Vehicles generated per day", is updated based on an input OD matrix (in Microsoft Excel). When *Road Nodes* generate *Vehicles*, the destination of *Vehicles* is set by looking up destination in the exogenous OD matrix. The values in the hypothetical OD matrix used were contrived in order to illustrate the results of considered policies. Four *Road Nodes* (one at each corner of the network) were set to each generate *Vehicles*. These four *Road Nodes* represent vehicle origins or destinations external to the considered network. The destinations for generated *Vehicles* were set to the five destination *Road Nodes* at various vehicle generation rates. In addition, two corner *Road Nodes* generated *Vehicles* having destinations of the opposite corner *Road Node* to represent *Vehicle*s originating and destined outside of the network.

Total *Vehicles* generated by *Road Node* is input as one table, and the breakdown of *Vehicle* type is input as a separate table. A summary of the OD matrix is given in Table 4.3, which gives the total *Vehicles* generated per day by each *Road Node* along with the breakdown of the destination of those *Vehicles*.

Table 4.3 Subset of Origin-Destination Matrix for Hypothetical Model.

Origin nodeID	Unit	Total Vehicles Generated	Destination nodeID						
			0	10	19	24	40	48	61
0	vpd	325	0	0	79	77	78	78	77
10	vpd	310	0	0	84	79	60	72	76
55	vpd	375	0	85	78	80	78	47	80
65	vpd	585	90	0	360	76	81	48	48

The *Road Nodes* used in Table 4.3 are highlighted in Figure 4.7 in the previous section. To input the traffic characteristics of light and heavy vehicles, a similar OD type matrix table is used with inputs for the percent of heavy vehicles for each OD pair as shown in Table 4.4.

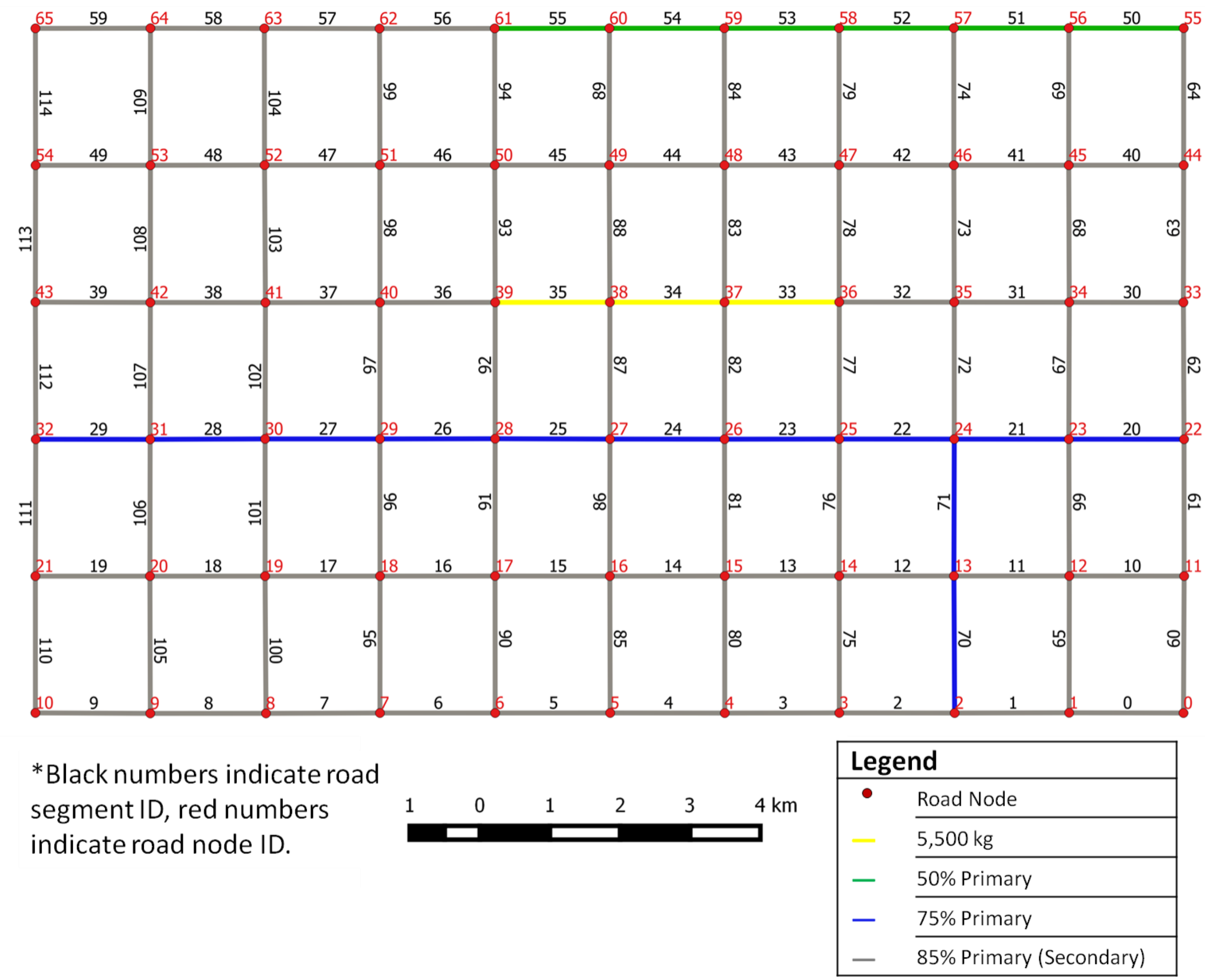
Table 4.4 Subset of Origin-Destination Matrix with Percentage of Heavy Vehicles for Hypothetical Model.

Origin nodeID	**Unit**	**Destination nodeID**						
		0	**10**	**19**	**24**	**40**	**48**	**61**
0	% truck traffic	0	0	33	33	33	33	33
10	% truck traffic	0	0	33	33	33	33	33
55	% truck traffic	0	33	33	33	33	33	33
65	% truck traffic	33	0	60	33	33	33	33

As shown in Table 4.4, it was assumed that most of the generated traffic in the hypothetical model was 33% trucks and 67% passenger vehicles with traffic generated from *Road Node* 65 to *Road Node* 19 having 60% truck traffic and 40% passenger traffic.

The *RM* sets weight restrictions on *Road Segments* (e.g., Primary weight, Secondary weight, etc.), which may vary by season as specified by inputs. For seasonal weight restrictions in the hypothetical default model, the entire network was set to Primary weights in the Winter, and Secondary weights in the Summer and Fall. In the Spring, most of the network is at Secondary weights (85% of Primary) with select segments set to 75% of Primary, 50% of Primary and 5,500 kg as shown in Figure 4.8.

The road weight restrictions shown in Figure 4.8 were selected for the hypothetical network to illustrate how weight restrictions would influence results; actual weight restrictions can be input based on the case study under consideration. The full table of input weight restrictions is given in Appendix A.



*Black numbers indicate road segment ID, red numbers indicate road node ID.

Figure 4.8 Spring Weight Restrictions for Hypothetical Road Network.

4.8. Submodels

The final section of this chapter covers the details for each process (or submodel) outlined in the agent state charts presented in Section 4.4. A list of submodels is presented first followed by details of each submodel and finally a table of parameters is presented. Several of the supporting equations in the submodels were developed and discussed in Chapter 3 allowing for more concise descriptions of processes within the submodels. For more details on the justification and sources for equations used in the submodels, refer to Chapter 3.

List of submodels:

- *Network Initialization*
- *Vehicle Update Costs*
- *Vehicle Least Cost Routing*
- *RM Update Costs*
- *RM Road Upgrade Decision*
- *RM Set Permit Fees*

Network Initialization

Immediately on model start-up, the road network agents are created. First, the *Road Nodes* are created based on Excel initialization (including latitude and longitude coordinates). Then the *Road Segments* are created based on Excel initialization (including starting and ending nodes, road type and speed limit). Each *Road Segment* that is created connects the starting and ending *Road Nodes*. Once this process is complete, the road network is considered fully developed and *Vehicles* may begin to be created within the road network.

Vehicle Update Costs

Refer to Section 3.3.1 for discussion and development of equations related to user costs.

Vehicles calculate their total user cost, $[UC_{Total}]_{<i,j>}$, for the *Road Segment* they just travelled over each time they arrive at a *Road Node*. *Vehicles* use Equation 3.4 to calculate their total user cost for each *Road Segment* travelled on throughout their route.

Note that *Vehicles* also use Equation 3.4 to support the least cost routing calculations, but during the least cost routing algorithm no costs are actually accumulated until the *Vehicle* has chosen its route and is actually travelling through the network.

Vehicle Least Cost Routing

Refer to Section 3.3.2 for discussion and development of supporting equations.

Before beginning a trip, *Vehicles* set their haul weight and their route to their destination. The objective for *Vehicles* is to minimize their costs for total haul of material (assuming multiple trips are required). To do this, *Vehicles* first consider the heaviest weight category and use Dijkstra's Algorithm to determine the least cost route to their destination. The algorithm uses the total user cost for travelling over a segment as the weighting of segments. Then *Vehicles* consider the next heaviest weight category and again calculate the least cost route, but now a cost factor is included to represent the additional trips required due to less payload hauled per trip. After considering each weight category, the *Vehicle* chooses the weight category that results in the lowest cost trip. Mathematically, this process is represented by Equation 4.1.[9]

$$Minimize\left([UC_{Total}]_{O-D,W} * UC_{WF,v} \right) \tag{4.1}$$

where:

$[UC_{Total}]_{O-D,W}$ = the total user costs for a given route beginning at origin, O and ending at destination, D, travelling at weight, W;

$UC_{WF,v}$ = the user cost weight factor for vehicle, v;

subject to:

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[9] The weight constraint of GVW to be less than the weight limit of the road segment was represented in the model by imposing an infinite cost to vehicles if their weight was above the weight limit of the road segment.

$GVW_v < WL_{<i,j>}$

where:

GVW_v = the gross vehicle weight of vehicle, v (tonne);

$WL_{<i,j>}$ = the weight limit imposed on road segment, <i,j> (tonne).

The ordered steps in this process were outlined in Figure 4.6.

RM Update Costs

The *RM* updates the incremental road provision costs each month based on the traffic levels of each *Road Segment*. Determining incremental costs for road provision per vehicle pass is quite difficult in practice. The unit values used in the model were based on two studies.

A study by (Zimmerman & Wolters, 2004) was used for default incremental road provision costs due to incremental traffic. The study was completed in South Dakota and produced a model that supports the road upgrade decision based primarily on traffic counts. The study produced linear relationships of LCC vs. ADT for various road types, similar to the approach outlined in Section 3.4.2. While the study did not report the incremental cost per vehicle pass, the linear relationship of LCC vs. ADT reported in the study was used to approximate the required inputs of incremental cost per vehicle pass on roads for passenger vehicles in the Summer. The study did not include a breakdown of costs by vehicle type nor by season.

A study was completed by (VEMAX Management, 2014) to investigate the incremental road damage of vehicles on gravel roads in Saskatchewan. The approach was to use statistical models based on the mechanics of load-road interactions for several case studies to consider any correlation of traffic with road provision activities and related costs. The findings of the study indicated that both light and heavy vehicles were significant indicators of road provision costs. The outputs from the study suggested weight-distance permit fees ($/tonne-km) for trucks that vary by season. Higher permit fees in the Spring (three times higher than in Summer) were due to roads being vulnerable while thawing and subject to significant damage by heavy vehicles.

Similarly in the Winter, the permit fees were lowest (half that of Summer) as when roads are frozen, they are least susceptible to road damage and related costs. These seasonal factors were applied to the incremental costs based on (Zimmerman & Wolters, 2004) described above to estimate the incremental cost per vehicle pass for each season. While the authors of the study point out several limitations such as the limited data set, and not including capital renewals of gravel roads (e.g., clay capping), the study was the most appropriate reference found in this area. And while the results may be fairly rough approximations, they provide sufficient default values in order to illustrate model functionality and feasibility.

In general, truck traffic has a more substantive impact on road damage and resulting costs to maintain the road. The relative impact of trucks on road costs is difficult to quantify, particularly for gravel roads. For default values, it was assumed that a truck pass has 20 times the impact of a passenger vehicle in terms of road provision costs, and an empty truck has 80% the impact of loaded trucks. The default values for the incremental cost of road provision per vehicle pass are given in Table 4.5.

Table 4.5 Default Incremental Costs due to Vehicle Pass.

Road Type	**Season**	**Unit**	**Vehicle Type**		
			Passenger	**Truck (loaded)**	**Truck (empty)**
Gravel					
	Summer	$/veh/km	0.015	0.300	0.240
	Fall	$/veh/km	0.015	0.300	0.240
	Winter	$/veh/km	0.015	0.150	0.120
	Spring	$/veh/km	0.015	0.900	0.720
Paved					
	Summer	$/veh/km	0.003	0.060	0.048
	Fall	$/veh/km	0.003	0.060	0.048
	Winter	$/veh/km	0.003	0.060	0.048
	Spring	$/veh/km	0.003	0.060	0.048

RM Road Upgrade Decision

The upgrade decision by the *RM* is initiated at the beginning of each year. If the ADT for a *Road Segment* in the past year was above a "trigger point", then the *RM* considers upgrading the *Road Segment*. *Road Segments* considered for upgrade are prioritized as follows: the *RM* creates an ordered list of all un-upgraded *Road Segments* that are above the trigger point based on ADT from the previous year (highest to lowest ADT), then the *RM* works down the list upgrading each *Road Segment* under the annual capital budget constraint. The costs for any upgrades completed are subtracted from the current year's budget and are tracked in cost tracking variables for the *RM*. The ordered steps in this process were outlined in Figure 4.3.

RM Set Permit Fees

The inclusion of permit fees must be specified by the modeler prior to beginning model runs. If permit fees are included, they are initiated at the beginning of the model run. Including permit fees simply adds the unit permit fee to each *Road Segment*, which is an additional cost to *Vehicles* travelling over the segment. The unit permit cost variable, $PC_{r_{<i,j>},v,l,s}$, in Equation 3.3 is set to the incremental cost per vehicle pass values outlined in Table 4.5, and so permit costs depend on the combination of road type, r, vehicle type, v, whether the vehicle is loaded, l, and season, s. Permit fee values for *Road Segments* are updated throughout model runs by the *RM* when there is a change in season or change in road type. Given the relatively small impact of passenger vehicles on RM costs, permit fees were assumed to be zero for passenger vehicles.

To this point, this section has outlined the various submodels included in the model, some of which have parameters that require input values. A summary of parameters and their default values for the hypothetical default road network is given in Table 4.6.

Table 4.6 Default Parameters for Hypothetical Model.

Agent	Parameter	Description	Default Value	Unit	Reference / Motivation
Main Model					
	startDate	Model run start date.	January 1, 2013	-	Hypothetical
	endDate	Model run end date.	January 1, 2018	-	Hypothetical
Road Node					
	nodeID	Unique identifier.	(Excel)	-	Unique ID
	y	Latitude.	(Excel)	-	Hypothetical
	x	Longitude.	(Excel)	-	Hypothetical
Road Segment					
	roadID	Unique identifier.	(Excel)	-	Unique ID
	node1†	Node at one end of road segment.	(Excel)	-	Hypothetical
	node2†	Node at opposite end of road segment from node1.	(Excel)	-	Hypothetical
	speedLimit	Speed limit of road.	(Excel)	km/hr	Hypothetical
Vehicle					
	vehID	Unique identifier.	(Excel)	-	Unique ID
	nodeOrigin	The node where the vehicle agent begins.	(Excel)	-	Hypothetical
	nodeDest	The node the vehicle agent wishes to drive to.	(Excel)	-	Hypothetical
	vehConfig	Vehicle configuration (Passenger, 5, 6, or 8-axle)	(Excel)	-	Hypothetical
	unitOC_DistType0Truck††	Unit operating costs for heavy truck driving on gravel road.	0.67	$/km	(Zimmerman & Wolters, 2004)
	unitOC_DistType1Truck††	Unit operating costs for heavy truck driving on paved road.	0.42	$/km	(Zimmerman & Wolters, 2004)
	unitOC_DistType0Pass††	Unit operating costs for passenger vehicle driving	0.20	$/km	(Zimmerman & Wolters, 2004)

		on gravel road.			
	unitOC_DistType1Pass[††]	Unit operating costs for passenger vehicle driving on paved road.	0.14	$/km	(Zimmerman & Wolters, 2004)
	unitOC_TimeTruck[†††]	Unit time-based costs for combination truck.	55.45	$/hr	(Apex Engineering Limited, 2012)
	unitOC_TimePass.[†††]	Unit time-based costs for passenger vehicle.	27.36	$/hr	(Apex Engineering Limited, 2012)
	vehCountRep[††††]	Number of vehicles the vehicle agent represents.	(Excel)	-	Hypothetical
RM					
	annualCapitalBudget	Annual Capital Upgrade Budget.	5,000,000	$	Hypothetical
	unitCostRoadUpgrade	Unit cost to upgrade road to paved.	620,000	$/km	Based on $1,000,000 / mile estimate (County of Grande Prairie No. 1, 2016)
	vpdTriggerToUpgrade	VPD value on road segment that triggers an upgrade.	500	vpd	Hypothetical
	permitFeeMult	A multiplier applied to the permit fee (for inclusion or exclusion of permit fees in run).	1	-	1: permit fee set to incremental cost per vehicle pass. 0: no permit fees
	incCostType0Pass	Incremental road provision costs per passenger vehicle pass on gravel road.	0.015	$/veh/km	Estimate based on (Zimmerman & Wolters, 2004)
	incCostType1Pass	Incremental road provision costs per passenger vehicle pass on paved road.	0.003	$/veh/km	Estimate based on (Zimmerman & Wolters, 2004)
	truckToPassMult	A multiplier applied to	20	-	Hypothetical

RM cost per passenger vehicle to translate to truck costs.

[†] The “start” or “end” of a *Road Segment* is arbitrary and does not affect model performance: *Vehicles* can travel both directions on all *Road Segments*.

[††] User costs are based on a flat road (zero grade) and a driving speed of 80 km/hr. Truck costs are based on 5 axle combination trucks.

[†††] Time costs are translated to 2015 dollars. The time costs for passenger vehicles was calculated using the unit hourly person rate multiplied by an average occupancy rate of 1.65 people/vehicle for Saskatchewan from (Natural Resources Canada, 2009). The unit time cost for trucks did not require consideration for occupancy rate as outlined in (Apex Engineering Limited, 2012) and are based on costs for combination trucks.

[††††] To reduce model run time, one *Vehicle* agent was created to represent multiple trips of the same vehicle type for each OD pair. This factor multiplies the *Vehicle* costs by the number of vehicles represented by the *Vehicle* agent (e.g., if there were 30 passenger vehicles originating and destined from node A to node B, then one *Vehicle* agent would be created and all outputs for that *Vehicle* would be multiplied by 30).

As alluded to earlier, any default values in Table 4.6 with an indication of "(Excel)" in the Default Value column are summarized in Appendix A.

CHAPTER 5 MODEL RUNS AND RESULTS

5.1. Introduction

This chapter describes the model runs and results for various scenarios considered using ABM with the hypothetical network inputs described in Chapter 4. The results of a sensitivity analysis are discussed.

5.2. Description of Scenarios

Various scenarios were considered in the model to investigate the results of different road provider policies. The main considerations differentiating the scenarios were permit fees and the road upgrade decision. The following scenarios were considered in the model:

S1: No permit fees, No road upgrades. (Base Case)
S2: With permit fees, No road upgrades.
S3: No permit fees, With road upgrades.
S4: With permit fees, With road upgrades.

To quantify the net benefit of scenarios, the scenario *S1: No permit fees, No road upgrades* was defined as the base case against which other scenarios were compared.

Each scenario was run over a five year model time frame. To quantify the full implications and potential benefits of scenarios involving road upgrade, a longer model run time would be desirable. The relatively short model run time of five years was chosen to expedite the modeling process (shorter model run times while developing and comparing scenarios).

A summary of the results of each scenario is presented in the next section.

5.3. Scenario Results

This section outlines the results of model runs for each scenario considered. Unless otherwise stated, results are presented in terms of cumulative values over full five year model runs. The main output cost results from model runs for each scenario are shown graphically in Figure 5.1. The outputs of the scenarios are summarized in more detail in Table 5.1, including an indication of the net benefit with respect to the *Base Case, S1*.

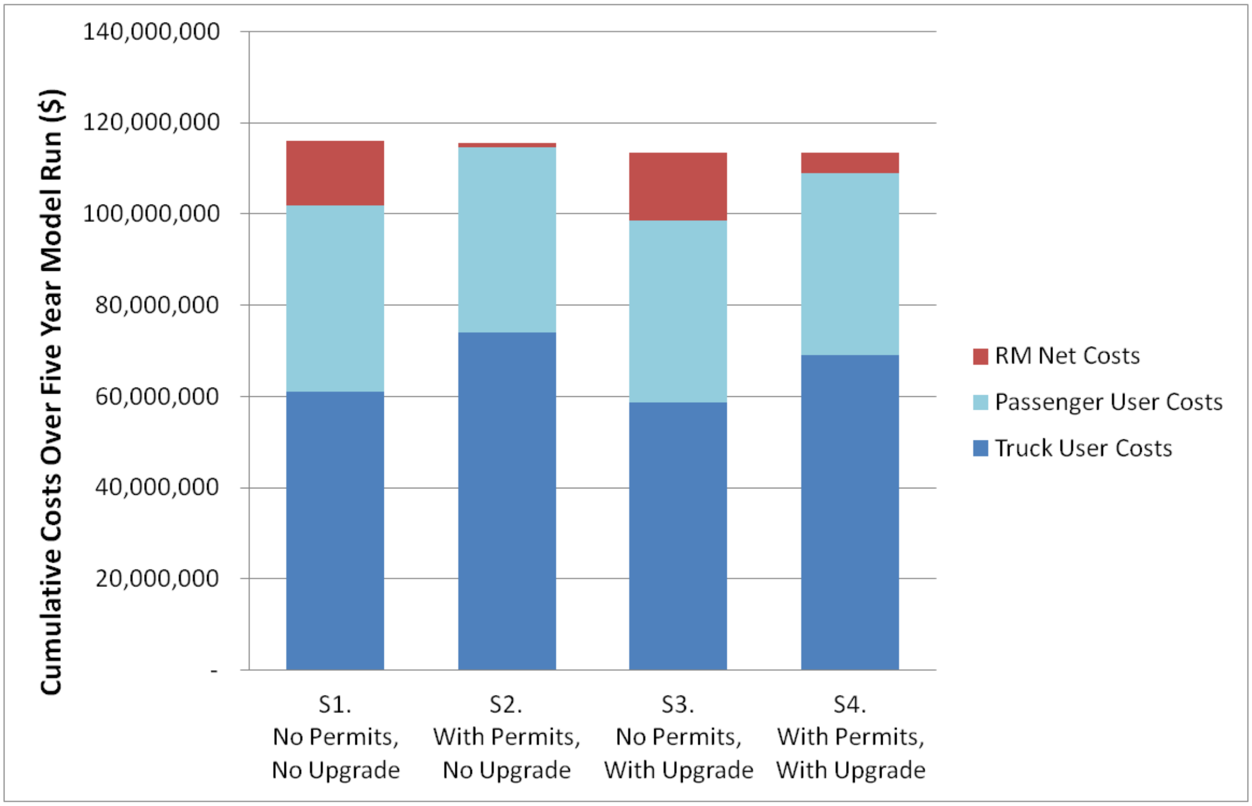

Figure 5.1 Scenario Results for Hypothetical Network.

Figure 5.1 illustrates how the inclusion of permit fees (*S2*, *S4*) shift the costs from the RM to road users. Recall that permit fees are based on the incremental road provision costs per vehicle pass, which are generally higher for gravel roads than paved roads. So the permit fees for users in the scenarios considered are higher for a gravel road segment than for a paved road segment of the same length, which gives further incentive to road users to travel on paved road segments.

Each scenario resulted in a net benefit (lower combined user and agency costs), albeit small in magnitude, compared to the base case.

