INVESTMENT AND POLICY DECISIONS INVOLVING
RURAL ROAD NETWORKS IN SASKATCHEWAN:
A NETWORK DESIGN APPROACH

A Thesis Submitted to the College of
Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in the Department of Civil Engineering
University of Saskatchewan
Saskatoon

By
Paul Normann Christensen

© Copyright P.N. Christensen, December 2003. All rights reserved.
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this dissertation.

While these forms may be included in the document page count, their removal does not represent any loss of content from the dissertation.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de ce manuscrit.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.
UNIVERSITY OF SASKATCHEWAN

College of Graduate Studies and Research

SUMMARY OF DISSERTATION

Submitted in partial fulfillment

of the requirements for the

DEGREE OF DOCTOR OF PHILOSOPHY

by

Paul Normann Christensen

Department of Civil Engineering

University of Saskatchewan

Summer 2003

Examinining Committee:

Dr. M. Stauffer

Dean/Associate Dean, Dean’s Designate, Chair
College of Graduate Studies and Research

Dr. D.E. Pufahl

Chair of Advisory Committee, Department of
Civil Engineering

Dr. G.A. Sparks

Co-supervisor, Department of Civil Engineering

Dr. J. Nolan

Co-supervisor, Department of Agricultural Economics

Dr. J.C. Stabler

Department of Agricultural Economics

Dr. C. Berthelot

Department of Civil Engineering

Dr. R. Srinivasan

Department of Mathematics and Statistics

External Examiner:

Dr. Eric Hildebrand

Department of Civil Engineering

University of New Brunswick

P.O. Box 4400

Fredericton, New Brunswick, E3B 5A3
Investment and policy decisions involving rural road networks in Saskatchewan: a network design approach

Investment and policy decisions involving rural road networks occur in the broader context of road use, road performance, preservation efforts and structural features of the surrounding rural economy. In Saskatchewan, recent developments in grain handling and transport within rural economies has dramatically altered truck haul volumes, patterns and characteristics. This has had a significant, deleterious impact on the performance of rural road networks in the Province. To respond effectively, Saskatchewan Department of Highways and Transportation (SDHT) is considering a range of road-related policy and investment (i.e., road structure modification) alternatives. The question is, facing the reality of limited budget monies, what arrangement of policy and costly road structure modifications is ‘best’ applied across a given rural road network.

To answer this question, a cost-based standard is employed within a modified network design problem (NDP) model. Endogenous components of the model determine a demonstrably good arrangement of road structure modifications across a given network in the context of interrelated road use, road performance and preservation costs. Exogenous to the model are considered policy regimes and rural economic features influencing observed road use volumes, patterns and characteristics. For a given rural road network, the modeling process allows the computation of net cost savings (benefits) subsequently applied to rank mutually exclusive policy and investment arrangements.

The model and corresponding algorithmic strategies were applied to a case study involving considered policy and road structure alternatives pertinent to the rural road network bounded within the rural municipality (RM) of Cote, Saskatchewan. Despite concerns regarding the reliability of available data, a number of important observations emerged through the modeling exercise. These include: road structure arrangements reached by the model are sensitivity to the policy regime in place; policy and road structure arrangements influence road use, performance and preservation costs; well-intentioned policy regimes can nonetheless lead to ‘bad’ consequences (suggesting that careful analyses must accompany policy design); and, regardless of available budget monies, the range of beneficial, yet costly, road structure improvements for a given road network is limited. Subsequent sensitivity analysis verified the capabilities of the modeling environment and sensibility of corresponding results.

BIOGRAPHICAL

June, 1964 Born in Edmonton, Alberta
May, 1988 Bachelors Degree in Economics, University of British Columbia
January, 1990 Masters Degree in Economics, University of British Columbia
1990-current Consulting economist
2001-current Researcher, ISIS research program, University of Saskatchewan
PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or make use of material in this thesis in whole or in part should be addressed to:

Head of the Department of Civil and Geological Engineering
University of Saskatchewan
57 Campus Drive
Saskatoon, Saskatchewan, 27N 5A9
CANADA
ABSTRACT


Worldwide, rural road networks serve a vital link in the chain leading goods to markets and people to places. The efficiency of rural road network services is influenced by road-related investment and policy decisions. Reaching good decisions, however, is complicated by: interrelationships among policy, investment, road use, road performance, and rural economies; and combinatorial challenges involving the distribution of discrete policy and investment arrangements across networks.

The main objective of this study is to address this complex problem as it pertains to rural road networks in Saskatchewan. Rural roads in Saskatchewan are suffering under increasing volumes of heavy truck traffic motivated principally by recent changes in the grain handling and transportation system. To address this problem, Saskatchewan Department of Highways and Transportation is considering a range of haul policy and road structure investment options. The question is, what (spatial) arrangement of available policy and investment options best meets this challenge.

To answer this question, a cost-based standard is incorporated within a network design modeling approach and solved using custom algorithmic strategies. Applied to a case study network, the model determines a demonstrably good arrangement of costly road structure modifications under each considered policy option. Resulting policy-
investment combinations are subsequently ranked according to total cost and equivalent net benefit standards.

A number of important findings emerge from this analysis. Policy and investment decisions are linked; spatial arrangement of road structure modifications is contingent on the haul policy regime in place. Road performance and use characteristics are indeed sensitive to policy and investment decisions. Optimal budget levels computed by the model contradict perceptions that rural road networks in Saskatchewan are grossly under-funded. Despite best intentions, ill-considered policy can actually reduce the net benefits of road provision and use.

Model application and design limitations suggest promising avenues for future research. These include: model larger networks in Saskatchewan and beyond; determine optimal road budgets under benefit-cost standards reflecting competing economic needs; employ model within regional economic planning investigations to forecast road-related implications; and model policy endogenously to aid design of heavy haul sub-networks and to address questions concerning network expansion or contraction.
ACKNOWLEDGEMENTS

The author wishes to thank those who contributed to the completion of this thesis:

The College of Graduate Studies and Research as well as Saskatchewan Highways and Transportation for providing financial support.

Dr. Gordon Sparks and Dr. James Nolan for supervising the research summarized in this dissertation. It’s not easy turning a consultant into an academic. Thanks for (patiently) steering the ship.

Dr. Curtis Berthelot, Dr. Jack Stabler, and Dr. Raj Srinivasan for participating as academic advisors during the course of this research. Your reasoned comments, questions and criticisms provided invaluable guidance.

Dr. Eric Hildebrand for participating as external examiner. I appreciate your thoughtful comments and the fact you endured an arduous journey to participate in the defence.

Dr. Dennis Pufahl and Dr. Bruce Sparling for chairing, respectively, advisory committee meetings and the thesis defence.

Mr. Ron Gerbrandt for evaluating the first draft of this dissertation. Thoughtful and encouraging comments from an experienced practitioner are always welcome.

Mr. Gerald Kreba for providing a guided tour of the RM of Cote road network.

Joanne Skeates, Debbie Forgie, Cynthia Hanke and Maureen Limet for excellent help with myriad administrative details during the course of my studies.

Finally, I would like to thank my family for their love, support and encouragement during this process. My wife, Kim, deserves special thanks for putting up with me these five (and a half) long years; I simply couldn’t have done this without her.

This dissertation is dedicated to my mom, Lisse, and brother, Per. I love you and I miss you.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERMISSION TO USE</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Problem Statement</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Research Objectives</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Scope of Research</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Methodology</td>
<td>5</td>
</tr>
<tr>
<td>1.5 Organization of Thesis</td>
<td>6</td>
</tr>
<tr>
<td>2. LITERATURE REVIEW</td>
<td>8</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Rural Road Networks</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Network Design Problem Models and Related Variants</td>
<td>16</td>
</tr>
<tr>
<td>2.3.1 Introduction to the Network Design Problem</td>
<td>16</td>
</tr>
<tr>
<td>2.3.2 Modifications to the Network Design Problem: Applications, Model Variants and Algorithms</td>
<td>19</td>
</tr>
</tbody>
</table>
2.4 Bi-level Optimization and the Rural Road Network Problem .................. 26
2.5 Concluding Remarks ........................................................................... 30

3. CONTEXT FOR MANAGEMENT DECISIONS INVOLVING RURAL ROAD NETWORKS IN SASKATCHEWAN ................................................................. 31
3.1 Introduction ....................................................................................... 31
3.2 Rural Economies, Road Use and Road Performance ....................... 33
3.3 Implications for Managers of Rural Road Networks ....................... 39
3.4 Concluding Remarks ........................................................................... 46

4. STANDARDS AND METHOD TO DETERMINE GOOD ARRANGEMENTS OF ROAD INVESTMENT AND POLICY ALTERNATIVES FOR RURAL ROAD NETWORKS ................................................................. 49
4.1 Introduction ....................................................................................... 49
4.2 Standards Employed to Rank Road Investment and Policy Arrangements .... 50
4.2.1 A Net Benefit Approach .............................................................. 51
4.2.2 Accounting Stance ....................................................................... 54
4.2.3 Adapting the Standard for Modeling Purposes ............................ 55
4.3 Method of Employing the Standard .................................................. 58
4.4 Concluding Remarks ........................................................................... 61

5. NETWORK DESIGN PROBLEM MODELING APPROACH .................. 63
5.1 Introduction ....................................................................................... 63
5.2 Root Model: Uncapacitated Network Design Problem (UNDP) ............ 64
5.3 Uncapacitated Network Structural Improvement Problem (UN SIP) with Side Constraint ................................................................. 70
5.4 Implications of Road Performance Characteristics ............................ 73
5.4.1 Modeling Discontinuous Costs .................................................. 75
5.4.2 UNSIP and Discontinuous Costs .................................................. 77
5.4.3 Incentive Conflicts and UNSIP ..................................................... 80
5.5 Concluding Remarks ..................................................................... 84

6. MODEL DECOMPOSITION AND ALGORITHMS ................................. 85
6.1 Introduction .................................................................................. 85
6.2 Model Decomposition .................................................................. 86
   6.2.1 Shortest Path (SP) Sub-problem ............................................. 87
   6.2.2 Knapsack (KS) Sub-problem .................................................. 90
6.3 Heuristic Algorithmic Strategies .................................................... 95
6.4 Concluding Remarks ..................................................................... 103

7. CASE STUDY: THE RM OF COTE, SASKATCHEWAN ............................ 105
7.1 Introduction .................................................................................. 105
7.2 Case Study and Data .................................................................... 105
   7.2.1 Network Configuration, Provision and Use Characteristics ........ 107
   7.2.2 Costs of Road Use and Provision ............................................ 115
   7.2.3 Policy Options Analyzed ........................................................ 120
7.3 Model Implementation and Results ................................................. 125
   7.3.1 Implementation and Algorithmic Performance .......................... 126
   7.3.2 Network Modeling Results ...................................................... 129
      7.3.2.1 Road Structure Allocations .............................................. 130
      7.3.2.2 Summary of Costs and Net Benefits ................................. 134
7.3.2.3 Edge Flows and Trip Routings ......................................................... 151

7.4 Concluding Remarks ............................................................................. 161

8. SENSITIVITY ANALYSIS .......................................................................... 163

8.1 Introduction ............................................................................................ 163

8.2 ‘What-if’ Scenarios and Parameter Adjustments ...................................... 164

8.2.1 Scenario 1: Road Use Costs ................................................................. 165

8.2.2 Scenario 2: Gravel Highway Standard Performance and Costs .......... 167

8.2.3 Scenario 3: Freight Truck Traffic Volumes and Roadway Candidates 168

8.3 Results of Sensitivity Analysis ................................................................. 169

8.3.1 Road Structure Allocations ................................................................. 169

8.3.2 Cost Results ....................................................................................... 174

8.4 Concluding Remarks.............................................................................. 181

9. STUDY SUMMARY, LIMITATIONS AND OPPORTUNITIES FOR FUTURE
   RESEARCH .................................................................................................. 183

9.1 Summary of Study .................................................................................. 183

9.2 Study Limitations and Opportunities for Future Research .................. 190

9.2.1 Limitations and Opportunities Related to Model Application .......... 190

9.2.2 Limitations and Opportunities Related to Model Design .................. 196

REFERENCES ............................................................................................... 200
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 7.1. Spatial and structural elements of RM of Cote Network</td>
<td>112</td>
</tr>
<tr>
<td>Table 7.2. Use characteristics of RM of Cote Network</td>
<td>113</td>
</tr>
<tr>
<td>Table 7.3. Unit user costs across vehicle type and road structure</td>
<td>116</td>
</tr>
<tr>
<td>Table 7.4. Agency capital, preservation and resurfacing cost data</td>
<td>118</td>
</tr>
<tr>
<td>Table 7.5. Affected segments and captive freight traffic under each HRMA</td>
<td>122</td>
</tr>
<tr>
<td>Table 7.6. Recommended road structure modifications under each policy option</td>
<td>131</td>
</tr>
<tr>
<td>Table 7.7. Cost-based results for policy options and road structure arrangements</td>
<td>135</td>
</tr>
<tr>
<td>Table 7.8. Net benefit incremental to base case</td>
<td>147</td>
</tr>
<tr>
<td>Table 7.9. Sample road segment traffic flows</td>
<td>152</td>
</tr>
<tr>
<td>Table 7.10. Sample non-spring freight flow assignments across policy options</td>
<td>160</td>
</tr>
<tr>
<td>Table 8.1. Unit user costs for sensitivity analysis</td>
<td>166</td>
</tr>
<tr>
<td>Table 8.2. Recommended road structure modifications</td>
<td>170</td>
</tr>
<tr>
<td>Table 8.3. Cost-based results for 'what-if' scenarios</td>
<td>175</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2.1</td>
<td>Model components of network design problem</td>
</tr>
<tr>
<td>2.2</td>
<td>Algorithms combined to solve network design problem models and related variants</td>
</tr>
<tr>
<td>3.1</td>
<td>A context pertinent to management decisions involving rural road networks in Saskatchewan</td>
</tr>
<tr>
<td>3.2</td>
<td>Damaged TMS roadway segment on Highway 19 near Hawarden, Saskatchewan</td>
</tr>
<tr>
<td>4.1</td>
<td>Components endogenous to modeling environment</td>
</tr>
<tr>
<td>5.1</td>
<td>Graph of contrived rural road network</td>
</tr>
<tr>
<td>5.2</td>
<td>Graph of contrived rural road network: UNSIP</td>
</tr>
<tr>
<td>5.3</td>
<td>Discontinuous variable passenger vehicle user costs</td>
</tr>
<tr>
<td>6.1</td>
<td>Overall algorithmic strategy</td>
</tr>
<tr>
<td>6.2</td>
<td>Pre-processing procedure for knapsack (KS) sub-problem</td>
</tr>
<tr>
<td>6.3</td>
<td>Drop-add heuristic for knapsack (KS) sub-problem</td>
</tr>
<tr>
<td>7.1</td>
<td>Rural road maps of the RM of Cote</td>
</tr>
<tr>
<td>7.2</td>
<td>RM of Cote rural road network</td>
</tr>
<tr>
<td>7.3</td>
<td>Model implementation</td>
</tr>
<tr>
<td>7.4</td>
<td>Change in base case annualized costs</td>
</tr>
<tr>
<td>7.5</td>
<td>Change in annualized flow costs</td>
</tr>
<tr>
<td>7.6</td>
<td>Total annualized costs</td>
</tr>
<tr>
<td>7.7</td>
<td>Annualized net benefits incremental to base case</td>
</tr>
<tr>
<td>9.1</td>
<td>Components endogenous to modeling environment</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Worldwide, rural road networks serve a vital link in the chain leading goods to markets and people to places—transactions easily valued in the billions of dollars. Yet managing rural road networks efficiently is a complex task. Structural shifts in rural economies (e.g., development, population growth or decline, community and commercial concentration) alter road use patterns and characteristics that can affect road performance and corresponding service levels. This, in turn, may influence the preservation, investment and policy decisions reached by rural road managers. Reciprocally, decisions reached by managers may affect road performance, road use patterns and characteristics, and ultimately the rural economic landscape. Complicating matters further are the sheer combinatorial challenges surrounding the allocation of discrete policy and investment arrangements across rural road networks of even modest size. To reach sound decisions, rural road network managers must therefore account explicitly for the interplay of numerous factors and the combinatorial nature of available investment and policy arrangements.

While research concerning cost-effective preservation practices for extant road networks (both rural and urban) is ubiquitous, few authors have studied pertinent
interrelationships among rural economies, road use, road performance, and road-related investment and policy decisions or tackled the combinatorial challenges of the problem at-hand. To-date, relevant work in this area includes: estimating incremental road upgrade and preservation costs given grain elevator consolidation forecasts and corresponding road use implications; comparing benefits and costs of rural road use and preservation efforts under a range of exogenously determined investment, divestment (i.e., road abandonment) and policy alternatives; employing connectivity criteria and heuristic network design algorithms to support cost-effective decisions involving network construction; and determining the cost-minimizing number and spatial arrangement of grain elevators given likely impacts on road use patterns and rural road preservation efforts. While each of these studies implicitly or explicitly considers the rural economic landscape, none seek an optimal arrangement of road-related investment and policy alternatives in the context of interrelated road performance and use effects.

Rural road networks in Saskatchewan (indeed in many parts of North America) are mature; the size and configuration of existing networks is essentially static. Road-related investment therefore involves modification of extant road structures (e.g., upgrade to paved road, reversion to gravel road) rather than new building. While road networks are static, however, the structure of rural economies is not. For instance, in recent times the grain handling and transportation system has undergone a revolution that has dramatically altered the economic landscape of rural communities in the Province – transforming a widely distributed network of country elevators to a concentrated network of massive inland grain terminals. Consequently, road use
patterns and characteristics have changed markedly. An important effect of this change is degrading quality of rural road networks.

To reverse this trend, managers within Saskatchewan Highways and Transportation (SHT) are considering a range of road-related investment and policy alternatives. For any given rural road network in the Province, the challenge SHT faces is to determine an optimal arrangement of road-related investment and policy alternatives. Practical considerations framing this challenge include: response of road users to varying road policy and investment arrangements; concomitant effects on road performance, preservation efforts and costs; standards (criteria) applied to rank mutually exclusive policy and investment combinations; budget monies allocated to costly road structure modifications; and computational means of ranking an explosive number of discrete policy and investment combinations for networks of non-trivial size.

1.2 Research Objectives

The principal objective of this research is to develop a practical and defensible analytical method to tackle the complexities of this important problem to support sound investment and policy decisions relevant to managers of mature rural road networks. Specific objectives include:

- Establish economically credible standards (criteria) with which to compare and rank mutually exclusive investment and policy arrangements.

- Develop corresponding analytical framework and computer-based models to determine an optimal arrangement of road-related investment and policy alternatives for any given network configuration according to pre-established standards and subject to relevant budget money constraints. Within the model environment:
account for interrelated road use and performance effects as well as structural features of local rural economies influencing observed road use characteristics; and determine a pragmatic means of addressing the combinatorial challenges inherent to the problem.

- Apply models to real-world case study in order to test capabilities and rank considered investment and policy combinations. Conduct subsequent sensitivity analysis to test adaptability of modeling environment and to evaluate the realism of corresponding results.

- More generally, assist in explaining causes underlying beneficial or perverse effects of prescribed policy, investment and/or preservation programs involving mature rural road networks.

- Identify and discuss wider applicability of modeling approach.

1.3 Scope of Research

The frame of reference for this research involves road-related investment and policy decisions facing managers of mature rural road networks – with principal emphasis on challenges facing decision-makers in Saskatchewan. Hence, investment and policy issues pertinent to new building and/or other jurisdictions are not considered. Additionally, although managers may influence decisions in related areas of transport investment and policy (e.g., rail running rights, bridge weight restrictions), these lie outside the scope of this study.
1.4 Methodology

Road-related policy and investment decisions are analyzed as a network design problem. The spatial, use, provision and performance characteristics of a rural road network are described using notational conventions of graph theory. The decision problem facing managers is then modeled as a modified network design problem (a mixed integer program) incorporating pre-established standards and real-world constraints (e.g., limited budget monies). The computational interplay between mutually exclusive investment and policy arrangements, road performance, preservation costs, and road use effects as well as the combinatorial explosiveness of the problem at-hand are tackled within a computer-based implementation of the network design model to generate rankings and thereby support sound decision-making practices.

Following Hamlett and Baumel (1990), the standards employed reflect cost-based net benefit criterion subject to road access provisions. The corresponding rural road network design model is separated into shortest path (SP) and knapsack (KS) components to facilitate the design of practical algorithms and subsequent computer modeling. The computational interplay of KS and SP is embedded within an overall heuristic to determine the choice and spatial allocation of considered road investment alternatives and corresponding road performance, preservation and use effects. The computer-based model is run once for each considered policy alternative to generate associated road investment arrangements and rankings in accord with pre-established standards and constraints.

The modeling approach adopted reasonably emulates rural road investment and policy challenges facing road agencies such as SHT. To test its efficacy, then, the
modeling approach is applied to a rural road network bounded within the Rural Municipality (RM) of Cote, Saskatchewan. Relevant investment and policy alternatives, structural features of local economies, road performance characteristics, and pertinent trip-making and road preservation cost data are incorporated within the computer-based modeling environment to generate comparable results and rankings. To investigate the sensitivity and realism of model results, model parameters are perturbed to emulate differing rural economic features and alternative road performance, use and provision characteristics. Corresponding results are then compared against logical expectations.

Computer-based implementation of the rural road network design model occurs within a C++ programming environment exploiting the capabilities of special-purpose optimization software. Iterative heuristics control the application of network simplex, pre-processing, branch-and-cut and greedy algorithms to generate model solutions and rankings. Although optimality is not guaranteed, the results produced are shown to be both stable and demonstrably good.

1.5 Organization of Thesis

The remaining chapters of the dissertation are organized as follows. Chapter 2 reviews literature pertaining to the study of rural road network investment and policy issues as well as network design problem models, algorithms and applications. Chapter 3 provides background information regarding use, provision and performance characteristics of rural road networks in Saskatchewan. Chapter 4 discusses the issue of standards and its pertinence to decision-making involving rural road networks, and describes an analytical method to evaluate and rank mutually exclusive policy and investment arrangements according to the chosen standards. Chapter 5 formally
describes the network design problem approach applied for modeling purposes. Chapter 6 outlines model decomposition and corresponding algorithmic strategies used to generate results and rankings. Chapter 7 describes the case study used to examine and test model capabilities, and reviews corresponding results. Chapter 8 reviews the subsequent sensitivity analysis. Study summary, limitations and opportunities for future research are found in Chapter 9.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The primary objective of this research is to develop a practical analytical method to support sound investment and policy decisions for managers of mature rural road networks. Beginning with the work of Mahoney et al (1978) and Golabi et al (1982), preservation of mature road networks (both rural and urban) has been a principal focus of academic investigation and related management practice. While resulting pavement (or more generally, asset) management systems support cost-effective preservation practices under real-world resource constraints, they are not designed to model complex interrelationships among rural economic structure, road use, and road-related investment and policy decisions.

Research pertinent to the principal objective of this study falls into one of three categories. The first category of research involves rural road networks per se. This body of research focuses on various relationships between rural economic structure, road use, preservation costs and road-related policy and investment decisions. The second category of research involves network design problem (NDP) models. Pertinent areas of investigation include related NDP model applications, variants and corresponding algorithms. The final category of research involves bi-level optimization.
Investigations of this nature focus on problems where incentive conflicts arise (e.g., inherent incentive conflicts between road network managers and self-interested trip-makers).