In *S2*, the only change in inputs from the base case was the inclusion of permit fees. The permit fees, which were based on incremental road costs on different road types (for trucks only, not passenger vehicles), incentivized truck *Vehicles* to alter their routing to drive on paved road segments rather than gravel road segments when the re-routing did not increase the trip distance too drastically. The slight increase in both distance based costs and time based costs are due to the increased distance in routes chosen by trucks when permit fees were implemented. The combined (road user plus road provider) costs in *S2* were decreased meaning the magnitude of increased user costs was less than the magnitude of decreased *RM* costs. So while the road provider had lower costs and road users had higher costs in *S2*, there was a reduction in combined total costs, indicating *S2* would be preferable over the base case assuming there could be appropriate mechanisms for equitably distributing the benefits between the road provider and road users.

Table 5.1 Scenario Results for Hypothetical Network.

Model Output	**Unit**	**Scenario**			
		S1. No Permits, No Upgrades	**S2. With Permits, No Upgrades**	**S3. No Permits, With Upgrades**	**S4. With Permits, With Upgrades**
User Costs					
Distance Based Costs	$	42,249,231	42,200,428	39,039,721	38,951,392
Time Based Costs	$	59,469,085	59,917,593	59,468,941	60,559,017
Permit Based Costs	$	-	12,556,870	-	9,304,176
Total User Costs	$	101,718,316	114,674,890	98,508,661	108,814,586
Agency Costs					
RM Upgrade Costs		-	-	20,123,475	20,147,092
RM Upgrade Costs (Annualized)	$	-	-	3,864,190	3,870,172
RM Annualized Costs (Without Upgrade Costs)	$	14,330,048	13,395,585	11,060,645	9,977,133
RM Revenues (Permits)	$	-	12,556,870	-	9,304,176
RM Net Costs	$	14,330,048	838,715	14,924,834	4,543,130
Combined Costs					
User + Agency Costs	$	116,048,364	115,513,605	113,433,495	113,357,716
Net Benefit Relative to S1					
Total Cost Savings	$	-	534,760	2,614,869	2,690,649
Percent Reduction in Costs	%	-	0.46%	2.25%	2.32%

While the net benefit in *S2* was small relative to the total combined costs (0.46%), it was nonetheless a reduction in combined costs. The magnitude of cost reduction resulting from implementing permit fees is highly dependent on OD patterns and the properties of the existing road network. Permit fees will only change *Vehicle* routing if the layout of the network and OD patterns allow for alternative routes on paved road segments. And due to the low value of permit fees relative to user costs, permit fees only result in modest differences in route distance.

RM net costs are the lowest in *S2*, with permits covering the majority of incremental costs on gravel road segments. This suggests a potential conflict of incentives under this permit fee structure: if the RM was fully compensated for incremental road provision costs, it would not be in the RM's interest to complete costly road upgrades. An annual permit fee allocated toward road upgrade or something similar may be appropriate to align incentives for RM decision making with the goal of reducing combined user and agency costs.

In *S3*, the only change from the base case was the inclusion of an *Annual Capital Upgrade Budget* value for the *RM*, which allowed the *RM* to upgrade road segments at the end of each year. The *RM* chooses gravel road segments with high traffic levels to upgrade, which reduces both user costs and *RM* costs. The net benefit is larger in S3 than in *S2*, as anticipated: upgrading a *Road Segment* with high traffic levels (above a trigger point as discussed in Chapter 3) will reduce both agency and user costs assuming static OD patterns, while implementing permit fees does not necessarily impact routing behavior and associated costs. More details on the upgraded *Road Segments* and impact on routing is discussed later in this section.

The largest net benefit was found in *S4*, which included both permit fees as well as the capital budget for road upgrade, although the magnitude of the net benefit in relation to base case costs was small. The inclusion of capital upgrades provided the majority of the net benefit (similar to *S3*), and the inclusion of permit fees increased the incentive for *Vehicles* to travel on upgraded road segments (lower permit fees and lower user costs) if the upgraded road segments were near their existing routes. The inclusion of permit fees from the beginning of the model run caused *Vehicles* to change their routing and thereby changed the traffic counts on select *Road Segments*. This change in routing changes the *Road Segments* selected by the *RM* for upgrade, as will be discussed later with more detailed results from the model. Note that the magnitude of the net benefit would be increased with longer model runs as *Vehicles* would have more time to complete more trips on upgraded road segments.

It is interesting to note the impact of road upgrades on RM Net Costs. The RM Net Costs increase slightly in S3 relative to S1 (with no permits included in either scenario). This small increase in RM Net Costs is due to the upgrade decision being based on combined road provision and road user costs, so more road segments are upgraded than would have been if the RM was concerned with only minimizing their own road provision costs. The RM Net Costs increase significantly in S4 relative to S2 (with permits included in both scenarios). This more significant increase in RM Net Costs is primarily due to the lost revenues from permit fees: in S4, gravel road segments are upgraded to paved road segments, which have lower permit fees. While S4 results in the largest net benefit when considering combined costs, the increase in RM Net Costs is of note because it suggests a disincentive to the RM to upgrade road segments under the permitting structure considered.

While the total cost summaries outlined above give insights into the results of the scenarios considered in the model, more detailed results were produced to better understand the features of the model runs. Additional details for *Vehicles* in the model runs are outlined in Table 5.2.

As seen in Table 5.2, the distance traveled by trucks when permit fees were included (in *S2*) was greater than that of the base case. This is because trucks were choosing longer routes to benefit from the lower permit fee costs on paved road segments. In *S4*, the distance travelled by trucks increased even higher as more paved road segments were established in the network and permit fees encouraged *Vehicles* to alter their routes to travel on paved road segments. When permit fees were included in scenarios, user costs for trucks (in addition to the actual permit fee) were increased due to higher distances travelled (increased distance and time based costs). The same reasoning for the changes in distance travelled can explain the variation in weight-distance across scenarios. When permit fees were included, the cost per unit distance and cost per unit weight-distance were highest for *Vehicles*.

Table 5.2 Scenario Outputs for Vehicle Agents for Hypothetical Network.

Model Output	Unit	Scenario			
		S1. No Permits, No Upgrades	**S2. With Permits, No Upgrades**	**S3. No Permits, With Upgrades**	**S4. With Permits, With Upgrades**
Passenger Vehicles					
Number of Vehicles Represented in Model[†]	#	2,158,143	2,158,143	2,158,143	2,158,143
Total User Costs	$	40,675,658	40,675,658	39,955,638	39,847,539
Total Distance Travelled	km	78,120,092	78,120,092	78,120,001	78,121,526
Average Unit User Cost (including time costs)	$/km	0.521	0.521	0.511	0.510
Trucks					
Number of Vehicles Represented in Model	#	1,331,062	1,331,062	1,331,062	1,331,062
Total User Costs	$	61,042,658	73,999,232	58,553,024	68,967,047
Total Distance Travelled	km	47,252,680	47,899,760	47,252,516	48,824,462
Average Unit User Cost (including time costs)	$/km	1.292	1.545	1.239	1.410
Total Payload Hauled	tonne	33,421,682	33,421,682	33,421,682	33,421,682
Total Weight-Distance	tonne-km	594,416,795	602,008,041	594,413,385	612,514,100
Average Cost per Weight-Distance	$/tonne-km	0.103	0.123	0.099	0.110

[†] Each *Vehicle* created completed a round trip. So the total one-way trips would be double the number of *Vehicles* created.

More detailed outputs for the *RM* and the road network are given in Table 5.3. Note that the total combined length of all road segments in the hypothetical network was 275.9 km.

Table 5.3 Scenario Outputs for RM and Road Network for Hypothetical Network.

Model Output	Unit	Scenario			
		S1. No Permits, No Upgrades	S2. With Permits, No Upgrades	S3. No Permits, With Upgrades	S4. With Permits, With Upgrades
Number of Road Segments Upgraded	#	-	-	16	18
Length of Road Segments Upgraded	km	-	-	32.5	32.5
Percent of Network Upgraded by Length	%	-	-	11.77%	11.78%
Average EUAC per Length of Road in Network (without permit fee revenue)	$/km/year	10,389	9,712	10,821	10,039
Percent of Total Distance Driven on Paved Road Segments	%	32.89%	34.25%	50.40%	54.46%

Table 5.3 shows the total distance driven by *Vehicles* on paved road segments increased from 32.89% in *S1* to 50.40% in *S3* indicating that *Road Segments* selected for upgrade were along existing OD routes and may have drawn additional traffic using nearby routes. In *S4*, the inclusion of permit fees reinforced the incentive for *Vehicles* to use paved road segments and the total distance travelled on paved road segments increased slightly higher than *S3*.

The average EUAC per unit road length for the *RM* (without including permit fee revenues) was lowest in *S2* when not considering road upgrade. This reflects the RM including road user costs in road upgrade decision making: if the RM were only considering road provision costs, fewer road segments would be upgraded in *S4*, which would likely result in the lowest EUAC per unit road length for the *RM*.

The results produced for the hypothetical network illustrate the impact that permit fees can have on the *RM* road upgrade decision. The *Road Segments* upgraded in the *S3* and *S4* scenarios are summarized in Table 5.4.

Table 5.4 Road Segments Upgraded during Model Run for Hypothetical Network.

Year	Unit	Scenario	
		S3. **No Permits,** **With Upgrades**	**S4.** **With Permits,** **With Upgrades**
1	Road Segment ID	0,2,58,59	0,2,58,59
2	Road Segment ID	1, 52, 104	1, 51, 52, 57
3	Road Segment ID	102,103	27, 50, 101
4	Road Segment ID	50,51,101	43, 53, 54, 55
5	Road Segment ID	37,43,54,55	19,56,110

As seen in Table 5.4, the first year of upgrades are the same in *S3* and *S4*, then differences occur in the order of *Road Segments* selected for upgrading (i.e., upgrades for certain segments occur in different years). In addition to altered ordering of road upgrade, there were differences in *Road Segments* selected for upgrade in *S3* compared to *S4*. The following segments were upgraded in *S3* and not upgraded in *S4*: *Road Segments* 37, 102, 103, and 104. And the following segments were upgraded in S4 and not upgraded in *S3*: *Road Segments* 19, 27, 53, 56, 57, and 110. The difference in road upgrade selection is due to the influence of permit fees on *Vehicle* routing. To illustrate this change in routing, Figure 5.2 shows routing alternatives with and without permit fees for a truck originating at *Road Node* 65 with destination of *Road Node* 19.

As shown in Figure 5.2, without permit fees, the least cost path for the truck was the shortest distance path, which turned out to be all gravel *Road Segments* and the truck followed the *Road Node* path: [65,64,63,52,41,30,19] (green line in Figure 5.2). When permit fees were included, the least cost path for the truck changed to a longer route that included paved road segments and the truck followed the *Road Node* path: [65,64,63,62,51,40,29,30,19] (red line in Figure 5.2). The route used in the S4 scenario alleviates traffic on *Road Segments* 102, 103, and 104 and increases traffic on *Road Segments* 27, and 57 enough for the *RM* to prioritize *Road Segments* 27, and 57 for upgrade. As discussed earlier in this section, while the permit fees of *S4* increase the user costs, the cost savings to the *RM* under the routing encouraged by permit fees is large enough to result in a net benefit when considering total combined road user and road provider costs.

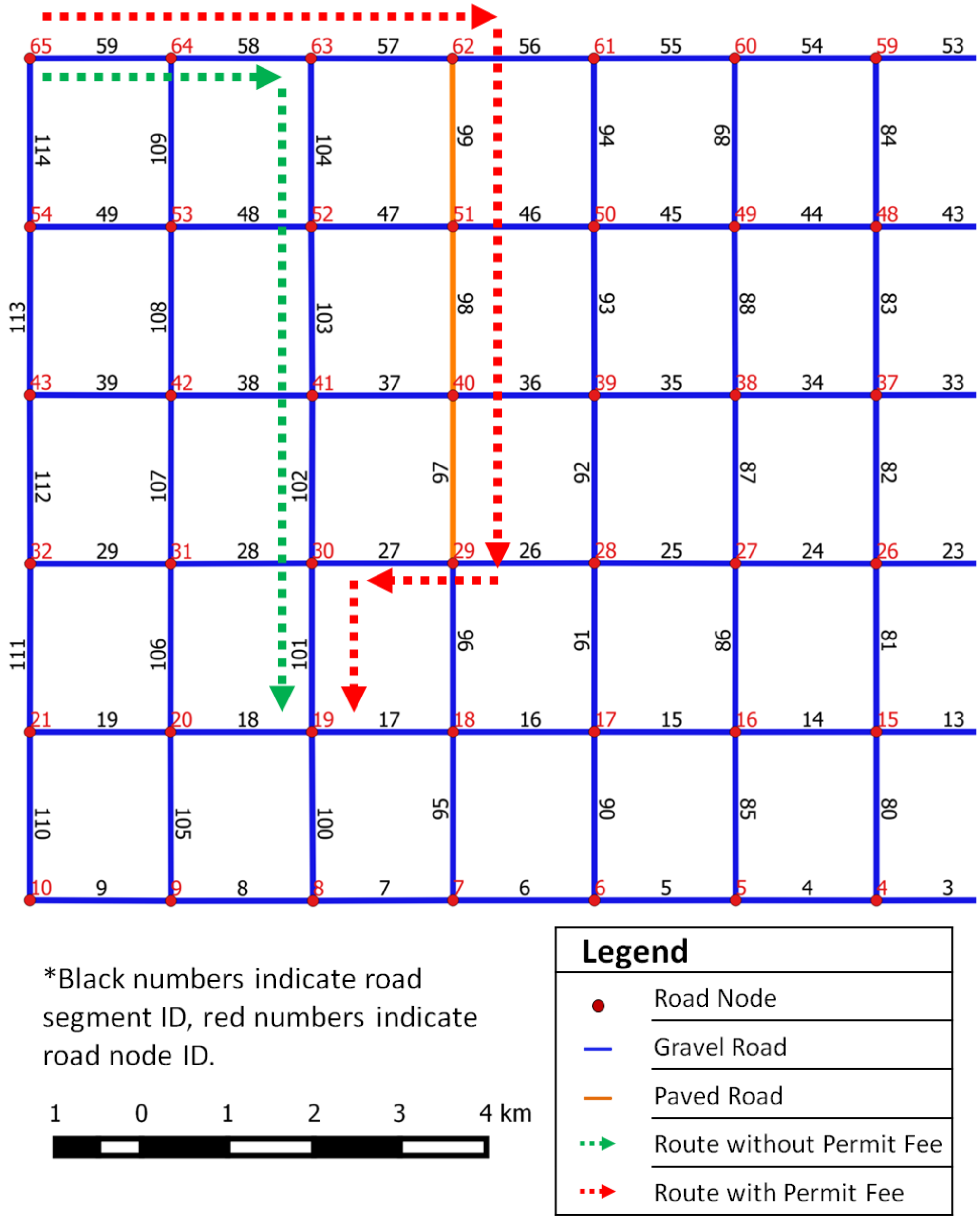

Figure 5.2 Sample Routing With and Without Permit Fees for Hypothetical Network.

While running various OD traffic patterns on different network configurations, there were several combinations of road network and OD traffic inputs where the inclusion of permit fees did not affect *Vehicle* routing and therefore provided no net benefit. Although results of the unaffected routing scenarios are not presented here, it is nonetheless noted to emphasize the importance of the combination of initialization values for road network and OD traffic loading: a set of OD traffic matrices may result in net benefits under permitting for one given road network configuration, and may have no change in routing on another network since route choice is dependent on the proximity of alternative routes. Since the magnitude of permit fees was based on incremental cost to the *RM*, and *RM* costs were generally low compared to the magnitude of user costs on a network (as seen in Figure 5.1, for example), permit fees had a limited influence on route choice.

5.4. Sensitivity Analysis

There were three additional scenarios considered in more detail where the following parameters were varied: the *VPD Trigger for Upgrade*, and the *Annual Capital Upgrade Budget*, and shifting OD patterns. All scenarios were completed with permit fees included.

5.4.1. Variation of VPD Trigger for Upgrade

Model runs were completed for *VPD Trigger for Upgrade* values ranging from 0 to 900 vpd in 50 vpd increments, using nominal values for all other variables except for *Annual Capital Upgrade Budget*, which was set to a sufficiently large number such that there were no budget constraints in any model run. This scenario was considered to understand the impacts of road upgrade selection without budget constraints. The combined cost results for all model runs are shown in Figure 5.3.

As seen in Figure 5.3, total combined costs for the five year model runs are highest (over 145 million dollars) when the *VPD Trigger for Upgrade* value is zero, which leads to all gravel road segments being upgraded. As the *VPD Trigger for Upgrade* value increases, the total combined costs are reduced. The total combined costs are high when the *VPD Trigger for Upgrade* value is low because upgrading gravel road segments has a large fixed cost and without sufficient traffic on the *Road Segment* there is insufficient user cost savings to justify the road upgrade cost. As the *VPD Trigger for Upgrade* increases, fewer road segments are upgraded and only road segments with higher traffic counts are upgraded. This results in lower total combined costs as higher traffic levels have reduced user costs on paved road segments to offset the high fixed costs of road upgrade.

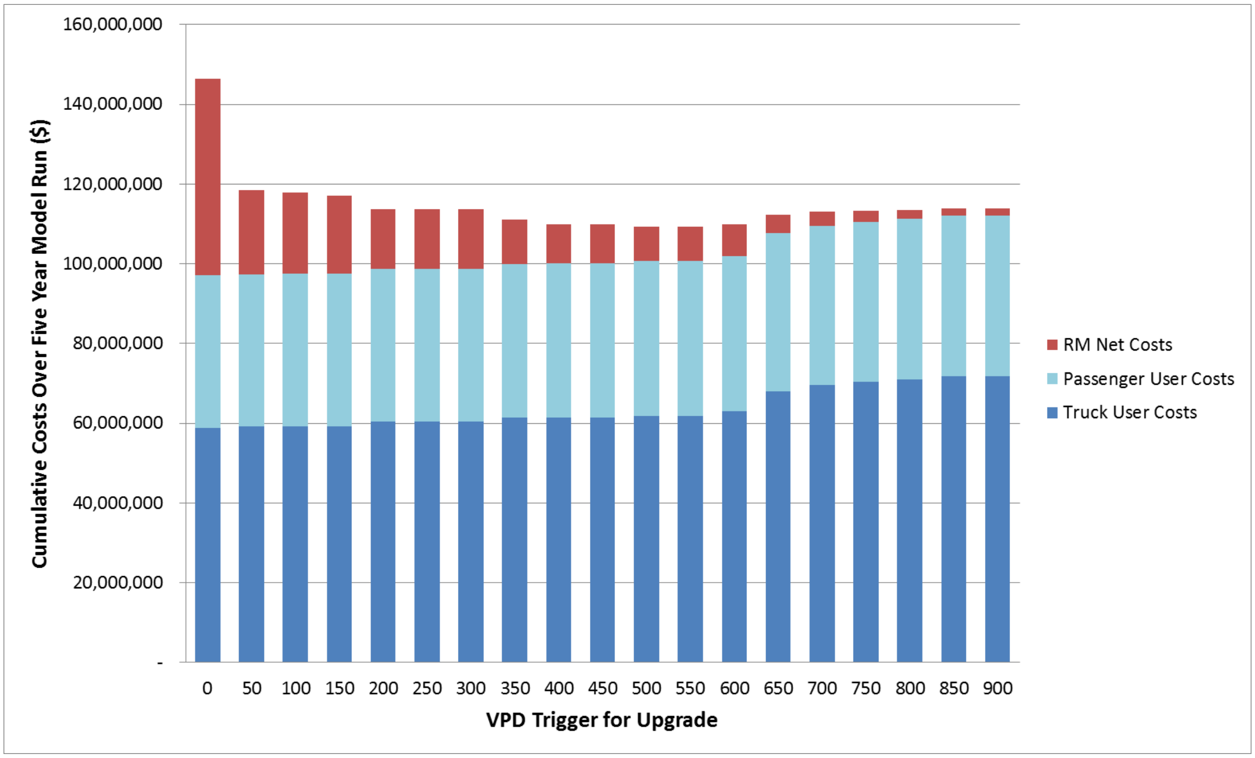

Figure 5.3 Costs under Variation in VPD Trigger for Upgrade for Hypothetical Network.

The lowest total combined costs occur with a *VPD Trigger for Upgrade* value of approximately 500 vpd. As the *VPD Trigger for Upgrade* increases past 500 vpd, the total combined costs increase because fewer road segments are upgraded: high *VPD Trigger for Upgrade* values lead to gravel road segments having very high traffic levels, which are costly for the *RM* to maintain and road upgrade would be suitable to reduce costs.

Intuitively, as *VPD Trigger for Upgrade* increases and fewer road segments are upgraded, user costs increase because users are travelling on non-upgraded gravel road segments, which have higher user costs. The *RM* costs under varying VPD Trigger for Upgrade values are what causes the net costs to have a minimum at a certain VPD Trigger for Upgrade value.[1]

The costs in Figure 5.3 include revenues from permit fees paid from *Vehicles* to the *RM*. The *RM* costs including permit fee revenues decrease with increasing *VPD Trigger for Upgrade*. When the *VPD Trigger for Upgrade* value is low, there are the highest number of *Road*

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[1] The *VPD Trigger for Upgrade* values resulting in minimum combined costs were not necessarily the optimal values. The references to "minimum" in this respect mean the minimum combined costs resulting from the values considered for the *VPD Trigger for Upgrade* value, which were limited.

Segments upgraded, which is costly for the *RM*. As the *VPD Trigger for Upgrade* value increases, fewer road segments are upgraded, reducing the *RM* fixed costs. With fewer upgrades, there is more distance driven by *Vehicles* on gravel road segments, which have higher permit fees than paved road segments, and so *RM* costs are reduced through permit fee revenues.

The permit fee structure used in this research was meant to serve as a mechanism for aligning incentives between road user and road provider to gain insights into system efficiency, rather than simply a cost recovery mechanism for the RM. So it is helpful to consider how the "true" *RM* costs (without permit fee revenues) are affected by varying the *VPD Trigger for Upgrade* value, shown in Figure 5.4.

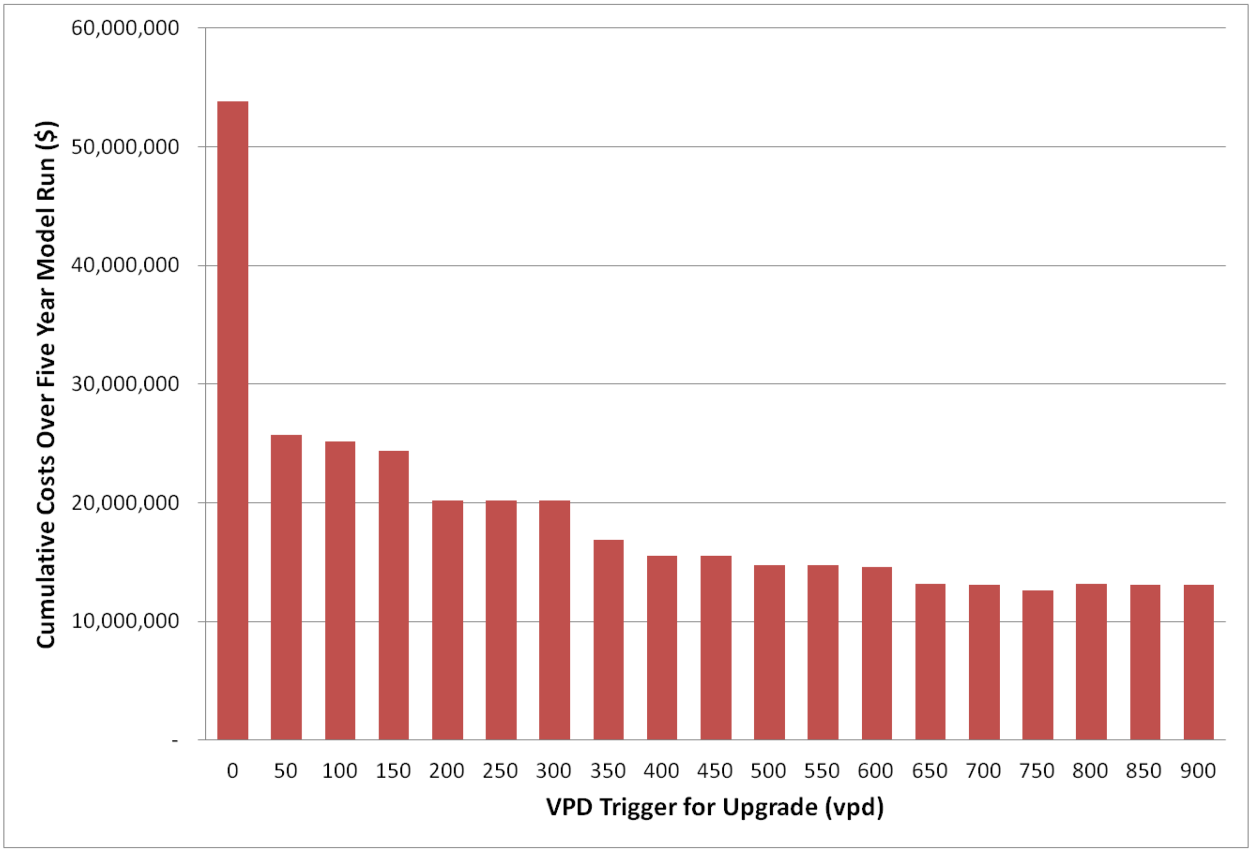

Figure 5.4 RM Costs Without Permit Revenue under Variation in VPD Trigger for Upgrade for Hypothetical Network.

As shown in Figure 5.4, the true *RM* costs (actual cost for road provision without permit fee revenues) follows roughly the same pattern as total combined costs under variation of the *VPD Trigger for Upgrade* value. Even as the *VPD Trigger for Upgrade* increases past 500 vpd, the value found to minimize total combined costs (as shown in n in Figure 5.3), *RM* costs continue to decrease as fewer road segments are upgraded. Figure 5.4 suggests that when considering only *RM* costs, the *VPD Trigger for Upgrade* value to minimize costs is higher than when considering combined costs: in this case, it occurs at approximately 750 vpd.

As discussed in Chapter 3, in practice, the road upgrade decision for a road provider would include considerations in addition to the traffic volume such as: traffic composition (number of trucks using the road), various geometric design considerations, dust reduction, public opinion etc. The *VPD Trigger for Upgrade* value was used as the sole indication of whether to upgrade the road for simplicity in modeling the road upgrade decision for this research. While there are several other factors to be included in the road upgrade decision, this type of modeling may be helpful to road providers in determining minimum traffic levels where road upgrade should be considered to minimize LCCs.

The *VPD Trigger for Upgrade* value to minimize the total combined costs of a single gravel road segment is not necessarily the same as the *VPD Trigger for Upgrade* value to minimize costs for a road network under given traffic levels. The reason for this difference when considering a single segment and a network is due to upgraded road segments affecting vehicle routing. When a road is upgraded, it may create a lower cost route for a given road users' OD trip. If the upgrade causes multiple road users to change their route, then traffic levels on other road segments in the network would be affected.

As a simple example to illustrate the potential impacts of road upgrade on traffic patterns, consider two parallel gravel road segments in a network, one with high traffic and the other with moderate traffic levels. With a low *VPD Trigger for Upgrade* value, perhaps both road segments would be upgraded meaning the fixed cost of upgrade is incurred for both road segments and vehicle routing would be unaffected. With a higher *VPD Trigger for Upgrade* value, perhaps only the road with high traffic levels would be upgraded. Once one road segment is upgraded, it may draw all traffic from the non-upgraded road segment, if the rerouting distance was small.

Using the higher *VPD Trigger for Upgrade* value would result in lower road provision costs as only one road upgrade cost was experienced and the traffic was drawn off the gravel road and onto the upgraded road. Assuming that the incremental user costs due to rerouting to the newly upgraded road were small, then in this simple example the higher *VPD Trigger for Upgrade* value would result in lower combined costs. This change in *VPD Trigger for Upgrade* value for the network is explored further in Section 5.4.3, which considers shifting OD patterns.

5.4.2. Variation of Annual Capital Upgrade Budget

Model runs were completed for the *Annual Capital Upgrade Budget* value ranging from 0 to 20 million dollars in 1 million dollar increments, using nominal values for all other variables. The combined cost results for all model runs are shown in Figure 5.5.

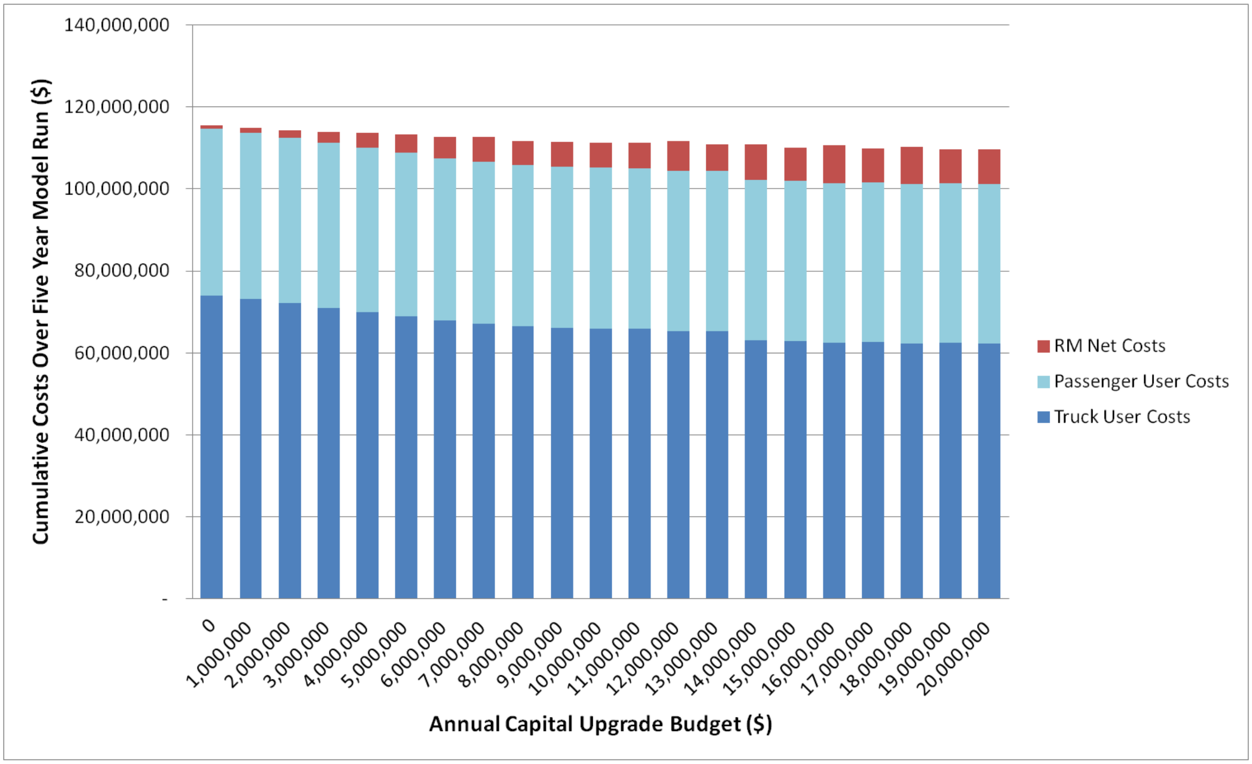

Figure 5.5 Costs for Variation of Annual Capital Upgrade Budget for Hypothetical Network.

As seen in Figure 5.5, generally, as *Annual Capital Upgrade Budget* is increased, combined costs are decreased. Road user costs are decreased, as alleviating budget constraints allows for more road upgrades to be completed sooner in the model run, and with more paved road segments it would be expected that user costs would be reduced if those paved road segments are along or near existing OD routes.

As the *Annual Capital Upgrade Budget* value increases, *RM* net costs are increased, as more upgrades are done, which increase capital costs, and there is less traffic on gravel road segments, which decrease permit fee revenues.

Recall that the permit fee structure used in the model is based on the incremental cost of road provision per vehicle pass. Since the incremental costs per vehicle pass is lower on paved road segments than on gravel road segments, as more road segments are upgraded, and higher distances are driven by *Vehicles* on paved road segments, the amount of permit fees paid by road users decreases. This decrease in permit fee revenues to the *RM* could be viewed as a disincentive to the *RM* to upgrade road segments, as they lose permit fee revenues with less gravel road segments. It is not necessarily suggested that the *RM* should be compensated for all incremental traffic costs; the permit fees used in this research were designed to help determine road use and road management strategies that combined may result in lower combined costs. It is assumed that if such a scenario could be found for a network, the benefits could be equitably distributed to road users and road providers.

A two-way sensitivity analysis was completed to investigate the resulting costs under various combinations of the *VPD Trigger for Upgrade* and *Annual Capital Upgrade Budget* values. The *VPD Trigger for Upgrade* was varied from 0 to 900 vpd in 50 vpd increments and the *Annual Capital Upgrade* Budget was varied from 0 to 20 million dollars in 2 million dollar increments. The results of model runs are shown in Figure 5.6.

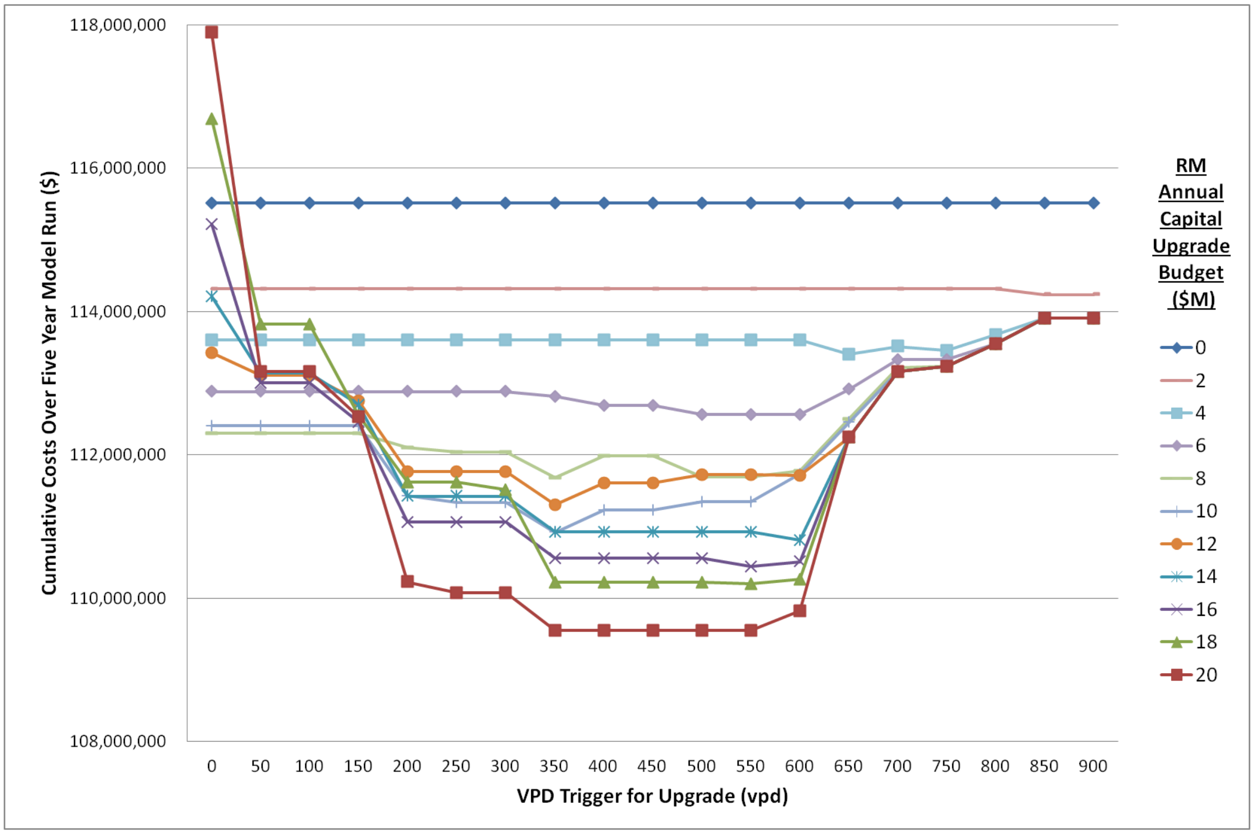

Figure 5.6 Costs for Two-way Sensitivity Analysis for Hypothetical Network.

Figure 5.6 shows how the total combined costs for model runs varies with the *VPD Trigger for Upgrade* value under various *Annual Capital Upgrade Budget* values. When the *Annual Capital Upgrade Budget* is zero, costs are not affected by the *VPD Trigger for Upgrade* value since no upgrades are completed. As the *Annual Capital Upgrade Budget* value increases, resulting combined costs become more sensitive to the *VPD Trigger for Upgrade* value. Lower budget levels are not sensitive to *VPD Trigger for Upgrade* values because budget constraints restrict the number of road segments that can be upgraded over the model run such that the majority of road segments chosen for upgrade have traffic levels above the range in *VPD Trigger for Upgrade* values. When the *VPD Trigger for Upgrade* value is low, higher *Annual Capital Upgrade Budget* values result in higher combined costs of model runs because many road segments are upgraded even when they have low traffic volumes and it is not cost effective to upgrade. In general, each *Annual Capital Upgrade Budget* value has one or more *VPD Trigger* *for Upgrade* values resulting in minimum combined costs: for most *Annual Capital Upgrade Budget* values, that range is between 350 and 650 vpd.[2]

Generally, as seen in Figure 5.6, higher *Annual Capital Upgrade Budget* values result in lower combined costs, with the 20 million dollar budget resulting in the lowest combined costs within the 350 to 650 *VPD Trigger for Upgrade* range. An interesting exception to higher budget levels resulting in lower costs is the *Annual Capital Upgrade Budget* value of 10 million dollars which resulted in lower combined costs than an *Annual Capital Upgrade Budget* value of 12 million dollars over most *VPD Trigger for Upgrade* values. While the magnitude of the resulting cost difference is relatively small, it is interesting to note this counterintuitive result where the constrained budget level of 10 million dollars limits road upgrades in each year. Upgrades in early years draw traffic from other road segments such that in subsequent years the traffic levels on the other road segments is lowered so as to not require an upgrade. The combination of traffic and existing road types turned out to have the 10 million dollar budget result in a more efficient upgrade strategy: fewer road segments were upgraded and combined costs were lowered than that found using a 12 million dollar budget. This type of analysis may be helpful for road providers in making road upgrade decisions under constrained budget levels or setting optimal budget levels.

5.4.3. Variation of Origin-Destination Patterns

Shifting traffic patterns can create challenges for road providers in choosing road segments for upgrades and the timing of those upgrades. In the oil and gas industry, for example, there may be variability in the location and number of oil wells and batteries established, which affects the locations for origins and destinations of vehicles. Other types of industrial or agricultural developments within RMs can also result in variability in traffic levels or traffic patterns.

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[2] The range in *VPD Trigger for Upgrade* values resulting in minimized costs, rather than a single value, was due to the limited traffic patterns imposed on the network. In these instances, there were not gravel roads with different traffic volumes within the range and so the change in *VPD Trigger for Upgrade* values did not impact the road upgrade decision. With more intricate traffic patterns, the traffic levels on road segments would be expected to be more variable and the range in *VPD Trigger for Upgrade* values resulting in minimum costs would be narrowed.

A scenario was considered to model the impacts of shifting origins for *Vehicles* heading to the same five static destinations considered in this chapter. To illustrate the impact of shifting origins, the origins used in generating traffic levels for the default inputs were switched to the opposite corner of the network beginning at the end of the second year of model runs. The origins and destinations used in this scenario when traffic patterns are switched in year two are given in Table 5.5.

Table 5.5 Origin-Destination Matrix for Shifting Traffic Scenario for Hypothetical Network.

Origin nodeID	Unit	Total Vehicles Generated	Destination nodeID						
			0	10	19	24	40	48	61
0	vpd	325	0	90	360	76	81	48	48
10	vpd	310	85	0	78	80	78	47	80
55	vpd	375	0	0	84	79	60	72	76
65	vpd	585	0	0	79	77	78	78	77

Model runs were completed for *VPD Trigger for Upgrade* values ranging from 0 to 900 vpd, using nominal values for all other variables except for the *Annual Capital Upgrade Budget* which was set to a sufficiently large number such that there were no budget constraints in any model run. This scenario was considered to understand the impacts of road upgrade selection without budget constraints under shifting traffic patterns. The combined cost results for all model runs are shown in Figure 5.7.

As seen in Figure 5.7, a similar pattern to that shown for static traffic patterns (illustrated in Figure 5.3) is found as the *VPD Trigger for Upgrade* value increases, with 500 vpd being a good value for minimizing total costs. The difference in this scenario is that as the *VPD Trigger for Upgrade* value increases past 500 vpd, the total costs are less sensitive to the *VPD Trigger for Upgrade* value and actually reach a minimum at 750 vpd (although the difference in costs are small). Select outputs for model runs under static traffic and shifting traffic are shown in Table 5.6, where both scenarios include permit fees and upgrades with annual budgets of five million dollars. The *VPD Trigger for Upgrade* for the static traffic and shifting traffic scenarios were 500 vpd and 750 vpd, respectively.

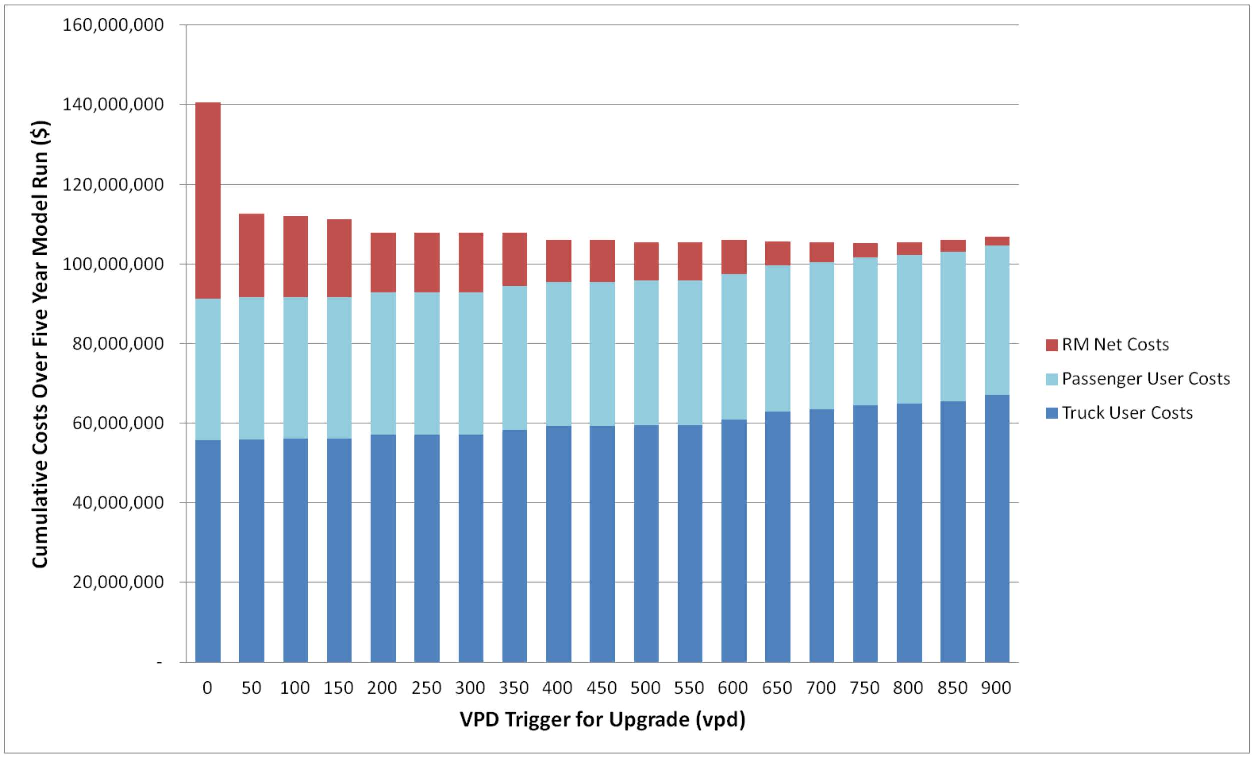


Figure 5.7 Costs under Variation in VPD Trigger for Upgrade for Shifting Origins for Hypothetical Network.

Table 5.6 Scenario Results for Shifting Traffic Patterns for Hypothetical Network.

Model Output	**Unit**	**Scenario** **S4.** **Static Traffic**	 **S4.** **Shifting Traffic**
Costs			
Total Vehicle Costs	$	108,814,586	102,266,792
RM Net Costs	$	4,543,130	3,385,403
Vehicle + RM Costs	$	113,357,716	105,652,196
Road Upgrade Summary			
Number of Road Segments Upgraded	#	18	11
Length of Road Segments Upgraded	km	32.5	17.9
Road Upgrade by Year			
Year 1	Road Segment ID	0,2,58,59	0,2,58,59
Year 2	Road Segment ID	1,51,52,57	1,57
Year 3	Road Segment ID	27,50,101	14,15,16,17
Year 4	Road Segment ID	43,53,54,55	13
Year 5	Road Segment ID	19,56,110	-

As shown in Table 5.6, the combined costs under shifting traffic is lower than that of the static traffic scenario. This is partially due to a decrease in the total distance driven (different traffic levels from different origins means a change in total distance driven by *Vehicles* to reach destinations) and partially due to the change in road segments selected for upgrade. Under shifting traffic, fewer road segments are upgraded (17.9 km) than under static traffic (32.5 km) due to the higher *VPD Trigger for Upgrade* value used under shifting traffic. Of the fewer road segments upgraded under shifting origins, there is some overlap in the *Road Segments* selected for upgrade compared to the static traffic scenario: generally, those are road segments with traffic levels well above the *VPD Trigger for Upgrade* value used in each scenario. After the traffic shifts at the end of year two, the road segments selected for upgrade are all road segments that were not selected for upgrade under static traffic.

These results suggest that if traffic levels are variable and uncertain, given that total costs have low sensitivity to the *VPD Trigger for Upgrade* value once it is high enough to be suitable for current traffic levels, it may be prudent to upgrade fewer road segments. Perhaps delaying road upgrades until traffic patterns were more constant (or at least predictable) would be more cost efficient as road providers could instead use the funds to accommodate operating and maintenance activities on a higher number of gravel road segments depending on the (variable) traffic levels each year. With uncertain traffic projections, the model could be used to run a variety of traffic patterns to explore whether there were common *Road Segments* to upgrade that would be beneficial under a range of traffic patterns. And if specific changes in traffic patterns were forecast, it would be possible to model the projected traffic shifts in the model to better understand the potential routes chosen by road users and the corresponding budget and road upgrade selection that would reduce combined costs going forward.

5.5. Chapter Summary

This chapter presented the key outputs of model runs for the various scenarios considered. The main results showed that the scenarios that include permit fees, based on incremental road provision costs due to vehicles, as well as road upgrade resulted in the largest net benefit (in terms of combined road user and road provision costs) compared to model runs without permit fees or road upgrade. The magnitude of net benefit in all scenarios was found to be small relative to the costs in the base case. The results are dependent on the various road network properties such as the number and location of existing paved road segments relative to gravel road segments, as well as the traffic levels imposed onto the network.