2.2 Rural Road Networks

West Central Municipal Government Committee (WCMGC, 1997) examined road-related implications of possible elevator consolidation and agricultural development scenarios in West Central Saskatchewan. The goal of the research was to estimate rural road upgrade and preservation costs associated with the resulting, forecasted rise in agricultural freight truck traffic in the region. To do so, researchers involved in the study first forecasted freight truck volumes and routing patterns over local road networks in the region according to agricultural production forecasts and alternative spatial distributions of high throughput grain elevators. Truck volumes and predicted routings were then translated to expected upgrade costs via upgrade probability curves generated from historical investment data obtained from Saskatchewan Highways and Transportation (SHT). The eventual allocation of roadway upgrades across the region’s network were then used to estimate concomitant preservation efforts and costs.

While WCMGC satisfy their principal goal, the analytical methods and assumptions underlying their work differs from this study in a number of important ways. First, since the cost estimates published in WCMGC are based on historical data, the influence of pre-established investment standards are naturally embodied in study calculations. These standards reflect road upgrade criteria based on the volume of loaded trucks traveling over rural roadways within the network. This differs from the (access constrained) net benefit criteria applied herein. Second, no attempt was made to
optimize – according to pre-selected standards – the spatial allocation of road upgrades given real-world budget constraints. Instead, an exhaustive list of road-related investments is generated and weakly prioritized according to corresponding upgrade probabilities. Third, while shortest path algorithms are applied to estimate initial freight truck volumes and patterns corresponding to alternative rural economic scenarios, the complex interrelationship between road investment (upgrade) decisions and road use was not considered. Finally, road-related policy considerations do not enter the analysis.

Clifton Associated Ltd. (Clifton, 2000) engaged in a consultative process to determine potential road upgrade and policy strategies intended to ameliorate deteriorating rural road network services in the Gardiner Dam Transportation Area. Combining road traffic, road condition, cost and budget forecasts with an assessment of stakeholder needs, Clifton developed a prioritized list of road upgrade, preservation and policy recommendations.

Although a range of pertinent issues are considered in Clifton, formal analysis is limited to traffic forecasts based on alternative elevator consolidation scenarios. In essence, a consultative process substitutes for an analytical method designed to determine favourable rural road upgrade and policy arrangements based on pre-established standards.

Martin et al (1978) incorporate the costs of road use and preservation within a mathematical programming model intended to emulate the total costs of grain handling and transportation within west-central Saskatchewan. The purpose of their research was to determine – under varying assumptions governing elevator closure and branch rail
line abandonment – a total cost-minimizing number and spatial arrangement of grain elevators within the region under study.

Although the work of Martin et al is not focused on road-related investments or policy alternatives, it shares important similarities with this research. First, it is conducted within the context of structural changes to Saskatchewan’s rural economies. Second, the model applied contains both road use and investment components. However, while the road use component deals explicitly with rural traffic flow prediction – a significant element of the modeling approach employed in this study – the investment component involves spatial assignment of delivery points rather than roadway investments. Hence, the specific modeling approach and computational algorithms employed by these authors differ substantively from those employed in this research.

It is important to note that the difference in research objectives between Martin et al and this study reflects alternative decision-making standpoints. The work of Martin et al implicitly presumes firms and agencies reaching grain handling decisions consider the broader impact on related transportation infrastructure. Hence, decisions governing the spatial allocation of grain delivery points are cost-minimizing from a system-wide perspective. In contrast, this study adopts the standpoint of a rural road network manager faced with the road-related consequences of independent decisions involving the rural economic landscape (including grain handling decisions). In an ideal world, of course, these decisions would be intertwined.

Hamlett and Baumel (1990) apply incremental cost-benefit criteria to guide road abandonment (divestment) decisions for rural regions in the United States affected by
structural shifts in local economies. In their study, benefits are estimated as the fall in the total cost of road network provision enjoyed by roadway agencies pursuing alternative divestment strategies. Losses are estimated as the rise in total road user costs incurred by trip-makers captured within the shrinking network. The authors then compare and rank a predetermined set of mutually exclusive abandonment strategies against the existing (base case) network in accord with incremental net benefits. If the relative cost savings enjoyed by roadway providers exceed the additional trip costs incurred by users, the corresponding strategy is viewed favourably (and vice-versa). The preferred strategy is that which generates the highest incremental net benefit.

The decision-making standards employed in this study closely emulate the standards employed by Hamlett and Baumber. First, cost-benefit criteria and related computational procedures are virtually identical. Second, road-related decisions are tempered by access provisions. In other words, divestment strategies (or investment and policy arrangements) must not prevent road-based travel between any trip origin and intended destination within the modeled network.

While standards are similar, the modeling strategy employed by Hamlett and Baumber differs importantly from the modeling strategy employed herein. In their study, alternative divestment strategies are exogenous to the modeling environment. Once imposed, the authors run a shortest path simulation model to generate concomitant road use effects and related costs. In this study, road-related investment decisions are endogenous to the modeling environment. Hence, investment decisions and concomitant road use effects are analyzed in tandem. Effectively, then, the shortest path
algorithmic strategies employed by Hamlett and Baumel represent only a subset of the algorithmic strategies employed in this study. Hamlett et al (1989) apply a cost-benefit approach to compare and rank a number of mutually exclusive road policy and divestment options including: rural road abandonment; lowering road maintenance standards; returning certain roads to private ownership; and bridge reconstruction. As in Hamlett and Baumel, the authors impose policy and divestment options exogenously and apply a road use simulation model to estimate corresponding net benefits. Again, the computation of net benefits is based on an assessment of cost changes experienced by both road users and providers under each policy and divestment option.

Baumhover et al (1990) employ a cost-benefit approach to compare and rank alternative investment and/or divestment strategies for rural roads and rail branch lines. In this case, changes in both road- and rail-related costs are computed to determine the net benefits corresponding to each considered strategy. The net benefit estimates are then used to compare and rank all considered strategies. Akin to Hamlett and Baumel as well as Hamlett et al, investment and divestment strategies are exogenous to the modeling environment; shortest path simulation is used to model only concomitant road use effects. Interestingly, one of the key conclusions reached by Baumhover et al mirrors observations reached by Martin et al: while branch line abandonment results in efficiency gains for rail companies, it concomitantly raises both vehicle trip and road costs. Hence, an appropriate balance must be struck to minimize overall system costs.

In Casavant and Lenzi (1989), data from the Washington State Department of Transportation Pavement Management System (WSDOT-PMS) is used to determine the
ex post costs of branch rail line abandonment. The WSDOT-PMS incorporates damage and roadway serviceability indices to estimate the roadway costs associated with increasing traffic levels on rural road networks. Casavant and Lenzi exploit this information to estimate the road-related costs associated with the abandonment strategies adopted by rail companies. The purpose of the analysis is to provide a means through which policy makers can reach rational decisions regarding rail abandonment policy. The goal, they suggest, is to design rail abandonment policy that minimizes combined rail and road costs.

Jessup and Casavant (1995) attempt to quantify the investment needs for wheat and barley hauls in Eastern Washington. Applying road damage coefficients obtained from previous work, the authors estimate the incremental damage costs imposed by increasing wheat and barley freight traffic on both country roads and state highways in Eastern Washington. These estimates form the basis for computations regarding the additional investment monies required to maintain reasonable roadway service standards on affected portions of the rural road network.

Although the rural issues motivating the work of Casavant and Lenzi as well as Jessup and Casavant resemble those motivating this study, the objectives and concomitant analysis differ widely. The research completed by these authors represent a broad brush attempt to quantify the road- and rail-related costs attributable to changes in Washington’s grain handling and transportation system. No attempt is made to explicitly model traffic flows or road structures in a detailed way. Hence, while the authors are interested in obtaining some measure of investment needs for rural road
infrastructure, their approach is not intended to determine the allocation of road-related infrastructure and potential implications for traffic flow through affected networks.

Patel and Madhavan (1984) develop an interactive decision support system to help reduce the fixed costs of connecting rural villages in India with all-weather roads. Although the system is designed to aid new building decisions, the methods employed are somewhat relevant to this thesis. Essentially, Patel and Madhavan develop a system – based on a heuristic network design algorithm – that attempts to balance village connectivity and total network length. System users are able to interactively generate alternative network configurations through parameter adjustments and arbitrary road segment additions or deletions. While optimality is not guaranteed, practical application demonstrates road investment cost savings in the neighbourhood of 30 percent relative to standard network configurations.

Unlike literature reviewed to this point, Patel and Madhavan model road-related investment issues explicitly. However, while connectivity roughly emulates the interests of road users, no explicit account of traffic flow implications enters the modeling environment. Additionally, where the other studies focus on investment and policy issues relevant to mature rural road networks, Patel and Madhavan focus on new building issues pertinent to the development of rural road networks.

The focus on new building and connectivity distinguishes Patel and Madhavan from this study as well. Herein, road-related investment and policy decisions involve mature rural road networks and concomitant road use effects. The computational models and methods employed by Patel and Madhavan therefore differ substantively from those employed in this study.
2.3 Network Design Problem Models and Related Variants

The network design problem (NDP) model – described mathematically in chapter 5 – is the central building block from which a rural road network problem model and associated solution strategies emerge. For this reason, literature pertinent to NDP-based model development, application and corresponding solution algorithms are reviewed in some detail below.

2.3.1 Introduction to the Network Design Problem

As illustrated in Figure 2.1, the NDP consists of two key components: a flow component and a fixed component. In the context of road-based transport networks, the flow component determines travel routings for a set of pre-specified trip ‘supplies’ and corresponding origin-destination (O-D) pairings through a network of given configuration. Since trip-making is a costly activity, the flow component logically determines traffic routings that minimize the total costs of trip-making through the network. The fixed component involves the discrete assignment of road segments (i.e., node-to-node road links) ultimately used to construct a network configuration through which vehicle traffic may flow. Since the design, construction and on-going preservation of roadways are costly activities, the fixed component determines a network configuration that facilitates desired trip-making activities at minimal cost. Working together, the flow and fixed components of an NDP model are intended to determine a network configuration that: (i) ensures all users can access intended destinations from trip origins (a condition of feasibility), and (ii) minimizes the sum of all road use and provision costs.
Figure 2.1. Model components of network design problem.

In economic terms, the objective and feasibility constraints embedded within NDP models reflect the cost-minimizing problem of the firm. Having selected a desired level of output, the firm allocates available (and positively-priced) resources in order to reach that level of production at minimum total cost. With regards road transport networks, the desired level of output corresponds to the number of trips road users wish to complete between chosen origin-destination (O-D) pairs distributed about the network. The network ultimately determined within the NDP modeling environment is,
ideally, the cost-minimizing configuration that supports the desired trip-making ‘output’
among various O-D pairs captured within the network.

NDP-based models include both continuous and integer variables that combine
to aid computation of total costs corresponding to any feasible network configuration.
Traffic flow variables are continuous and non-negative. Total flow costs are computed
via a linear function applying unit costing parameters to traffic flows traveling over
some collection of network links between various O-D pairs. Fixed variables, in
contrast, involve discrete assignment of network links used to configure a feasible
network and are therefore restricted to binary values (denoting ‘yes/no’ decision
alternatives). Total fixed costs are computed through simple multiplication of binary
variables and corresponding unit costs (representing the costs of link design,
construction and on-going operation). Total use and provision costs corresponding to a
particular network configuration equals the sum of all flow and fixed costs.

In the language of mathematical programming, models seeking to achieve
optimal (i.e., minimal or maximal) solutions in the presence of pre-established
constraints are known as constrained optimization problem (COP) models. Constrained
optimization problem models that contain both linear and linear-integer components are
termed mixed integer programming (MIP) models. Since NDP models contain both
linear and linear-integer components, and seek a cost-minimizing objective in the
presence of various constraints, it belongs to the class of MIP models.

As discussed by Hillier and Lieberman (1995, pp. 511-515), most MIP models
are notoriously difficult to solve. Since the introduction of integer variables may lead to
explosive combinatorial implications, MIP models often frustrate the application of
efficient solution algorithms. For this reason, mixed integer NDP models often require the application of sophisticated algorithmic strategies to determine good – if not optimal – solutions.

2.3.2 Modifications to the Network Design Problem: Applications, Model Variants and Algorithms

The network design problem (NDP) model has been modified in a number of ways to suit the demands of various applications and problem types. From the standpoint of this study, the benefit of model modifications is two-fold. First, changes to the root NDP model structure suggest means by which the rural road network problem at-hand may be adequately represented within a NDP-based framework. Second, the computational difficulties experienced by other researchers has led to the development of numerous algorithms intended to converge on good (if not optimal) solutions to NDP-based models. These algorithms provide the fodder necessary to construct algorithmic strategies for the rural road network problem faced in this study.

Applications, Model Variants and Related Computational Challenges

Network design problem models have been adapted in a number of ways to address a range of real-world problems. Road-related applications have focused on network expansion and/or link improvements to address traffic capacity issues. Examples may be found in Billheimer and Gray (1973), Boyce et al (1973), Leblanc (1975), Boffey and Hinxman (1979), ElDessouki et al (1998), and Bard (1998, 391-413). In addition to road-related applications, NDP-based models have been modified and applied to address issues pertinent to: (i) design and expansion of telecommunication systems, (ii) multi-item production planning, (iii) facility location problems, (iv) electricity distribution
planning, (v) less-than-truckload (LTL) consolidation, (vi) flight scheduling, (vii) design of wastewater systems, and (viii) gas pipeline dimensioning. See Ahuja et al (1995) and Balakrishnan et al (1997) for a brief overview of these applications and related references. Recently, Newton et al (1998) and Barnhart et al (2000) have modified and applied NDP-based models to improve blocking practices pertinent to rail car operations.

While the specific features of NDP model variants are as unique as the real-world challenges they address, some common adaptations have emerged. These include: (i) optimal network problem (Boyce et al, 1973; Boffey and Hinxman, 1979; Rothengatter, 1979), (ii) capacitated and uncapacitated network design problems (Magnanti and Wong, 1984), (iii) fixed charge problem (Hochbaum and Segev, 1989), (iv) multi-period network design problem (Chang and Gavish, 1995; ElDessouki et al, 1998), (v) multi-level network design problem (Balakrishnan et al, 1994a, 1994b, and 1996), and (vi) bi-level optimization variant of the network design problem (Bard, 1998).

Although not one of these variants precisely satisfies the needs of the rural road network problem examined in this study, certain features pivotal to the corresponding model designs are pertinent to the requirements of the model constructed herein. These features include:

- **Multi-commodity flows:** A flow commodity is any set of network traffic flows uniquely distinguished by some collection of characteristics. For instance, with regards rural road networks, vehicle type (e.g., freight versus passenger vehicle), seasonal trip characteristics, and desired origin-destination (O-D) trip pairing may
together serve as criteria distinguishing each flow commodity. If all traffic through a network can be grouped into one all-encompassing commodity, then a single-commodity flow characterization may be embedded in the resulting NDP-based model. However, where multiple commodities exist, model design must reflect a multi-commodity flow requirement. Since, in this study, rural road network traffic flows must be distinguished by vehicle type, seasonal trip characteristics and O-D pairing, a multi-commodity flow representation is embedded in the corresponding NDP-based model. See Minoux (1989, 315-317) for a description and mathematical treatment of this important distinction.

- **Capacity constraints:** By nature, certain physical networks are characterized by limited capacity. Intercity roadways, for instance, possess capacity constraints that limit throughput during peak traffic flow periods. To adequately emulate reality, then, it is necessary to impose capacity constraints within a NDP intended to model intercity road networks. See, for example, Billheimer and Gray (1973). Since, in general, the traffic capacity of rural roadways far exceeds the traffic volumes experienced, capacity constraints need not be included in the NDP-based model developed herein.

- **Budget constraint:** Typically, network construction and improvement involves the allocation of limited capital budget monies. To ensure expenditures do not exceed this limit, it is necessary to incorporate a budget constraint within a NDP model. Since capital budget monies frequently limit the scope of rural road investment opportunities, a budget constraint must be included in the model developed in this
study. A road-related example containing budget (and capacity) constraints may be found in Leblanc (1975).

- **Bi-level (optimization) design:** Discussed in greater detail later in this chapter, bi-level NDP model designs correspond to real-world problems characterized by incentive conflicts. Since the incentives of rural road network managers are frequently incompatible with the incentives motivating self-interested road users, a bi-level optimization model best represents the rural road network problem at-hand.

A common challenge pertinent to all NDP models and related variants involves computational complexity. Both Johnson et al (1978) and Wong (1980) have demonstrated that the network design problem is NP-hard. In other words, NDP models and related variants cannot be solved by existing efficient (polynomial time) algorithms. For this reason, the development of algorithms designed to solve NDP-based models is dominated by heuristics – computational strategies intended to converge on reasonably good (if not optimal) solutions within an acceptable period of time.

**Algorithms**

The algorithmic strategies used to solve NDP-based models come from two sources. Researchers facing real-world problems frequently develop sophisticated algorithmic strategies to determine good (if not optimal) solutions to the challenge at-hand. A related body of research focuses on the development of algorithmic strategies intended to solve contrived instances of ‘pure’ NDP models and related variants. The purpose of the latter body of academic investigation is to support the activities of researchers facing real-world problems that include a network design component. Regardless of the
source, the work of these researchers provide fodder for those seeking to develop algorithmic strategies pertinent to the unique challenges they face.

Figure 2.2 depicts the range and general relationship of algorithms frequently applied to determine good and/or optimal solutions to NDP-based models. Although the relationships among various algorithms within an overall computational strategy may be quite complex, the basic role of each algorithm falls into one of three categories (corresponding to the three levels of Figure 2.2) combined to derive solutions to NDP-based models:

- **Network Construction**: The add-drop or branch-and-bound algorithms actually ‘construct’ the network by adding and/or deleting the discrete network linkages through which traffic flows. In this role, the add-drop or branch-and-bound algorithms alternatively supply and obtain information from other algorithms in the process of constructing a feasible and – relative to predefined model criteria – ‘good’ network configuration.

  A range of common add-drop algorithms pertinent to network design problems may be found in Dionne and Florian (1979). An introduction to branch-and-bound algorithms may be found in Lawler and Wood (1966). Early, descriptive applications of branch-and-bound algorithms to optimal network problems (a NDP-based model variant) may be found in Billheimer and Gray (1973), Boyce et al (1973), Boffey and Hinxman (1979) and Rothengatter (1979).

- **Link Addition or Deletion Recommendations**: The intermediary algorithms support decisions regarding network configuration and traffic flow routings within the network. In essence, the intermediary algorithms communicate valuable
information that shape the evolving network configuration in promising ways. As shown in Figure 2.2, a range of algorithms may be employed alone or in tandem to satisfy this goal.


Note that certain authors apply some combination of intermediary algorithms to reach a solution to the network design problem at-hand. For example, Chang and Gavish (1995) apply an algorithmic strategy combining both lagrangian relaxation and dual ascent.

- Traffic Flow Routings: A shortest path algorithm determines optimal traffic routings through a pre-configured network. This supplies valuable traffic-related information to the intermediary algorithms that, in turn, influence decisions regarding link deletions from, and/or additions to, the evolving network. Note that many efficient shortest path algorithms exist. Ahuja et al (1993) review a number of these.
As discussed earlier in this chapter, the algorithmic strategies applied by various researchers are as unique as the network design problems faced. This study is no exception to this general rule. The rural road network problem posed is sufficiently complex and distinct to encourage the development of unique algorithmic strategies well-suited to the corresponding mathematical structure. That said, a number of the algorithmic components applied by other researchers are relevant here. As discussed in chapter 6, similar components are applied in two algorithmic strategies designed to address the rural road network problem at-hand. These components include an add-drop
heuristic, branch-and-bound algorithm, cutting planes and, to model roadway traffic
flows, a shortest path algorithm.

2.4 Bi-level Optimization and the Rural Road Network Problem

Users of rural road networks tend to behave in a self-interested way. The routes chosen
by freight truck users in Saskatchewan, for instance, demonstrate little concern for the
damage certain roadways may suffer during the trip. Since society as-a-whole shares
the cost of the resulting road damage, individual users are effectively insulated from the
true impact of the decisions they reach. Hence, while decisions reached by individual
users are optimal from their own standpoint, they may not prove optimal from the wider
standpoint of society. This reflects the classic problem motivating the field of bi-level
optimization: user versus system optimization (Boyce, 1979).

Contrast, for example, optimal design and/or improvement of a rail network as
opposed to a road network. Typically, the owners of rail companies maintain complete
control over both the provision and use of rail networks under their purview. Hence,
owners may take a system optimal approach to determine, for example, cost-minimizing
capital improvements or additions to an existing rail network. Since the ensuing
response of network users is under the complete control of company owners, system-
wide optimality is guaranteed (i.e., total cost minimization with regards both network
provision and use is a practicable objective).

Public managers of road networks, however, enjoy no such luxury. Since users
are generally free to choose trip quantities and routings that, arguably, minimize the
costs of personal trip-making, managers – in the absence of marginal-cost pricing
policies – do not exercise sufficient control over the response of network users to ensure
network improvements or additions are cost-minimizing with regards the entire road transport system. Instead, any decisions reached by public managers must account for the self-interested response of system (network) users. When considering network design issues, then, public road transport providers must account for extant incentive conflicts dividing genuine system optimality from (lesser) user optimality based purely on the self-interested behaviour of trip-makers.

To explicitly account for incentive conflicts within a model intended to achieve second-best system optimization for network design problems, a bi-level programming approach may be pursued. With regards NDP models, bi-level programming effectively separates the system-wide objectives of network managers from the self-interested objectives of network users. In terms of mathematical structure (discussed in Chapter 5), a bi-level programming approach implies the simultaneous representation of two cost-minimizing objective functions within a single constrained optimization problem: (a) an overall objective function representing total system cost-minimization, and (b) a secondary objective function – contained in model constraints – representing total user cost-minimization. Hence, the primary objective of system optimization is literally subject to a model constraint representing the desire of users to minimize the personal trip costs they incur.

Literature on this subject appears limited to issues involving road networks where capacity constraints arise (e.g., congested intercity highways). In these instances, the lack of marginal congestion cost pricing leads to sub-optimal use of available road network capacity from a systems-wide perspective. This motivates the development of bi-level NDP formulations where capacity may be adjusted in a continuous mode to
achieve second-best system optimization (i.e., cost-minimization over both user and provider costs). Note that such formulations typically model user costs as an increasing function of traffic volume since congestion arises where roadway capacity is strained by desired use.

LeBlanc and Boyce (1986), for instance, develop a bi-level representation of a capacitated NDP model where incentive conflicts arise and capacity may be adjusted in a continuous way. Although an algorithmic approach intended to solve such problems is developed, it is not implemented and tested. Similarly, Ben-Ayed et al (1988) develop a general bi-level formulation of the network design problem to suit the implementation of linear programming solution approaches. In this case, however, specific algorithmic strategies are neither specified nor implemented. Bard (1998, pp. 391-413), in contrast, both specifies and implements a bi-level NDP model to determine relatively good capacity improvement strategies for an intercity highway network in Tunisia. For this modestly-sized network, Bard determines a relatively good, second-best, system optimal solution.

Although a bi-level representation of the rural road network problem addressed in this thesis serves a useful illustrative purpose, corresponding bi-level optimization algorithms are generally impractical from a computational standpoint. As discussed above, Bard (1998) developed and implemented a bi-level NDP model—and corresponding algorithmic strategy—for a road network located in Tunisia. Although modestly-sized, the efforts of a Cray supercomputer were required to develop a good solution within a 15 minute time period (Bard, 1998, 410-411). Worse yet, the problem tackled by Bard presumed continuous capacity adjustment. The rural road network
problem, in contrast, requires discrete representation of structural change to extant road segments. Since discrete representations imply additional combinatorial challenges, it is likely that any solution strategy developed to tackle a bi-level representation of the rural road network problem would prove, from a computational standpoint, even more taxing than the problem tackled by Bard.