Additional scenarios were considered that further investigated the traffic levels at which the RM would consider a road for upgrade, the impact of annual budget constraints, which limit the number of upgrades the RM could complete each year, and shifting traffic patterns. Results showed: that the *VPD Trigger for Upgrade* value was lower for minimizing combined road use and road provision costs than the value that minimized only road provision costs; that a higher annual capital budget generally resulted in lower combined costs, with some exceptions where a lower budget that limited road upgrades and shifted traffic such that fewer road segments required upgrade and combined costs were lower; and that under shifting traffic patterns, a higher *VPD Trigger for Upgrade* value resulting in lower combined costs than the value found under static traffic patterns, suggesting under shifting traffic patterns it may be more advantageous to upgrade fewer road segments. These general findings are dependent on road network properties and traffic characteristics.

It is anticipated that the model could be helpful in supporting decision making for road providers. If specific changes in traffic patterns were forecasted (associated with a new industry development, for example), it would be possible to model the projected traffic shifts in the model to better understand the potential routes chosen by road users and the corresponding budget and road upgrade selection that would reduce combined user and provider costs going forward.

CHAPTER 6 CASE STUDY: RM OF WILTON

6.1. Introduction

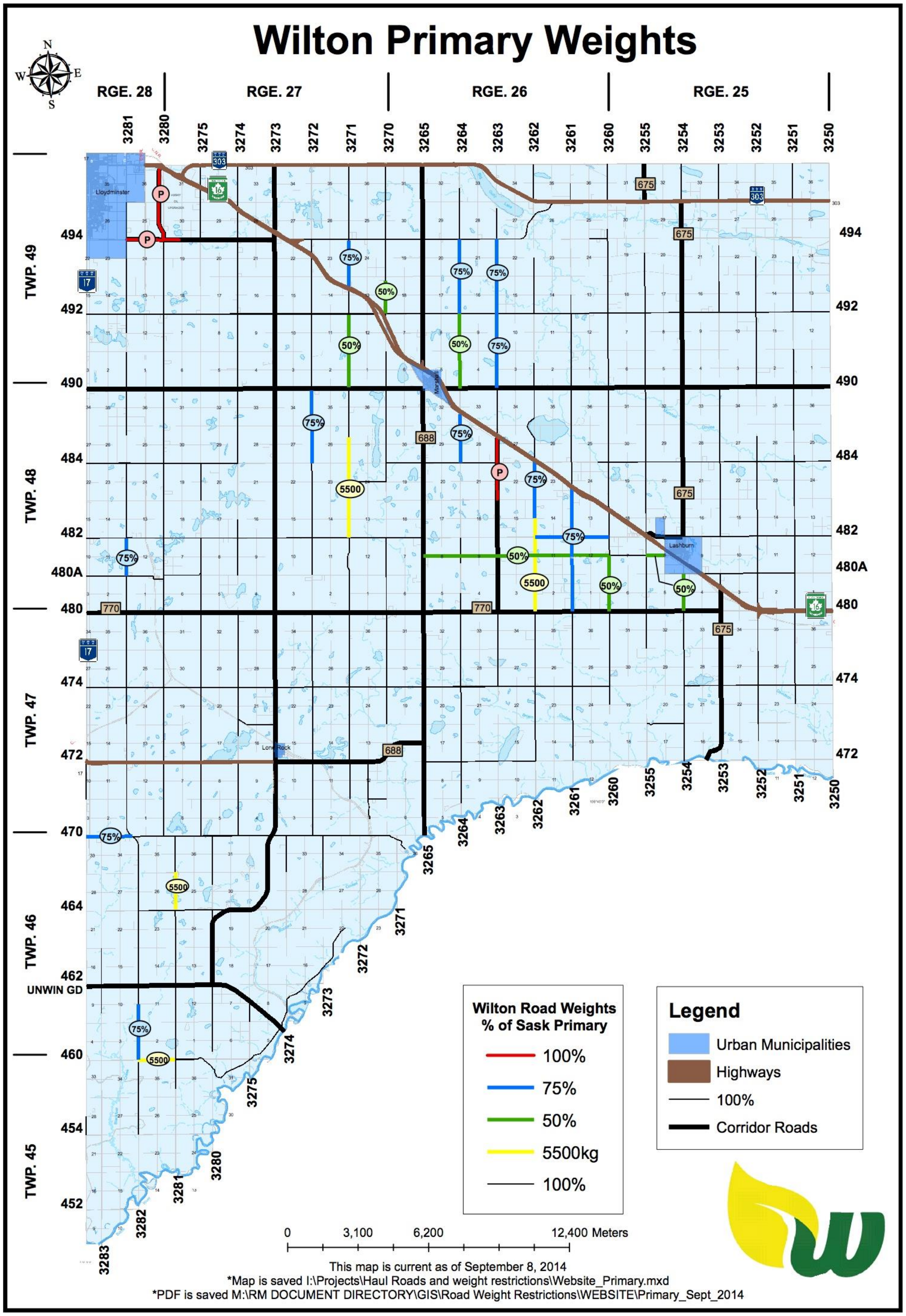
This section describes the case study that was represented in the ABM described in Chapter 4. As discussed previously, the ABM developed in this research was developed with the intent of maximizing the model applicability to any RM. However, the nature of ABMs requires models to be fairly specific to the case study they are meant to represent in order to produce meaningful results. This section outlines the case study specific input values used to represent the case study in the model. Additional details for how input values were established, along with the details of model testing (verification and validation) are presented in Appendix C.

6.2. Case Study Background

The case study considered in the developed ABM was the RM of Wilton, No. 472, Saskatchewan. The RM of Wilton is located southeast of the City of Lloydminster, adjacent to the Alberta border. The RM of Wilton is rich in oil and gas resources and has had a significant amount of oil and gas industry development.

As illustrated in Figure 6.1, the RM of Wilton has a well-defined corridor road network with select road segments under weight restrictions that vary seasonally.

A subset of the full RM of Wilton network was used in the model. While the RM of Wilton has several types of roads (different types of gravel roads, paved roads and sealed roads), the road types were grouped into either gravel or paved roads for model inputs. The details of how the RM of Wilton network was represented in the model along with generated results are presented in the following section.



This map is current as of September 8, 2014
*Map is saved I:\Projects\Haul Roads and weight restrictions\Website_Primary.mxd
*PDF is saved M:\RM DOCUMENT DIRECTORY\GIS\Road Weight Restrictions\WEBSITE\Primary_Sept_2014

Figure 6.1 RM of Wilton Case Study Road Network (RM of Wilton No. 472, 2014).

6.3. Description of Scenarios

The scenarios considered for the case study were similar to the scenarios discussed in Chapter 5 in order to gain insights into the implications of various road provision policies. The main considerations differentiating the scenarios were permit fees and the road upgrade decision. The following scenarios were considered in the model:

S1: No permit fees, No road upgrades. (Base Case)
S2: With permit fees, No road upgrades.
S3: No permit fees, With road upgrades.
S4: With permit fees, With road upgrades.

To quantify the net benefit of scenarios, the scenario *S1: No permit fees, No road upgrades* was defined as the base case against which other scenarios were compared.

When scenarios included road upgrades (*S3*, *S4*), the *RM* annual budget was set to six million dollars. Each scenario was run over a five year time frame. The initialization and input values are described in the following section.

6.3.1. Initialization and Input Values

This section covers the values used for the initialization and input requirements outlined in Section 4.6 and Section 4.7, respectively. As described in Chapter 4, Excel sheets are used for some model inputs for agents. A description of the model inputs is given in this section, but the full input data set is included in Appendix B.

First, the time period of simulation runs were input as beginning on January 1, 2013 and ending on January 1, 2018 (five years).

A subset of the full RM of Wilton road network was used for this case study in order to have a more manageable set of inputs.[1] Road network GIS data from the RM of Wilton was used, which included location and other properties such as road type and speed limit for road segments. The GIS data for road segments was in shapefile format and required manipulation (using QGIS software) prior to being used as inputs to support creating *Road Nodes* and *Road Segments* in the model.[2] Appendix B includes the data used as direct inputs for *Road Nodes* and *Road Segments*.

Initialization values were required for *Road Nodes* for y and x location (GIS latitude/longitude). *Road Node* coordinates were found using each end of each road segment from the road network GIS inputs described previously. Initialization values required for *Road Segments* included: starting and ending node (the unique ID of the *Road Node* at each end of the *Road Segment*), road type, and speed limit. Details for *Road Segments* were included in the RM of Wilton GIS data for the road network. For the subset of the network considered, there were a total of 197 *Road Nodes* and 234 *Road Segments* created. The subset of the RM of Wilton road network represented in the model is illustrated in Figure 6.2.

Input values for *Road Nodes* during the course of a model run include the *Vehicles* generated per day. Note that in Figure 6.2, four *Road Nodes* were added to the network at each corner of the network to represent origins or destinations for *Vehicles* that were external to the road network considered. The traffic levels used in the model were based on traffic counts collected by the RM of Wilton combined with the locations of oil wells and major oil installations within the RM. Origins used in the model included the four "corner nodes" (one at each corner of the network) representing external origins as well as eleven nodes throughout the network that were chosen based on higher densities of oil wells. Destinations used in the model also included the four corner nodes in the network as well as twelve nodes throughout the

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[1] Using big O notation, Dijkstra's shortest path algorithm is O(SlogN), where: N is the number of nodes, and S is the total number of segments. Model run time is increased as networks become larger (more segments and nodes to consider in the algorithm) and as more OD trips are included (more instances of running the algorithm). Increased model run time may become an issue if larger road networks were considered. There may be potential areas to reduce model run time through using simpler heuristics for how road users select their route rather than requiring the shortest path to be calculated. Model run times for the case study road network and traffic levels were often around three minutes long using a mid-range laptop.

[2] QGIS is an open source geographic information system, which was used to modify raw case study data for model inputs and to generate various road network images used in figures throughout this document. (http://www.qgis.org/)

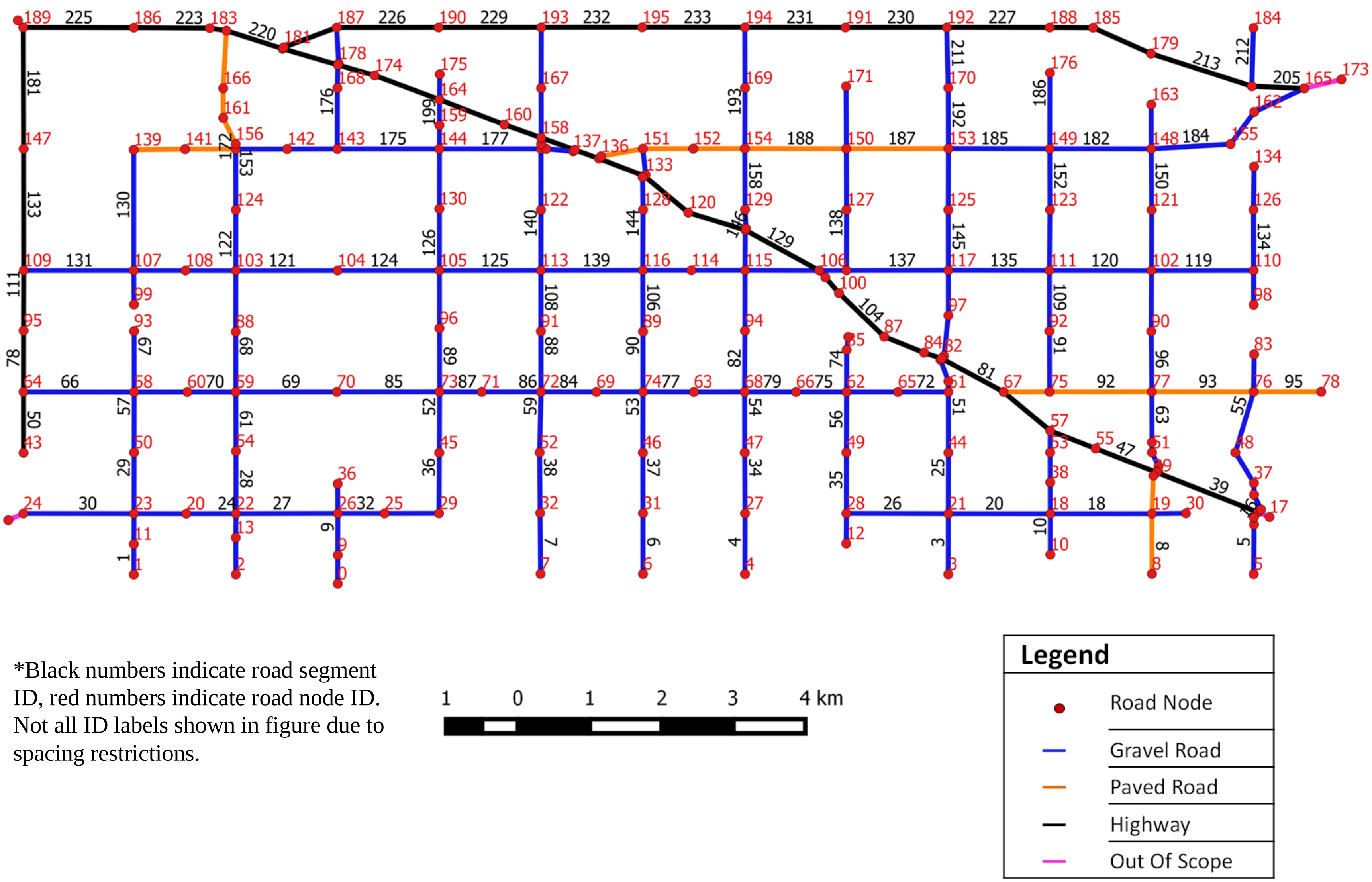
network at the location of major oil installations (e.g., battery sites where heavy oil is cleaned and treated, or disposal sites).

Traffic levels for each OD pair were initially set to be uniform from all origins to all destinations. Then the traffic levels for each OD pair were varied in order to match actual traffic counts collected by the RM of Wilton in 2013. The details of the values used for vehicle generation rates are described in Appendix C. The traffic levels in the model, which represent the actual traffic patterns in the case study, were a rough approximation to actual traffic levels. Representing existing traffic patterns for the case study is a difficult task, which is even more difficult given the limited traffic count locations. Further data would be desirable to better understand existing traffic patterns (e.g., OD survey data, additional traffic count locations).

A summary of the OD matrix is given in Table 6.1, which gives the total *Vehicles* generated per day by each *Road Node* along with the breakdown of the destination of those *Vehicles*.

Input values for the *RM* included weight restrictions on *Road Segments* that vary by season. The weight restrictions were not known exactly for each season, so they were approximated based on previous road weight restrictions used by the RM of Wilton during 2013. As an example, Spring weight restrictions are shown in Figure 6.3.

The weight restrictions in the Summer and Fall are the same as that shown in Figure 6.3, except with all Secondary weight restrictions increased to Primary weight. The weight restrictions in the Winter are Primary for all *Road Segments*. A summary of the results of each scenario are presented in the next section.

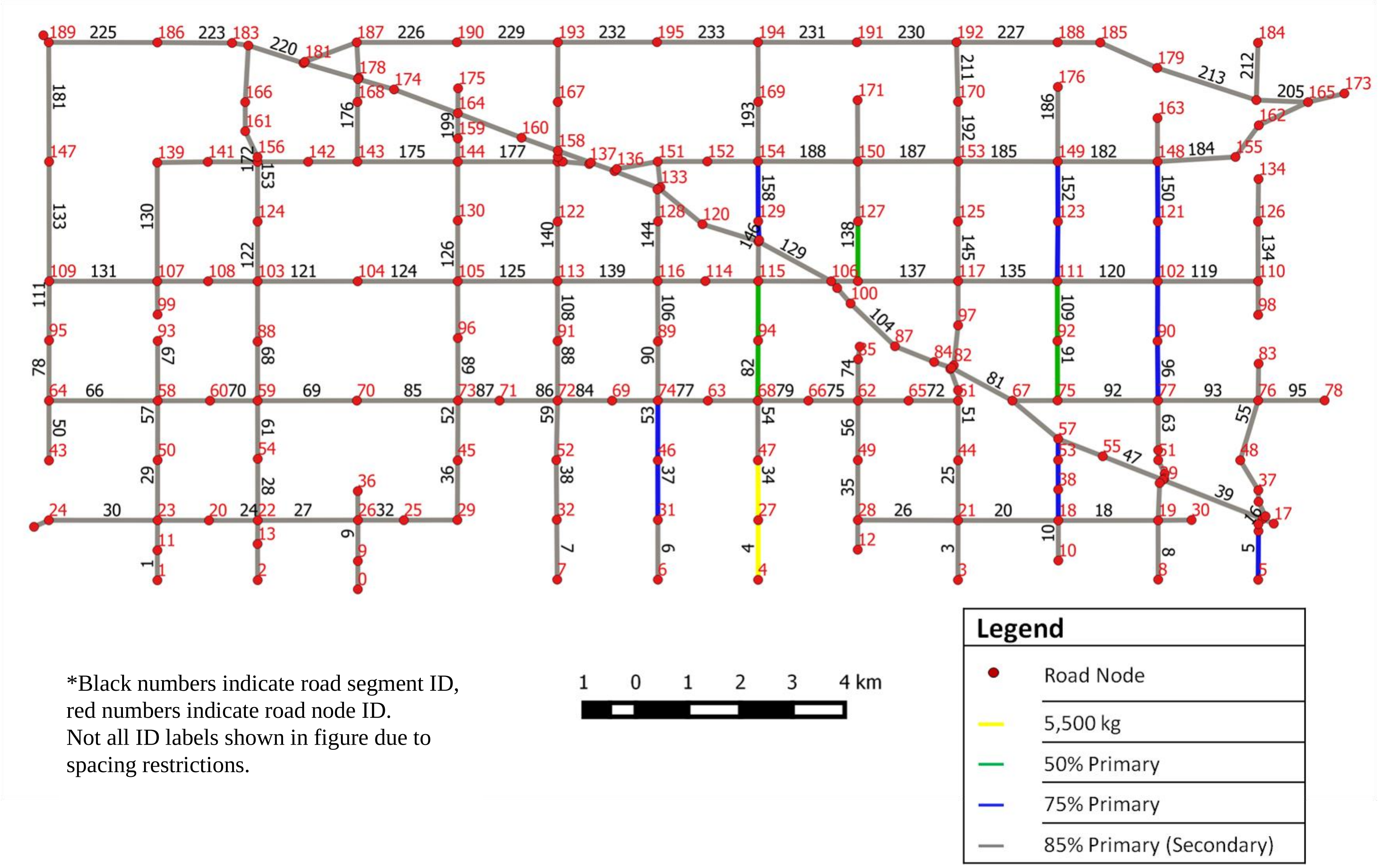


*Black numbers indicate road segment ID, red numbers indicate road node ID. Not all ID labels shown in figure due to spacing restrictions.

Figure 6.2 Subset of Road Network used for Case Study.

Table 6.1 Subset of Origin-Destination Matrix for Case Study.

Origin nodeID	Unit	Total Vehicles Generated	Destination nodeID															
			0	**3**	**15**	**17**	**31**	**45**	**54**	**70**	**78**	**97**	**101**	**107**	**119**	**139**	**173**	**196**
2	vpd	79	8	2	8	8	8	8	0	0	10	3	8	0	8	0	8	0
6	vpd	111	8	10	8	8	8	8	0	8	10	3	8	8	8	8	0	8
15	vpd	142	8	10	0	15	8	8	8	13	10	0	8	8	8	8	15	15
17	vpd	182	8	10	15	0	8	8	8	8	10	3	8	8	8	50	15	15
44	vpd	119	8	10	8	8	8	8	0	8	10	3	8	8	8	8	8	8
58	vpd	310	17	10	8	8	8	15	3	25	10	3	8	2	8	2	8	175
88	vpd	56	0	0	0	8	0	0	0	0	0	3	8	8	8	5	8	8
114	vpd	121	8	20	8	8	8	8	3	8	10	0	8	8	8	8	0	8
123	vpd	216	8	15	8	8	8	8	8	8	10	0	8	8	8	8	8	12
124	vpd	83	0	10	8	8	0	0	0	0	10	3	8	8	8	8	4	8
143	vpd	115	0	10	8	8	8	8	0	8	10	3	8	8	8	20	0	8
167	vpd	121	8	10	8	8	8	8	0	13	10	0	8	8	8	8	8	8
173	vpd	338	8	10	15	15	3	8	8	8	10	0	0	8	0	230	0	15
191	vpd	192	8	0	8	0	8	8	2	8	10	0	8	8	8	100	8	8
196	vpd	534	8	63	15	15	8	8	3	75	50	0	8	8	8	250	15	0



*Black numbers indicate road segment ID, red numbers indicate road node ID. Not all ID labels shown in figure due to spacing restrictions.

Figure 6.3 Spring Weight Restrictions for Case Study Road Network.

6.4. Scenario Results

This section outlines the results of model runs for each scenario considered. Most key outputs found using the case study data were similar to the results found using the hypothetical network outline in Chapter 5. As such, the discussion and interpretation of results is limited in this section in attempts to avoid repetition and highlight only new findings using the case study data. Unless otherwise stated, results are presented in terms of cumulative values over full five year model runs. The main output cost results from model runs for each scenario are shown graphically in Figure 6.4. The outputs of the scenarios are summarized in more detail in Table 6.2, including an indication of the net benefit with respect to the *Base Case, S1*.

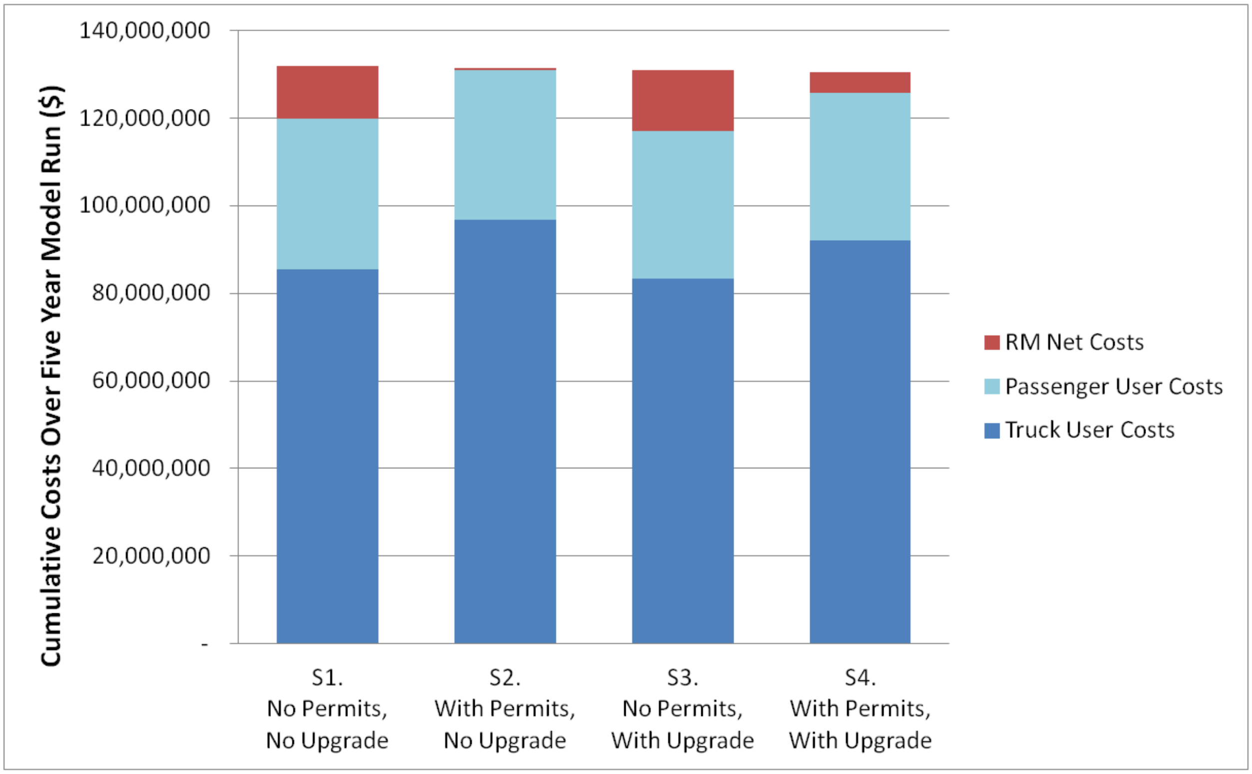


Figure 6.4 Scenario Results for Case Study.