Further complicating the application of a bi-level approach is the issue of damage costs and its relationship to the performance of certain rural road structures. Discussed more fully in chapters 3 and 5, the damage costs incurred by road users are a discontinuous function of road performance. Hence, the user cost-minimization component of a conventional bi-level program could, in and of itself, generate perverse traffic flow predictions — confounding further the search for a second-best system optimal solution.

An important objective of this research is to develop a practicable model and corresponding algorithms to support sound, road-related investment and policy decisions among managers of rural road networks. A bi-level optimization computational approach is not likely to satisfy this objective in the face of the challenges posed by the rural road network problem at-hand. If implemented in practice, the models and algorithms developed in the context of this study might be applied to any range of network configurations within the province (including, potentially, substantive components of the entire network). Moreover, for each network configuration, a range of exogenous policy options and likely rural economic scenarios may require testing. Uncertainty governing cost and other model parameters may also require evaluation as part of routine sensitivity analyses. Practical use, then, demands that models and
algorithms addressing the rural road network problem generate demonstrably good results in a reasonable period of time. For this reason, a formal bi-level approach is rejected.

2.5 Concluding Remarks

The foregoing literature review included three categories of research: investigations involving rural road networks per se; network design problem (NDP) applications, models and algorithms; and the practice and relevance of bi-level optimization. Some key observations emerged through this review. First, while the work of many authors is pertinent to the subject of this study, none have specifically addressed the rural road network problem posed herein. Second, while none match the precise demands of the rural road network problem, certain features of NDP-based models and algorithms are pertinent to model and algorithmic design within this study. Finally, although a bi-level representation of the NDP-based rural road network problem is certainly illustrative of incentive conflicts between rural road managers and road users, corresponding algorithmic strategies are not suited to the practical objectives of this research.
CHAPTER 3

CONTEXT FOR MANAGEMENT DECISIONS INVOLVING RURAL ROAD NETWORKS IN SASKATCHEWAN

3.1 Introduction

Investment, policy and preservation decisions involving mature rural road networks occur in a broader context of rural economies, road use and related road performance issues. What is true in general is certainly true of Saskatchewan. Figure 3.1 illustrates a decision-making context pertinent to manager of rural road networks in Saskatchewan. As shown, shifts in the rural economic landscape can alter road use characteristics and patterns. Changes in road use may affect the performance of rural roads and thereby exert a reciprocal influence on road use (since poor quality roads repel trip-makers and good quality roads attract trip-makers). Both road use and road performance can sway investment, policy and preservation decisions reached by network managers. In turn, the decisions reached by managers can influence road performance and use. Over a longer time span, the decisions reached by network managers may ultimately shape changes in the rural economic landscape through its impact on road use and performance.

The purpose of this chapter is to explore, more fully, the complex context of rural road management decisions in Saskatchewan today. This context frames the rural
road network problem that is the subject of this study and shapes the subsequent
development of models and algorithms intended to address the problem. The
organization of this chapter emulates the structure of Figure 3.1. Issues pertaining to
rural economies, road use and road performance are first examined. Attendant
implications for rural road network management are then discussed.

![Diagram](image)

**Figure 3.1.** A context pertinent to management decisions involving rural road
networks in Saskatchewan.
3.2 Rural Economies, Road Use and Road Performance

The structure of Saskatchewan’s rural economies today reflect a history of gradual trends and abrupt changes. Long-standing trends include rural depopulation, increasing farm size, and community concentration. From 1936 to 1996, for example, the rural population of Saskatchewan gradually declined from 651,274 to 363,059 while the population of the entire province remained virtually constant at just under one million (Stabler and Olfert, 2000). Over the same time period, average farm size in the province rose from approximately 400 acres to over 1,150 acres (Saskatchewan Agriculture and Food, 1997).

Trends in community concentration are reflected in functional classification studies undertaken by Stabler and Olfert (1997). According to their work, from 1961 through 1996 few communities in the province maintained a population sufficient to support a rich variety of business and public services. In fact, the vast majority of communities in Saskatchewan have seen a gradual recession of business and public services as local populations dwindle. In 1961, for instance, 271 communities served as Minimum Convenience Centres (the least ‘functional’ economic classification). By 1996, this number had risen to 419 – reflecting a general and widespread decline in business and public services offered within many rural communities in Saskatchewan.

In part, trends in community concentration appear linked to road preservation practices and policy shifts involving rural education services. According to Bantjes (1992), community cohesion and attendant road travel patterns and characteristics in Saskatchewan remained relatively stable between 1920 and 1950 (contradicting conventional wisdom regarding the impact of evolving automobile technology). In the
1950s, however, widespread clearing of winter roads promoted all-season travel and hastened the process of community concentration. This trend was further accelerated by rural school consolidation during the 1960s.

More recent and abrupt changes to rural economies in Saskatchewan involve rail line abandonment and concomitant elevator consolidation. Traditionally, a dense network of branch rail lines in the Prairie provinces supported a widespread country elevator system. Changes in legislation governing grain handling and transportation, however, spurred an increase in the abandonment of branch rail lines deemed ‘uneconomic’ (Bonsor, 1995, 65-77). In response, grain handling companies are aggressively transforming the prairie landscape: literally demolishing country elevators in favour of an increasingly concentrated network of strategically located inland grain terminals. Between 1998 and 2008, Grant et al (1998) estimate that the number of grain delivery points in Saskatchewan will fall from approximately 400 to as few as 50.

The changing structure of rural economies in Saskatchewan has strongly influenced the use of rural road networks. For instance, while rural depopulation suggests fewer passenger vehicle trips, community concentration implies longer trips, altered origin-destination (O-D) patterns and, potentially, increasing passenger vehicle trips (to access work and shopping opportunities previously offered locally). These counter-balancing forces are reflected in observations documented in Stabler and Olfert (1987). For example, from 1981 to 1991, average commuter trip lengths to/from rural Saskatchewan rose by about 10 percent. Over the same period, the daily number of commuter trips undertaken by Saskatchewan residents rose from 38,585 to 44,835. Despite falling rural population, then, it appears both commuter trip length and volume
have risen due at least in part to increasing community concentration in Saskatchewan. Presuming this trend extends to other trip types (e.g., shopping), structural changes to the province’s rural economy are likely precipitating an increasing dependence on rural road networks.

The magnitude of trends evident among passenger vehicle users in the province, however, pales in comparison to trends among freight vehicle users. For example, due structural changes in the grain handling and transportation system, average grain haul distances in Saskatchewan doubled from 15 to 30 kilometers over the period 1984 to 1997 (Government of Saskatchewan et al, 1999, 12). By 2005, the average distance is predicted to reach 53 kilometers. Motivated by considerations of efficiency, longer haul distances are causing a rapid migration to larger trucks. From 1980 to 1990, for instance, travel by combination vehicles (i.e., 3 or more axles) in Saskatchewan increased by approximately 34 percent (Grant et al, 1998, 374). Since grain must still travel from farm gate to delivery point, these changes imply a dramatic shift in grain haul from local rail lines to local roads – with concomitant implications for O-D patterns and volumes on rural road networks in the province. Of course, the long-standing trend towards increasing farm size can only exacerbate this problem – economies of scale in agricultural production may imply a more rapid movement towards larger trucks. Reflecting trends evident among passenger vehicle users, the statistics suggest that structural changes to Saskatchewan’s rural economy are increasing dependence on rural road networks among freight truck users as well.

Trends in road use patterns and characteristics hold important implications for the performance of rural road networks in Saskatchewan. Larger trucks traveling from
farm gate to ever more disparate delivery points is precipitating rapid deterioration of existing rural roadways. This is particularly true of the province’s thin membrane surfaced (TMS) secondary highways. Originally designed and constructed to facilitate dust-free travel for passenger vehicles and small straight-axle farm trucks, TMS roadways simply do not possess the structural strength to support increasing volumes of large tandem-axle vehicles hauling up to 40 tonnes of grain. This is aptly illustrated in Figure 3.2. Pictured is a TMS road segment on Highway 19 near Hawarden, Saskatchewan. As can be seen this roadway has been critically damaged by heavy vehicle traffic traveling through the region.

Since the reciprocal relationship between road use and road performance is an important constituent of the problem addressed in this study, it serves well to explore this relationship more fully.¹ Rural roadway structures considered within this thesis may be lumped, roughly, into two categories: (i) those suffering gradual deterioration, and (ii) those suffering sudden deterioration under the strain of heavy vehicle traffic. Roadways possessing adequate sub-grade, base and surface preparation – including asphaltic concrete (AC), granular, and cold in-place recycled (CIR) structures – suffer flexure and fatigue under heavy vehicle traffic. Hence, deterioration suffered over time is relatively gradual. In contrast, roadways absent sufficient preparation – including gravel and TMS structures – suffer sudden failure at some critical volume of heavy freight traffic. Hence, the performance deterioration pattern of these road structures is marked by sudden and precipitous decline.

¹ The following discussion draws on personal conversations held with Dr. Gordon Sparks, Dr. Curtis Berthelot (both of the University of Saskatchewan), and Mr. Ron Gerbrandt (Preservation Director, Saskatchewan Highways and Transportation).
In general, given corresponding preservation efforts across attendant service lives, roadways of category (i) perform reasonably well over a broad range of heavy truck traffic volumes. Hence, while not entirely divorced, the performance of AC, granular and CIR structures is relatively insensitive to the low volumes of freight truck traffic typically found on rural roadways within Saskatchewan.

Roadways of category (ii), on the other hand, perform reasonably well up to a critical volume of freight traffic. The critical volume in question, however, is highly sensitive to the degree of moisture present in underlying sub-grade materials. If the sub-grade of either TMS or gravel roads is ‘high and dry’ (or better yet, frozen), the structure performs adequately over a wide range of freight truck volumes. In contrast, if the sub-grade is relatively ‘wet’ (as is typical of spring months), the road structure may collapse
after only a few heavy vehicle trips. In either case, once a structure has collapsed the roadway service levels experienced by users are – in the absence of additional preservation efforts – roundly poor.

Even where road performance is relatively good, the service level corresponding to each road structure varies. The smoothest of available structures is most definitely AC pavements. Well-constructed and preserved, AC pavements provide a consistently smooth ride to road users. Granular, TMS and CIR roadways belong to the next tier of performance from users’ standpoint. Exhibiting somewhat rough and uneven surfaces, the level of comfort and noise experienced by users of these road structures exceeds that experienced of AC pavements. Gravel roadways, of course, provide the lowest level of service. Since at best the surface consists of loose gravel, roughness and noise exceed that of all other structures considered. Moreover, in the absence of dust inhibitors the experience of users is further diminished by dust clouds raised by other vehicles.

The performance characteristics of rural roadways affect the service levels and therefore the costs of road use experienced by both freight and passenger vehicle travellers. Deteriorating road performance, for instance, can affect user costs in three ways. First, vehicle operating costs may be affected since poorly performing roadways influence both fuel economy (through an increase in rolling resistance) and maintenance expenditures (through jarring potholes, washboard and other surface fractures). Second, since poor road surfaces discourage travel at typical highway speeds, the time taken to complete intended trips may rise – increasing the opportunity cost of travel. Finally, roads in an advanced state of deterioration can pose a safety hazard that effectively
increases the probability of vehicle accidents – causing a rise in expected property, injury and fatality costs.

Reciprocally, the costs incurred by road users may affect the performance of rural roadways. As the performance of certain segments (i.e., road links) within rural road networks deteriorates, road users may choose to alter their travel patterns in an effort to lower trip-related costs. Should sufficient freight vehicles change routing from trip origin to intended destination, vulnerable road segments along new routings may similarly suffer performance deterioration. This precipitates another round of user cost changes that may, in turn, influence the performance of yet another collection of road segments within rural road networks. In the absence of intervention by road agencies (e.g., preservation activities), this process could theoretically continue until substantive components of rural road networks suffer extensive damage and a perverse stability in trip routing is achieved.

3.3 Implications for Managers of Rural Road Networks

In Saskatchewan, rural road network managers at the provincial and municipal levels are responsible for approximately 200 thousand kilometers of roads. Of this total, approximately 106,000 kilometers are low standard gravel roads. Another 59,000 kilometers constitute grid and GHS gravel roadways (Saskatchewan Highways and Transportation, 1997, 9). Remaining road structures include: 8,900 kilometers of AC pavements, 4,600 kilometers of granular pavements, and 7,000 kilometers of TMS roadways (Government of Saskatchewan, 2003, 3). While the bulk of gravel roadways fall within municipal jurisdictions, the bulk of remaining road structures lie within the
jurisdiction of the Province’s transport agency: Saskatchewan Highways and Transportation (SHT).

Shifts in Saskatchewan’s rural economic landscape and attendant road use and performance consequences both influence and react to decisions reached by managers of rural roadways in the Province. In Figure 3.1, the reciprocal nature of this relationship is indicated by arrows connecting ‘Network Management Decisions’ with road use, road performance and, ultimately, the rural economic landscape.

As discussed earlier in this chapter, recent trends in rural road use and performance are driven to a large extent by structural shifts in the grain handling and transportation system. The impact on TMS roadways within Saskatchewan’s rural secondary highway network has been dramatic. Of the 7,000 kilometers of TMS roadways in the Province, approximately 4,000 kilometers have deteriorated to poor or critical condition – exhibiting damage similar to that illustrated in Figure 3.2. In the face of increasing dependence on rural road networks, this state of affairs presents a serious challenge to SHT.

Conventional solutions to challenges posed by deteriorating roadways typically involve upgrade of existing TMS road segments to granular or pavement structures – at capital design and construction costs ranging from approximately 120,000 to 430,000 dollars per kilometer (SHT, 2001). The total capital cost of applying conventional upgrade solutions to 4,000 kilometers of TMS roads within Saskatchewan would therefore range between 480 million and 1.7 billion dollars. To put this in perspective,
if SHTs entire rural highway restoration budget were allocated to this task, work efforts would stretch over 21 to 78 years.²

To deal with this issue in a timely and effective way, then, creative solutions and a more judicious application of available capital budget monies is required. Among solutions currently pursued by SHT are policy and road structure options intended to ameliorate – at modest cost – the negative impacts of deteriorating TMS roadways in rural regions of the Province. Key policy options include:

- **Spring weight restrictions**: As noted above, during the spring period the sub-grade underlying TMS roadways is relatively ‘wet’ and therefore structurally weak. Under these conditions, TMS roads are particularly vulnerable to damage by heavy freight vehicles. To ameliorate this damage to some degree, SHT imposes spring weight restrictions that limit gross vehicle weight according to number of axles, tire size, et cetera.

- **Haul road management agreements (HRMA)**: SHT is now in the practice of negotiating with rural municipalities to re-route heavy freight vehicles from TMS to municipal gravel roads. Through introduction of stringent weight restrictions on select road segments within SHT jurisdiction, heavy freight vehicles must travel alternative routes to reach intended destinations. This alleviates damage on TMS road segments supporting higher traffic volumes – lowering overall trip costs for passenger vehicle users due to subsequent improvements in road performance.

Key road structure options include:

---

• **Conventional structures:** As discussed above, conventional granular and AC pavement upgrades constitute an effective yet relatively costly set of road structure options available to SHT.

• **Gravel reversion:** Gravel reversion implies replacement of TMS roads with so-called gravel highway standard (GHS) roads. These gravel roadways possess sufficient drainage characteristics and structural integrity to permit heavy freight hauls at relatively modest preservation cost.

• **Cold In-place Recycling (CIR):** Cold in-place recycling is a relatively new technology that permits in situ recycling of road surface and underlying materials. Typically, heavy equipment is applied to recycle – literally ‘rototill’ – the roadway while simultaneously introducing a stabilizing agent (e.g., cement kiln dust, fly ash, chemically modified polymers) to improve the structural strength of sub-grade materials. Once completed, the surface is treated with a double-seal to resemble a smooth, dust-free pavement.

The capital design and construction costs attributable to gravel reversion and CIR are, to some degree, sensitive to circumstances characterizing the existing TMS road structure (e.g., grade height, road width). At present, SHT estimates the capital costs of gravel reversion at approximately 100,000 dollars per kilometer (SHT, 2001). In contrast, liberal capital cost estimates related to CIR range from 90,000 to 120,000 dollars per kilometer.³

With regards application to rural road networks, there exists an important difference between policy and structural options. The implementation of spring weight

---

³ Capital cost estimates pertaining to CIR provided by Dr. Gordon A. Sparks and Dr. Curtis Berthelot (University of Saskatchewan).
and/or HRMA policies involve a significant component of an existing network. In other words, a substantive collection of individual road segments within a rural road network will fall under the terms of policy options designed to ameliorate the impact of heavy freight vehicles. For this reason, policy options are considered 'global' in nature. In contrast, structural options are applied on a segment-by-segment basis. Hence, each individual road segment within a rural road network may be considered a candidate for structural modification of one sort or another.

As indicated in Figure 3.1, the implementation of policy and structural options is related. There is no a priori reason to expect that the 'best' allocation of considered structural modifications across network segments remains invariant across alternative global policy options. Therefore, to ensure available capital budget monies are judiciously allocated it behoves public agents to consider structural allocations in the context of alternative policy options.

The consequences of applying policy and/or road structure alternatives extend beyond capital design and construction costs alone. For instance, the implementation of a HRMA may affect agency preservation efforts as well as service levels and trip costs experienced by users of rural road networks. For SHT, diversion of heavy freight vehicles from TMS highways improve the effectiveness of existing preservation efforts at relatively modest cost (in practice, the sum of compensation expenditures negotiated with the RM as part of the HRMA). For freight vehicle users, the HRMA may increase haul costs due to route diversion. For passenger vehicle users, the HRMA leads to substantive improvement in the quality of TMS roads covered under the agreement.
This, in turn, implies an incremental decrease in road trip costs for all those attracted by the superior service levels resulting through implementation of the HRMA.

In like manner the consequences attributable to the upgrade of TMS road segments to, for example, granular structures extend beyond capital costs alone. Freight and passenger vehicle users, for instance, will experience an improvement in road service levels where granular structures have been installed. This will in turn reduce the trip costs they incur. Counter to intuitive expectations, however, the preservation efforts and costs incurred by SHT would in all likelihood increase. While granular structures improve service levels and reduce the frequency of preservation activities, they do require periodic and costly resurfacing. Hence, under traffic volumes sufficient to motivate the upgrade of TMS roads to granular structures, one would expect an increase in the cost of preserving the roadway over its useful life. Note that the same may be said of every structural option discussed above excepting gravel reversion (GHS roads are relatively inexpensive to preserve on an on-going basis).

Interestingly, the direct linkage between rural road performance and the preservation costs incurred by SHT is somewhat tenuous. First, as recent events suggest, the amount of monies allocated to the preservation of roadways under provincial jurisdiction is relatively insensitive to road performance. While priorities are set (with the aid of an asset management system), the reality of limited and generally unresponsive funding commitments imply the overall deterioration of the secondary highway network witnessed today. It is important to note, however, that a certain rationale does support this ‘insensitivity’. Once damaged, existing TMS and gravel roadways are best repaired when ‘high and dry’. Therefore, presuming damage occurs
during spring months (a common phenomena), repair activities are unlikely to occur prior to late summer or fall – implying acceptable performance over, perhaps, six to eight months in a given year. Should this cycle of damage and repair become a frequent event, it makes little sense – in the context of alternative and superior preservation opportunities – to continue funding activities of limited impact. In other words, there is no point putting ‘good money to inferior ends’. Second, as discussed above, the performance characteristics of a number of roadway structures – including CIR, granular, and AC pavement structures – are relatively consistent across a broad range of truck traffic volumes normally experienced in rural regions. Hence, typical preservation efforts associated with these road structures are generally sufficient to sustain acceptable levels of service.

Do these arguments imply consistent preservation efforts and costs across road structures? No. In fact, data from SHT suggest expected maintenance and resurfacing costs do vary across road structure type. The arguments do suggest, however, that preservation efforts and costs corresponding to each structure type do not vary substantially across a broad range of traffic volume and road performance levels. For this reason, simplistic relationships linking preservation expenditures to truck traffic and/or road performance likely misrepresent real-world decision-making regarding the amount and allocation of available preservation monies across road networks in Saskatchewan.

Since preservation budgets and attendant efforts are relatively insensitive to the performance of rural road networks, the primary victims of deteriorating TMS and gravel roadways are freight and passenger vehicle users. By the same token, users are
the primary beneficiaries of road structure upgrades. Hence, the stakeholders enjoying the bulk of benefits gained through capital expenditures on structural modification of existing TMS and gravel road segments are freight and passenger vehicle users. The only exception involves reversion to gravel structures (GHS), where SHT enjoys a net reduction in preservation expenditures (and users suffer rough and dusty travel conditions).  

The interdependent nature of relationships among policy and investment decisions, preservation efforts and costs, road use and road performance extend – as illustrated in Figure 3.1 – to Saskatchewan’s rural economic landscape as well. Although pertinent interrelationships are not addressed directly in this study, it is interesting to note in particular the influence network management decisions may hold for rural economies. As mentioned at the beginning of this chapter, SHT’s decision to expand winter road clearing operations encouraged all-weather vehicle use and contributed to community concentration in the Province. While road investment and policy decisions may not effect such dramatic change, widespread improvement of rural roadway networks may in time alter further the character of rural economies in Saskatchewan.

3.4 Concluding Remarks

Figure 3.1 suggests a range of interdependent relationships among rural economies, road use, road performance and management decisions pertinent to mature rural road networks. In essence, it describes a context and related challenges faced by managers of

---

4 The foregoing arguments are supported by comments provided by Mr. Ron Gerbrandt (Preservation Director, Saskatchewan Highways and Transportation).
rural road networks in Saskatchewan today – challenges relevant to the rural road network problem that is the subject of this study.

Recent changes in grain handling and transportation within the Canadian prairie provinces has had a dramatic and deleterious impact on many rural roads in Saskatchewan. Facing budget limitations inadequate to address this problem through conventional means (e.g., upgrading roads to granular or asphaltic concrete structures), Saskatchewan Highways and Transportation (SHT) is examining a range of alternative road structure and policy options in order to improve current circumstances at more moderate cost.

The introduction of road structure and policy options altering the character and quality of rural road network services, however, may influence a range of stakeholders in various ways. Through changes in preservation efforts and costs, SHT itself may well be affected by policy and structural options implemented to improve rural road network services. Similarly, through the concomitant influence on trip-making costs, both freight and passenger vehicle users traveling rural roadways will feel the impact of decisions reached and implemented by managers within SHT. Over a longer time period, rural citizens may be directly affected since the shape of the rural economic landscape may be influenced by the road structure modifications and policy options pursued today. From the standpoint of all such stakeholders, this begs an important question: for a given rural road network and available capital budget, what strategic mix of policy and road structure alternatives is ‘best’ applied? To answer this question it is necessary to establish: (i) a standard against which to measure the relative merits of mutually exclusive investment and policy arrangements, and (ii) a computational
method within which to implement the standard in the context of stakeholder interests. That is the subject of the next chapter.
CHAPTER 4

STANDARDS AND METHOD TO DETERMINE GOOD ARRANGEMENTS OF
ROAD INVESTMENT AND POLICY ALTERNATIVES FOR RURAL ROAD
NETWORKS

4.1 Introduction

Standards are explicitly or implicitly employed to reach decisions involving the
allocation of scarce resources. A principal objective of this study is to determine a
relatively good arrangement of considered road investment and policy alternatives
pertinent to rural road networks in Saskatchewan under a range of real-world
constraints. The definition of 'good arrangement', however, depends largely on the
standards employed to commit scarce resources to a particular course of action. One
purpose of this chapter is to establish and discuss the standards employed herein to
defend road investment and policy arrangements ultimately derived.

The import of standards, however, is dependent on practical implementation.
Good standards employed within methods and models inadequate to the task at-hand are
rendered useless. As discussed later in this chapter, the combinatorial implications
surrounding the rural road network problem at-hand are explosive. For this reason, it
serves well to develop a pragmatic method to determine a demonstrably good – if not
optimal – arrangement of available road investment and policy options relative to the
standards employed. A second purpose of this chapter, then, is to discuss the methods applied to derive good solutions to the rural road network problem. A formal mathematical description of resulting models and corresponding computational algorithms are postponed to chapters 5 and 6, respectively.

4.2 Standards Employed to Rank Road Investment and Policy Arrangements

In this study, the term standards has a dual meaning. On the one hand are engineering design standards that establish the definitive set of road structure investment options available for substitution among segments constituting a given rural road network. With regards rural road networks in Saskatchewan, for instance, current engineering design standards suggest four discrete options: TMS, GHS, granular pavement, and AC pavement (SHT, 2001).

On the other hand, the term standards refers to the criteria employed to distinguish relatively 'good' road structure investment (and/or policy) arrangements from relatively 'poor' arrangements. For instance, current standards in Saskatchewan employ a traffic volume criteria to distinguish relatively 'good' from relatively 'poor' arrangements of available road structures within rural road networks. Upgrade to an AC pavement structure, for example, is deemed justified only where average daily traffic volumes exceed 1200 (SHT, 2001).

In this study, the term standards generally refers to the criteria employed to determine relatively 'good' road structure and policy arrangements for rural road networks. Yet the discrete list of road structures and corresponding cost estimates

---

1 Although an engineered road structure alternative included in this study and employed in practice, CIR is not represented in current design standards.
included in supporting analyses implicitly reflect applicable engineering design standards.

4.2.1 A Net Benefit Approach

For a given rural road network, the standards employed by managers will influence the choice of investment and policy arrangements ultimately implemented. For instance, a standard based principally on traffic volume criteria might lead to a substantively different arrangement than a standard based principally on initial design and construction costs. In this study, the standard established and subsequently employed to rank alternative road investment and policy arrangements for a given network reflects net benefit criteria subject to certain constraints.

The choice of net benefit criteria reflects long-standing and defensible economic principles embodied in the practical field of cost-benefit analysis (Townley, 1998). At its most basic level, cost-benefit analysis quite logically argues that public agents (e.g., politicians and bureaucrats) must carefully evaluate and prioritize considered investment, policy and/or program initiatives to reasonably ensure decisions reached improve – rather than reduce – the economic welfare of the citizens they represent. From this standpoint, any considered initiative should satisfy a so-called compensation test to prove worthy of implementation.

In and of themselves, public initiatives are rarely 'win-win'. Instead, while certain stakeholders enjoy the benefits of these initiatives, other stakeholders endure the concomitant costs. Suppose, however, that the forecasted benefits surrounding a given initiative exceed the forecasted costs. Then it is at least theoretically possible to redistribute the total benefits such that the 'losers' are fully compensated and the
‘gainers’ still enjoy a net increase in economic benefits. In other words, should benefits exceed costs, then implementation of a perfect and costless compensation mechanism would effectively convert a ‘win-lose’ situation to a ‘win-no lose’ situation. Since under this arrangement no citizen loses and at least some subset of citizens gain, the economic welfare of society cannot help but rise. While no such ‘perfect and costless’ mechanism exists, the principles underlying the practice of cost-benefit analysis ensure that gainers could fully compensate losers and still enjoy a net increase in economic welfare.

In practice, the net benefit approach employed in this study emulates the incremental approach of Hamlet and Baumel (1990). Changes in rural road investment and policy arrangements are compared against a predefined base case to determine the incremental net benefits enjoyed or losses suffered. In this study, benefits incremental to the predefined base case are generally attributable to trip-makers who enjoy improvements in road performance that concomitantly lower travel costs. The related incremental rise in costs is incurred by the road agency (SHT) implementing the associated investment and policy arrangement. Net benefits are computed as the difference between incremental benefits and incremental costs. Alternative road investment and policy arrangements are ranked according to the magnitude of net benefits estimated.

The base case against which alternative investment and policy arrangements is compared corresponds to existing road structure allocations and ubiquitous spring (truck load) weight restrictions. The chosen base case best emulates present circumstances in Saskatchewan and therefore permits a convenient means of estimating the incremental
net benefits or losses attributable to changes in the existing policy environment and/or road structure arrangements for any rural road network under investigation.

While the net benefit criteria permits a consistent ranking of alternative investment and policy arrangements relative to the base case, certain practical features constrain its application in this study. First, access provision is a necessary feature of any considered policy-investment arrangement. In other words, no policy or investment combination may prevent a traveler from reaching the intended trip destination from the trip origin. In Hamlett and Baunel (1990), imposition of this constraint limited the range of road abandonment strategies examined (for obvious reasons). In this study, the access provision constraint limits the application of haul road management agreements (HRMAs) across users. Since certain freight travelers are effectively 'captive' to particular rural roadways, the application of HRMAs are generally sensitive to the trip-making needs of these users – effectively exempting them from punitive fines under the terms of the agreement. Hence, application of net benefit criteria in this study is sensitive to the terms of considered HRMAs.

The second practical feature constraining the application of the net benefit criteria involves available budget monies. Road structure modification is a particularly costly activity subject to fixed funding allocations. Hence, while net benefit criteria may suggest the modification of a significant subset of rural road network segments, capital budget monies allocated to the task may well limit the number of segments SHT can, in reality, modify. To adequately emulate reality, then, the application of net benefit criteria is subject to a budget money constraint.
In sum, the standard employed herein reflects net benefit criteria subject to certain practical constraints. Road access provision is guaranteed to avoid undue penalty to ‘captive’ users within a given rural road network. Budget monies limit the range of potentially advantageous road structure allocations a net benefit criteria may advocate.

4.2.2 Accounting Stance

To justify the application of a net benefit standard in this study requires the adoption of a particular accounting stance (Stabler, 1988; Townley, 1998, 149-151). Since funds allocated to secondary highway components of rural road networks are obtained from the provincial purse, the accounting stance adopted herein is provincial as well. From an economist’s standpoint, however, this reasoning is likely insufficient to defend the allocation of tax revenues to capital projects involving secondary highways in rural regions. For this, it is necessary to more carefully define assumptions underlying the accounting stance adopted.

Presume, for sake of argument, Saskatchewan’s allocation of available tax dollars is controlled by an economic manager. Surveying the landscape, the economist identifies a long list of projects, programs and policy initiatives potentially worthy of funding. Constrained by available budget monies, however, the economist must prioritize implementation in the hope of maximizing the welfare gains enjoyed by Saskatchewan’s citizens. Given the range of important issues facing Saskatchewan – in areas of health care, primary and post-secondary education, agriculture, et cetera – concerns involving remote and uncongested roadway networks in sparsely populated rural regions might rank low on the economist’s list of priorities.
In the real world, however, economic logic is not the sole rationale underlying the allocation of available tax revenues. Instead, other considerations enter the debate and lead to political decisions that may contradict the economist's logic. In practice then, a certain proportion of provincial tax revenues are regularly allocated to the repair of ailing rural road networks for the benefit of rural citizens.

The accounting stance adopted herein therefore presumes that some amount of provincial budget monies will be allocated to capital projects involving rural road networks. What needs to be determined, then, is how the available monies are best distributed across a rural road network given a set of mutually exclusive road investment and policy arrangements. In this study, the net benefit standard described above is employed to address this requirement.

4.2.3 Adapting the Standard for Modeling Purposes

As discussed in Chapter 2, the model employed in this study is based on the network design problem (NDP). A solution to a NDP-based model typically involves the implementation of cost-minimizing criteria within an objective function subject to constraints ensuring that the resulting network configuration permits desired trip-making quantities between chosen origin-destination (O-D) pairings. In essence, the NDP is akin to the problem of the firm seeking to minimize the cost of reaching a pre-selected level of output. Given the standard advocated above, this raises a pertinent question: how can cost-based and net benefit-based criteria be reconciled in the context of the rural road network problem that is the subject of this study?

To answer this question, suppose network configurations A and B are compared. Let A represent the base case network and B represent a network differentiated by the
inclusion of a number of upgraded road segments. In this case, total user costs attributable to trip completion through each network configuration may be represented by TUC_A and TUC_B, respectively. Total fixed costs attributable to each network configuration are F_A and F_B (where F_A is zero since the base case implies no structural improvement of any road segment within the existing network) and total preservation costs are P_A and P_B.

Applying the net benefit approach implies that network configuration B is no worse than network configuration A if: (TUC_A - TUC_B) - (F_B + P_B - P_A) \geq 0 (recall, F_A = 0). In words, B is no worse than A if incremental user benefits less incremental agency costs equal or exceed zero. Through straight-forward algebraic manipulation, this implies that B is no worse than A if: TUC_A + P_A \geq TUC_B + F_B + P_B. In words, B is no worse than A if the total costs of A exceed or equal the total costs of B. Hence, whether one applies a net benefit or total cost approach to rank alternative road investment and policy arrangements, the results are the same.

It is important to note that equivalence between cost- and net benefit-based standards is met only where the cost of travel does not influence the quantity of trips undertaken within a road network (i.e., only where the quantity of trips desired is insensitive to the corresponding ‘price’). Although a restrictive assumption, presumed equivalence greatly simplifies modeling efforts since it is not necessary to explicitly model the (iterative) interplay between user costs and trip quantity. Moreover, while the substitution of road structures and imposition of varying policy regimes does change the trip-making costs experienced by users, the magnitude of the change is unlikely to substantively alter trip-making quantities throughout the network. Following Hamlett
and Baumel (1990), then, cost- and net benefit-based standards are presumed equivalent for the purposes of modeling.

From a computational standpoint, the advantage of a cost-based standard over a net benefit-based standard involves the phenomena of negative cost cycling (Ahuja et al, 1993, 135-6). If travel over each segment in a network permits some positive benefit, mere trip completion is insufficient to maximize the net benefit of network improvement. Instead, the flow (trip-making) component of a NDP-based model will exploit benefit accumulation by repeating attendant journeys over and over again. Under such circumstances, infinite iteration of trip completion is implied.

In contrast, if trip completion involves non-negative cost, the flow component of a NDP-based model will satisfy required trip-making demands only once. Presuming the rural road network in question contains sufficient connectivity to satisfy trip-making demands, therefore, the flow component will converge on a definitive solution.

It is important to note that the application of cost-based criteria within the rural road network model applied in this study does not preclude a post-analysis computation of net benefits incremental to the base case. As the argument above illustrates, straightforward algebraic manipulation permits convenient computation of incremental net benefits attributable to various road investment and policy arrangements. A practical demonstration of the equivalence of the two criteria is found in chapter 7, where the rural road network model is applied to a case study to generate pertinent results and rankings according to both cost-based and net benefit-based standards.
4.3 Method of Employing the Standard

In practice, the application of cost-benefit analyses typically involves comparison and ranking across all mutually exclusive options considered within a given project. In the case of rural road networks, then, this would involve the comparison and ranking of all mutually exclusive investment and policy arrangements pertinent to a given network. A modest example, however, serves to illustrate the impractical nature of this approach.

Suppose a given road network contains 20 TMS segments – all of which are potential candidates for structural modification. Presume further that four 'global' policy options and three segment-specific road structure options (including the existing TMS structure) are under consideration. In this case, there exist approximately 14 billion mutually exclusive investment and policy arrangements for evaluation within an incremental cost-benefit analysis (i.e., $4(3^{20})$). Clearly, then, exhaustive enumeration of all mutually exclusive combinations is an impractical means of determining an optimal policy-structure mix for a given network. Instead, a more clever computational approach is required.

With this in mind, the computational approach adopted within this study derives from mathematical programming techniques and corresponding algorithms. In general terms, the purpose of such programming techniques and algorithms is to determine good – if not optimal – solutions to large-scale problems that defy exhaustive enumeration. Since the use of algorithms imply the iterative application of various computational techniques, the use of computer technology is paramount to successful implementation. Hence, in practice, mathematical programming and computer programming are synonymous.
In the context of the rural road network problem that is the subject of this thesis, the mathematical programming approach and corresponding computer models developed permit ranking of road investment and policy arrangements according to both cost-based and net benefit-based standards. The constituent elements of this modeling approach are illustrated in Figure 4.1. As can be seen, endogenous model components include: investment alternatives pertinent to managers of mature rural road networks; associated changes in preservation efforts (and costs); and interrelated road use and performance effects. Exogenous components to the modeling environment include both policy options and features of the rural economic landscape affecting the network in question. To generate the costs and net benefits necessary to rank potential road investment and policy arrangements, a step-wise computational method controls the application of various models and corresponding mathematical programming algorithms. In broad terms, the computational method employed proceeds as follows:

- **Predefined rural economic landscape (exogenous):** Current arrangement of significant elements underlying evident trip volumes, patterns and characteristics in a rural region (e.g., grain elevators, municipal services, farmstead locations) are used to estimate trip origins and destinations within the corresponding rural road network.

- **Policy imposed (exogenous):** Each considered policy option pertinent to the rural road network examined is pre-imposed on the NDP-based model through the introduction of mathematical constraints (e.g., budget constraints) and modification of model parameters (e.g., unit cost estimates sufficiently high to discourage freight travel on TMS roadways covered under HRMAs).
Figure 4.1. Components endogenous to modeling environment.

- **Spatial allocation of considered road investments (endogenous):** Under each policy option (including the base case), computer-based algorithms and the cost-based standards combine within the NDP-based modeling environment to determine a demonstrably good spatial allocation of available road structure options across secondary highway segments within a predefined rural road network. It is important to note that interrelated preservation, road use and road performance effects are
included within the computational search for a good spatial allocation of road structures. Costs considered in the analysis include both user and agency (SHT) costs.

- **Compare and rank road investment and policy arrangements:** Subtracting policy-specific cost estimates from base case cost estimates provides a measure of the incremental net benefits corresponding to various road investment and policy arrangements. Hence, both cost-based and net benefit-based standards may be employed to rank the road investment and policy arrangements evaluated within the overall modeling environment.

Since there exists only a handful of policy options requiring evaluation under the predefined economic features pertinent to a given rural road network in Saskatchewan, this computational method provides a reasonable means of determining a demonstrably good arrangement of road investments and policy. Moreover, as discussed in chapter 7, practical application of this method leads to good solutions relatively quickly.

### 4.4 Concluding Remarks

A good arrangement of policy and investment alternatives for a given rural road network varies according to the standard employed. In this study, the standard employed reflects net benefit criteria subject to road access and budget constraints. A predefined base case establishes the benchmark against which changes to existing policy or road structure allocations are compared. Should an alternative arrangement of policy and road structures generate benefits incremental to the base case, then further consideration is warranted. Otherwise, base case arrangements remain the preferred alternative.
Combinatorial challenges surrounding the rural road network problem, however, can frustrate the application of the standard in practice. For this reason, it is necessary to develop a computational method of implementing the standard that delivers demonstrably good solutions within a practical period of time. In this study, the method developed and applied combines a range of mathematical programming algorithms within an overall, step-wise computational approach to determine a relatively good spatial arrangement of considered road structure alternatives under a range of predefined policy regimes.

To more precisely describe the models and algorithms applied in this study, it is necessary to turn to the language of mathematics. A mathematical description of the rural road network problem model is provided in Chapter 5. Corresponding model decompositions and algorithms are outlined in Chapter 6.
CHAPTER 5

NETWORK DESIGN PROBLEM MODELING APPROACH

5.1 Introduction

The purpose of this chapter is to review the mathematical model underlying the spatial allocation of rural road network investments under each considered policy regime (reflecting the model structure illustrated in Figure 4.1). Based on a network design problem (NDP) formulation, this model contains: (i) a flow component that assigns traffic flow routings – sensitive to road performance implications – through a network of given configuration, and (ii) a fixed component that allocates available and costly road structure alternatives across the rural road network in question. Reflecting discussions in Chapter 4, the resulting model incorporates the cost-based standard necessary to compute the incremental net benefits ultimately attributable to alternative road investment and policy arrangements. It should be noted that preservation efforts and costs are also represented within the modeling environment implemented. However, to avoid additional complication herein, pertinent discussions are postponed to chapter 6.

Elucidation of the NDP-based model occurs in a step-wise manner: progressing gradually from a straightforward root model to a complete description of the rural road network problem at-hand. The logic underlying each incremental step in model development is described in literal terms and reflected in additions to the root model.
5.2 Root Model: Uncapacitated Network Design Problem (UNDP)

Rural roadways suffer little if any traffic congestion. Hence, the traffic capacity of rural roads is rarely strained. For this reason, rural road networks may be described as ‘uncapacitated’. An appropriate root for subsequent model development is therefore the uncapacitated network design problem (UNDP) model. Since mathematical elucidation of UNDP generally relies on notation adopted from graph theory, this section begins with a brief review of pertinent graph theory notation.

Road networks – indeed any spatial or temporal network – may be described by notational conventions established within graph theory (Foulds, 1992). A graph (G) is defined as set of nodes, N, connected to some degree by a set of edges, E (where each edge is a line segment connecting exactly two nodes). In this context, a graph $G = (N,E)$ of a road network consists of: (i) a node set representing spatially disparate intersections, towns, businesses, households, arbitrary road segment markers, et cetera, and (ii) an edge set representing the extant road segments connecting the various nodes. The resulting network graph serves, effectively, as a spatial ‘road map’ facilitating mathematical description of roadway use and provision.

A simple example illustrates the manner in which graph theory may be applied to describe a road network and characterize its provision and use. Figure 5.1 presents a contrived road network subject to use and provision by individual agents. In this case, the network configuration presented consists of 5 nodes (i.e., $N = \{1, 2, 3, 4, 5\}$) and 6 edges (or, road segments). Each edge contained within the set $E$ is described by the nodes it connects. Hence, the edge connecting nodes 4 and 5 is represented by the tuple
(4,5). The edge set of Figure 5.1 is therefore fully described by: \( E = \{(1,2), (1,3), (1,4), (2,5), (3,5), (4,5)\} \). The network graph is then completely described by \( G = (N,E) \).

![Graph of contrived rural road network.](image)

**Figure 5.1.** Graph of contrived rural road network.

Although it is sufficient to describe an actual road segment as an edge within a network graph, it is necessary to extend set \( E \) in order to describe the use of road segments by users. Typically, road segments facilitate travel in either direction. Users are free, for example, to traverse to node 2 from node 1 (i.e., travel in direction (1,2)) or traverse to node 1 from node 2 (i.e., travel in direction (2,1)). To formally accommodate two-way travel within a network it is necessary to introduce an arc set, \( A \). Referring, again, to Figure 5.1, the relevant arc set may be described as: \( A = \{(1,2), (2,1), (1,3), (3,1), (1,4), (4,1), (2,5), (5,2), (3,5), (5,3), (4,5), (5,4)\} \). Although it may seem somewhat schizophrenic at this point, the network graph can now be defined as \( G = \)
\((N,E)\) and \(G = (N,A)\). As demonstrated later in this section, both descriptions will prove useful to model development.

With regards Figure 5.1, two unique user trip types (or commodities) are presumed: (a) user trips originating from node 1 and destined for node 5, and (b) user trips originating from node 4 and destined for node 2. The quantity of trips supplied by each commodity is represented by \(R(1)\) and \(R(2)\), respectively. Trip supplies indicate the start of attendant journeys from trip origins, \(O(k) = R(k)\) for all \(k \in K\) (where set \(K = \{1, 2\}\)). In contrast, since trips demands reside at intended destinations, \(D(k) = -R(k)\) for all \(k \in K\). Note that node 3 is neither a trip origin or destination for any \(k \in K\). Therefore, node 3 is labelled a transhipment node and assigned a net trip volume of zero (i.e., any trips ‘arriving’ at node 3 during the course of a journey must ‘leave’ node 3 to reach intended destination).

Note that the representation of trips described above ensures that trip completion through the network is formally acknowledged as ‘conservation of mass’ (i.e., \(O(k) + D(k) = R(k) - R(k) = 0\), for all \(k \in K\)). To satisfy conservation of mass, user motivated traffic flows must proceed from origin node destination node over a series of connected network arcs termed a ‘path’. For example, to conduct a supply of \(R(1)\) trips from node 1 to node 5, the user may choose path \([(1,3), (3,5)]\), path \([(1,2), (2,5)]\), or any other path connecting nodes 1 and 5 within the network.

In this study, it is presumed that the path selection reached by each road user (or trip commodity) will minimize the total, quantifiable, cost of travel. To this end, presume: (i) the unit (average) cost of travel over each arc traversed along a given path by the \(k^{th}\) trip commodity is represented by \(c_{ij}^k\), and (ii) the volume of trips across each
such arc by the $k$th trip commodity is represented by $x_{ij}^k$ (for all $(i,j) \in A$, $k \in K$). The total travel costs credited a particular arc $(i,j)$ for a given commodity $k$ is then calculated as $c_{ij}^k x_{ij}^k$. Note that $c_{ij}^k$ and $c_{ji}^k$ are presumed identical (i.e., direction of travel along a network segment is irrelevant to unit travel cost). However, since path selection is left to each individual trip commodity, $x_{ij}^k$ need not equal $x_{ji}^k$.

The total cost incurred by user (trip commodity) $k$ to complete all his or her intended journeys along the chosen path through the network sum to $\sum_{(i,j) \in A} c_{ij}^k x_{ij}^k$ (where $x_{ij}^k = 0$ for all arcs not belonging to the user’s chosen path). The sum of all travel-related costs across all trip commodities is therefore $\sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k$.

To facilitate desired travel patterns within the considered road network, there must exist sufficient road segments to support at least one path between each origin-destination (O-D) pair. The provision of road segments, however, comes at some cost. In Figure 5.1, one component of provision costs is implicitly considered: capital design and construction cost, $F_{ij}$ (for all $(i,j) \in E$). Note that $F_{ij}$ is edge- as opposed to arc-specific. Since any two-lane road segment facilitates two-way travel, its provision is not subject to ‘directional’ considerations.

Representing a road agency’s decision to provide a particular road segment is variable $y_{ij}$ (for all $(i,j) \in E$). Since this decision is binary in nature (i.e., either the entire segment is provided, 1, or not provided, 0), all $y_{ij}$ are restricted to the set \{0,1\}.

Combining decision variables, $y_{ij}$, and capital costs, $F_{ij}$, the total capital cost of road provision corresponding to a particular network configuration is described by $\sum_{(i,j) \in E} F_{ij} y_{ij}$.
Considering in tandem the variable decision elements corresponding to users and providers of road network services (the $x_{ij}^k$ and $y_{ij}$, respectively), an important interrelationship emerges. In order to facilitate trip-making, service providers must design and construct a network configuration that contains at least one path linking the O-D pair pertinent to each user. The network configuration provided, however, influences the path choice reached by each user. The heart of the UNDP is therefore the interplay between decisions reached by both network providers and users. Ideally, the solution to UNDP is a network configuration that optimally reconciles the desires of users and providers with regards a predefined standard.