Figure 6.4 illustrates how the inclusion of permit fees (*S2*, *S4*) shift the costs from the RM to road users. Each scenario resulted in a net benefit (lower combined user and agency costs), albeit small in magnitude, compared to the base case.

Table 6.2 Scenario Results for Case Study.

Model Output	Unit	Scenario			
		S1. No Permits, No Upgrades	S2. With Permits, No Upgrades	S3. No Permits, With Upgrades	S4. With Permits, With Upgrades
User Costs					
Distance Based Costs	$	50,105,374	50,248,422	47,383,083	47,637,166
Time Based Costs	$	69,589,992	70,214,429	69,617,636	70,120,189
Permit Based Costs	$	-	10,456,937	-	8,037,520
Total User Costs	$	119,695,366	130,919,789	117,000,719	125,794,875
Agency Costs					
RM Upgrade Costs	$	-	-	18,195,145	15,831,739
RM Upgrade Costs (Annualized)	$	-	-	4,553,073	4,135,942
RM Annualized Costs (Without Upgrade Costs)	$	12,152,538	10,917,754	9,314,307	8,407,980
RM Revenues (Permits)	$	-	10,456,937	-	8,037,520
RM Net Costs	$	12,152,538	460,817	13,867,380	4,506,402
Combined Costs					
User + Agency Costs	$	131,847,904	131,380,606	130,868,100	130,301,277
Net Benefit Relative to S1					
Total Cost Savings	$	-	467,299	979,805	1,546,627
Percent Reduction in Costs	%	-	0.35%	0.74%	1.17%

The change in net benefits for the case study considered in this chapter was lower than the net benefit found using the hypothetical model in Chapter 5, and was small in magnitude compared to existing cost outputs in the base case. The decrease in net benefit relative to the hypothetical model was due to the different traffic loading characteristics and different initial network configuration. Traffic volumes for the case study were generally lower than traffic volumes used for the hypothetical model. The initial road network represented in the model was established through past RM efforts in upgrading select road segments to accommodate traffic levels, so the initial network properties were already well suited to accommodate the existing traffic levels. As such, the net benefit for completing additional upgrades was lower than that of the hypothetical model, which had higher traffic levels on a network that was not well suited to accommodate them.

In *S3*, the only change from the base case was the inclusion of a capital budget for the *RM*, which allows the *RM* to upgrade *Road Segments* at the end of each year. The *RM* chooses gravel road segments with high traffic levels to upgrade, which reduces both *Vehicle* costs and *RM* costs. The net benefit is larger in S3 than in *S2*, as anticipated: upgrading a *Road Segment* with high traffic levels (above a trigger point as discussed in Chapter 3) will reduce both agency and user costs assuming static OD patterns, while implementing permit fees does not necessarily impact routing behavior and associated costs. More details on the upgraded *Road Segments* and impact on routing is discussed later in this section.

Albeit still small in magnitude, the largest net benefit of the scenarios was found in *S4*, which included both permit fees as well as the capital budget for road upgrade. The inclusion of capital upgrades provided the majority of the net benefit (similar to *S3*), and the inclusion of permit fees increased the incentive for *Vehicles* to travel on upgraded road segments (lower permit fees and lower user costs) if the upgraded road segments were near their existing routes. The inclusion of permit fees from the beginning of the model run caused *Vehicles* to change their routing and thereby changed the traffic counts on select *Road Segments*. This change in routing changes the *Road Segments* selected by the *RM* for upgrade, as will be discussed later with more detailed results from the model. Note that the magnitude of the net benefit would be increased with longer model runs as *Vehicles* would have more time to complete more trips on upgraded road segments.

Also note that the case study network included highways that were not under RM jurisdiction, so *Vehicles* travelling on highways did not increase *RM* road provision costs. Model results may be helpful in understanding how implementing a permit fee on road segments under RM jurisdiction may influence the traffic levels on surrounding infrastructure outside of RM jurisdiction.

While the total cost summaries outlined above give insights into the results of the scenarios considered in the model, more detailed results were produced to better understand the features of the model runs. Additional details for *Vehicles* in the model runs are outlined in Table 6.3.

Table 6.3 Scenario Outputs for Vehicle Agents for Case Study.

Model Output	**Unit**	**Scenario** **S1. No Permits, No Upgrades**	**S2. With Permits, No Upgrades**	**S3. No Permits, With Upgrades**	**S4. With Permits, With Upgrades**
Passenger Vehicles					
Number of Vehicles Represented in Model†	#	2,375,480	2,375,480	2,375,480	2,375,480
Total User Costs	$	34,285,293	34,285,293	33,775,828	33,806,000
Total Distance Travelled	km	72,421,942	72,421,942	72,301,387	72,262,558
Average Unit User Cost (including time costs)	$/km	0.47	0.47	0.47	0.47
Trucks					
Number of Vehicles Represented in Model†	#	2,437,560	2,437,560	2,437,560	2,437,560
Total User Costs	$	85,410,073	96,634,496	83,224,892	91,988,875
Total Distance Travelled	km	74,535,657	75,974,649	74,451,495	75,700,116
Average Unit User Cost (including time costs)	$/km	1.15	1.27	1.12	1.22
Total Payload Hauled	tonne	67,306,496	67,306,496	67,306,496	67,306,496
Total Weight-Distance	tonne-km	1,035,697,604	1,057,395,349	1,034,482,555	1,052,319,371
Average Cost per Weight-Distance	$/tonne-km	0.08	0.09	0.08	0.09

†Each *Vehicle* created completed a round trip. So the total one-way trips would be double the number of *Vehicles* created.

As seen in Table 6.3, the distance traveled by trucks when permit fees were included (in *S2*) was greater than that of the base case. This is because trucks were choosing longer routes to benefit from the lower permit fee costs on paved road segments. In *S4*, the distance travelled by trucks increased even higher as more paved road segments were established in the network and permit fees encouraged *Vehicles* to alter their routes to travel on paved road segments. When permit fees were included in scenarios, user costs for trucks (in addition to the actual permit fee) were increased due to higher distances travelled. The same reasoning for the changes in distance travelled can explain the variation in weight-distance across scenarios. When permit fees were included, the cost per unit distance and cost per unit weight-distance were highest for *Vehicles*.

More detailed outputs for the *RM* and the road network are given in Table 6.4. Note that the total combined length of all road segments under RM jurisdiction for the road network considered in this section was 214.5 km.

Table 6.4 Scenario Outputs for RM and Road Network for Case Study.

Model Output	**Unit**	**Scenario**			
		S1. No Permits, No Upgrades	**S2. With Permits, No Upgrades**	**S3. No Permits, With Upgrades**	**S4. With Permits, With Upgrades**
Number of Road Segments Upgraded	#	-	-	30	25
Length of Road Segments Upgraded	km	-	-	29.4	25.5
Percent of Network Upgraded by Length	%	-	-	10.9%	9.5%
Average EUAC per Length of Road in Network (without permit fee revenue)	$/km/year	9,047	8,128	10,324	9,338
Percent of Total Distance Driven on Paved Road Segments	%	59.70%	61.33%	71.19%	71.86%

Table 5.3 shows the total distance driven by *Vehicles* on paved road segments increased from 59.70% in *S1* to 71.19% in *S3* indicating that *Road Segments* selected for upgrade were along existing OD routes and may have drawn additional traffic using nearby routes. In *S4*, the inclusion of permit fees reinforced the incentive for *Vehicles* to use paved road segments and the total distance travelled on paved road segments increased slightly higher than *S3*.

The average EUAC per unit road length for the *RM* (without including permit fee revenues) increases in *S4* compared to *S1*. This suggests the existing road network was adequate to accommodate exiting traffic levels from the RM's costing perspective. When including user costs into the road upgrade decision, additional road segments were upgraded, which reduced combined costs, but increased RM costs. This is the opposite of the findings from the hypothetical network considered in Chapter 5, where *S4* resulted in decreased RM costs compared to *S1*. As mentioned previously, the hypothetical model had higher traffic volumes than the case study and this decrease in RM costs in *S4* suggest that the hypothetical road network (considered in Chapter 5) was not adequate to accommodate existing traffic volumes when considering road provision costs.

The results produced for the case study illustrate the impact that permit fees can have on the *RM* road upgrade decision. The *Road Segments* upgraded in the *S3* and *S4* scenarios are summarized in Table 6.5.

Table 6.5 Road Segments Upgraded during Model Run for Case Study.

Year	**Unit**	**Scenario**	
		S3. No Permits, With Upgrades	**S4. With Permits, With Upgrades**
1	Road Segment ID	30,52,65,66,70,71,97,98,125,167,179	30,52,65,66,70,71,97,98,125
2	Road Segment ID	31,32,36,51,76,77,84,86,87,168	31,32,36,51,76,77,84,86,87
3	Road Segment ID	27,69,72,73,75,79,83,175	27,69,72,73,75,79,83
4	Road Segment ID	177	-
5	Road Segment ID	-	-

As seen in Table 6.5, more *Road Segments* are upgraded in *S3* than in *S4*. In S4, all of the *Road Segments* upgraded are also upgraded in S3. In S3, there were additional upgraded road segments that were not upgraded in S4 which include *Road Segments* 167, 179, 168, 175, and 177. The difference in road upgrade selection is due to permit fees and previous road upgrades altering the least cost routing for *Vehicles*. The inclusion of permit fees in *S4* resulted in more concentrated traffic on existing paved road segments that reduced the traffic levels on gravel road segments such that they were not selected for upgrade.

6.5. Sensitivity Analysis

There were three additional scenarios considered in more detail where the following parameters were varied: the *VPD Trigger for Upgrade*, and the *Annual Capital Upgrade Budget*, and shifting OD patterns. All scenarios were completed with permit fees included.

6.5.1. Variation of VPD Trigger for Upgrade

Model runs were completed for *VPD Trigger for Upgrade* values ranging from 0 to 900 vpd in 50 vpd increments, using nominal values for all other variables except for *Annual Capital Upgrade Budget*, which was set to a sufficiently large number such that there were no budget constraints in any model run. This scenario was considered to understand the impacts of road upgrade selection without budget constraints. The combined cost results for all model runs are shown in Figure 6.5.

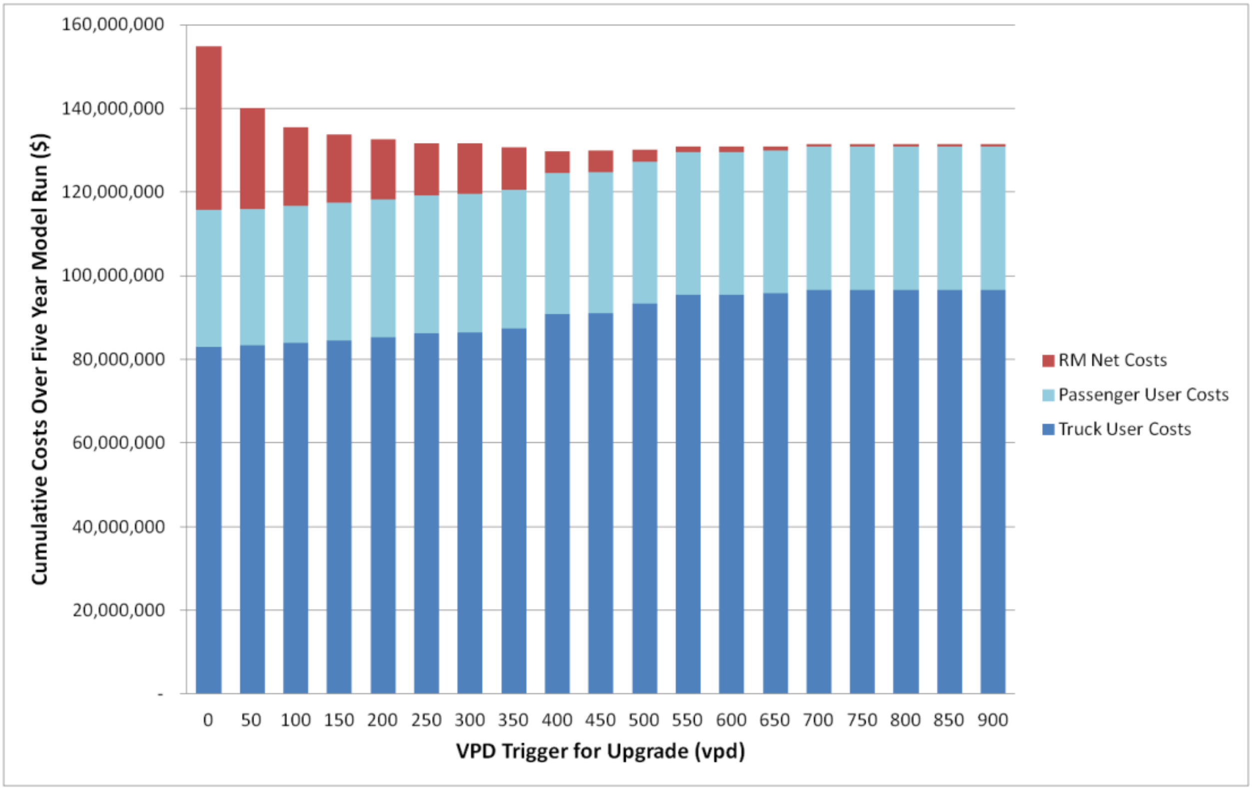


Figure 6.5 Costs under Variation in VPD Trigger for Upgrade Road for Case Study.

As seen in Figure 6.5, the combined costs decrease as the *VPD Trigger for Upgrade* value increases until the point at which combined costs begin to increase. This pattern in combined costs is similar to that found using the hypothetical network and more details on the causes of these results are discussed in Chapter 5. As seen in Figure 6.5, the *VPD Trigger for Upgrade* value of approximately 400 results in the lowest combined costs in model runs. This value of 400 was used as the nominal value for all other runs considered in this chapter.

The combined costs do not increase significantly for high *VPD Trigger for Upgrade* values because the existing traffic volumes on the network were not significantly above the 400 vpd value and so there were not high costs associated with high traffic levels on gravel road segments. If traffic volumes were increased, then the combined costs would increase more significantly as the *VPD Trigger for Upgrade* value increased above 400 vpd.

6.5.2. Variation of Annual Capital Upgrade Budget

Model runs were completed for the *Annual Capital Upgrade Budget* value ranging from 0 to 15 million dollars in 1 million dollar increments, using nominal values for all other variables. The combined cost results for all model runs are shown in Figure 6.6.

As seen in Figure 6.6, the combined costs decrease as the *Annual Capital Upgrade Budget* increases, and tends to level off with high values of *Annual Capital Upgrade Budget*. This pattern in combined costs is similar to that found using the hypothetical network in Chapter 5 where the causes of this trend of decreasing combined costs is discussed.

The combined costs do not change as the *Annual Capital Upgrade Budget* value increases above 15 million dollars because all of the road upgrades were accommodated within the budget at that point. If traffic volumes increased, then increased *Annual Capital Upgrade Budget* values would generally result in lowered combined costs. It is anticipated that this type of analysis may be useful for road providers in understanding the implications of funding restrictions and selecting a desirable budget levels.

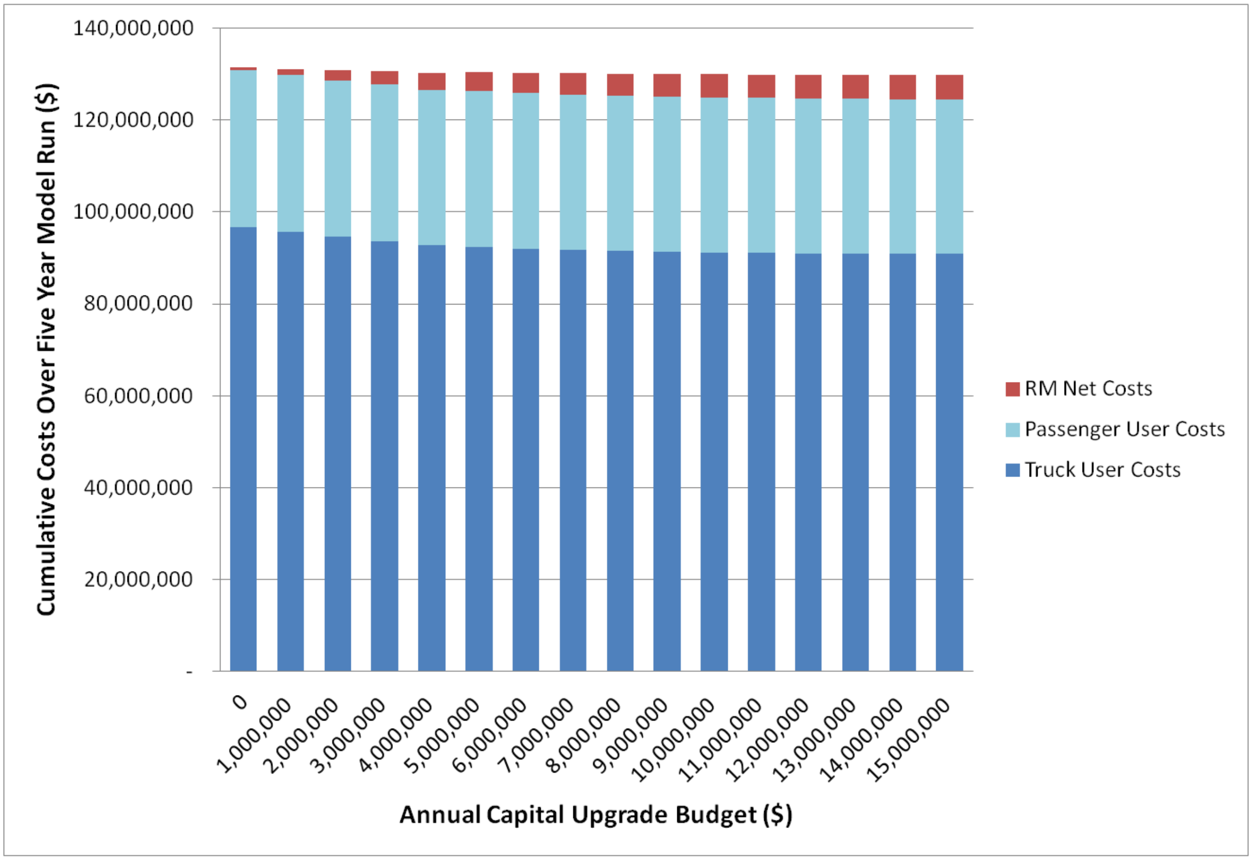


Figure 6.6 Costs for Variation of Annual Capital Upgrade Budget for Case Study.

6.5.3. Variation of Origin-Destination Patterns

A scenario was considered to represent a new major vehicle destination being established within the RM of Wilton. The new destination represented an oil by rail facility that would draw significant traffic, primarily trucks hauling oil to the facility. The location of the facility was southeast of the subset of the road network considered, so the destination for *Vehicles* driving to facility was *Road Node* 17 at the southeast corner of the network. The amount of traffic drawn to the facility was uncertain, so the number of *Vehicles* driving to the facility in the model runs were illustrative only. To illustrate the impacts of the facility, it was assumed that 25% of traffic from each existing destination in the network switches to have a destination of *Road Node* 17 when the facility is established at the end of year two.

Model runs were completed for *VPD Trigger for Upgrade* values ranging from 0 to 900 vpd, using nominal values for all other variables except for the *Annual Capital Upgrade Budget*, which was set to a sufficiently large number such that there were no budget constraints in any model run. This scenario was considered to understand the impacts of road upgrade selection without budget constraints under shifting traffic patterns. The combined cost results for all model runs are shown in Figure 6.7.

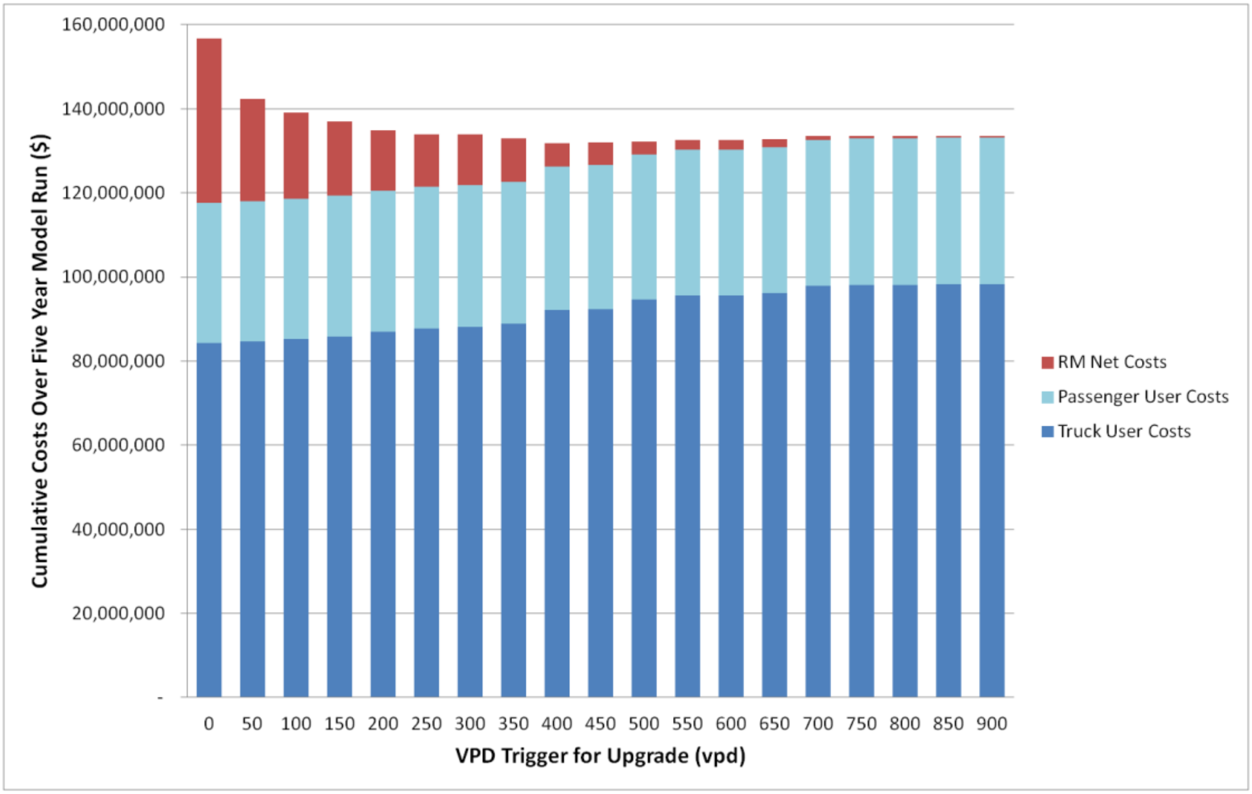


Figure 6.7 Costs under Variation in VPD Trigger for Upgrade for Shifting Destinations for Case Study.

As seen in Figure 6.7, a similar pattern to that shown for static traffic patterns (illustrated in Figure 6.5) is found as the *VPD Trigger for Upgrade* value increases. The *VPD Trigger for Upgrade* value of 400 vpd, which resulted in minimized combined costs under static traffic patterns, was unchanged in this scenario. This indicates that the change in traffic considered in this scenario was not large enough to cause a change in the road providers' decision for road upgrade selection. Select results using *S4* under the static traffic patterns and under the shifting traffic patterns are outlined in Table 6.6. Both scenarios outlined in Table 6.6 include permit fees and upgrades with annual budgets of six million dollars.

As shown in Table 6.6, the combined costs under shifting traffic is higher than that of the static traffic scenario. This is primarily due to the increased distance driven by *Vehicles* once the new destination is introduced at the end of year two.

Table 6.6 Scenario Results for Shifting Traffic Patterns for Case Study.

Model Output	**Unit**	**Scenario** **S4.** **Static Traffic Patterns**	**Scenario** **S4.** **Shifting Traffic Patterns**
Costs			
Total Vehicle Costs	$	125,794,875	127,769,758
RM Net Costs	$	4,506,402	4,634,728
Vehicle + RM Costs	$	130,301,277	132,404,486
Road Upgrade Summary			
Number of Road Segments Upgraded	#	25	26
Length of Road Segments Upgraded	km	25.5	27.18
Road Upgrade by Year			
Year 1	Road Segment ID	30,52,65,66,70,71,97,98,125	30,52,65,66,70,71,97,98,125
Year 2	Road Segment ID	31,32,36,51,76,77,84,86,87	31,32,36,51,76,77,84,86,87
Year 3	Road Segment ID	27,69,72,73,75,79,83	27,69,72,73,75,79,83
Year 4	Road Segment ID	-	85
Year 5	Road Segment ID	-	-

The results of the model runs in this section show that the introduction of one destination that draws a portion of the traffic from existing origins does not have significant influence on the road upgrade decision and resulting costs (one additional road upgrade completed under shifting traffic patterns). Because the vehicle origins were fixed, several road segments with high traffic under static traffic patterns also had high traffic under the shifting traffic. If the new development were to attract vehicles from new origin locations or attract increased traffic from that considered in the static traffic level scenario, then the impact on road upgrade selection and resulting costs would likely be more significant (as explored for shifting origins in the hypothetical network discussed in Chapter 5).

6.6. Chapter Summary

This chapter presented the application of the developed ABM to a subset of the RM of Wilton road network. In general, the main results were consistent with findings from Chapter 5 using a hypothetical road network. As expected, the magnitude and relative change in costs for various scenarios were different when using case study data, as network properties combined with traffic patterns have a significant impact on model results, as previously discussed. The scenarios that include permit fees, based on incremental road provision costs due to vehicles, as well as road upgrade resulted in the largest net benefit (in terms of combined road user and road provision costs) compared to model runs without permit fees or road upgrade. The magnitude of the net benefit was small in relation to the existing base case cost outputs (reduction of total costs over five year model run by 1.17%).

Results showed a lower *VPD Trigger for Upgrade* value than that found using the hypothetical road network resulted in the lowest combined costs. As discussed, the *VPD Trigger for Upgrade* value resulting in lowest combined costs is dependent on the combination of road network properties and traffic patterns. The case study data had a higher number of OD pairs and generally higher traffic levels that lead to an increased number of alternative routes for vehicles to choose. The increased availability of alternative routes combined with locations of existing paved road segments resulted in the lower *VPD Trigger for Upgrade* value that resulted in the lowest combined costs.

A scenario was considered that represented an industrial development that drew traffic from existing destinations within the road network. The impact of this traffic shift on road upgrade selection was less significant than expected, as vehicles were routed onto several of the same road segments as pre-development traffic levels. The scenario found increased combined costs, longer distances driven by vehicles, and minor differences in road upgrade decision.

This chapter demonstrated how the developed model may be used to represent real world case study road networks and may be used to understand the implications of road management decisions. With further model testing and refinement, it is anticipated that the model could be used to support decision making for road providers under variable traffic characteristics and variable funding levels.

CHAPTER 7 SUMMARY AND CONCLUSIONS

7.1. Summary

Industry in Saskatchewan, including natural resource, manufacturing and agriculture, is dependent on road infrastructure to reach suppliers and markets. The 296 Rural Municipalities (RMs) in Saskatchewan are responsible for the construction and provision of the extensive rural road network consisting of mostly gravel roads, which can be costly to maintain under heavy vehicle traffic. Providing an acceptable level of service on rural roads is important for supporting industry and not imposing transportation constraints that may impede industry growth.

In general, road users do not directly pay the road provider for their road use; however, the decisions of road users can affect the costs incurred by road providers and vice versa. This suggests there may be efficiencies to be had by coordinating road user and road provider decision making. The goal of this research was to determine the feasibility of applying an agent-based model (ABM) to represent the road use and road provision of a rural road network in Saskatchewan. The main objective was to develop an ABM to determine whether pricing a rural road network on an incremental cost basis would result in a net benefit when considering combined road use and road provision costs.

An ABM was developed to investigate whether rational permitting for road use would lower combined road use and road provision costs. The ABM included: road segments, road nodes, road users, and a road provider. Simple decision heuristics were used to represent road use and road provision decision making, including least cost routing and traffic-based prioritization for road upgrade decisions. Various scenarios were considered with combinations of road permitting and road upgrade decision making to explore the implications for both road user and road provider costs. The default values used in the model were for a hypothetical rural road network with 66 *Road Nodes* and 115 *Road Segments* with hypothetical traffic patterns. The model was applied to a subset of an RM case study road network with 197 *Road Nodes* and 234 *Road Segments* with traffic patterns based on existing traffic count data.

The permit fees considered in this research essentially shifted the incremental costs for road provision under traffic loading from the road provider to the road users. The purpose of this type of permit fee structure was to investigate road management policies that may be more cost effective when considering combined costs. This type of permitting could provide a more direct linkage between road use and payment to fund road provision, which may be more equitable than the current road funding mechanisms (e.g., gas tax, property tax).

The primary scenarios considered in the model used a five year time period and established a base case model run, which did not include permit fees and did not include road upgrades. Model runs were then completed for three scenarios: with permit fees (based on incremental road costs), with road upgrades, and with both permit fees and road upgrades.

7.2. Conclusions

Model runs showed that the inclusion of permit fees incentivized road users for some OD pairs to change their routing and drive longer distances in order to drive larger percentages of their routes on upgraded road segments. This change in routing caused road user costs to increase with longer distances driven, and road provision costs to decrease due to lower traffic on gravel road segments. When considering the combined costs (road use and road provision costs) the inclusion of permit fees resulted in a marginal net benefit compared to the base case (a reduction in combined costs of 0.46% for the hypothetical network, and 0.35% for the case study).

Model runs including road upgrades (but not permit fees) had a more significant impact on costs, although the net benefit was still small relative to the base case (a reduction in combined costs of 2.25% for the hypothetical network, and 0.74% for the case study). After each year of the model run, the RM upgraded gravel road segments with high traffic volumes, under budget constraints. Road segments were prioritized based on highest traffic counts in the previous year and were upgraded if they were over a pre-calculated traffic level (the "trigger point" for road upgrade), above which the total life cycle costs (LCCs), including road use and road provision, were calculated to be lower for paved roads than for gravel roads.

Model runs including both permit fees and road upgrades resulted in the largest net benefit, although still marginal in relation to the base case (a reduction in combined costs of 2.32% for the hypothetical network, and 1.17% for the case study). The inclusion of permit fees affected the RM road upgrade decision: the shift in routing caused traffic to increase on certain gravel road segments such that the road would become prioritized for upgrade over another road that would have been upgraded in the scenario without permit fees.

While each considered scenario resulted in a net benefit, the magnitude of the net benefit was consistently marginal in relation to the base case combined costs. Since permit fees were based on the incremental road provision cost, and, generally, road provision costs were small relative to road use costs, the magnitude of the permit fee does not impose strong incentives for altering road user behavior. Permit fees only altered road user route choice if there were alternative routes for which the road users did not have to significantly increase their trip distance (and costs) to find routes with paved road segments. Given the relatively low impact of permit fees on resulting combined costs found in the scenarios considered, the associated administrative costs may not be worthwhile for a road provider to implement such a permit fee structure.

A sensitivity analysis was completed which found that as the trigger point for road upgrade increases, combined costs decrease until a point at which combined costs reach a minimum. Then as the trigger point for road upgrade continues to increase, the combined costs begin to increase as fewer road segments with high traffic volumes are upgraded. The trigger point for upgrade resulting in lowest costs was found to be lower when considering combined costs than when considering only road provision costs. This suggests that more road segments would be upgraded when attempting to minimize combined costs than would be if only considering minimizing road provision costs.

For the hypothetical network considered in the model, it was found that a *VPD Trigger for Upgrade* value of 500 resulted in lowest combined costs when not imposing budget constraints. For the RM case study, the *VPD Trigger for Upgrade* value of 400 resulted in lowest combined costs, which was lower than that found for the hypothetical model. As discussed, the *VPD Trigger for Upgrade* value resulting in lowest combined costs is dependent on the combination of road network properties and traffic patterns. The case study data had a higher number of OD pairs and generally higher traffic levels that lead to an increased number of alternative routes for vehicles to choose. This increased availability of alternative routes, combined with locations of existing paved road segments resulted in a lower *VPD Trigger for Upgrade* value to result in the lowest combined costs. As discussed in Chapter 3, in practice, the road upgrade decision for a road provider would include considerations in addition to the traffic volume such as: traffic composition (amount of trucks using the road), various geometric design considerations, dust reduction, public opinion etc. The *VPD Trigger for Upgrade* value was used as the sole indication of whether to upgrade the road for simplicity in modeling the road upgrade decision for this research.

Additional sensitivity analysis showed that the increasing the annual capital upgrade budget was found to have the largest impact on combined costs when budget levels were low, and a decreased impact on combined costs when budget levels were high and most road segments with high traffic levels could be accommodated within the budget. Under shifting traffic patterns for the hypothetical road network, a higher trigger point for upgrade was found to be more appropriate to reduce combined costs; this suggests that under shifting traffic patterns it may be more advantageous to upgrade fewer road segments. Using the case study road network with a less drastic traffic shift, there was not a change in the trigger point for road upgrade that minimized combined costs. A two-way sensitivity analysis showed how combined costs were impacted by increased budget levels for various trigger points for road upgrade. At some budget levels, it was found that a lower budget resulted in lowered combined costs: budget constraints limited the number of road segments upgraded such that the following year, the altered routing due to the upgrade lowered traffic levels on other road segments and eliminated the need to upgrade those road segments.

The model developed in this research illustrates the feasibility of using an ABM to support decision making involving road use and road provision policies. While the permit fees considered in the model may not have shown significant benefit, the model developed in this research process would be anticipated to have potential for further development in order to be useful for supporting consideration of various road management policies. Potential alternative policies for consideration in the model include: road upgrade selection, alternate haul weight restrictions (or permitting vehicles to travel above posted weight restrictions), or the impacts of a proposed development that may alter existing traffic levels or traffic patterns.

The complexities involved in road use, road provision and road performance required several simplifying assumptions to complete the ABM. Nonetheless, the results produced with the model illustrate the potential implications of various road use and road provision decisions. Further work to expand simplifying assumptions and refine model inputs may allow the model to become useful for road providers in understanding the impacts of alternative road provision policies for real world road networks.

7.3. Limitations and Future Work

Due to the bottom-up nature of ABMs, several inputs and assumptions were required at the road segment level and the individual vehicle level in order to gain insights at the system level. The complexities involved in road use, road provision and road performance required several simplifying assumptions and input values that were uncertain. Further work to expand some simplifying assumptions may allow the model to become useful for road providers keen to explore the impacts of alternative road provision policies. Some potential areas for future work are outlined below:

- Consider additional road types. The model was scoped to only gravel and paved roads, while there are several other road types often found in RMs such as: TMS (Thin Membrane Surface), chip seal, or different types of paved or gravel roads.

- Consider reversion of paved roads to gravel roads or road abandonment.

- Consider alternate permit fee structures such as including a component allocated towards capital upgrade. Consideration of permits that allow vehicles to travel above existing weight restrictions may also be of interest for road providers.

- Refine incremental road costing inputs by vehicle type, road type and season. High traffic levels (particularly heavy vehicle traffic) on gravel roads can result in high costs for road maintenance and repair. The linear road costing functions for gravel roads could be expanded to include provisions for increased costs (perhaps non-linear) under high traffic loading.

- Add agents to the model to handle traffic generation. For example, an "oil and gas company" or "farm" agent could be represented in the model with vehicle generation rates based on the traffic generated by production values. The GIS based environment used in the model lends itself well to importing location based information to support these new agents such as oil well location, crop type and location, etc. This inclusion of agents driving vehicle generation rates could be used to expand decision making for vehicle trip timing (e.g., waiting to haul until permit fees are lower), or perhaps agents would choose not to make a trip if permit fees were high. These types of additional agents could support the inclusion of vehicle fleets that may have unique hauling policies that may differ across fleets and other vehicles.

- Allow for shift in vehicle traffic by season driven by permit fee.

- Agent learning could be included in the road upgrade decision to allow the road provider to use traffic projections based on previous years to determine whether road upgrade would be beneficial.

- In reality, road users do not necessarily take the least cost route every trip. Some randomization could be introduced to represent uncertainty in least cost trip for road users, particularly when there are alternative routes that are similar in distance. Alternate heuristics could be used to represent user route choice.

- Allow for noncompliance of road users for speed limits, weight limits and obtaining permits.

- Consider larger road networks. Perhaps consider multiple road providers (RMs) to consider inter-jurisdictional interactions resulting from different road provision policies. These considerations may provide insights into efficient methods of coordinating policies between RMs that may lead to increased net benefit.

- Larger networks and an increased number of OD pairs used in the model result in longer run times, primarily due to the shortest path algorithm. There may be potential methods to model run times by using specialized variants of Dijkstra's algorithm (e.g., Fibonacci heap implementation or the A* algorithm).

The validation of the model was narrow due to limited available data from the case study which reduces confidence in model validity. Future work is required to further validate the model against case study data. Going forward, as RMs collect more information, the model may be validated with a richer dataset. It is anticipated that further validating the model and expanding on the potential areas listed above may help to develop a tool that could be helpful for road provider agencies in understanding the potential implications of their road management decision making.

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APPENDIX A HYPOTHETICAL MODEL DATA

This appendix contains the initialization and input data used in the model for the hypothetical network described in Chapter 4 with model results presented in Chapter 5. While some model inputs were highlighted in Chapter 4, the full set of initialization and input data is outlined in this appendix. Initialization data are required at model start-up while input data are used throughout model runs. Much of the initialization and input data are input through Microsoft Excel spreadsheets linked to the model. The tables in this appendix show the data within each sheet of the Excel input file.

Some of the initialization and input data covered in this appendix are categorical. For ease of handling inputs in the model, the categories of variables were translated to have integer representation. Table A.1 shows the integer representation of each input category in the model.

Table A.1 Integer Representation of Categorical Variables for Model Initialization and Inputs.

Model Integer Representation	**Real Value**		
Speed Limits (speedLimit) (km/hr)			
0	110		
1	100		
2	90		
3	80		
4	70		
Weight Limits (weightLimit & vehWeightCat)			
0	100 % Primary		
1	85 % Primary (Secondary)		
2	75 % Primary		
3	50 % Primary		
4	5,500 kg		
Vehicle Configurations			
	vehConfig	**vehTareWeight (kg)**	**vehMaxPossibleGVW (kg)**
0	8-axle	20,500	62,500
1	6-axle	16,500	47,000
2	5-axle	15,000	40,000

Road Type	
0	Gravel
1	Paved
88	Out of scope (for handling external OD traffic - no influence on costs/routing)
99	Out of RM jurisdiction (for Highways - influence user costs, but not RM costs)

Initialization data

Model run time was set to begin January 1, 2013 and end on January 1, 2018 for a five year model run time.

For *Road Nodes*: ID, y, and x location (GIS latitude/longitude) must be specified prior to the model run, where nodeID is simply a unique integer identifier. *Road Node* initialization data are given in Table A.2.

Table A.2 Road Node Agents' Initialization Values for Hypothetical Network.

nodeID	**y (latitude)**	**x (longitude)**
0	53.0743020	-109.5646500
1	53.0743494	-109.5889300
2	53.0742938	-109.6132400
3	53.0743190	-109.6377300
4	53.0742863	-109.6620600
5	53.0743146	-109.6863900
6	53.0743031	-109.7108100
7	53.0743050	-109.7352800
8	53.0742271	-109.7594800
9	53.0742199	-109.7840500
10	53.0743229	-109.8084400
11	53.1034015	-109.5645200
12	53.1034230	-109.5889000
13	53.1034233	-109.6134000
14	53.1034260	-109.6377600
15	53.1034139	-109.6620700
16	53.1033890	-109.6864600
17	53.1034128	-109.7108400

18	53.1033960	-109.7352600
19	53.1033922	-109.7596700
20	53.1033839	-109.7841200
21	53.1033870	-109.8084400
22	53.1324752	-109.5645400
23	53.1324889	-109.5889900
24	53.1325050	-109.6133300
25	53.1325174	-109.6377300
26	53.1324877	-109.6621000
27	53.1325160	-109.6864400
28	53.1325848	-109.7108200
29	53.1325416	-109.7352900
30	53.1325439	-109.7596600
31	53.1324475	-109.7840800
32	53.1324683	-109.8083700
33	53.1615505	-109.5646800
34	53.1615794	-109.5889100
35	53.1616056	-109.6133300
36	53.1616266	-109.6377400
37	53.1615882	-109.6621100
38	53.1615899	-109.6864600
39	53.1615592	-109.7108100
40	53.1615336	-109.7352700
41	53.1615197	-109.7595900
42	53.1615379	-109.7840300
43	53.1616138	-109.8084400
44	53.1907131	-109.5646200
45	53.1907080	-109.5890100
46	53.1907157	-109.6134100
47	53.1907362	-109.6377800
48	53.1907154	-109.6621200
49	53.1907269	-109.6865900
50	53.1907318	-109.7109000
51	53.1907416	-109.7353000
52	53.1907294	-109.7597800
53	53.1906914	-109.7840200

54	53.1906951	-109.8084000
55	53.2198315	-109.5646200
56	53.2198531	-109.5890000
57	53.2198522	-109.6134300
58	53.2198454	-109.6377800
59	53.2198158	-109.6621500
60	53.2198086	-109.6865500
61	53.2197779	-109.7109100
62	53.2197523	-109.7353700
63	53.2197846	-109.7598300
64	53.2198181	-109.7840200
65	53.2197860	-109.8084300

For *Road Segments*: ID, starting and ending node (the nodeID at each end of the *Road Segment*), road type, and speed limit must be specified prior to the model run, where roadID is simply a unique identifier. *Road Segment* initialization data are given in Table A.3.

Table A.3 Road Segment Agents' Initialization Values for Hypothetical Network.

roadID	node1	node2	roadType	speedLimit
0	0	1	0	3
1	1	2	0	3
2	2	3	0	3
3	3	4	0	3
4	4	5	0	3
5	5	6	0	3
6	6	7	0	3
7	7	8	0	3
8	8	9	0	3
9	9	10	0	3
10	11	12	0	3
11	12	13	0	3
12	13	14	0	3
13	14	15	0	3
14	15	16	0	3
15	16	17	0	3
16	17	18	0	3

17	18	19	0	3
18	19	20	0	3
19	20	21	0	3
20	22	23	0	3
21	23	24	0	3
22	24	25	0	3
23	25	26	0	3
24	26	27	0	3
25	27	28	0	3
26	28	29	0	3
27	29	30	0	3
28	30	31	0	3
29	31	32	0	3
30	33	34	1	3
31	34	35	1	3
32	35	36	0	3
33	36	37	0	3
34	37	38	0	3
35	38	39	0	3
36	39	40	0	3
37	40	41	0	3
38	41	42	0	3
39	42	43	0	3
40	44	45	0	3
41	45	46	0	3
42	46	47	0	3
43	47	48	0	3
44	48	49	0	3
45	49	50	0	3
46	50	51	0	3
47	51	52	0	3
48	52	53	0	3
49	53	54	0	3
50	55	56	0	3
51	56	57	0	3
52	57	58	0	3

53	58	59	0	3
54	59	60	0	3
55	60	61	0	3
56	61	62	0	3
57	62	63	0	3
58	63	64	0	3
59	64	65	0	3
60	0	11	0	3
61	11	22	0	3
62	22	33	0	3
63	33	44	0	3
64	44	55	0	3
65	1	12	0	3
66	12	23	0	3
67	23	34	0	3
68	34	45	0	3
69	45	56	0	3
70	2	13	0	3
71	13	24	0	3
72	24	35	0	3
73	35	46	0	3
74	46	57	0	3
75	3	14	1	3
76	14	25	1	3
77	25	36	1	3
78	36	47	1	3
79	47	58	1	3
80	4	15	0	3
81	15	26	0	3
82	26	37	0	3
83	37	48	0	3
84	48	59	0	3
85	5	16	0	3
86	16	27	0	3
87	27	38	0	3
88	38	49	0	3

89	49	60	0	3
90	6	17	0	3
91	17	28	0	3
92	28	39	0	3
93	39	50	0	3
94	50	61	0	3
95	7	18	0	3
96	18	29	0	3
97	29	40	1	3
98	40	51	1	3
99	51	62	1	3
100	8	19	0	3
101	19	30	0	3
102	30	41	0	3
103	41	52	0	3
104	52	63	0	3
105	9	20	0	3
106	20	31	0	3
107	31	42	0	3
108	42	53	0	3
109	53	64	0	3
110	10	21	0	3
111	21	32	0	3
112	32	43	0	3
113	43	54	0	3
114	54	65	0	3

Input data

An OD matrix is taken as inputs for *Road Nodes* to generate *Vehicles*. There were 7 destination nodes included in the Hypothetical network as shown in Table A.4.

Table A.4 Road Node Agents' Input Values for Vehicle Generation Rates.

nodeID (origin)	**nodeID (destination)**						
	0	**10**	**19**	**24**	**40**	**48**	**61**
0	0	0	65	65	65	65	65

…	0	0	0	0	0	0	0
10	0	0	70	65	50	60	65
…	0	0	0	0	0	0	0
55	0	75	65	65	65	40	65
…	0	0	0	0	0	0	0
65	75	0	300	65	65	40	40

The percent of trucks that make up the number of *Vehicles* generated in Table A.4 are input in as another OD type matrix as shown in Table A.5.

Table A.5 Road Node Agents' Input Values for Generated Vehicle Composition.

nodeID (origin)	**nodeID (destination)**						
	0	**10**	**19**	**24**	**40**	**48**	**61**
0	0	0	33	33	33	33	33
…	0	0	0	0	0	0	0
10	0	0	33	33	33	33	33
…	0	0	0	0	0	0	0
55	0	33	33	33	33	33	33
…	0	0	0	0	0	0	0
65	33	0	60	33	33	33	33

The RM inputs are for weight restrictions on *Road Segments* (e.g., Primary weight, Secondary weight etc.) that may vary by season as shown in given in Table A.6.

Table A.6 RM Agent Input Data for Road Segment Weight Restrictions.

roadID	**Winter Weight**	**Spring Weight**	**Summer Weight**	**Fall weight**
0	0	1	1	1
1	0	1	1	1
2	0	1	1	1
3	0	1	1	1
4	0	1	1	1
5	0	1	1	1
6	0	1	1	1
7	0	1	1	1
8	0	1	1	1
9	0	1	1	1

10	0	1	1	1
11	0	1	1	1
12	0	1	1	1
13	0	1	1	1
14	0	1	1	1
15	0	1	1	1
16	0	1	1	1
17	0	1	1	1
18	0	1	1	1
19	0	1	1	1
20	0	2	1	1
21	0	2	1	1
22	0	2	1	1
23	0	2	1	1
24	0	2	1	1
25	0	2	1	1
26	0	2	1	1
27	0	2	1	1
28	0	2	1	1
29	0	2	1	1
30	0	1	1	1
31	0	1	1	1
32	0	1	1	1
33	0	4	1	1
34	0	4	1	1
35	0	4	1	1
36	0	1	1	1
37	0	1	1	1
38	0	1	1	1
39	0	1	1	1
40	0	1	1	1
41	0	1	1	1
42	0	1	1	1
43	0	1	1	1
44	0	1	1	1
45	0	1	1	1

46	0	1	1	1
47	0	1	1	1
48	0	1	1	1
49	0	1	1	1
50	0	3	1	1
51	0	3	1	1
52	0	3	1	1
53	0	3	1	1
54	0	3	1	1
55	0	3	1	1
56	0	1	1	1
57	0	1	1	1
58	0	1	1	1
59	0	1	1	1
60	0	1	1	1
61	0	1	1	1
62	0	1	1	1
63	0	1	1	1
64	0	1	1	1
65	0	1	1	1
66	0	1	1	1
67	0	1	1	1
68	0	1	1	1
69	0	1	1	1
70	0	2	1	1
71	0	2	1	1
72	0	1	1	1
73	0	1	1	1
74	0	1	1	1
75	0	1	1	1
76	0	1	1	1
77	0	1	1	1
78	0	1	1	1
79	0	1	1	1
80	0	1	1	1
81	0	1	1	1

82	0	1	1	1
83	0	1	1	1
84	0	1	1	1
85	0	1	1	1
86	0	1	1	1
87	0	1	1	1
88	0	1	1	1
89	0	1	1	1
90	0	1	1	1
91	0	1	1	1
92	0	1	1	1
93	0	1	1	1
94	0	1	1	1
95	0	1	1	1
96	0	1	1	1
97	0	1	1	1
98	0	1	1	1
99	0	1	1	1
100	0	1	1	1
101	0	1	1	1
102	0	1	1	1
103	0	1	1	1
104	0	1	1	1
105	0	1	1	1
106	0	1	1	1
107	0	1	1	1
108	0	1	1	1
109	0	1	1	1
110	0	1	1	1
111	0	1	1	1
112	0	1	1	1
113	0	1	1	1
114	0	1	1	1

For *Vehicles*: configuration, unit distance based costs for each road type, and unit time based costs are input and used when *Road Nodes* create *Vehicles*. The inputs for *Vehicles* are shown in Table A.7.