In this case, the standard against which the optimal network configuration is determined involves minimization of total use and provision costs subject to a connectivity (access provision) constraint satisfying conservation of mass. The constrained optimization problem at-hand may be expressed as follows:

\[
\text{Minimize}_{\{x,y\}} \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k + \sum_{(i,j) \in E} F_{ij} y_{ij} \quad (5.0)
\]

subject to

\[
\sum_{j: (i,j) \in A} x_{ij}^k - \sum_{j: (j,i) \in A} x_{ji}^k = \begin{cases} 
R(k), & \text{if } i = O(k) \\
-R(k), & \text{if } i = D(k) \\
0, & \text{otherwise, } \forall i \in N, k \in K
\end{cases} \quad (5.1)
\]

\[
x_{ij}^k + x_{ji}^k \leq y_{ij} R(k), \quad \forall (i,j) \in E, k \in K \quad (5.2)
\]

\[
x_{ij}^k \geq 0, \quad \forall (i,j) \in A, k \in K \quad (5.3)
\]

\[
y_{ij} = 0 \text{ or } 1, \quad \forall (i,j) \in E \quad (5.4)
\]

In literal terms, (5.0) represents the desire to minimize the total costs of network design, construction and use – modeled as the sum of user costs and agency capital costs. Equalities (5.1) are the conservation of mass constraints that ensure the final
network design facilitates desired travel patterns among all trip commodities (i.e., the sum of outbound trips less the sum of inbound trips corresponding to each node i equals the net trip supply or demand required of that node for each trip commodity k). Inequalities (5.2) ensure non-existent road segments facilitate zero traffic flows (and extant segments facilitate a maximum of R(k) traffic flows for each trip commodity k). Note that these inequalities express a particular property of consistent path choice: if, in order to reach an intended destination, user k travels segment (i,j) in direction (i,j), then user k will not – during the same journey – travel in direction (j,i). Doing so would only increase total trip length and, therefore, increase the costs corresponding to trip completion (Balakrishnan et al, 1989, 719-720). Inequalities (5.3) restrict all segment-specific traffic flows to positive values. Expressions (5.4) ensure each road segment is either provided or not provided.

As discussed in chapter 2, the problem type expressed in (5.0) through (5.4) is known as a mixed integer programming (MIP) problem since extant decision variables include both real and integer types. Since both the objective function, (5.0), and constraints, (5.1) through (5.4), are expressed in linear and/or linear-integer terms, a number of useful computational strategies exist to converge upon an optimal or ‘good’ solution.

In order to exploit such computational strategies, extensions of the root model maintain linear and linear-integer terms. Where potential non-linearity occurs, accommodations are made to adequately address extant non-linearity within a linear MIP framework. Model extensions and corresponding logic are described, step-by-step, below.
5.3 Uncapacitated Network Structural Improvement Problem (UNSIP) with Side Constraint

Since rural road networks in Saskatchewan are mature, the network configurations evident today are the network configurations foreseeable in even the distant future. For this reason, the UNDP model must be modified to address road investment options of interest to managers of rural road networks in the Province. Rather than adding or deleting road segments from a given network configuration, UNDP must be adapted to model possible substitution of existing road structures (e.g., existing TMS roads) with alternative road structures (e.g., granular or CIR road structures). Since the extent of road structure modifications throughout a given network is limited by available budget monies, the UNDP model must also be adapted to ensure forecasted expenditures do not exceed available monies.

Figure 5.2 is a modified version of the road network depicted in Figure 5.1. As can be seen, the key changes involve the addition of index \( m \) and capital budget \( B \). The index \( m \) denotes the road structure assigned a particular segment. In this case, \( m \) refers to any specific element within the set \( M \) containing a predetermined number of mutually exclusive road structure investment options (e.g. \( M = \{\text{existing TMS, AC pavement, granular, CIR, GHS}\} \)). The capital budget \( B \) denotes the maximum design and construction expenditures a road agency may incur to modify a network’s constituent road segment structures over an arbitrary time period. With regards the network example illustrated in Figure 5.2, \( B \) represents the maximum capital outlay an agency may allocate to modify existing TMS road segment structures over a one-year period.
Figure 5.2. Graph of contrived rural road network: UNSIP.

In contrast to the root model, then, UNSIP is not designed to add or delete network segments. Instead, the existing road structure of each network segment may be substituted by an alternative structure. From the standpoint of road users, substitution to superior structures may well imply substantive performance gains and, thereby, concomitant decrease in trip costs. Of course, no good substitution goes unpunished: the cost savings enjoyed by network users is offset by capital outlays incurred by road providers. Given a constrained capital budget, the objective of UNSIP is to allocate segment-specific road structure improvements such that the total cost of network use and provision is minimized.

In mathematical terms, UNSIP may be expressed as follows:

\[
\text{Minimize}_{\{x,y\}} \sum_{m \in M} \left[ \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^{km} x_{ij}^{km} + \sum_{(i,j) \in E} f_{ij}^{m} y_{ij}^{m} \right] \\
\text{subject to} \sum_{m \in M} \left[ \sum_{j:(i,j) \in A} x_{ij}^{km} - \sum_{j:(j,i) \in A} x_{ji}^{km} \right] = \begin{cases} 
R(k), & \text{if } i = O(k) \\
-R(k), & \text{if } i = D(k) \\
0, & \text{otherwise}, \; \forall \; i \in N, \; k \in K
\end{cases}
\]  

(5.0a)  

(5.1a)
\[ \sum_{m \in M} y_{ij}^m = 1, \forall (i,j) \in E \] (5.2a)

\[ \sum_{m \in M} \sum_{(i,j) \in E} F_{ij}^m y_{ij}^m \leq B \] (5.3a)

\[ x_{ij}^k + x_{ji}^k \leq y_{ij}^m R(k), \forall (i,j) \in E, k \in K, m \in M \] (5.4a)

\[ x_{ij}^k \geq 0, \forall (i,j) \in A, k \in K, m \in M \] (5.5a)

\[ y_{ij}^m = 0 \text{ or } 1, \forall (i,j) \in E, m \in M \] (5.6a)

Expression (5.0a) reflects the desire to minimize the total use and provision costs attributable to structural modification of existing network segments across all available structural options. Equalities (5.1a) are the familiar conservation of mass constraints. In this instance, however, it is necessary to sum over all possible road structure options. Equalities (5.2a) limit to one the number of structures assigned each road segment. In other words, each network segment must be assigned precisely one of either TMS (i.e., existing road structure), AC pavement, granular, CIR or GHS road structure – it is impossible to assign more than one structure to a segment. Inequality (5.3a) is the side constraint corresponding to a limited capital budget. As can be seen, the sum of all capital expenditures across network segments and available road structures may not exceed the prescribed budget. Inequalities (5.4a) ensure zero traffic flows on non-existent segment structures (i.e., traffic may flow only over the road structure specifically assigned a segment). In a manner emulating inequalities (5.2), inequalities (5.4a) restrict the sum of bi-directional flows to \( R(k) \) for each user \( k \). Expressions (5.5a) and (5.6a) simply bound both real and binary decision variables.

In sum, UNSIP extends UNDP in two ways. First, UNDP suggests the addition or deletion of road segments within a given network. UNSIP, in contrast, considers structural modification opportunities for segments within an existing, mature rural road.
network. Hence, the index m is introduced to denote the availability of multiple road structure options. Second, a capital budget, B, is introduced as a side constraint to ensure total structural modification expenditures do not exceed available budget monies.

5.4 Implications of Road Performance Characteristics

To this point, total user costs have been presumed to rise linearly with traffic flows. In other words, the average variable costs — and therefore marginal costs — of road use have been presumed constant. In certain cases, however, this supposition is invalid. As discussed below, this has important implications for the rural road network problem at-hand.

As discussed in chapter 3, TMS and GHS road structures exhibit an interesting pattern of performance. Up to a critical volume of heavy freight truck movements, these roads tend to perform relatively well. However, at and beyond this critical volume the structural integrity of these roads literally collapse and performance suffers sudden and precipitous decline.

From the standpoint of both freight and passenger users of roadways, the odd behaviour of TMS and gravel road structures imply discontinuous average variable costs. For illustrative purposes, Figure 5.3 presents a hypothetical average variable cost curve corresponding to freight traffic volumes conducted over a TMS road segment. Within Figure 5.3, let $x$ represent total, bi-directional freight traffic on an arbitrary network segment. Let $c$ represent common unit costs experienced by passenger vehicle users traversing the segment. For the time being, unit costs attributable to freight truck travelers are ignored.
Figure 5.3. Discontinuous variable passenger vehicle user costs.

As shown in Figure 5.3, the average variable costs corresponding to freight traffic volumes within the interval \([a_0, a_1]\) is \(c_1\). Once a critical volume of freight traffic \((a_1)\) is reached, however, average variable costs rise to \(c_2\). Presuming maximum possible freight volumes over the segment equal \(a_2\), \(c_2\) represents average variable costs over the closed interval \([a_1, a_2]\).

The introduction of discontinuous costs holds three important implications for UNSIP. First, to accommodate the discontinuity, UNSIP requires fundamental modification. Second, since affected road structures typically exhibit seasonal variations in performance, the required modifications must apply uniquely to spring and non-spring periods captured within the model. Finally, the discontinuity introduces an incentive conflict between user and broader social interests that influences the application of potential computational strategies.
5.4.1 Modeling Discontinuous Costs

In order to accommodate discontinuous costs within UNSIP, a procedure common to non-linear separable programming is modified and adopted (Williams, 1999, 136-142; Nemhauser and Wolsey, 1999, 11-12). In addition to the descriptive parameters of Figure 5.3, let each $\lambda_h$ ($h = 1, 2$) be a real numbered variable restricted to the closed interval [0,1]. Let each $\phi_h$ be a binary variable corresponding to each $\lambda_h$ (i.e., $\phi_h \in \{0,1\}$ for $h = 1, 2$).

Given these definitions, let $x$ be limited to the closed interval $[a_0,a_2]$ and described as:

$$x = a_0 + \lambda_1 a_1 + \lambda_2 a_2 = \lambda_1 a_1 + \lambda_2 a_2 , \text{ since } a_0 = 0$$

or

$$x - (\lambda_1 a_1 + \lambda_2 a_2) = 0$$

where $\lambda_1 \leq \phi_1, \lambda_2 \leq \phi_2$ and $\phi_1 + \phi_2 \leq 1$

In literal terms, $x$ is represented by a share-weighted linear function of non-negative, definitive points on a real number line. To ensure only one share weight (i.e., one of $\lambda_h$) is active at any time, each is subject to constraints involving the binary decision variables $\phi_h$. Hence, either: (i) $\lambda_1$ is non-zero and $\lambda_2$ is zero, (ii) $\lambda_1$ is zero and $\lambda_2$ is non-zero, or (iii) both $\lambda_1$ and $\lambda_2$ are zero.

This definition of $x$ leads naturally to the following definition of $f(\lambda_1,\lambda_2)$ — a more descriptive variant of which will be added to the objective function (5.0a):

$$f(\lambda_1,\lambda_2) = c_1 \lambda_1 a_1 + c_2 \lambda_2 a_2$$

Since only one of $\lambda_h$ ($h = 1, 2$) may assume a non-zero value, $f(\lambda_1,\lambda_2)$ is effectively a linear function of the lower average cost ($c_1$), the higher average cost ($c_2$), or neither (i.e., $f(\lambda_1,\lambda_2) = 0$ if $\lambda_1 = \lambda_2 = 0$). Moreover, since values of $x$ exceeding $a_1$ can only be
expressed as some proportion of \( a_2 \) – necessitating a non-zero \( \lambda_2 \) – freight traffic at or above the critical volume ‘activate’ the higher cost coefficient. This is precisely the behaviour required of UNSIP.

Before such modifications are introduced to model objective (5.0a) and constraints (5.1a) through (5.6a), it is necessary to elucidate the scope of change required. Above, it was arbitrarily assumed that cost coefficients \((c_1 \text{ and } c_2)\) correspond to passenger vehicle flows. When a given road structure collapses, the average variable costs experienced by passenger vehicle users rise suddenly. What is true for passenger vehicle users is, of course, true for freight vehicle users. Average variable costs experienced by freight vehicle users are therefore also expected to rise once a road structure suffers a sudden decline in performance. For this reason, required model modifications must explicitly account for both freight and passenger vehicles.

In addition, certain road structures tend to behave differently during spring and non-spring periods. During spring periods, underlying sub-grade materials are relatively ‘wet’ and therefore structurally weak. During non-spring periods, however, underlying sub-grade materials are relatively ‘dry’ (or frozen) and therefore structurally strong. For this reason, the critical heavy freight truck volumes precipitating sudden and drastic performance reductions differ across spring and non-spring periods. The critical volume corresponding to the spring period is therefore expected to be lower than the critical volume corresponding to the non-spring period.

Due to these phenomena, it is convenient to partition the traffic commodity set \( K \) and the road structure set \( M \). Set \( K \) is partitioned into four categories: \( K_\alpha, K_\delta, K_\eta, K_\theta \) (i.e., \( K = \{K_\alpha, K_\delta, K_\eta, K_\theta\} \)). Set \( K_\alpha \) represents all freight traffic commodities engaged in
travel during the non-spring period of any given year. In contrast, set $K_d$ represents freight traffic commodities engaged in travel during the spring period. Set $K_n$ represents passenger traffic commodities engaged in travel during the non-spring period. Set $K_h$ represents passenger traffic commodities engaged in travel during the spring period. With regards set $M$, define the subset $M'$ as road structures exhibiting sudden and precipitous decline in performance once freight vehicle traffic reaches a critical volume (implying subset $M/M'$ represents all remaining road structures). Below, the denoted partitions are used to extend model (5.0a) through (5.6a).

### 5.4.2 UNSIP and Discontinuous Costs

To incorporate discontinuous costs within UNSIP, it is first necessary to define model parameters and variables akin to those described in general terms above (for $h = 1, 2$). Let $\phi_{nij}^m$ emulate the role of $\phi_h$ above for each road segment in $E$ and road structure in $M'$. Similarly, let $\lambda_{naij}^m$ emulate the role of $\lambda_h$ above for bi-directional freight traffic flows during the non-spring period (denoted by $\alpha$) over each segment in $E$ and each road structure in $M'$. The remaining share weight definitions simply repeat the foregoing and extended definitions of $\lambda_h$ for $\alpha, \eta, \eta$, and $\eta_h$, respectively.

Note that $\phi_{nij}^m$ are not differentiated by vehicle type or season (i.e., $\phi_{nij}^m$ are insensitive to $\alpha, \eta, \eta$, and $\eta_h$). With regards on-going road performance it makes little difference whether a road segment is damaged during the spring or non-spring period: once damaged, the unit costs incurred – from the users’ standpoint – are fixed across both periods. Therefore, $\phi_{nij}^m$ require no further distinction. This stance and its implications is reflected in the design of model constraints described later in this section.
Let $a_{1d}^m$ represent critical bi-directional freight flow volumes during the non-spring period for each road structure in $M'$ (presume this is constant across any subset of segments possessing road structure $m$). Similarly, let $a_{2a}$ represent maximum possible bi-directional freight flow volumes during the non-spring period (i.e., $a_{2a} = \Sigma_{k \in K_a} R(k)$). Note that $a_{2a}$ does not vary over $M'$. Regardless of road structure, the maximum possible flows over any segment of the network is the sum of all intended O-D journeys across the specified subset of commodities ($K_a$, in this case). Repeating these definitions for $a$ establishes critical and maximum bi-directional freight traffic flow volumes during the spring period.

Although freight vehicles can overwhelm the strength of certain road structures, passenger vehicles cannot. With regards passenger vehicles, then, there exists no ‘critical’ volume at which a road structure might collapse. For this reason, bi-directional passenger vehicle flow volumes along any segment over the non-spring and spring periods may be represented, respectively, as share-weighted functions of maximum possible volumes $a_{\eta}$ and $a_{\bar{\eta}}$ (where, $a_{\eta} = \Sigma_{k \in K_{\eta}} R(k)$, and, $a_{\bar{\eta}} = \Sigma_{k \in K_{\bar{\eta}}} R(k)$). Note, however, that a share weight representation is still required since it controls the application of appropriate unit costs. This reflects the fact that sufficient freight volumes can trigger a sudden road performance reduction that increases the unit costs experienced by both freight and passenger users.

With regards variable vehicle user cost coefficients, let $c_{ij}^{km}$ emulate the role of $c_1$ above for bi-directional traffic flows over each segment in $E$, each commodity in some $K_q$ ($q \in \{a, \bar{a}, \eta, \bar{\eta}\}$), and road structure in $M'$. Repeat this definition for $c_2$ to generate the remaining cost coefficients.
Given these definitions, USNIP may now be restated as follows:

\[
\text{Minimize}_{\{\lambda, \mu, j, n\}} \quad \sum_{m \in M'} \left\{ \sum_{k \in K} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{aij}^{m} a_{1}^{m} + c_{2ij}^{km} \lambda_{2aij}^{m} a_{2}^{m} \right] 
+ \sum_{k \in K} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{aij}^{m} a_{1}^{m} + c_{2ij}^{km} \lambda_{2aij}^{m} a_{2}^{m} \right] a_{\eta} \right\}
+ \sum_{k \in K} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{aij}^{m} + c_{2ij}^{km} \lambda_{2aij}^{m} \right] a_{\eta} \right\}
+ \sum_{m \in M \setminus M'} \sum_{k \in K} \sum_{(i,j) \in E} c_{ij}^{km} y_{ij}^{m} + \sum_{m \in M} \sum_{(i,j) \in E} F_{ij}^{m} y_{ij}^{m}
\]

\[
\text{subject to}
\sum_{m \in M} [\sum_{i \in \{i,j\} \in E} x_{ij}^{km} - \sum_{j \in \{i,j\} \in A} x_{ji}^{km}] = \begin{cases} R(k), & \text{if } i = O(k) \\ -R(k), & \text{if } i = D(k) \\ 0, & \text{otherwise}, \forall \ i \in \mathbb{N}, k \in K \end{cases}
\]

\[
\sum_{m \in M} y_{ij}^{m} = 1, \forall \ (i,j) \in E
\]

\[
\sum_{m \in M} \sum_{(i,j) \in E} F_{ij}^{m} y_{ij}^{m} \leq B
\]

\[
x_{ij}^{km} + x_{ji}^{km} \leq y_{ij}^{m} R(k), \forall \ (i,j) \in E, k \in K, m \in M
\]

\[
\sum_{k \in K} (x_{ij}^{km} + x_{ji}^{km}) - (\lambda_{aij}^{m} a_{1}^{m} + \lambda_{2aij}^{m} a_{2}^{m}) = 0, \forall \ (i,j) \in E, m \in M'
\]

\[
\sum_{k \in K} (x_{ij}^{km} + x_{ji}^{km}) - (\lambda_{aij}^{m} a_{1}^{m} + \lambda_{2aij}^{m} a_{2}^{m}) = 0, \forall \ (i,j) \in E, m \in M'
\]

\[
\sum_{k \in K} (x_{ij}^{km} + x_{ji}^{km}) - (\lambda_{aij}^{m} a_{1}^{m} + \lambda_{2aij}^{m} a_{2}^{m}) = 0, \forall \ (i,j) \in E, m \in M'
\]

\[
\lambda_{aij}^{m} \leq \phi_{aij}^{m}, \forall \ (i,j) \in E, m \in M', q \in \{\alpha, \alpha, \eta, \eta\}, h = 1, 2
\]

\[
\phi_{ij}^{m} + \phi_{2ij}^{m} \leq 1, \forall \ (i,j) \in E, m \in M'
\]

\[
x_{ij}^{km} \geq 0, \forall \ (i,j) \in A, k \in K, m \in M
\]

\[
y_{ij}^{m} = 0 \text{ or } 1, \forall \ (i,j) \in E, m \in M
\]

\[
0 \leq \lambda_{aij}^{m} \leq 1, \forall \ (i,j) \in E, m \in M', q \in \{\alpha, \alpha, \eta, \eta\}, h = 1, 2
\]

\[
\phi_{aij}^{m} = 0 \text{ or } 1, \forall \ (i,j) \in E, m \in M, h = 1, 2
\]

Model objective (5.0b) extends objective (5.0a) in that it contains a satisfactory representation of discontinuous costs for each subset of $K$ (i.e., $K_{\alpha}, K_{\eta}, K_{\eta}, K_{\eta}$). For road structures in $M'$, cost coefficients ($c_{ij}^{km}$) and variables ($x_{ij}^{km}$) are replaced with the
necessary discontinuous cost coefficients \((c_{1ij}^{km}, c_{2ij}^{km})\), critical and maximum traffic volumes \((a_{1a}^{m}, a_{2a}, a_{1q}^{m}, a_{2q}, a_{q}, a_{h})\), and share-weight variables \((\lambda_{hij}^{m}, h = 1, 2\) and \(q \in \{a, A, \eta, \eta\}\)). For road structures outside \(M'\) (i.e., \(m \in M/M')\), (5.0b) repeats (5.0a) with regards coefficients \(c_{ij}^{km}\) and variables \(x_{ij}^{km}\). Finally, for all road structures in \(M\), the fixed cost component (i.e., all \(F_{ij}^{m}, y_{ij}^{m}\)) of (5.0b) is identical to the fixed cost component of (5.0a).

With regards model constraints, (5.5b) through (5.10b), (5.13b) and (5.14b) are additions required to accommodate discontinuous costs. Constraints (5.5b) and (5.6b) ensure the sum of all bi-directional non-spring and spring freight traffic flows across any segment are identically represented by the corresponding share weight functions. Constraints (5.7b) and (5.8b) ensure the same for all bi-directional non-spring and spring passenger traffic flows. Constraints (5.9b) ensure share weights do not exceed the value assigned to the corresponding binary control variables, \(\phi_{hij}^{m}\), for road segments in \(E\) and road structures in \(M'\). Constraints (5.10b) limit the sum of binary control variables, \(\phi_{1ij}^{m}\) and \(\phi_{2ij}^{m}\), to one or zero. This ensures that either the higher or lower user cost coefficient is assigned within the modeling environment. Constraints (5.13b) and (5.14b) simply specify the allowable bounds for share weights and corresponding binary control variables.

### 5.4.3 Incentive Conflicts and UNSIP

Boyce (1979) differentiates system optimal (SO) and user optimal (UO) solutions to problems involving road networks. Network models pursuing SO solutions implicitly presume either: (i) monopolistic control of both network modification (e.g., structural changes to road segments) and traffic flow patterns through the network, or (ii) a
perfectly aligned incentive structure among all agents engaged in provision and use of the road network. Models designed to produce UO solutions, in contrast, avoid potential incentive conflicts by focusing strictly on capital budget allocation issues. Generally, UO models optimize network modification with regards total user costs subject to available capital budget monies (similar, in fact, to the budget constraint imposed within UNSIP). Of course, models generating UO solutions do not implicitly compare the fixed costs of modification against the resulting flow savings enjoyed by network users. Hence, UO solutions may well recommend a network modification strategy generating an incremental net loss (should agency expenditures enter net benefit computations).

In the absence of discontinuous costs, UNSIP facilitates practicable SO solutions. First, considered policy applications affecting rural road networks are enforced by rule of law and common consent. In this sense then, policy embodies elements of monopolistic control. Second, structural upgrades occur only where incremental cost savings enjoyed by system users exceed the incremental capital costs incurred by the public agent (e.g., SHT). Hence, no incentive conflict occurs: the public agent implicitly serves network users and, in turn, network users serve themselves in a way that achieves system optimization from the standpoint of the public agent.