Table A.7 Vehicle Agents' Input Values.

vehConfig	unitOC_DistType0 ($/km)	unitOC_DistType1 ($/km)	unitOC_Time ($/hr)
0	0.20	0.14	27.36
2	0.67	0.42	55.45

The data outlined in this appendix were used for the "Base Case" in Chapter 5. To consider alternate scenarios in Chapter 5, such as road upgrade and road permit fees, the "RM Capital Budget" and "Permit Fee Multiplier" parameters in the model were varied.

APPENDIX B RM OF WILTON CASE STUDY DATA

This appendix contains the initialization and input data used in the model for the RM of Wilton case study used to generate the results presented in Chapter 6. While some model inputs were highlighted in Chapter 6, the full set of initialization and input data is outlined in this appendix. Initialization data are required at model start-up while input data are used throughout model runs. Much of the initialization and input data are input through Microsoft Excel spreadsheets linked to the model. The tables in this appendix show the data within each sheet of the Excel input file.

Some of the initialization and input data covered in this appendix are categorical. For ease of handling inputs in the model, the categories of variables were translated to have integer representation. Table B.1 shows the integer representation of each input category in the model.

Table B.1 Integer Representation of Categorical Variables for Model Initialization and Inputs.

<table>
<tr><th>Model Integer Representation</th><th colspan="3">Real Value</th></tr>
<tr><td colspan="4">Speed Limits (speedLimit) (km/hr)</td></tr>
<tr><td>0</td><td colspan="3">110</td></tr>
<tr><td>1</td><td colspan="3">100</td></tr>
<tr><td>2</td><td colspan="3">90</td></tr>
<tr><td>3</td><td colspan="3">80</td></tr>
<tr><td>4</td><td colspan="3">70</td></tr>
<tr><td colspan="4">Weight Limits (weightLimit & vehWeightCat)</td></tr>
<tr><td>0</td><td colspan="3">100 % Primary</td></tr>
<tr><td>1</td><td colspan="3">85 % Primary (Secondary)</td></tr>
<tr><td>2</td><td colspan="3">75 % Primary</td></tr>
<tr><td>3</td><td colspan="3">50 % Primary</td></tr>
<tr><td>4</td><td colspan="3">5,500 kg</td></tr>
<tr><td colspan="4">Vehicle Configurations</td></tr>
<tr><td></td><td>vehConfig</td><td>vehTareWeight (kg)</td><td>vehMaxPossibleGVW (kg)</td></tr>
<tr><td>0</td><td>8-axle</td><td>20,500</td><td>62,500</td></tr>
<tr><td>1</td><td>6-axle</td><td>16,500</td><td>47,000</td></tr>
<tr><td>2</td><td>5-axle</td><td>15,000</td><td>40,000</td></tr>
</table>

Road Type	
0	Gravel
1	Paved
88	Out of scope (for handling external OD traffic - no influence on costs/routing)
99	Out of RM jurisdiction (for Highways - influence user costs, but not RM costs)

Initialization data

Model run time was set to begin January 1, 2013 and end on January 1, 2018 for a five year model run time.

For *Road Nodes*: ID, y, and x location (GIS latitude/longitude) must be specified prior to the model run, where nodeID is simply a unique integer identifier. For each *Road Node*, y and x coordinates were taken from each end coordinates of each road segment from the shapefile of the RM of Wilton road network. *Road Node* initialization data are given in Table B.2.

Table B.2 Road Node Agents' Initialization Values for Case Study.

nodeID	**y (latitude)**	**x (longitude)**
0	53.144764000000000	-109.930260000000000
1	53.146954700000000	-109.979100000000000
2	53.146985500000000	-109.954660000000000
3	53.147015699999900	-109.784040000000000
4	53.147064800000000	-109.832730000000000
5	53.147074199999900	-109.710890000000000
6	53.147102699999900	-109.857150000000000
7	53.147115800000000	-109.881680000000000
8	53.147116400000000	-109.735260000000000
9	53.151641099999900	-109.930250000000000
10	53.151756700000000	-109.759590000000000
11	53.154254299999900	-109.979100000000000
12	53.154401399999900	-109.808470000000000
13	53.155795500000000	-109.954690000000000
14	53.158934000000000	-109.710820000000000
15	53.159974516314200	-110.009160755287000
16	53.160624400000000	-109.710840000000000

17	53.160744965710000	-109.707082956193000
18	53.161519699999900	-109.759590000000000
19	53.161533599999900	-109.735270000000000
20	53.161535299999900	-109.966530000000000
21	53.161538000000000	-109.784030000000000
22	53.161548400000000	-109.954640000000000
23	53.161553499999900	-109.979060000000000
24	53.161579900000000	-110.005550000000000
25	53.161599199999900	-109.919040000000000
26	53.161601400000000	-109.930229999999000
27	53.161602999999900	-109.832710000000000
28	53.161613899999900	-109.808440000000000
29	53.161624099999900	-109.906009999999000
30	53.161626499999900	-109.727120000000000
31	53.161651399999900	-109.857159999999000
32	53.161686899999900	-109.881790000000000
33	53.161880799999900	-109.709819999999000
34	53.162547199999900	-109.709100000000000
35	53.166089900000000	-109.710810000000000
36	53.168676599999900	-109.930280000000000
37	53.168877100000000	-109.710849999999000
38	53.169035299999900	-109.759620000000000
39	53.170636299999900	-109.734900000000000
40	53.171401000000000	-109.734110000000000
41	53.171720899999900	-109.733760000000000
42	53.172915600000000	-109.733670000000000
43	53.176119499999900	-110.005510000000000
44	53.176147600000000	-109.784009999999000
45	53.176148900000000	-109.905940000000000
46	53.176159400000000	-109.857180000000000
47	53.176164800000000	-109.832780000000000
48	53.176182699999900	-109.715270000000000
49	53.176195200000000	-109.808440000000000
50	53.176201499999900	-109.979050000000000
51	53.176203800000000	-109.735249999999000
52	53.176209499999900	-109.881900000000000

53	53.176210099999900	-109.759640000000000
54	53.176525200000000	-109.954650000000000
55	53.177147400000000	-109.748760000000000
56	53.178640999999900	-109.735260000000000
57	53.181387299999900	-109.759620000000000
58	53.190670300000000	-109.979020000000000
59	53.190683999999900	-109.954680000000000
60	53.190686300000000	-109.966280000000000
61	53.190691500000000	-109.784020000000000
62	53.190695099999900	-109.808400000000000
63	53.190695699999900	-109.844970000000000
64	53.190696799999900	-110.005520000000000
65	53.190697200000000	-109.796080000000000
66	53.190698599999900	-109.820490000000000
67	53.190699500000000	-109.770790000000000
68	53.190703100000000	-109.832809999999000
69	53.190703900000000	-109.868300000000000
70	53.190706599999900	-109.930490000000000
71	53.190709800000000	-109.895750000000000
72	53.190721500000000	-109.881590000000000
73	53.190722200000000	-109.905869999999000
74	53.190723400000000	-109.857159999999000
75	53.190729400000000	-109.759780000000000
76	53.190731800000000	-109.710900000000000
77	53.190741600000000	-109.735300000000000
78	53.190744299999900	-109.694700000000000
79	53.193235600000000	-109.784020000000000
80	53.198405999999900	-109.785910000000000
81	53.198708799999900	-109.785630000000000
82	53.199314299999900	-109.785060000000000
83	53.199711499999900	-109.710790000000000
84	53.200109099999900	-109.789840000000000
85	53.200763500000000	-109.808390000000000
86	53.203851899999900	-109.807990000000000
87	53.203936300000000	-109.799380000000000
88	53.205094299999900	-109.954690000000000

89	53.205142700000000	-109.857150000000000
90	53.205190399999900	-109.735420000000000
91	53.205203900000000	-109.881600000000000
92	53.205226900000000	-109.759810000000000
93	53.205242599999900	-109.979040000000000
94	53.205319600000000	-109.832740000000000
95	53.205358400000000	-110.005500000000000
96	53.205923900000000	-109.905900000000000
97	53.209021399999900	-109.784009999999000
98	53.211570100000000	-109.710900000000000
99	53.211649500000000	-109.979060000000000
100	53.214356100000000	-109.810210000000000
101	53.218119399999900	-109.813480000000000
102	53.219752300000000	-109.735370000000000
103	53.219756199999900	-109.954680000000000
104	53.219764499999900	-109.930300000000000
105	53.219768000000000	-109.905919999999000
106	53.219769800000000	-109.814920000000000
107	53.219770400000000	-109.979130000000000
108	53.219771399999900	-109.966730000000000
109	53.219777299999900	-110.005460000000000
110	53.219777899999900	-109.710910000000000
111	53.219784599999900	-109.759829999999000
112	53.219785999999900	-109.808430000000000
113	53.219794100000000	-109.881609999999000
114	53.219810199999900	-109.845590000000000
115	53.219810600000000	-109.832710000000000
116	53.219814300000000	-109.857209999999000
117	53.219818099999900	-109.784020000000000
118	53.229437900000000	-109.832660000000000
119	53.229795799999900	-109.832480000000000
120	53.233651999999900	-109.846300000000000
121	53.234284199999900	-109.735339999999000
122	53.234294100000000	-109.881590000000000
123	53.234306900000000	-109.759680000000000
124	53.234307299999900	-109.954680000000000

125	53.234309699999900	-109.784040000000000
126	53.234327299999900	-109.710939999999000
127	53.234330800000000	-109.808409999999000
128	53.234343400000000	-109.857140000000000
129	53.234366600000000	-109.832710000000000
130	53.234546799999900	-109.905919999999000
131	53.242126900000000	-109.857260000000000
132	53.242420099999900	-109.856900000000000
133	53.242677399999900	-109.856540000000000
134	53.244651300000000	-109.710810000000000
135	53.246586600000000	-109.867710000000000
136	53.247112000000000	-109.867189999999000
137	53.248317100000000	-109.873880000000000
138	53.248654999999900	-109.873490000000000
139	53.248671600000000	-109.979130000000000
140	53.248837399999900	-109.954700000000000
141	53.248844099999900	-109.966810000000000
142	53.248859699999900	-109.942359999999000
143	53.248882199999900	-109.930359999999000
144	53.248885100000000	-109.905910000000000
145	53.248890199999900	-109.880330000000000
146	53.248893199999900	-109.881600000000000
147	53.248895300000000	-110.005489999999000
148	53.248897399999900	-109.735420000000000
149	53.248919100000000	-109.759730000000000
150	53.248921500000000	-109.808449999999000
151	53.248922299999900	-109.857190000000000
152	53.248940699999900	-109.845110000000000
153	53.248962499999900	-109.784009999999000
154	53.248964299999900	-109.832759999999000
155	53.250033899999900	-109.716430000000000
156	53.250042000000000	-109.954700000000000
157	53.250061299999900	-109.881540000000000
158	53.251544500000000	-109.881530000000000
159	53.254548399999900	-109.905900000000000
160	53.2547104000000	-109.8903700000000

161	53.2563135999999	-109.9576900000000
162	53.2577343999999	-109.7107500000000
163	53.2595053000000	-109.7354299999990
164	53.2606881000000	-109.9059000000000
165	53.2633805999999	-109.6987400000000
166	53.2633907000000	-109.9577000000000
167	53.2634198000000	-109.8815500000000
168	53.2634283000000	-109.9303500000000
169	53.2634613000000	-109.8327199999990
170	53.2634946000000	-109.7840400000000
171	53.2638627999999	-109.8085100000000
172	53.2638859999999	-109.7113400000000
173	53.2654952655588	-109.6898865256800
174	53.2664751000000	-109.9214300000000
175	53.2667555000000	-109.9058299999990
176	53.2670958000000	-109.7597000000000
177	53.2689993999999	-109.9302200000000
178	53.2693483999999	-109.9300400000000
179	53.2717140000000	-109.7355000000000
180	53.2728843000000	-109.9435000000000
181	53.2732054000000	-109.9432000000000
182	53.2771826999999	-109.9569300000000
183	53.2777980999999	-109.9609100000000
184	53.2778447999999	-109.7109399999990
185	53.2778977999999	-109.7493700000000
186	53.2779113000000	-109.9791000000000
187	53.2779375000000	-109.9305200000000
188	53.2779475000000	-109.7597600000000
189	53.2779539000000	-110.0055799999990
190	53.2779566000000	-109.9061100000000
191	53.2779579999999	-109.8086700000000
192	53.2779723000000	-109.7844000000000
193	53.2779735000000	-109.8815199999990
194	53.2779826000000	-109.8327599999990
195	53.2779937999999	-109.8573700000000
196	53.2796715344411	-110.0068802250760

For *Road Segments*: ID, starting and ending node (the nodeID at each end of the *Road Segment*), road type, and speed limit must be specified prior to the model run, where roadID is simply a unique identifier. *Road Segment* initialization data are given in Table B.3.

Table B.3 Road Segment Agents' Initialization Values for Case Study.

roadID	node1	node2	roadType	speedLimit
0	0	9	0	3
1	1	11	0	3
2	2	13	0	4
3	3	21	0	3
4	4	27	0	3
5	5	14	0	3
6	6	31	0	3
7	7	32	0	3
8	8	19	1	3
9	9	26	0	3
10	10	18	0	3
11	11	23	0	3
12	12	28	0	3
13	13	22	0	4
14	14	16	0	3
15	15	24	88	0
16	16	33	0	3
17	17	33	88	0
18	18	19	0	3
19	18	38	0	3
20	18	21	0	3
21	19	30	0	3
22	19	39	1	3
23	20	23	0	3
24	20	22	0	3
25	21	44	0	3
26	21	28	0	3
27	22	26	0	3
28	22	54	0	4
29	23	50	0	3

30	23	24	0	3
31	25	29	0	3
32	25	26	0	3
33	26	36	0	3
34	27	47	0	3
35	28	49	0	3
36	29	45	0	3
37	31	46	0	3
38	32	52	0	3
39	33	40	99	0
40	33	34	0	3
41	34	35	0	3
42	35	37	0	3
43	37	48	0	3
44	38	53	0	3
45	39	40	1	3
46	40	41	0	3
47	40	55	99	0
48	41	42	0	3
49	42	51	0	3
50	43	64	99	1
51	44	61	0	3
52	45	73	0	3
53	46	74	0	3
54	47	68	0	3
55	48	76	0	3
56	49	62	0	3
57	50	58	0	3
58	51	56	0	3
59	52	72	0	3
60	53	57	0	3
61	54	59	0	4
62	55	57	99	0
63	56	77	0	3
64	57	67	99	0
65	58	60	0	3

66	58	64	0	3
67	58	93	0	3
68	59	88	0	3
69	59	70	0	3
70	59	60	0	3
71	61	79	0	3
72	61	65	0	3
73	62	65	0	3
74	62	85	0	3
75	62	66	0	3
76	63	68	0	3
77	63	74	0	3
78	64	95	99	1
79	66	68	0	3
80	67	75	1	3
81	67	81	99	0
82	68	94	0	3
83	69	74	0	3
84	69	72	0	3
85	70	73	0	3
86	71	72	0	3
87	71	73	0	3
88	72	91	0	3
89	73	96	0	3
90	74	89	0	3
91	75	92	0	3
92	75	77	1	3
93	76	77	1	3
94	76	83	0	3
95	76	78	1	3
96	77	90	0	3
97	79	80	0	3
98	80	81	0	3
99	81	82	0	3
100	81	84	99	0
101	82	97	0	3

102	84	87	99	0
103	85	86	0	3
104	87	100	99	0
105	88	103	0	3
106	89	116	0	3
107	90	102	0	3
108	91	113	0	3
109	92	111	0	3
110	94	115	0	3
111	95	109	99	1
112	96	105	0	3
113	97	117	0	3
114	98	110	0	3
115	99	107	0	3
116	100	101	99	0
117	101	106	99	0
118	102	121	0	3
119	102	110	0	4
120	102	111	0	4
121	103	104	0	3
122	103	124	0	3
123	103	108	0	3
124	104	105	0	3
125	105	113	0	3
126	105	130	0	3
127	106	112	0	3
128	106	115	0	3
129	106	118	99	0
130	107	139	0	3
131	107	109	0	3
132	107	108	0	3
133	109	147	99	1
134	110	126	0	3
135	111	117	0	4
136	111	123	0	3
137	112	117	0	3

138	112	127	0	3
139	113	116	0	3
140	113	122	0	3
141	114	115	0	3
142	114	116	0	3
143	115	118	0	3
144	116	128	0	3
145	117	125	0	3
146	118	119	0	3
147	118	120	99	0
148	119	129	0	3
149	120	132	99	0
150	121	148	0	3
151	122	146	0	3
152	123	149	0	3
153	124	140	0	3
154	125	153	0	3
155	126	134	0	3
156	127	150	0	3
157	128	131	0	3
158	129	154	0	3
159	130	144	0	3
160	131	132	0	3
161	132	133	0	3
162	132	135	99	0
163	133	151	0	3
164	135	136	1	3
165	135	138	99	0
166	136	151	1	3
167	137	138	0	3
168	137	145	0	3
169	138	158	99	0
170	139	141	1	3
171	140	142	0	3
172	140	156	1	3
173	140	141	1	3

174	142	143	0	3
175	143	144	0	3
176	143	168	0	3
177	144	146	0	3
178	144	159	0	3
179	145	146	0	3
180	146	157	0	3
181	147	189	99	3
182	148	149	0	3
183	148	163	0	3
184	148	155	0	3
185	149	153	0	3
186	149	176	0	3
187	150	153	1	3
188	150	154	1	3
189	150	171	0	3
190	151	152	1	3
191	152	154	1	3
192	153	170	0	3
193	154	169	0	3
194	155	162	0	3
195	156	161	1	3
196	157	158	0	3
197	158	160	99	1
198	158	167	0	3
199	159	164	0	3
200	160	164	99	1
201	161	166	1	3
202	162	165	0	3
203	164	175	0	3
204	164	174	99	1
205	165	172	99	1
206	165	173	88	0
207	166	182	1	3
208	167	193	0	3
209	168	177	0	3

210	169	194	0	3
211	170	192	0	3
212	172	184	0	3
213	172	179	99	1
214	174	177	99	1
215	177	178	0	3
216	177	180	99	1
217	178	187	0	3
218	179	185	99	1
219	180	181	99	3
220	180	182	99	3
221	181	187	99	1
222	182	183	99	3
223	183	186	99	3
224	185	188	99	1
225	186	189	99	3
226	187	190	99	1
227	188	192	99	1
228	189	196	88	0
229	190	193	99	1
230	191	192	99	1
231	191	194	99	1
232	193	195	99	1
233	194	195	99	1

Input data

An OD matrix is taken as inputs for *Road Nodes* to generate *Vehicles*. There were 16 destination nodes included in the Case Study network as shown in Table B.4.

Table B.4 Road Node Agents' Input Values for Vehicle Generation Rates.

nodeID (origin)	**nodeID (destination)**															
	0	**3**	**15**	**17**	**31**	**45**	**54**	**70**	**78**	**97**	**101**	**107**	**119**	**139**	**173**	**196**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	8	2	8	8	8	8	0	0	10	3	8	0	8	0	8	0
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	8	10	8	8	8	8	0	8	10	3	8	8	8	8	0	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	8	10	0	15	8	8	8	13	10	0	8	8	8	8	15	15
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	8	10	15	0	8	8	8	8	10	3	8	8	8	50	15	15
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	8	10	8	8	8	8	0	8	10	3	8	8	8	8	8	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	17	10	8	8	8	15	3	25	10	3	8	2	8	2	8	175
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	8	0	0	0	0	0	3	8	8	8	5	8	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	8	20	8	8	8	8	3	8	10	0	8	8	8	8	0	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123	8	15	8	8	8	8	8	8	10	0	8	8	8	8	8	12
124	0	10	8	8	0	0	0	0	10	3	8	8	8	8	4	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
143	0	10	8	8	8	8	0	8	10	3	8	8	8	20	0	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	8	10	8	8	8	8	0	13	10	0	8	8	8	8	8	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	8	10	15	15	3	8	8	8	10	0	0	8	0	230	0	15
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	8	0	8	0	8	8	2	8	10	0	8	8	8	100	8	8
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	8	63	15	15	8	8	3	75	50	0	8	8	8	250	15	0

The percent of trucks that make up the number of *Vehicles* generated in Table B.4 are input in as another OD type matrix as shown in Table B.5.

Table B.5 Road Node Agents' Input Values for Generated Vehicle Composition.

nodeID (origin)	**nodeID (destination)**															
	0	**3**	**15**	**17**	**31**	**45**	**54**	**70**	**78**	**97**	**101**	**107**	**119**	**139**	**173**	**196**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
124	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
143	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

For the shift in traffic patterns explored in Section 6.5.3, the updated OD matrix is given in Table B.6.

Table B.6 Road Node Agents' Input Values for Vehicle Generation Rates for Shifting Traffic Scenario.

nodeID (origin)	**nodeID (destination)**															
	0	**3**	**15**	**17**	**31**	**45**	**54**	**70**	**78**	**97**	**101**	**107**	**119**	**139**	**173**	**196**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	6	2	6	25	6	6	0	0	8	2	6	0	6	0	6	0
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6	8	6	33	6	6	0	6	8	2	6	6	6	6	0	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	6	8	0	46	6	6	6	10	8	0	6	6	6	6	11	11
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	6	8	11	0	6	6	6	6	8	2	6	6	6	38	11	11
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	6	8	6	35	6	6	0	6	8	2	6	6	6	6	6	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	13	8	6	82	6	11	2	19	8	2	6	2	6	2	6	131
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	20	0	0	0	0	0	2	6	6	6	4	6	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	6	15	6	36	6	6	2	6	8	0	6	6	6	6	0	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123	6	11	6	39	6	6	6	6	8	0	6	6	6	6	6	9
124	0	8	6	26	0	0	0	0	8	2	6	6	6	6	3	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
143	0	8	6	34	6	6	0	6	8	2	6	6	6	15	0	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167	6	8	6	35	6	6	0	10	8	0	6	6	6	6	6	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
173	6	8	11	95	2	6	6	6	8	0	0	6	0	173	0	11
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
191	6	0	6	47	6	6	2	6	8	0	6	6	6	75	6	6
…	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
196	6	47	11	145	6	6	2	56	38	0	6	6	6	188	11	0

The RM inputs are for weight restrictions on *Road Segments* (e.g., Primary weight, Secondary weight etc.) that may vary by season as shown in given in Table B.7.