Unfortunately, the introduction of discontinuous costs upsets this harmony. The conflict, in this case, is not simply between the public agent and network users. It extends to include conflict amongst network users as well. Presume, for example, an arbitrary segment \((i,j)\) is assigned some structure within set \(M'\). Suppose further that the critical freight traffic volume corresponding to segment \((i,j)\) is 45 vehicles per day. A situation can be easily contrived to generate a solution where the segment facilitates
precisely 44 freight vehicles per day – diverting the remaining vehicles to routes not traversing segment \((i,j)\).

Although feasible in a technical sense, such concerted effort amongst network users clearly defies reasonable expectations. Network users are a parochial bunch. Each will choose the least costly route connecting origin and intended destination. The consequences to other users – in the absence of marginal cost pricing – is simply not considered. Therefore, one would not expect freight vehicle users to altruistically self-administer trip-making activities on susceptible road segments. From the standpoint of public agents, of course, the self-interested behaviour of trip-makers may confound attempts to achieve system-wide optimization. Similarly, from the standpoint of users, the route choices reached by individual freight trip-makers may well impose external damage costs above and beyond an optimal level.

As demonstrated later in this study, the challenge of discontinuous costs extends to problem representation and the design of corresponding algorithms. More particularly, discontinuous costs force an implicit bi-level representation of the UNSIP model reflected in the decomposition and algorithms outlined in chapter 6. Essentially, a bi-level representation of UNSIP presumes the agent charged with efficient management of existing rural road networks (e.g., SHT) must predicate his actions on the self-interested behaviour of individual users of the networks. Note that this situation is akin to oligopolistic circumstances described by the Stackelberg model (Varian, 1999, 469-475). In the Stackelberg model, the output decisions of a natural market leader are predicated on the likely behaviour of market followers. In this case, a road agency is the natural leader predicing its actions on likely behaviour of road users (followers).
A bi-level programming variant of UNSIP may be expressed as follows (where
constraints beyond (5.5c) identically emulate constraints (5.1b) to (5.14b) above):

\[
\text{Minimize}_{y_i} \quad \sum_{m \in M} \left\{ \sum_{k \in K_a} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1ai} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right] \\
+ \sum_{k \in K} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right] \\
+ \sum_{k \in K} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right] \right\}
\]

\[
\text{subject to}
\]

\[
\text{Minimize}_{\lambda_a} \quad \sum_{m \in M} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right], \forall \ k \in K_a
\]

\[
\text{Minimize}_{\lambda_d} \quad \sum_{m \in M} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right], \forall \ k \in K_d
\]

\[
\text{Minimize}_{\lambda_n} \quad \sum_{m \in M} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right], \forall \ k \in K_n
\]

\[
\text{Minimize}_{\lambda_h} \quad \sum_{m \in M} \sum_{(i,j) \in E} \left[ c_{ij}^{km} \lambda_{1aij} m a_{1i} m + c_{2ij}^{km} \lambda_{2aij} m a_{2i} m \right], \forall \ k \in K_h
\]

\[
\text{Minimize}_{\lambda} \quad \sum_{m \in M} \sum_{(i,j) \in A} c_{ij}^{km} x_{ij}^{km}, \forall \ k \in K
\]

In this representation of UNSIP, the objective function (5.0c) is identical to
objective function (5.0b) excepting the range of variables available to decision-makers.

In (5.0c), only binary decision variables, \( y_{ij}^{m} \), can be adjusted to minimize the sum of
road use and provision costs. Rural roadway service providers, in other words, control
only the allocation of road structure modifications across the network in question – they
exercise absolutely no direct control over the route choices reached by road users.

Instead, as reflected in constraints (5.1c) to (5.5c), users individually choose their
preferred (cost-minimizing) routings predicated on the structural characteristics of the
road network. Combined, then, objective function and constraints (5.0c) to (5.5c)
extplicitly emulate the interplay between road service providers and road users. Service

83
providers — as the natural ‘market leaders’ — allocate road structure modifications across the network based on the projected response of road users. Road users, in turn, predicate their personal route choices based on road structure decisions reached by service providers. Moreover, since service providers cannot exercise direct control over the behaviour of road users, a truly system optimal allocation of road structures is not likely reached.

5.5 Concluding Remarks

To solve the rural road network problem that is the subject of this study, it is necessary to employ the chosen net benefit standard within a modeling environment that facilitates the design of pragmatic computer-based algorithms needed to reach demonstrably good solutions. The first step in this process is to develop a formal modeling framework that mathematically specifies the objective and constraints pertinent to the rural road network problem and chosen standard. In this chapter, a network design problem modeling framework was developed — in a stepwise manner — to address this need.

An important issue affecting model development and subsequent algorithms involves incentive conflicts between road users and road agencies, and amongst individual road users. The individualistic behaviour of freight vehicle users can damage road segments. In the absence of marginal damage pricing this cost is absorbed, principally, by other road users — frustrating a truly system optimal approach to rural road management. As discussed in chapter 6, the practical manifestations of incentive conflicts shape the design of algorithms intended to determine demonstrably good solutions to the rural road network problem at-hand.
CHAPTER 6

MODEL DECOMPOSITION AND ALGORITHMS

6.1 Introduction

The incentive conflicts discussed in previous chapters combined with the inherent computational difficulties of a bi-level program suggest the need for a practical, approximate method to solve the rural road network problem at-hand. Ideally, the solution generated should possess two qualities: (a) stability, and (b) goodness. In this case, stability implies a ‘settling’ of incentive conflicts – given a predetermined arrangement of policy options and road structure allocations across a network, computed traffic flow patterns are consistent with self-interested trip-making behaviour. Goodness implies that any alternative policy and road structure arrangements generated by the model demonstrate clear gains over existing arrangements.

This chapter provides an overview of the model decomposition and corresponding algorithmic strategies proposed to generate demonstrably good policy and investment arrangements for real-world rural road networks. Chapter 7 in turn describes the real-world case study to which the algorithmic strategies are applied, reviews accompanying data and modeling results, and discusses the stability and goodness of those results.
6.2 Model Decomposition

As discussed by Williams (1999, 48), model decomposition is not the act of "...splitting a model up into sub-models." Instead, model decomposition expresses a disaggregate computational approach intended to derive optimal or 'good' solutions to large and complex problems relatively quickly. Not surprisingly, then, heuristic algorithms intended to solve complex network design problems frequently reflect an underlying decomposition of simpler problems -- each contributing information relevant to the construction of a relatively good solution.

The incentive conflicts discussed earlier in this thesis suggest a logical approach to model decomposition involving the rural road network problem at-hand. Since trip-makers are generally insensitive to the potentially damaging consequences of their route choices, each is likely to select the cost-minimizing (or 'shortest') path connecting trip origin and intended destination. However, since road agencies such as SHT must contend with the self-interested behaviour of trip-makers, the suggested allocation of road structures must be sensitive to any corresponding change in route choices. This suggests an inherent interplay of route choice and road structure allocation -- under each exogenously imposed policy environment -- that should be part of any computational approach intended to determine relatively good solutions to the rural road network problem.

In light of this, two heuristic algorithmic strategies are constructed and employed to derive solutions to the rural road network problem at-hand. Both strategies are based on a particular decomposition consisting of: (a) a shortest path sub-problem, and (b) a concomitant knapsack sub-problem. The purpose of the shortest path sub-problem is to
determine cost-minimizing route choices for each trip-maker (where there exist K trip-makers, or commodities, in total) given a static set of road structure allocations across a rural road network. The purpose of the knapsack sub-problem, in turn, is to determine the allocation of road structures that generates the greatest net cost-savings given a static set of route choices across all trip commodities. For each exogenously determined policy regime, this process is iterated until a stable solution is found.

Below, the shortest path and knapsack sub-problems are formally delineated and described. The interrelationship of the sub-problems within the context of the heuristic algorithmic strategies is also discussed.

6.2.1 Shortest Path (SP) Sub-problem

Recall that the rural road network problem described in this thesis is uncapacitated. In other words, traffic volumes on rural roadways in Saskatchewan are generally insufficient to stress available capacity and, therefore, insufficient to generate anything but negligible congestion. This implies that each trip-maker is free to ignore capacity constraints and simply choose the shortest path connecting trip origin and intended destination. From a modeling standpoint, this permits a convenient representation of the flow component corresponding to the NDP-based model at-hand.

Eliminating all fixed elements from (5.0a) (i.e., eliminating $\sum_{(i,j) \in E} F_{ij}^{m} y_{ij}^{m}$) and adding constraints (5.1a) and (5.5a) results in the following uncapacitated, multi-commodity shortest path sub-problem:

\[
\text{Minimize}_{\{x\}} \quad \sum_{m \in M} \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^{km} x_{ij}^{km} \\
\text{subject to} \quad \sum_{m \in M} \left( \sum_{j:(i,j) \in A} x_{ij}^{km} - \sum_{j:(j,i) \in A} x_{ji}^{km} \right) = \begin{cases} 
R(k), & \text{if } i = O(k) \\
-R(k), & \text{if } i = D(k) \\
0, & \text{otherwise}, \forall i \in N, k \in K
\end{cases}
\]

87
\[ x_{ij}^{km} \geq 0, \forall (i,j) \in A, k \in K, m \in M \quad (6.3a) \]

If extant structural allocations across network segments are presumed constant, (6.0a) through (6.3a) are reduced to:

\begin{equation}
\text{Minimize}_{[s]} \quad \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k \quad (6.0b)
\end{equation}

subject to

\[ \sum_{j:(i,j) \in A} x_{ij}^k - \sum_{j:(j,i) \in A} x_{ji}^k = \begin{cases} 
R(k), & \text{if } i = O(k) \\
-R(k), & \text{if } i = D(k) \\
0, & \text{otherwise, } \forall i \in N, k \in K
\end{cases} \quad (6.1b) \]

\[ x_{ij}^k \geq 0, \forall (i,j) \in A, k \in K \quad (6.3b) \]

In this case, computed traffic flows (i.e., all \( x_{ij}^k \)) are implicitly presumed to occur over a predetermined (static) set of road structures – permitting the elimination of all references to \( m \in M \). Since (6.0b) to (6.3b) is a constrained optimization problem consisting of purely linear functions in continuous variables (i.e., the \( x_{ij}^k \)), it can be solved efficiently through application of linear programming algorithms such as the network simplex method (Ahuja et al, 1993, 415-430; Hillier and Lieberman, 1995, 378-388).

In order to simplify the model and speed convergence towards an optimal solution, however, the shortest path problem is modified in two ways. First, commodity supplies are normalized to unity (implying, due conservation of mass, that commodity demands are normalized to \(-1\)). Second, the bounds of the linear program are ‘tightened’ through introduction of additional cuts. Each of these changes is described, in turn, below.

As discussed in Holmberg and Hellstrand (1998, p. 248), an uncapacitated multi-commodity shortest path problem may be simplified by adjusting unit costs (\( c_{ij}^k \)) in accord with commodity-specific traffic supply (\( R(k) \)) – enabling the elimination of \( R(k) \)
from the model specification. Multiplying unit costs by corresponding traffic supplies therefore permits the following normalization of the shortest path problem at-hand:

\[
\text{Minimize}_{k} \quad \sum_{k \in K} \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k \\
\text{subject to} \quad \sum_{j: (i,j) \in A} x_{ij}^k - \sum_{j: (j,i) \in A} x_{ji}^k = \begin{cases} 
1, & \text{if } i = O(k) \\
-1, & \text{if } i = D(k) \\
0, & \text{otherwise}, \quad \forall \, i \in N, \, k \in K 
\end{cases} \\
0 \leq x_{ij}^k \leq 1 , \quad \forall \, (i,j) \in A, \, k \in K
\]  

(6.0c)

(6.1c)

(6.3c)

In this representation, \(c_{ij}^k\) equals \(R(k)c_{ij}^k\) for all \((i,j)\) belonging to arc set \(A\) and all \(k\) belonging to trip commodity set \(K\). Since traffic supplies are now restricted to unity, the maximum commodity-specific flow across any arc within the network must be unity as well. This is reflected in the design of constraints (6.3c).

The normalization of the shortest path problem permits convenient introduction of constraints intended to tighten the bounds of the linear program. These are:

\[
x_{ij}^k + x_{ji}^k \leq 1 , \quad \forall \, (i,j) \in E, \, k \in K
\]  

(6.2c)

The design of constraints (6.2c) reflect a straight-forward, intuitive logic: if the optimal path connecting origin and destination includes flow over road segment \((i,j)\) in direction \((i,j)\), then the optimal path cannot simultaneously include flow in direction \((j,i)\). As discussed in Balakrishnan et al (1998, 719-720), introduction of such constraints tend to improve algorithmic performance since an entire set of sub-optimal solutions is eliminated from consideration within the solution search.

From this point forward, the shortest path sub-problem comprising (6.0c), (6.1c), (6.2c) and (6.3c) is denoted \(\text{SP}\). As discussed later in this chapter, sub-problem \(\text{SP}\) is one modeling component of an overall algorithmic strategy intended to determine relatively ‘good’ solutions to the rural road network problem at-hand.
6.2.2 Knapsack (KS) Sub-problem

The knapsack problem is a common one within the mathematical programming field. Given a collection of lumpy valuable objects and a knapsack of fixed volume, the problem asks: what mix and quantity of objects that should be placed in the knapsack in order to maximize the total value of all objects contained by the knapsack? With regards the fixed component of the rural road network problem, this question might be rephrased as: given a collection of lumpy beneficial road structure modifications and a limited capital budget, what mix and quantity of upgrades should be allocated across the road network to maximize the total net benefit (cost savings) of upgrades 'contained' by the available capital budget?

Given an initial set of structural allocations and pre-selected unit cost coefficients (i.e., the $c_{ij}^k$ used to compute the corresponding $c_{ij}^k$), presume SP is solved to determine all commodity-specific vehicle traffic flows over all road segments comprising a given rural road network. Summing the computed $x_{ij}^k$ over each subset of $K$ (i.e., $k \in K_q$, where $q \in \{a, \hat{a}, \eta, \hat{\eta}\}$) provides the total freight and passenger vehicle flows traversing each road segment ($i,j$) during both spring and non-spring periods. Comparing the freight traffic totals against the critical flow parameters corresponding to extant road structures (i.e., the relevant $a_{1a}^m$ and $a_{1a}^m$) permits an appropriate assignment of unit cost coefficients to each road segment (i.e., appropriate assignment of $c_{ij}^{km}$ or $c_{ij}^{km}$).

Once assigned, the unit cost coefficients and computed bi-directional traffic flows can be multiplied together to estimate the total cost of travel incurred on each road segment by all trip-makers traversing the network. More precisely, $\Sigma_{k \in K} c_{ij}^k (x_{ij}^k + x_{ji}^k)$
can be calculated for each road segment \((i,j)\) given extant road structure allocations. Let parameter \(C_{ij}\) equal \(\sum_{k \in K} c_{ij}^k (x_{ij}^k + x_{ji}^k)\) for each road segment \((i,j)\) in the network.

Since each available road structure corresponds to a unique set of unit cost coefficients (i.e., \(c_{1ij}^{km}\) or \(c_{2ij}^{km}\), depending on the magnitude of freight flows on each segment), it is a straight-forward matter to estimate the segment-specific trip costs incurred by all vehicle users traversing each segment in the network across all possible structural allocations. Of course, since some road structures perform better than others (e.g., an AC pavement structure provides better service than a TMS structure), the estimated segment-specific costs incurred by users invariably decrease as road structures of increasing quality are substituted for extant structures.

The estimated cost reductions enjoyed by users, however, must be balanced against any capital upgrade costs incurred by road agencies (i.e., the \(F_{ij}^m\)). For instance, there is little doubt that the allocation of AC pavements to all 'suffering' road segments will provide the best service – and therefore lowest trip cost – to trip-makers. However, the capital upgrade costs may well prove outrageous relative to the cost-savings enjoyed. Hence, both trip cost-savings and upgrade costs must be involved in any analysis attempting to determine a sensible allocation of available capital budget monies.

It is important to note that, while the focus of the investigation herein involves allocation of fixed costs relative to available capital budget monies, non-negligible differences in on-going preservation costs across road structures must be included within the analysis as well to ensure an accurate accounting of all costs pertinent to road structure modification decisions. Furthermore, to ensure all costs derived within the
modeling environment express a common metric, it is necessary to mate annual flow
cost estimates to annualized capital and preservation cost estimates. For these reasons,
initial capital costs, \( F_{ij}^m \), are differentiated from annualized capital and preservation
costs, \( F'_{ij}^m \). Letting \( P_{ij}^m \) represent annualized preservation costs corresponding to edge
\((i,j)\) and road structure \( m \), \( F'_{ij}^m \) may be defined as: \( F'_{ij}^m = rF_{ij}^m + P_{ij}^m \) (where \( r \) represents
the compound annual discount rate applied within the analysis). The derivation of \( F'_{ij}^m \)
reflects an implicit assumption regarding roadways: although periodic resurfacing of
certain road structures is required, the roadway itself – once constructed – possesses an
indefinite lifespan. Note that leaving extant road structures intact results in zero capital
charge. Hence, the only agency costs pertinent to extant road structures are
corresponding preservations costs. For extant road structures, therefore, let \( F'_{ij} = P_{ij} \)
(where lack of index \( m \) indicates costs pertinent to existing road structures only).

To express the necessary trade-offs, the knapsack sub-problem developed herein
implicitly compares trip-cost savings against capital upgrade and preservation costs in
reaching decisions regarding the allocation of road structures across network segments.
The first step in this process is computing the total trip costs corresponding to extant
road structure allocations for each road segment in the network given shortest path
traffic flows (i.e., parameter \( C_{ij} \) is calculated for each road segment \((i,j)\) in the network).
Next, presuming computed traffic flows remain static, the total cost corresponding to
each potential upgrade is calculated (i.e., \( \sum_{k \in K} C_{ij}^{km}(x_{ij}^k + x_{ji}^k) + F'_{ij}^m \) is calculated for
each possible segment-structure combination). Finally, the incremental cost-savings (or
negative-valued incremental costs) corresponding to each possible structural
modification is computed for each segment (i.e., \( C_{ij} + F'_{ij} - \sum_{k \in K} C_{ij}^{km}(x_{ij}^k + x_{ji}^k) + F'_{ij}^m \)
is computed for each possible segment-road structure combination). Let $C_{ij}^m$ represent the potential incremental cost-savings or costs attributable to each possible segment-road structure combination.

The objective of the knapsack sub-problem is to allocate road structures to network segments in order to maximize the sum of incremental cost-savings subject to a capital budget and other constraints. In mathematical terms, this can be expressed as follows:

$$\text{Maximize}_{y_{ij}} \sum_{m \in M} \sum_{(i,j) \in E} C_{ij}^m y_{ij}^m \quad (6.4a)$$

$$\sum_{m \in M} y_{ij}^m = 1, \forall (i,j) \in E \quad (6.5a)$$

$$\sum_{m \in M} \sum_{(i,j) \in E} F_{ij}^m y_{ij}^m \leq B \quad (6.6a)$$

$$y_{ij}^m = 0 \text{ or } 1, \forall (i,j) \in E, m \in M \quad (6.7a)$$

In literal terms, objective (6.4a) expresses the desire to allocate road structures across the rural road network such that the attendant sum of cost-savings is maximized. Constraints (6.5a), however, limit to one the number of road structure modifications allocable to each segment (i,j). In practical terms, this eliminates the possibility of allocating more than one modification per segment. Constraint (6.6a) argues that expenditures on road structure modifications may not exceed the available budget $B$. Finally, constraints (6.7a) restrict all $y_{ij}^m$ to binary values. From this point forward, the knapsack model expressed as (6.4a) through (6.7a) is denoted $KS$.

It is instructive to note an important relationship between $KS$ and the net benefit standard employed in this study (see Chapter 4). Implicit to decision-making within $KS$ is a benefit-cost ratio of 1.0. Should the total flow and fixed costs of current road structure arrangements exceed the flow and fixed costs associated with an incremental
change to existing arrangements (i.e., should the ratio of current costs to potential costs exceed 1.0), then \( KS \) will ‘add’ the change to existing arrangements if sufficient budget monies remain. This is reflected directly in the computation of coefficient \( C_{ij}^c \), where the costs of existing arrangements must exceed the costs of a considered change to generate a positive coefficient value within the objective function (6.4a).

Suppose, however, wider economic concerns within an economy insist a higher standard govern investments in rural road infrastructure. For instance, suppose economic managers impose a benefit-cost standard of at least 1.5 to justify road-related investments. To account for this hypothetical standard, express the computation of \( C_{ij}^c \) as:

\[
C_{ij} + F'_{ij} - \tau [\sum_{k \in K} C_{ij}^{km} (x_{ij}^k + x_{ji}^k) + F'_{ij}^m]\]

where \( \tau \) is a constant equal to the benefit-cost ratio imposed. Assigned a value of 1.0, \( \tau \) would reflect the current computational process embedded in \( KS \). Assigned a value of 1.5, however, \( \tau \) would reflect the hypothetical standard required by economic managers — the costs of existing arrangements must exceed the costs of modified arrangements by a factor of at least 1.5 to warrant investment of public funds.

In all likelihood, a higher benefit-cost standard would narrow the range of suggested road structure modifications reached within \( KS \). Beyond this obvious implication for structural modification, however, the benefit-cost ratio imposed could have an important impact on network-based budgeting. Removing constraint (6.6a) from \( KS \) effectively eliminates the ‘volume constraint’ of the ‘knapsack’ — permitting the implementation of all road structure modifications posting non-negative cost-savings (i.e., all segment-road structure combinations where \( C_{ij}^c \geq 0 \)). The sum of corresponding capital costs \( (\sum_{m \in M} \sum_{(i,j) \in E} F_{ij}^{m, y_{ij}^m}) \) would then establish the
recommended budget (B) for the rural road network in question (a model capability demonstrated in Chapter 7). Clearly, since a higher benefit-cost standard reduces opportunities for road structure modification, the concomitant budget estimate would fall. In this way, the budget implications of higher benefit-cost standards can be estimated within the KS modeling framework.

6.3 Heuristic Algorithmic Strategies

The foregoing discussion provides some clues regarding the interrelationship of sub-problems SP and KS. In this section, the manner in which the interrelationship functions in order to derive solutions to the rural road network problem is described in the context of the two heuristic algorithmic strategies employed.

Figure 6.1 is a flowchart that outlines the generic computational strategy governing both heuristic algorithms. The key steps in this computational strategy are:

1. START by setting all $x_{ij}^k$ of the SP sub-problem to zero. This facilitates subsequent comparison and 'decision-making' within the overall algorithmic strategy. Assign sp and ks to one (counters relevant to SP and KS sub-models). Go to step 2.

2. Set all corresponding $c_{ij}^k$ to their lowest value based on existing road structure allocations (i.e., implicitly presume all road segments within the existing network are performing well and, therefore, assign value $c_{ij}^{km}$ to $c_{ij}^k$). Go to step 3.

3. Given predetermined $c_{ij}^k$, compute corresponding $c^*_{ij}^k$. Then compose and solve SP sub-problems for each trip commodity, $k \in K$. This generates required traffic flow estimates on each segment within the network (i.e., generates $x_{ij}^k$). Go to step 4.

4. Determine whether or not at least one $x_{ij}^k$ has changed from its previous assignment. If so, go to step 5. If not, go to step 7.

5. Determine whether or not sp is greater than spMax (a pre-selected limit on SP model iterations). If so, go to step 7. If not, go to step 6.
Figure 6.1. Overall algorithmic strategy.
6. Based on traffic flow assignments (i.e., $x_{ij}^k$), increase any $c_{ij}^k$ where predicted freight traffic flows exceed corresponding critical flow values. Let $sp \rightarrow sp + 1$. Return to step 3.

7. Determine whether or not $ks$ exceeds $ksMax$ (an arbitrary limit on KS sub-model iterations within the overall algorithmic strategy). If so, STOP (and retain current solution). If not, go to step 8.

8. Implement pre-processing procedure – outlined in detail below – and compute required KS cost-saving coefficients ($C_{ij}^{m}$). Go to step 9.

9. Compose and solve KS sub-problem to determine optimal (or good) structural allocations for each segment in the network (i.e., determine $y_{ij}^m$). Go to step 10.

10. Based on road structure allocations ($y_{ij}^m$), predetermined, ‘stabilized’ traffic flows ($x_{ij}^k$), and critical flow values ($a_{ij}^m, q = \alpha, \delta$), update unit variable costs ($c_{ij}^k$). Let $ks \rightarrow ks + 1$ and $sp = 1$. Return to step 3.

With regards this generic computational strategy, three points must be made.

First, the SP sub-problems are solved by a network simplex algorithm embedded within the software program, CPLEX (ILOG S.A.). Second, the algorithm employed to solve the KS sub-problem effectively divides the two heuristic strategies developed to solve the overall rural road network problem. In one strategy, the KS sub-problem is solved by a branch-and-cut algorithm – a branch-and-bound algorithm implementing various cuts at the root node of the corresponding search tree – embedded within CPLEX (ILOG, 2001, 156-67). In the other strategy, the KS sub-problem is solved by a custom heuristic reviewed in greater detail later in this chapter. The final point involves computational efficacy. As discussed in Chapter 7, practical computer-based implementation of the algorithmic strategies advocated result in demonstrably good solutions within a reasonable period of computation time.

Pre-processing procedures often accompany the implementation of algorithmic strategies. In essence, a pre-processing procedure exploits the underlying structure of
particular problems to eliminate solutions that cannot possibly belong to an optimal or ‘good’ model outcome. In doing so, the procedure reduces the size of the model which must be solved – often saving considerable computation time (Billheimer and Gray, 1972, 58-60; Balakrishnan et al, 1995, 66; Magnanti and Wong, 1986, 128-130). With regards the rural road network problem, the pre-processing procedure implemented exploits three facts limiting the number of possible solutions to KS. These are:

- Segment-upgrade combinations where the corresponding capital costs exceed available budget monies (i.e., $F_{ij}^m > B$) cannot belong to the solution set of KS. For example, the cost of upgrading a particularly long road segment to an AC pavement structure may well exceed the capital budget allocated to the entire network. Hence, the corresponding segment-upgrade combination can be ‘pre-removed’ from consideration within KS.

- Segment-upgrade combinations where $C_{ij}^m$ lie at or below zero cannot belong to the solution set of KS. In other words, if the cost-saving corresponding to a particular segment-upgrade combination is non-positive, then it need not belong to the set of combinations investigated within KS.

- Suppose a given segment-upgrade combination is a favourable candidate (i.e., $C_{ij}^m > 0$ and $F_{ij}^m \leq B$). Label this candidate the ‘incumbent’. Then any other segment-upgrade combination where the comparable cost savings are lower and the capital costs are equal or higher (i.e., $C_{ij}^v < C_{ij}^m$ and $F_{ij}^v \geq F_{ij}^m$, for $v \in \{M: v \neq m\}$) can be removed from the set of combinations considered within the KS sub-model. Of course if the converse is true, then the incumbent (m) can be removed and replaced by the superior segment-upgrade candidate (v).
The algorithmic counterpart to these observations is illustrated as the flowchart in Figure 6.2. The key steps in the pre-processing procedure include:

1. START by numbering all \((i,j)\) network segments \((e = 1, 2, 3, \ldots, E)\) and let \(e = 1\). Go to step 2.

2. Number all possible segment upgrades \((m = 1, 2, 3, \ldots, M)\) and let \(m = 1\). Go to step 3.

3. Let \(D\) be an arbitrary negative number. Go to step 4.

4. Determine if all segments have been examined (i.e., if \(e > E\)). If so, STOP. If not, go to step 5.

5. Determine whether or not the cost of the current segment-road structure tuple \((e,m)\) is greater than the available capital budget (i.e., if \(F_{ij}^m > B\)). If so, go to step 6. If not, go to step 8.

6. Let \(C_{ij}^m = D\) (effectively ‘drops’ the current tuple \((e,m)\) from further consideration). Let \(m \rightarrow m + 1\) and go to step 7.

7. Determine if all road structures in the current iteration have been examined (i.e., if \(m > M\)). If so, let \(m = 1\), let \(v = 1\), and go to step 9. If not, return to step 5.

8. Determine whether or not net cost savings of current tuple \((e,m)\) is greater than zero (i.e., if \(C_{ij}^m > 0\)). If so, let \(m \rightarrow m + 1\) and return to step 7. If not, return to step 6.

9. Determine if \(C_{ij}^m > 0\). If so, go to step 11. If not, let \(m \rightarrow m + 1\) and go to step 10.

10. Determine if \(m > M\). If so, let \(m = 1\), let \(e \rightarrow e + 1\), and return to step 4. If not, return to step 9.

11. Determine if \(v \neq m\) and \(C_{ij}^m > 0\). If so, go to step 13. If not, let \(v \rightarrow v + 1\) and go to step 12.

12. Determine if \(v > M\). If so, let \(v = 1\), let \(m \rightarrow m + 1\) and return to step 10. If not, return to step 11.

13. Determine if \(C_{ij}^v < C_{ij}^m\) and \(F_{ij}^v \geq F_{ij}^m\). If so, go to step 14. If not, let \(v \rightarrow v + 1\) and return to step 12.

14. Let \(C_{ij}^v = D\), let \(v \rightarrow v + 1\) and return to step 12.
Figure 6.2. Pre-processing procedure for knapsack (KS) sub-problem.
Note that all segment-road structure combinations where the corresponding $C_{ij}^m$ (or equivalently, $C_{ij}^{m^*}$) equal D are excluded from the set of candidates examined within the KS sub-model. As discussed in chapter 7 of this study, in practice the pre-processing procedure substantively reduces the set of segment-upgrade combinations considered within the modeling procedure.

The two algorithmic strategies employed to solve the rural road network problem are divided by the method used to solve the KS sub-problem. While one strategy employs branch-and-cut code native to CPLEX, the other strategy employs a custom heuristic algorithm emulating, to some degree, a drop-add procedure developed by Dionne and Florian (1979, pp. 49-53) for general network design problems. The heuristic algorithm is illustrated as a flowchart in Figure 6.3. Its constituent elements include:

1. START the drop-add heuristic by ranking each segment-road structure combination (i.e., each (e,m) tuple surviving the pre-processing procedure) according to the corresponding ratio of cost-savings to road structure capital cost (i.e., according to $C_{ij}^{m^*}/F_{ij}^m$). Note that the ranking procedure employs a modified insertion sort algorithm (Brassard and Bratley, 1996, 62). Go to step 2.

2. Number ranked segment-road structure combinations ($s = 1, 2, 3, \ldots, S$) and explicitly ‘drop’ them from consideration. In other words, set all corresponding $y_{ij}^m(s)$ to zero. Go to step 3.

3. Let $s = 1$ and let parameter residual budget, RB, equal the total capital budget B. Go to step 4.

4. Determine whether or not the road structure capital cost corresponding to $s$, $F_{ij}^m(s)$, is less than or equal to RB. If so, go to step 6. If not, let $s \rightarrow s + 1$ and go to step 5.

5. Determine whether or not $s$ exceeds $S$ (where $S$ is the total number of segment-road structure combinations under consideration). If so, compute total road structure capital costs and corresponding cost savings and STOP. If not, return to step 4.
6. ‘Add’ segment-road structure combination $s$ to ‘knapsack’ (i.e., set $y_{ij}^m(s) = 1$). Reduce the residual budget by the capital cost of the road structure modification (i.e., let $RB \rightarrow RB - F_{ij}^m(s)$). Let $s \rightarrow s + 1$ and return to step 5.

As discussed in chapter 7, in practice the solutions generated by this heuristic across policy-driven variants of the KS sub-problem compare favourably to those determined within the branch-and-cut algorithm. In half the cases, the heuristic procedure generates an optimal solution to the KS sub-problem (i.e., a recommended
road structure allocation identical to that produced by the branch-and-cut algorithm). Of the remaining cases, the heuristic procedure generates solutions that post total cost-savings within 1.65 percent of the optimal solutions reached by the branch-and-cut algorithm.

6.4 Concluding Remarks

To reach demonstrably good investment and policy arrangements pertinent to rural road networks within a reasonable period of computation time, it was necessary to develop a model decomposition and related algorithms corresponding to the bi-level UNSIP model described in Chapter 5. The algorithmic strategies ultimately derived through this process are based on iterative application of two sub-models: a shortest path (SP) sub-model, and a knapsack (KS) sub-model. Within the iterative algorithmic strategies, the results corresponding to each sub-model ‘communicate’ in order to determine demonstrably good results to the rural road network problem at-hand.

Ideally, the solutions generated by these algorithms possess two desirable properties: stability and goodness. Stability implies a settling of incentive conflicts – the origin-destination paths chosen by trip-makers reflect self-interested behaviour. Goodness implies that alternative policy and investment arrangements advocated within model results demonstrate clear gains (e.g., positive incremental net benefits) over base case arrangements.

In the next chapter, the two algorithmic strategies are employed to generate demonstrably good road investment and policy arrangements for a real-world test case. As will be shown, while optimality cannot be guaranteed the solutions generated appear reasonable given the circumstances governing the rural economic landscape, network
configuration, road use and performance, and the range of road structure and policy options pertinent to managers. Moreover, the computation time required to reach demonstrably good solutions is acceptable for practical use.
CHAPTER 7

CASE STUDY: THE RM OF COTE, SASKATCHEWAN

7.1 Introduction

In this chapter, the algorithmic strategies developed in Chapter 6 are applied to a real-world rural road network to determine a good spatial allocation of available road structure options under a range of considered policy alternatives. Both cost- and net benefit-based standards are used to rank the resulting policy-road structure arrangements. Results examined in this chapter include: road structure allocations corresponding to each policy alternative; summary of cost and net benefit findings; and a sample review of edge flows and trip routings associated with various policy and road structure arrangements.

The chapter is divided into two sections. The first section describes a range of characteristics and costs pertinent to the case study per se. The second section discusses model implementation, algorithmic performance and results of the analysis.

7.2 Case Study and Data

The case study analyzed herein pertains to the rural road network captured within the boundaries of the Rural Municipality (RM) of Cote, Saskatchewan. Although modestly-sized, the rural road network bounded within the RM of Cote was selected for two principal reasons. First, the Cote network has been the subject of some study within
Saskatchewan Highways and Transportation (SHT, 2000) – furnishing data and policy options directly relevant to model application and testing. Second, the sheer computational challenges of the rural road network problem at-hand suggest a ‘small success’ is reachable and certainly preferable to a ‘big failure’. Moreover, lessons learned through successful implementation – for even a modest network – are undoubtedly transportable to larger networks (e.g., entire transport areas within Saskatchewan).

One potential drawback of employing the model and corresponding algorithmic strategies to a modestly-sized network is that the results obtained may, in hindsight, appear trivial. In other words, a consummate observer may conclude the results reached are simply obvious. Yet the results reached and reviewed below confound this expectation. First, certain results counter intuitive ‘hunches’ (e.g., at least one well-intentioned haul policy option actually reduces the net benefits attributable to road use and provision). Second, the difficult interrelationships between road use, road performance, road structure allocations and policy prove relevant to results obtained in even this modest example – suggesting that the most educated of forecasts might prove sorely deficient for networks of greater size and complexity. For these reasons, the quality of decisions involving policy and investment arrangements for rural road networks would likely improve through implementation of the proposed model and associated algorithmic strategies.

In the discussion to follow, the case study is described in terms of network configuration, provision and use characteristics, costs of road use and road structure options, and relevant policy alternatives.
7.2.1 Network Configuration, Provision and Use Characteristics

Figure 7.1 illustrates components of the road network within the RM of Cote, Saskatchewan. Part (a) depicts SHT highways criss-crossing the RM. Part (b) provides greater resolution – illustrating both SHT highways and local RM roads.

As shown in part (a) of Figure 7.1, the SHT network within the RM includes highways 5, 8, 57, 357 and 369. From its junction with Highway 57 east of Kamsack, to the western border of the RM, Highway 5 is an AC pavement structure. South of the junction and down through the village of Togo to the Manitoba border, however, Highway 5 is a TMS structure. North of Kamsack and south of its junction with Highway 357, Highway 8 is a granular structure. South of Kamsack to its junction with Highway 357, however, Highway 8 is a TMS structure. Highway 57 is an AC pavement structure along its entire length. Highway 357 is, in contrast, a TMS structure along its entire length. Finally, the portion of Highway 369 within the RM of Cote is a gravel structure.

Part (b) of Figure 7.1 includes RM roads – all of which are gravel structures – in addition to SHT highways. Since local and extra-regional trip-makers travel within and through the RM, it is necessary to encode a substantive portion of the SHT and RM roads within a Cote network model in order to adequately estimate segment-specific traffic volumes and corresponding route (or path) choices. This is particularly important in the context of considered policy alternatives and potential structural modification of existing SHT highways – both of which may induce concomitant changes in path choice among freight and passenger vehicle users traveling in and through the network.
Figure 7.1. Rural road maps of the RM of Cote.
Illustrated in Figure 7.2, the network ultimately encoded within the model includes the entire network of SHT highways and a substantive portion of local roads captured within the RM of Cote. Among local roads, the modeled network includes all good gravel roads as well as all roads posting average traffic volumes greater than 10 vehicle trips per day (based on SHT historical traffic count data). Note that some local roads satisfying these criteria were eliminated from consideration since the trip ‘supplies’ generated could be adequately accounted for at adjoining nodes (e.g. segment (30,38) of Figure 7.2 is not included in the analysis).

Based on variations in traffic count data, SHT roadway segmentation (i.e., segmentation used to determine and prioritize preservation activities), and network configuration (e.g., road intersections), the network is divided into a number of constituent road segments. These segments are defined through the introduction of numbered nodes (of which there are 61 in total), where each segment is defined as a two-lane (or in some cases, four-lane) roadway structure connecting any two of the numbered nodes. For instance, as illustrated in Figure 7.2, segment (39,40) denotes a granular structure roadway supporting two-way traffic between nodes 39 and 40.

Any trip conducted through the network must follow a path consisting entirely of linked segments in order to join trip origin and intended destination. For instance, a feasible journey connecting node 1 (Manitoba border crossing near Togo) to node 61 (centre of Kamsack) may include segments (1,4), (4,9), (9,12), (12,15), (15,19), (19,26), (26,27), (27,28), (28,29), (29,36), and (36,61). To minimize trip-making costs, each trip commodity, \( k \in K \), must complete its intended journey by ‘constructing’ a feasible, cost-minimizing path through the network. Of course, the cost-minimizing path may be
influenced by both road structure allocations and the policy environment in effect. For example, haul road management agreements that impose onerous weight restrictions on particular segments within the network are likely to cause path diversion among some number of freight truck trip commodities.

Figure 7.2. RM of Cote rural road network.
To model the Cote road network, it is necessary to quantitatively describe its spatial arrangement as well as characteristics surrounding its provision and use. A quantitative description of the network’s spatial arrangement essentially amounts to a quantitative translation of the network map presented in Figure 7.2. The key elements of this description involve a representative edge set, \((i,j) \in E\), and corresponding edge lengths. The first four columns of Table 7.1 provide the necessary data.

As shown in Table 7.1, column 1 (Edge #) simply numbers the edges (road segments) defining the spatial arrangement of the Cote network. Columns 2 and 3, in turn, describe the nodal links corresponding to each edge, \((i,j) \in E\). Column 4 completes the spatial description through provision of corresponding edge lengths (in kilometers). It should be noted that edge lengths were determined through careful measurement of scaled road network maps of the RM of Cote provided by SHT.

Provision of rural road network services in the RM of Cote may be described in terms of extant road structure characteristics and matters of jurisdiction (relevant policy issues are discussed later in this section). Columns 5 and 6 of Table 7.1 provide the necessary information. As can be seen, column 5 lists the extant road structure corresponding to each segment and includes gravel, TMS, granular and AC pavement structures. Column 6 divides network road segments by jurisdiction. Numbered roadways correspond to SHT highway numbers (i.e., highway segments under SHT jurisdiction). In contrast, any edge labelled ‘RM road’ is a roadway under municipal jurisdiction. Note that road segments labelled ‘Kamsack’ simply indicate SHT highways (in this case, highways 5 and 8) that pass within the boundaries of the Kamsack township.
Table 7.1. Spatial and structural elements of RM of Cote network.

<table>
<thead>
<tr>
<th>Edge #</th>
<th>I</th>
<th>j</th>
<th>Edge Length (kms)</th>
<th>Road Structure</th>
<th>Highway #</th>
<th>Edge Length (kms)</th>
<th>Road Structure</th>
<th>Highway #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1.01</td>
<td>TMS</td>
<td>5</td>
<td>4.86</td>
<td>Gravel</td>
<td>RM road</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>11</td>
<td>1.62</td>
<td>Gravel</td>
<td>RM road</td>
<td>36</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>23</td>
<td>19.12</td>
<td>AC pavement</td>
<td>57</td>
<td>5.04</td>
<td>Gravel</td>
<td>RM road</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>8</td>
<td>0.61</td>
<td>TMS</td>
<td>357</td>
<td>39</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>9</td>
<td>0.77</td>
<td>TMS</td>
<td>5</td>
<td>40</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>6</td>
<td>5.83</td>
<td>Gravel</td>
<td>369</td>
<td>41</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>7</td>
<td>3.24</td>
<td>Gravel</td>
<td>369</td>
<td>42</td>
<td>34</td>
<td>42</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>8</td>
<td>3.24</td>
<td>Gravel</td>
<td>369</td>
<td>43</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>13</td>
<td>6.48</td>
<td>Gravel</td>
<td>RM road</td>
<td>44</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>9</td>
<td>0.54</td>
<td>TMS</td>
<td>369</td>
<td>45</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>14</td>
<td>6.48</td>
<td>TMS</td>
<td>357</td>
<td>46</td>
<td>39</td>
<td>53</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>10</td>
<td>2.70</td>
<td>Gravel</td>
<td>RM road</td>
<td>47</td>
<td>41</td>
<td>44</td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>12</td>
<td>7.80</td>
<td>TMS</td>
<td>5</td>
<td>48</td>
<td>42</td>
<td>43</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>11</td>
<td>3.24</td>
<td>Gravel</td>
<td>RM road</td>
<td>49</td>
<td>42</td>
<td>46</td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>12</td>
<td>4.86</td>
<td>Gravel</td>
<td>RM road</td>
<td>50</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>15</td>
<td>3.00</td>
<td>TMS</td>
<td>5</td>
<td>51</td>
<td>44</td>
<td>49</td>
</tr>
<tr>
<td>17</td>
<td>13</td>
<td>14</td>
<td>3.24</td>
<td>Gravel</td>
<td>RM road</td>
<td>52</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>18</td>
<td>14</td>
<td>17</td>
<td>1.62</td>
<td>TMS</td>
<td>357</td>
<td>53</td>
<td>46</td>
<td>50</td>
</tr>
<tr>
<td>19</td>
<td>15</td>
<td>16</td>
<td>1.62</td>
<td>Gravel</td>
<td>RM road</td>
<td>54</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>19</td>
<td>0.81</td>
<td>TMS</td>
<td>5</td>
<td>55</td>
<td>47</td>
<td>52</td>
</tr>
<tr>
<td>21</td>
<td>17</td>
<td>18</td>
<td>4.86</td>
<td>Gravel</td>
<td>RM road</td>
<td>56</td>
<td>48</td>
<td>49</td>
</tr>
<tr>
<td>22</td>
<td>17</td>
<td>21</td>
<td>5.16</td>
<td>TMS</td>
<td>357</td>
<td>57</td>
<td>49</td>
<td>56</td>
</tr>
<tr>
<td>23</td>
<td>18</td>
<td>19</td>
<td>3.24</td>
<td>Gravel</td>
<td>RM road</td>
<td>58</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>24</td>
<td>19</td>
<td>26</td>
<td>8.76</td>
<td>TMS</td>
<td>5</td>
<td>59</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>27</td>
<td>4.05</td>
<td>Gravel</td>
<td>RM road</td>
<td>60</td>
<td>51</td>
<td>57</td>
</tr>
<tr>
<td>26</td>
<td>21</td>
<td>22</td>
<td>3.24</td>
<td>Gravel</td>
<td>RM road</td>
<td>61</td>
<td>52</td>
<td>54</td>
</tr>
<tr>
<td>27</td>
<td>21</td>
<td>33</td>
<td>6.48</td>
<td>Gravel</td>
<td>RM road</td>
<td>62</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>28</td>
<td>22</td>
<td>34</td>
<td>6.48</td>
<td>Gravel</td>
<td>RM road</td>
<td>63</td>
<td>54</td>
<td>58</td>
</tr>
<tr>
<td>29</td>
<td>23</td>
<td>24</td>
<td>3.42</td>
<td>Gravel</td>
<td>RM road</td>
<td>64</td>
<td>55</td>
<td>56</td>
</tr>
<tr>
<td>30</td>
<td>23</td>
<td>28</td>
<td>0.41</td>
<td>AC pavement</td>
<td>57</td>
<td>65</td>
<td>56</td>
<td>59</td>
</tr>
<tr>
<td>31</td>
<td>24</td>
<td>25</td>
<td>6.48</td>
<td>Gravel</td>
<td>RM road</td>
<td>66</td>
<td>56</td>
<td>60</td>
</tr>
<tr>
<td>32</td>
<td>26</td>
<td>27</td>
<td>0.96</td>
<td>TMS</td>
<td>5</td>
<td>67</td>
<td>35</td>
<td>41</td>
</tr>
<tr>
<td>33</td>
<td>26</td>
<td>35</td>
<td>6.60</td>
<td>Gravel</td>
<td>RM road</td>
<td>68</td>
<td>36</td>
<td>61</td>
</tr>
<tr>
<td>34</td>
<td>27</td>
<td>28</td>
<td>3.00</td>
<td>TMS</td>
<td>5</td>
<td>69</td>
<td>37</td>
<td>41</td>
</tr>
<tr>
<td>35</td>
<td>28</td>
<td>29</td>
<td>2.76</td>
<td>AC pavement</td>
<td>5</td>
<td>70</td>
<td>41</td>
<td>61</td>
</tr>
</tbody>
</table>

112
Network use characteristics involve origin-destination (O-D) pairings and traffic volumes by vehicle type and season. Pertinent data are provided in Table 7.2. As can be seen, Table 7.2 divides data into freight and passenger vehicle categories. Within each vehicle category, data include departure node, arrival node and average annual daily traffic (AADT) volumes for both non-spring and spring periods.

Table 7.2. Use characteristics of RM of Cote network.