Table B.7 RM Agent Input Data for Road Segment Weight Restrictions.

roadID	Winter Weight	Spring Weight	Summer Weight	Fall weight
0	0	1	0	0
1	0	1	0	0
2	0	1	0	0
3	0	1	0	0
4	0	4	4	4
5	0	2	2	2
6	0	1	0	0
7	0	1	0	0
8	0	1	0	0
9	0	1	0	0
10	0	1	0	0
11	0	1	0	0
12	0	1	0	0
13	0	1	0	0
14	0	2	2	2
15	0	1	0	0
16	0	2	2	2
17	0	1	0	0
18	0	1	0	0
19	0	2	2	2
20	0	1	0	0
21	0	1	0	0
22	0	1	0	0
23	0	1	0	0
24	0	1	0	0
25	0	1	0	0
26	0	1	0	0
27	0	1	0	0
28	0	1	0	0
29	0	1	0	0
30	0	1	0	0

31	0	1	0	0
32	0	1	0	0
33	0	1	0	0
34	0	4	4	4
35	0	1	0	0
36	0	1	0	0
37	0	2	2	2
38	0	1	0	0
39	0	1	0	0
40	0	1	0	0
41	0	1	0	0
42	0	1	0	0
43	0	1	0	0
44	0	2	2	2
45	0	1	0	0
46	0	1	0	0
47	0	1	0	0
48	0	1	0	0
49	0	1	0	0
50	0	1	0	0
51	0	1	0	0
52	0	1	0	0
53	0	2	2	2
54	0	1	0	0
55	0	1	0	0
56	0	1	0	0
57	0	1	0	0
58	0	1	0	0
59	0	1	0	0
60	0	2	2	2
61	0	1	0	0
62	0	1	0	0
63	0	1	0	0
64	0	1	0	0
65	0	1	0	0
66	0	1	0	0

67	0	1	0	0
68	0	1	0	0
69	0	1	0	0
70	0	1	0	0
71	0	1	0	0
72	0	1	0	0
73	0	1	0	0
74	0	1	0	0
75	0	1	0	0
76	0	1	0	0
77	0	1	0	0
78	0	1	0	0
79	0	1	0	0
80	0	1	0	0
81	0	1	0	0
82	0	3	3	3
83	0	1	0	0
84	0	1	0	0
85	0	1	0	0
86	0	1	0	0
87	0	1	0	0
88	0	1	0	0
89	0	1	0	0
90	0	1	0	0
91	0	3	3	3
92	0	1	0	0
93	0	1	0	0
94	0	1	0	0
95	0	1	0	0
96	0	2	2	2
97	0	1	0	0
98	0	1	0	0
99	0	1	0	0
100	0	1	0	0
101	0	1	0	0
102	0	1	0	0

103	0	1	0	0
104	0	1	0	0
105	0	1	0	0
106	0	1	0	0
107	0	2	2	2
108	0	1	0	0
109	0	3	3	3
110	0	3	3	3
111	0	1	0	0
112	0	1	0	0
113	0	1	0	0
114	0	1	0	0
115	0	1	0	0
116	0	1	0	0
117	0	1	0	0
118	0	2	2	2
119	0	1	0	0
120	0	1	0	0
121	0	1	0	0
122	0	1	0	0
123	0	1	0	0
124	0	1	0	0
125	0	1	0	0
126	0	1	0	0
127	0	1	0	0
128	0	1	0	0
129	0	1	0	0
130	0	1	0	0
131	0	1	0	0
132	0	1	0	0
133	0	1	0	0
134	0	1	0	0
135	0	1	0	0
136	0	2	2	2
137	0	1	0	0
138	0	3	3	3

139	0	1	0	0
140	0	1	0	0
141	0	1	0	0
142	0	1	0	0
143	0	1	0	0
144	0	1	0	0
145	0	1	0	0
146	0	2	2	2
147	0	1	0	0
148	0	2	2	2
149	0	1	0	0
150	0	2	2	2
151	0	1	0	0
152	0	2	2	2
153	0	1	0	0
154	0	1	0	0
155	0	1	0	0
156	0	1	0	0
157	0	1	0	0
158	0	2	2	2
159	0	1	0	0
160	0	1	0	0
161	0	1	0	0
162	0	1	0	0
163	0	1	0	0
164	0	1	0	0
165	0	1	0	0
166	0	1	0	0
167	0	1	0	0
168	0	1	0	0
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222	0	1	0	0
223	0	1	0	0
224	0	1	0	0
225	0	1	0	0
226	0	1	0	0
227	0	1	0	0
228	0	1	0	0
229	0	1	0	0
230	0	1	0	0
231	0	1	0	0
232	0	1	0	0
233	0	1	0	0

For *Vehicles*: configuration, unit distance based costs for each road type, and unit time based costs are input and used when *Road Nodes* create *Vehicles*. The inputs for *Vehicles* are shown in Table B.8.

Table B.8 Vehicle Agents' Input Values.

vehConfig	**unitOC_DistType0 ($/km)**	**unitOC_DistType1 ($/km)**	**unitOC_Time ($/hr)**
0	0.20	0.14	27.36
2	0.67	0.42	55.45

The data outlined in this appendix were used for the "Base Case" in Chapter 6. To consider alternate scenarios in Chapter 6, such as road upgrade and road permit fees, the "RM Capital Budget" and "Permit Fee Multiplier" parameters in the model were varied.

Setting Vehicle Generation Rates

This section describes the process of setting the input *Vehicle* generation rates for *Road Nodes* in order to represent initial traffic patterns in the RM case study.

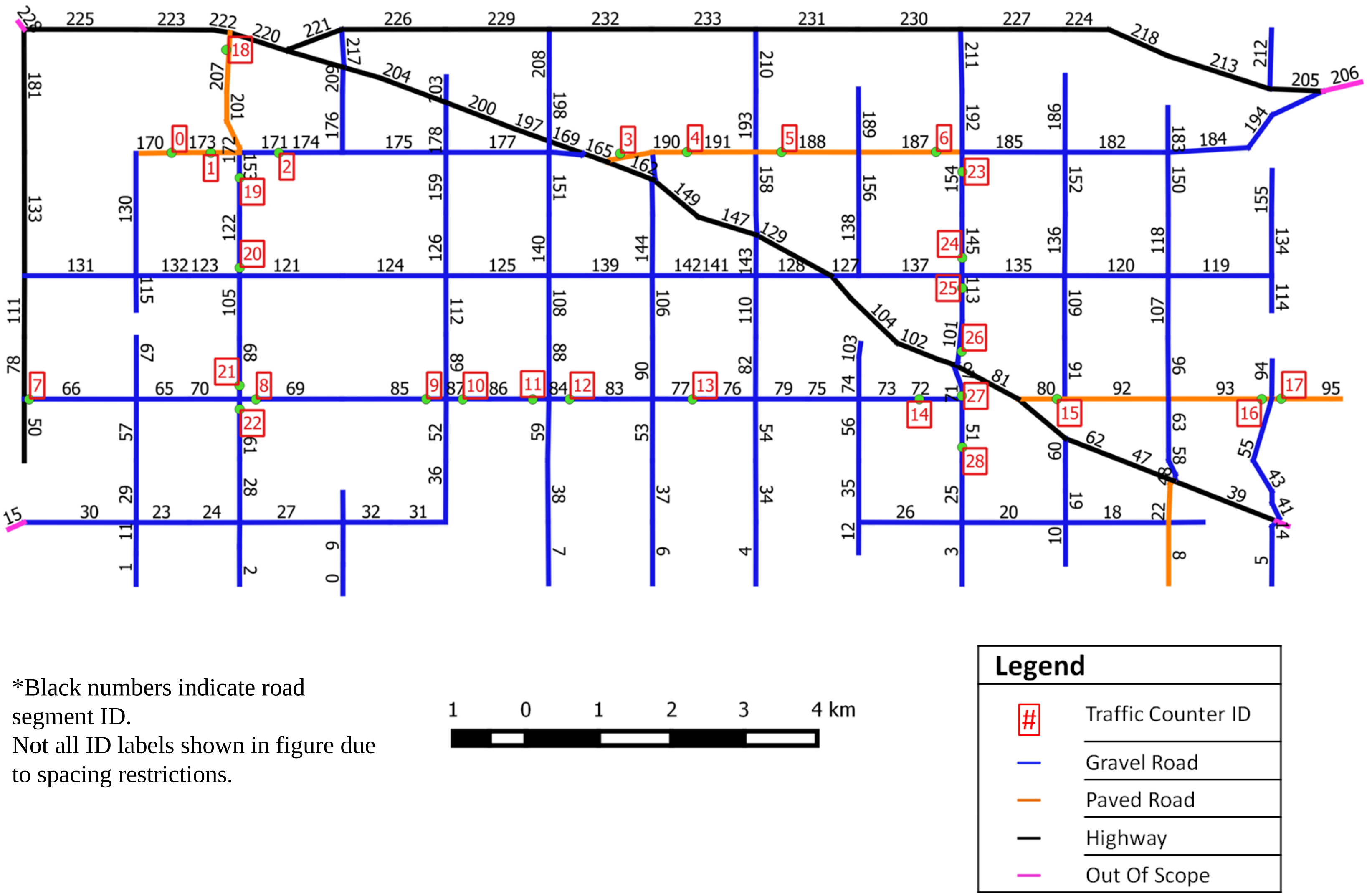
To set the initial traffic levels in the model, existing traffic counts from 2013 were used for select segments of the RM of Wilton road network (RM of Wilton No, 472, 2014). OD data was not available for the network. The approach was to begin with placeholder values for the generated vpd for the major origins and destinations established in Chapter 6 and then change the generated vpd values for various OD pairs until traffic levels more closely matched the actual traffic counts. For this process, one year model runs were completed without permit fees. Recall that the four corners of the network were used to represent external origins or destinations to the network. Major destinations were associated with the oil and gas industry based on the locations of major oil installations (e.g., battery sites where heavy oil is cleaned and treated, or disposal sites). Major origins were approximated from oil well location clustering. This was a rough approximation of origins and destinations in the absence of OD survey data. In reality there would be other types of traffic such as residential, agricultural, etc. that may have different origins and destinations.

The final traffic count data used in model runs, along with the model traffic data (ADT over a one year model run) is given in Table B.9 along with the percent difference from the real traffic count values. The location of the traffic counters is shown in Figure B.1.

Table B.9 Comparison of Model Traffic Counts to Real Traffic Counts for Select Segments.

Traffic Counter ID	Road Segment ID	Real Traffic Count (ADT)	Model Traffic Count (ADT)	Difference (Model ADT - Real ADT)	Percent Difference from Real ADT
0	170	1,752	1,470	-282	-16%
1	173	1,659	1,470	-189	-11%
2	171	394	394	0	0%
3	166	152	88	-64	-42%
4	190	95	113	18	19%
5	188	91	94	3	3%
6	187	69	94	25	36%
7	66	728	622	-106	-15%
8	69	596	366	-230	-39%
9	85	438	262	-176	-40%
10	87	377	464	87	23%
11	86	409	464	55	13%
12	84	432	464	32	7%
13	77	413	469	56	14%
14	72	397	366	-31	-8%
15	80	355	315	-40	-11%
16	93	349	340	-9	-3%
17	95	357	360	3	1%
18	207	1,290	1,360	70	5%
19	153	295	336	41	14%
20	122	215	234	19	9%
21	68	169	246	77	46%
22	61	141	86	-55	-39%
23	154	75	38	-37	-49%
24	145	74	38	-36	-49%
25	113	75	86	11	15%
26	101	83	98	15	18%
27	71	667	676	9	1%
28	51	497	470	-27	-5%

As seen in Table B.9, the percent difference of model traffic counts were less than 50% for all segments where traffic counts were available. This process was a fairly rough approximation of actual traffic patterns and it was difficult to achieve low percent difference to actual counts: modifying one OD pair may result in one road's traffic count becoming fairly close to actual counts, but another road segment's traffic count would become further off, and so on. Also, there may be multiple solutions to OD pairs that result in matching actual counts, so without OD survey data it is difficult to say how accurate the OD patterns used in the model represent reality. Methods have been established for estimating an OD matrix given traffic counts as outlined in (Bera & Rao, 2011), but these methods were too complex for the scope of this research. A more thorough process for establishing traffic levels would be desirable with the inclusion of any additional information regarding origins and destinations (perhaps OD survey data).



*Black numbers indicate road segment ID.
Not all ID labels shown in figure due to spacing restrictions.

Figure B.1 Case Study Network with Traffic Counter Locations.

APPENDIX C MODEL TESTING

This appendix describes the testing procedures for the model developed in this research. While there are not well-defined and agreed upon methods for testing for ABMs, the general model testing approach used was based on the outline given by (Castle & Crooks, 2006) for verification and validation.[1] Verification is the process of checking that the model behaves as expected (sometimes referred to as 'inner-validity'). This is done through a series of tests for specific components within the model with a range in inputs. Validation is confirming that the model accurately represents the real world situation. This is done by comparing model outputs to data collected from the real world.

Model Verification

Verification consists of checking the model to ensure that the intended calculations are being implemented correctly during model runs. The calculations outlined in this section were completed "by hand" and then model runs were completed to confirm the results in this section matched outputs from the model. The main aspects of the model that were verified in detail were: vehicle routing, vehicle cost per trip (with and without permit fees), RM cost per total vehicle trips and RM upgrade costs.

To test vehicle routing, a simple three node, three segment road network was used with only one vehicle OD trip as shown in Figure C.1. The vehicle routing was verified by holding all parameters constant and changing permit fees on the selected route. Once the least cost route

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[1] (Castle & Crooks, 2006) also include calibration in the model testing process. Calibration involves setting the model structure and model parameters such that the model accurately reflects the real world situation that is represented in the model. This is done primarily by setting the agent parameters. Calibration typically requires data on the micro-level processes that the ABM is based upon. Calibration was not included in the modelling process for this research. The term 'calibration' can have different connotations in different modeling fields. It was thought best to avoid the term 'calibration' term in order to avoid any confusion or implication that the fundamentals of the model developed herein were modified in order to match reality. In the context of ABMs, the term 'calibration' could likely be used to describe the process completed for setting initial parameters in the model such as establishing road segment and road node locations and establishing initial traffic levels, as described in Appendix B.

was chosen by the vehicle, a permit fee along the route was implemented to confirm that the vehicle routing and resulting costs (for both the vehicle and the RM) were altered.

Inputs:

Model runs were from January 1, 2013 to January 1, 2014 (1 year model run). One OD pair was input: 100 vpd with origin nodeID: 0 and destination nodeID: 1, with 25% of traffic being truck traffic using all 6-axle vehicle configuration for trucks. All roads were set to Primary weight allowance. The inputs for *Vehicles* was the same as that used for the case study in Chapter 6 (distance and time based unit costs).

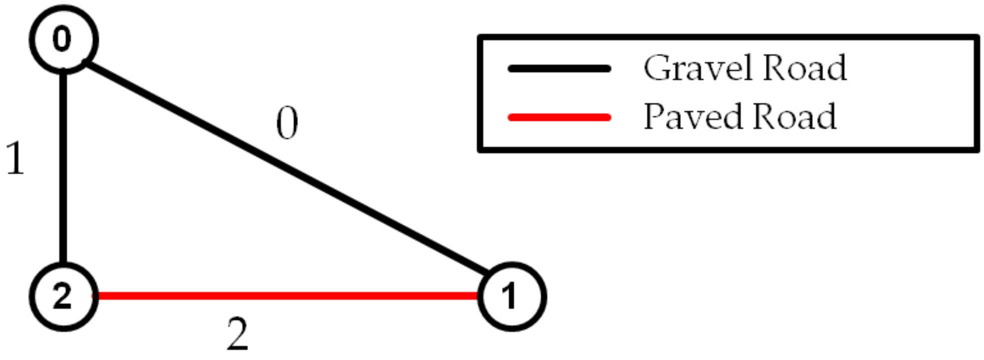

Figure C.1 Simple Road Network used for Verification.

Outputs:

Given the model inputs, the following outputs would be expected from the model run.

Number of *Vehicles* created over full model run:

Number of trucks = 100vpd * 25% trucks * 365 days/year * 1 year = 9,125.

Number of passenger vehicles = 100vpd * 75% passenger * 365 days/year * 1 year = 27,375.

Length of roads

Road length from online GIS tool that calculates distance between coordinates using the coordinates of *Road Nodes* at the end of each *Road Segment*.

roadID: 0 = 1.118548 km

roadID: 1 = 0.500679 km

roadID: 2 = 1.000287 km

Least cost route for passenger vehicle from nodeID: 0 to nodeID: 1

Potential Route Choice A: Node order: [0,2,1]. Road order: [1,2].

Cost = (0.500679km * $0.2/km) + (0.500679km * $27.36/hr / 100km/hr) + (1.000287km * $0.14/km) + (1.000287km * $19.32/hr / 100km/hr) = $0.6508/trip.

Potential Route Choice B: Node order: [0,1]. Road order: [0].

Cost = (1.118548km * $0.2/km) + (1.118548km * $27.36/hr / 100km/hr) = $0.5297/trip.

Least cost route is node order [0,1] with user cost **$0.5297 / one-way trip.**

Least cost route for truck vehicle from nodeID: 0 to nodeID: 1

Potential Route Choice A: Node order: [0,2,1]. Road order: [1,2].

Cost = (0.500679km * $0.67/km) + (0.500679km * $55.45/hr / 100km/hr) + (1.000287km * $0.67/km) + (1.000287km * $53.30/hr / 100km/hr) = $1.5879/trip.

Potential Route Choice B: Node order: [0,1]. Road order: [0].

Cost = (1.118548km * $0.67/km) + (1.118548km * $55.45/hr / 100km/hr) = $1.3697/trip.

Least cost route is node order [0,1] with user cost **$1.3697 / one-way trip.**

Total User Costs after 1 Year:

Passenger Vehicles:

Number of vehicles = 100 vpd * 75% passenger * 365 days/year * 1 year = 27,375.

Total one-way trips completed = 27,375 * 2 (for return trips) = 54,750 trips.

Total user costs: = $0.5297/trip * 54,750 one-way trips = **$29,003.50.**

Trucks:

Number of vehicles = 100 vpd * 25% passenger * 365 days/year * 1 year = 9,125.

Total one-way trips completed = 9,125 * 2 (for return trips) = 18,250 trips.

Total user costs: = $1.3697/trip * 18,250 one-way trips = **$24,996.33.**

Payload per trip = 47,000 tonne (maximum GVW) - 16,500 tonne (tare weight) = 30,500 tonne.

Total weight hauled: 30,500 tonne/trip * 9,125 trips = 278,312,500 tonne.

RM:

Total Winter days = from January 1, 2013 to March 21, 2013 and from December 21, 2013 to January 1, 2014 = 90 days.

Total Spring days = March 21, 2013 to June 21, 2013= 92 days.

Total Summer days = June 21, 2013 to September 21, 2013= 92 days.

Total Fall days = September 21, 2013 to December 21, 2013= 91 days.

Total Winter Cost = Cost due to passenger vehicles + Cost due to loaded trucks + Cost due to empty trucks =

[(90 days/Winter) * (100 vpd) * (1.118548 km/trip)] * {

[(75% passenger) * ($0.015/passenger vehicle/km) * (2 one-way trips/vehicle)] +

[(25% passenger) * $0.15/loaded truck/km)] +

[(25% passenger) * $0.12/empty truck/km)] } = $906.02.

Total Spring Cost =

[(92 days/Spring) * (100 vpd) * (1.118548 km/trip)] * {

[(75% passenger) * ($0.015/passenger vehicle/km) * (2 one-way trips/vehicle)] +

[(25% passenger) * $0.90/loaded truck/km)] +

[(25% passenger) * $0.72/empty truck/km)] } = $4,399.25.

Total Summer Cost =

[(92 days/Summer) * (100 vpd) * (1.118548 km/trip)] * {

[(75% passenger) * ($0.015/passenger vehicle/km) * (2 one-way trips/vehicle)] +

[(25% passenger) * $0.30/loaded truck/km)] +

[(25% passenger) * $0.24/empty truck/km)] } = $1,620.78.

Total Fall Cost =

[(91 days/Fall) * (100 vpd) * (1.118548 km/trip)] * {

[(75% passenger) * ($0.015/passenger vehicle/km) * (2 one-way trips/vehicle)] +

[(25% passenger) * $0.30/loaded truck/km)] +

[(25% passenger) * $0.24/empty truck/km)] } = $1,603.16.

Total RM Costs = Winter cost + Spring cost + Summer cost + Fall cost

= $8,529.

Combined Costs:

Net Combined Costs = Passenger vehicle costs + Truck costs + RM Costs

= ($24,079/passenger vehicles) + ($24,557/trucks) + ($8,529.21/RM)

= 57,165.

A similar model run was completed as outlined above but with the inclusions of permit fees. In the Spring, permit fees affect truck vehicle routing for a loaded truck as follows:

<u>Least cost route for truck vehicle from nodeID: 0 to nodeID: 1 (with permits)</u>

Potential Route Choice A: Node order: [0,2,1]. Road order: [1,2].

Cost = (0.500679km * $0.67/km) + (0.500679km * $55.45/hr / 100km/hr) + (0.500679km * $0.9/km) + (1.000287km * $0.67/km) + (1.000287km * $53.30/hr / 100km/hr) + (1.000287km * $0.06/km) = $2.0985/trip.

Potential Route Choice B: Node order: [0,1]. Road order: [0].

Cost = (1.118548km * $0.67/km) + (1.118548km * $55.45/hr / 100km/hr) + (1.118548km * $0.9/km) = $2.3764/trip.

Least cost route is node order [0,2,1] with user cost **$2.0885 / one-way trip.**

Other aspects of the model were verified such as:

- Increasing traffic counts on gravel road segment to confirm that road upgrade was completed once traffic counts were above the upgrade trigger (confirms upgrade decision is working as well as upgrade cost tracking for output summaries).
- Road restriction to confirm trucks do not travel across road segments at weights above weight restriction.

Model Validation

The validation of ABMs has yet to be firmly established and accepted in the modeling community. Due to limited data availability, the main model validation completed herein was fairly limited and focused on RM average costs per year for road provision.

The real value used for this validation was based on the RM of Wilton consolidated financial statements for the "Transportation Services Expenditure" of $10,278,105 for the 2015 year (RM of Wilton No. 472, 2016). Since the model considered a subset of the full RM road network, the total costs were scaled down based on the length of roads within the subset considered in the model. The total length of roads considered in the model under RM jurisdiction was 214.5 km. The total length of the actual RM of Wilton road network is 714 km. So the subset of the RM road network considered in the model represents approximately 30% of the total road network. Using this ratio to scale down the total transportation expenses gives $3,088,432.

To compare model results to real RM costs, the most appropriate scenario to represent the current reality of the RM case study would be *S3* (without permit fee, with upgrades). From Table 6.2, the net RM LCCs over the five year model run were $13,867,380. Dividing the net RM costs by five (five year model runs), gives an average dollar value per year for RM LCC of $2,773,476.

The average dollars per year for RM net costs from model runs ($2,773,476) was found to have approximately an 11% difference to the estimated real RM costs for a subset of their network in 2015 ($3,088,432).

While there were several assumptions used in comparing model results to the real RM case study costs, this generally good agreement between model results and real values builds confidence in model validity.

This comparison is a rough validation at this point in order to confirm that the order of magnitude of model results were similar to real values. There are some difficulties in directly comparing model outputs to RM costs: model results are in terms of LCC which are not necessarily the same as the actual expenditures in any given year (due to annualized lump sum costs such as capital upgrades), and the model considered only two road types, while in reality the RM case study had several road types that would have different costing considerations.

Further detailed model testing and validation would be desirable to build confidence in the model. Ideally, data would be available for RM costs per year broken down into operating, maintenance, rehabilitation and upgrade costs. Costs tracked by road segment would be ideal for direct comparison against road costing in the model on a segment-by-segment basis. Tracking of specific road upgrades would also be desirable to allow comparison to RM decision making in model runs for selection and timing of road upgrade under given traffic levels and budget constraints.

It is difficult to validate the impact of permitting on vehicle and RM decision making as this style of permitting is not currently being used in the case study.

Validation of user costs was not possible as actual user cost data was not available. This could be an area for future model testing if more detailed user costs were available for a subset of the road users on the network.