<table>
<thead>
<tr>
<th>Freight Vehicles</th>
<th></th>
<th></th>
<th></th>
<th>Passenger Vehicles</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure Node</td>
<td>Arrival Node</td>
<td>AADT (Non-Spring)</td>
<td>AADT (Spring)</td>
<td>Departure Node</td>
<td>Arrival Node</td>
<td>AADT (Non-Spring)</td>
<td>AADT (Spring)</td>
</tr>
<tr>
<td>1</td>
<td>41</td>
<td>39</td>
<td>12</td>
<td>1</td>
<td>61</td>
<td>196</td>
<td>196</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>18</td>
<td>5</td>
<td>2</td>
<td>61</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>22</td>
<td>22</td>
<td>3</td>
<td>61</td>
<td>678</td>
<td>678</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>13</td>
<td>4</td>
<td>5</td>
<td>61</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>61</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>41</td>
<td>6</td>
<td>2</td>
<td>10</td>
<td>61</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>13</td>
<td>41</td>
<td>12</td>
<td>4</td>
<td>13</td>
<td>61</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>16</td>
<td>41</td>
<td>10</td>
<td>3</td>
<td>16</td>
<td>61</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>18</td>
<td>41</td>
<td>9</td>
<td>3</td>
<td>18</td>
<td>61</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>20</td>
<td>41</td>
<td>8</td>
<td>2</td>
<td>20</td>
<td>61</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>22</td>
<td>41</td>
<td>2</td>
<td>1</td>
<td>22</td>
<td>61</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>24</td>
<td>41</td>
<td>7</td>
<td>2</td>
<td>24</td>
<td>61</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>25</td>
<td>41</td>
<td>8</td>
<td>2</td>
<td>25</td>
<td>61</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>30</td>
<td>41</td>
<td>11</td>
<td>3</td>
<td>30</td>
<td>61</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>31</td>
<td>41</td>
<td>9</td>
<td>3</td>
<td>31</td>
<td>61</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>32</td>
<td>41</td>
<td>40</td>
<td>12</td>
<td>32</td>
<td>61</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>38</td>
<td>41</td>
<td>2</td>
<td>2</td>
<td>38</td>
<td>61</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>40</td>
<td>41</td>
<td>189</td>
<td>189</td>
<td>40</td>
<td>61</td>
<td>1,411</td>
<td>1,411</td>
</tr>
<tr>
<td>42</td>
<td>41</td>
<td>3</td>
<td>1</td>
<td>42</td>
<td>61</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>43</td>
<td>41</td>
<td>3</td>
<td>1</td>
<td>43</td>
<td>61</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>45</td>
<td>41</td>
<td>8</td>
<td>2</td>
<td>45</td>
<td>61</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>48</td>
<td>41</td>
<td>4</td>
<td>1</td>
<td>48</td>
<td>61</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>50</td>
<td>41</td>
<td>4</td>
<td>1</td>
<td>50</td>
<td>61</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>53</td>
<td>41</td>
<td>7</td>
<td>2</td>
<td>53</td>
<td>61</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>55</td>
<td>41</td>
<td>5</td>
<td>2</td>
<td>55</td>
<td>61</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>57</td>
<td>41</td>
<td>3</td>
<td>1</td>
<td>57</td>
<td>61</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>58</td>
<td>41</td>
<td>8</td>
<td>2</td>
<td>58</td>
<td>61</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>59</td>
<td>41</td>
<td>152</td>
<td>152</td>
<td>59</td>
<td>61</td>
<td>848</td>
<td>848</td>
</tr>
<tr>
<td>60</td>
<td>41</td>
<td>9</td>
<td>3</td>
<td>60</td>
<td>61</td>
<td>51</td>
<td>51</td>
</tr>
</tbody>
</table>
Data in Table 7.2 are based on traffic count and vehicle classification data provided by SHT. The only exception to this involves freight truck volume estimates during the spring period. These are arbitrarily assigned at approximately 30 percent of non-spring volumes. Although the period over which spring weight restrictions apply varies by jurisdiction and year, a period of 60 days is selected for sake of analysis.

Interpreting Table 7.2 is relatively straight-forward. Departure node indicates trip origin. Arrival node, in contrast, indicates the corresponding trip destination. Non-spring and spring AADT data are the season-specific traffic volumes associated with each O-D pair. Hence, across vehicle type, each row of Table 7.2 indicates the average number of daily trips conducted during non-spring and spring periods between a corresponding O-D pair.

Note that arrival nodes across vehicle type are remarkably consistent (i.e., all freight vehicle trips ‘arrive’ at node 41 and all passenger vehicle trips ‘arrive’ at node 61). Since SHT does not possess pertinent O-D information for this road network, it was necessary to estimate the assignment of trip origins and destinations. Since Kamsack is the lifeblood of the RM, O-D assignments are arranged such that all trips arrive within the township. Freight trips are assigned node 41 as arrival point since most industrial facilities – grain elevators, concrete plant, et cetera – are near or actually border the western edge of Kamsack. Passenger trips are assigned node 61 as arrival point since most consumer business and public institutions – stores, schools, health care facilities, et cetera – are located near the centre of town. Although some trips will pass through Kamsack (e.g., tourist trips to and from Duck Mountain Provincial Park), the manner of O-D assignment provides reasonable assurance that traffic patterns and
volumes on roadways within the RM conform to logical expectations. For instance, traffic count data suggest a substantive number of passenger vehicle trips occur between nodes 59 (western border of Kamsack) and 3 (the park border with Manitoba). Whether one assigns O-D pair (3,59) or O-D pairs (3,61) and (59,61) to estimate flows through Kamsack is irrelevant from a modeling perspective. Either assignment will lead, logically, to traffic flow assignments that match expectations (i.e., direct flow between nodes 3 and 59 over paved highways 5 and 57).

Regardless of the judiciousness applied, the procedure used to assign the O-D pairings presented in Table 7.2 is clearly less than ideal. However, since the path choices reached by vehicle users are likely sensitive to road structure allocation and policy implementation, it is necessary to impose some manner of assignment in order to reasonably estimate their combined effect on network-level costs. Of course, should superior data emerge in time (e.g., O-D survey information), alternative O-D assignments can be substituted for those presumed herein.

7.2.2 Costs of Road Use and Provision

Decisions regarding road structure allocation and policy implementation rely, in large part, on associated costs. To estimate the flow and fixed cost components associated with varying policy-road structure combinations applicable to the Cote road network, therefore, a range of user and agency cost inputs are required. Of course, these cost inputs must correspond to the rural road network model decomposition outlined in Chapter 6.

Table 7.3 lists unit user cost estimates across road structure and vehicle type (in $/km). The estimates are derived from variable passenger and freight vehicle cost
estimates computed by Hanson et al (1986) for paved and gravel surfaced roads.

Included within variable cost estimates are fuel, oil, tire, maintenance (including
mileage-dependent depreciation) and time costs. Since the estimates in Hanson et al are
from 1982, a presumed inflation rate of 1.5 percent was applied over a 20 year period to
obtain 2002 equivalents. An average exchange rate of 1.5 was applied to convert the US
dollar estimates to Canadian dollar equivalents. To derive a reasonable estimate for all
freight vehicles, the vehicle-specific estimates in Hanson et al were averaged over
equivalent vehicle types observed traveling within the RM of Cote. This last step was
completed using vehicle classification data obtained from SHT.

**Table 7.3.** Unit user costs across vehicle type and road structure.

<table>
<thead>
<tr>
<th>Variable cost estimates ($/km)</th>
<th>Cars and pickups</th>
<th>Freight vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Pavements</td>
<td>0.273</td>
<td>0.496</td>
</tr>
<tr>
<td>Granular</td>
<td>0.300</td>
<td>0.545</td>
</tr>
<tr>
<td>CIR</td>
<td>0.300</td>
<td>0.545</td>
</tr>
<tr>
<td>TMS – good</td>
<td>0.300</td>
<td>0.545</td>
</tr>
<tr>
<td>TMS - bad</td>
<td>0.381</td>
<td>0.720</td>
</tr>
<tr>
<td>Gravel (GHS) – good</td>
<td>0.381</td>
<td>0.720</td>
</tr>
<tr>
<td>Gravel (GHS) – bad</td>
<td>0.419</td>
<td>0.792</td>
</tr>
</tbody>
</table>

In order to distribute the adjusted passenger and freight vehicle cost estimates
across road structures, some simplifying assumptions were made. First, adjusted cost
estimates related to 'paved' and 'gravel' roads were assigned directly to AC pavements
and Gravel Highway Standard (GHS) roadways. Second, since TMS (in good
condition), granular and CIR road structures exhibit somewhat rougher surface
conditions, user costs for these structures were set 10 percent higher than corresponding estimates for AC pavements. Third, it was assumed that a TMS road structure in poor condition imposed unit user costs equivalent to those experienced while traveling on a good gravel road. Finally, the unit user costs for a gravel road structure in poor condition were presumed 10 percent higher than corresponding costs for a gravel road structure in good condition.

Recall from previous discussions that the volume of freight traffic over TMS and gravel facilities determines the assignment of unit user costs. More particularly, where freight truck traffic reaches a 'critical' level, the affected road segment suddenly falls from good to poor condition – triggering a concomitant rise unit trip costs. While the critical level of truck traffic varies from locale-to-locale, two sets of critical volumes were imposed within the modeling environment (based on personal communication with Dr. Gordon Sparks): one corresponding to the non-spring period and the other to the spring period. For TMS road structures, the critical freight volumes were set at 40 trips a day during the non-spring period and 10 trips per day during the spring period. For gravel road structures, corresponding critical volumes were set at 35 and 8 trips per day.

Within the modeling environment, the variable unit costs assigned to freight vehicles are adjusted in accord with spring weight restrictions imposed by SHT. An investigation of SHT spring and non-spring gross vehicle weight restrictions suggests an average increase in trucking costs of approximately 21 percent during the spring period (necessary data obtained from SHT website at www.highways.gov.sk.ca). Where spring weight restrictions are imposed within the modeling environment, then, average variable freight vehicle costs are increased by 21 percent for any truck trips conducted during the
spring period. It should be noted that this cost penalty is not applied to all freight vehicle trips over the RM of Cote road network. Since freight vehicle traffic conducted solely over AC pavements and granular structures are unaffected by spring weight restrictions, certain freight trip commodities were excluded from the cost penalty.

Table 7.4 presents agency costs pertinent to the rural road network problem. As can be seen, the five road structures discussed previously in this study are included in Table 7.4: thin membrane surfaced (TMS), gravel highway standard (GHS), cold in-place recycled (CIR), granular, and asphaltic concrete (AC) pavement. Each road structure is uniquely described by a set of initial capital costs, preservation costs, resurfacing costs, and surface design life (SHT, 2000).\(^1\) Initial capital costs are presumed to occur at some ‘time 0’ (e.g., the year corresponding to initial construction of the upgrade). Maintenance costs represent the annual on-going costs of maintaining the road structure in question. Resurfacing costs apply to road structures whose surface requires periodic reconstruction. The time interval separating successive resurfacing activities is referred to as the surface design life.

<table>
<thead>
<tr>
<th>Costs</th>
<th>TMS</th>
<th>GHS</th>
<th>CIR</th>
<th>Granular</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital upgrade ($/km)</td>
<td>n/a</td>
<td>100,000</td>
<td>105,000</td>
<td>120,000</td>
<td>430,000</td>
</tr>
<tr>
<td>Maintenance ($/km/year)</td>
<td>3,250</td>
<td>1,800</td>
<td>1,400</td>
<td>1,400</td>
<td>1,000</td>
</tr>
<tr>
<td>Resurfacing ($/km)</td>
<td>n/a</td>
<td>n/a</td>
<td>82,500</td>
<td>110,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Surface design life (years)</td>
<td>n/a</td>
<td>n/a</td>
<td>15</td>
<td>15</td>
<td>17.5</td>
</tr>
</tbody>
</table>

\(^1\) Cost and other data involving CIR road structures are based on discussions with Dr. Curtis Berthelot and Dr. Gordon Sparks. Data pertinent to the remaining road structures are from SHT (2000).
Note that neither TMS or GHS road structures require periodic resurfacing. Instead, these facilities are simply maintained on an indefinite basis. Note also that no capital upgrade cost corresponds to TMS facilities. Although the construction of TMS roadways is indeed accompanied by initial capital cost, SHT no longer builds TMS facilities. Therefore, only on-going preservation costs are pertinent to the analysis conducted herein.

Within the modeling environment, all user and agency costs are converted to annual equivalent dollar values. For users, variable unit costs are adjusted by annual average daily traffic (AADT) estimates and travel days per year to derive annual unit trip cost estimates. Note that travel days over the year are split into spring and non-spring components reflecting the 60-day spring weight restriction period (and attendant unit costs) presumed in this study. For SHT, initial capital costs are annualized under the assumption that, once constructed, a roadway lasts indefinitely. Resurfacing costs are annualized given the corresponding surface design life. Since maintenance costs are in annual terms, no further adjustments are required. Total annualized resurfacing and maintenance costs are combined to derive annualized preservation costs across road structure type. Following Treasury Board Secretariat of Canada cost-benefit analysis guidelines (follow links from www.tbs-sct.gc.ca), a discount rate of 10 percent is applied to derive annualized cost estimates.

Incorporating all annualized cost estimates within the shortest path (SP) and knapsack (KS) sub-models permits computation of all relevant cost and cost-savings coefficients necessary to derive good solutions to the rural road network problem as it applies to the RM of Cote. This in turn permits the practical application of the
algorithmic strategies described in Chapter 6 of this thesis. Prior to reviewing model implementation and results, however, it is first necessary to discuss the policy options analyzed and the manner in which they were incorporated within the modeling environment.

7.2.3 Policy Options Analyzed

Application of the algorithmic strategies used to derive solutions to the rural road network problem of Cote is policy dependent. Herein, three basic policy regimes are combined to derive a mutually exclusive set of policy options for analysis: (i) haul road management agreements (HRMA), (ii) spring weight restrictions, and (iii) capital budget money restrictions. In each case, the algorithmic strategies are employed to derive corresponding road structure allocations and a range of comparable cost and net benefit estimates.

With regards the RM of Cote, a number of HRMA are currently under consideration by SHT. These are summarized within the RM of Cote Heavy Haul Route Study (SHT, 2000, 19-25). The key to interpreting a HRMA involves attendant weight restrictions. In essence, a HRMA establishes a set of weight-restricted road segments within a rural road network. Although the precise terms of the HRMA are established in consultation with the RM, the weight restrictions are normally sufficiently onerous to cause outright freight truck diversion (i.e., eliminate freight truck traffic from affected segments).² Although this will increase trucking costs for at least some freight truck

---

² Comments in this section regarding HRMA are supported by personal communication with Ron Gerbrandt (Preservation Director, SHT).
trip-makers, passenger vehicle users will benefit since affected roadways can be repaired and maintained in good condition thereafter.

It should be noted that certain users are exempt from the weight restrictions imposed through a HRMA. Typically, these users are ‘captive’ to certain haul routes due to their spatial location. In other words, if forced to comply with the HRMA these users would experience very high freight costs to complete required trips. Although such exemptions permit some freight truck trips on weight-restricted segments, the total traffic generated is usually within the tolerance of affected road structures. At most, approximately 10 to 20 percent of original freight truck traffic volumes might continue to operate, unrestricted, on segments covered by the HRMA.

Of the seven HRMA options discussed in the SHT heavy haul route study, six are analyzed within the modeling environment. Option 3 is not considered since it identically mirrors option 2 excepting structural modification of Highway 369. Given that the key objective of the model is to determine road structure allocations across the Cote network, no a priori structural modifications should be imposed. Table 7.5 lists the collection of segments and captive freight vehicle traffic (by node of trip origin) covered under each HRMA option considered in this study. Unless otherwise noted, all HRMA policy options implicitly presume the implementation of ubiquitous spring weight restrictions. For consistency’s sake, the segment and node designations of Table 7.5 correspond to the RM of Cote ‘road map’ illustrated in Figure 7.2.
Table 7.5. Affected segments and captive freight traffic under each HRMA policy option.

<table>
<thead>
<tr>
<th>HRMA policy option</th>
<th>Segments included under policy</th>
<th>Origin nodes of captive freight traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (base case)</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>(26,27), (27,28), (4,9), (9,12), (12,15), (15,19), (17,21), (21,33)</td>
<td>20, 27, 15, 16</td>
</tr>
<tr>
<td>4</td>
<td>(4,9), (9,12), (12,15), (15,19)</td>
<td>15, 16</td>
</tr>
<tr>
<td>5</td>
<td>(26,27), (27,28)</td>
<td>20, 27</td>
</tr>
<tr>
<td>6</td>
<td>(26,27), (27,28), (4,9), (9,12), (12,15), (15,19), (21,33)</td>
<td>20, 27, 15, 16</td>
</tr>
<tr>
<td>7</td>
<td>(26,27), (27,28), (8,14), (14,17), (17,21), (21,33)</td>
<td>20, 27</td>
</tr>
</tbody>
</table>

Haul road management agreement (HRMA) option 1 is, essentially, a ‘do nothing’ option. Excepting ubiquitous secondary and spring weight restrictions, no additional segment-specific weight restrictions are applied. Note that this option represents the base case used for comparative purposes in this study. Option 2 imposes weight restrictions on a number of SHT highway segments. These include:

- **Highway 5 from its junction with Highway 57 east of Kamsack to a point 3.92 kilometers south.** This corresponds to segments (26,27) and (27,28) in Figure 7.2. Under this arrangement, freight traffic originating from nodes 20 or 27 is held captive by the HRMA. It is likely, therefore, that affected freight vehicle users will be exempt from attendant weight restrictions.

- **Highway 5 from its intersection with north-south Grid 0.6 kilometers west of Runnymede, southeast to the Saskatchewan-Manitoba border.** This corresponds to segments (4,9), (9,12), (12,15) and (15,19). Note that segment (1,4) is not included among weight restricted segments. Analysis of traffic data suggest a significant number of freight trips emanate from the border crossing near Togo.
Since such trips may be considered captive, they would likely be exempted from weight restrictions on (1,4). Therefore, segment (1,4) is not considered in the analysis. Under this arrangement, trips originating from nodes 15 and 16 are presume captive to the HRMA.

- **Highway 357 from its junction with Highway 8 to its intersection with north-south Grid at a point 11.89 kilometers east.** This corresponds to segments (17,21) and (21,33). Note that these restrictions do not capture any freight truck trip-makers given O-D pairings presumed in the analysis.

  As summarized in Table 7.5, HRMA policy option 4 includes the following weight restrictions and captive freight vehicle traffic:

- **Highway 5 from its intersection with north-south Grid 0.6 kilometers west of Runnymede, southeast to the Saskatchewan-Manitoba border.** This corresponds to segments (4,9), (9,12), (12,15) and (15,19) of Figure 7.2. Under this arrangement, trips originating from nodes 15 and 16 are presume captive to the HRMA.

  HRMA policy option 5 includes the following weight restrictions and captive freight vehicle traffic:

- **Highway 5 from its junction with Highway 57 east of Kamsack to a point 3.92 kilometers south.** This corresponds to segments (26,27) and (27,28) in Figure 7.2. Under this arrangement, any freight traffic originating from nodes 20 or 27 is held captive by the HRMA.

  Option 6 is identical to option 2 excepting the exclusion of one road segment, (17,21). As detailed in Table 7.5, option 6 includes the following weight restrictions:
• **Highway 5 from its junction with Highway 57 east of Kamsack to a point 3.92 kilometers south.** This corresponds to segments (26,27) and (27,28) in Figure 7.2. Under this arrangement, freight traffic originating from nodes 20 or 27 is held captive by the HRMA.

• **Highway 5 from its intersection with north-south Grid 0.6 kilometers west of Runnymede, southeast to the Saskatchewan-Manitoba border.** This corresponds to segments (4,9), (9,12), (12,15) and (15,19). Under this arrangement, trips originating from nodes 15 and 16 are held captive by the HRMA.

• **Highway 357 from its junction with Highway 8 to its intersection with north-south Grid at a point 6.44 kilometers east.** This corresponds to segment (21,33). Note that this restriction does not capture any freight truck trip-makers given O-D pairings presumed in the analysis.

HRMA policy option 7 includes the following weight restrictions and captive freight vehicle traffic:

• **Highway 5 from its junction with Highway 57 east of Kamsack to a point 3.92 kilometers south.** This corresponds to segments (26,27) and (27,28) in Figure 7.2. Under this arrangement, freight traffic originating from nodes 20 or 27 is held captive by the HRMA.

• **Highway 357 from its junction with Highway 5 in the village of Togo west to Highway 8.** This corresponds to segments (8,14), (14,17), (17,21) and (21,33) of Figure 7.2. Although road segment (4,8) may be included among these segments, it has no effect on freight traffic flow routings given the extant network configuration and O-D pairings postulated. Within the modeling environment, therefore, it has not
been included. Note that the weight restrictions corresponding this HRMA do not capture any freight truck trip-makers operating within the network.

In addition to HRMA policy options, the relative efficiency of spring weight restrictions is also tested within the modeling environment. Within the modeling process, spring weight restrictions are ‘removed’ from consideration – permitting secondary freight truck weights year-round. Presumably, this will lower overall freight truck trip costs while concomitantly increasing passenger vehicle trip costs (due increasing road damage). The allocation of road structures across the network may also be affected by this policy. For purposes of comparison, HRMA option 1 (the base case policy environment) accompanies the presumed lifting of spring weight restrictions.

Finally, leaving the base case policy environment intact, the capital budget money constraint is removed from consideration within the modeling environment. In effect, this ‘frees’ the knapsack sub-model (KS) to assign any and all road structure allocations that generate positive cost-savings. Comparing the results to the budget-restricted case provides the means to estimate the additional net benefits available through a loosening of extant capital budget constraints.

7.3 Model Implementation and Results

The purpose of this section of the chapter is two-fold. First, to review the manner in which the algorithmic strategies were applied to the case study in order to generate results and evaluate algorithmic performance. Second, this section examines a range of results generated within the modeling environment.
7.3.1 Implementation and Algorithmic Performance

To generate results pertinent to the RM of Cote rural road network, the algorithmic strategies reviewed in Chapter 6 were mated to the data and policy options discussed above. The modeling environment chosen to implement and complete this task includes a mix of Visual C++ 6.0, Excel 2000, Concert Technology 1.1, and CPLEX 7.1. The manner in which these software packages function and interrelate to represent and solve the rural road network problem at-hand is illustrated in Figure 7.3.

![Programming Environment (Visual C++ 6.0)](image)

**Figure 7.3.** Model implementation.

As shown in Figure 7.3, the C++ programming environment is used to perform certain functions and control input and output communication among the various software tools. Excel is used to prepare model data and policy information for

---

3 Visual C++ 6.0 served as the required C++ programming environment and is produced by Microsoft. Excel 2000 is a spreadsheet package produced by Microsoft. Concert Technology 1.1 and CPLEX 7.1 are special-purpose optimization software produced by ILOG S.A.
subsequent analysis within the algorithmic strategies. In addition, Excel serves to conduct ex post analyses of model results generated by each model run. Concert Technology is designed as a ‘lightweight’ (in terms of computer memory usage) application programming interface (API) that functions specifically within a C++ programming environment. In essence, the class libraries that make up Concert Technology are used – in addition to standard C++ libraries – to develop data structures, read corresponding data, program models and algorithms, and communicate with the CPLEX optimization engine to generate results. As discussed in Chapter 6, CPLEX is a collection of mathematical programming algorithms capable of solving linear and linear-integer programming problems. The iterative application of CPLEX to the SP and KS sub-problems is controlled by commands issued within the C++ / Concert Technology program. Working together, the various software components facilitate the entire modeling process – from data preparation to analysis of model results.

Prior to reviewing the results of the analysis, it is worthwhile discussing the performance of the algorithmic strategies implemented within the aforementioned modeling environment. This provides some measure of the usefulness of the strategies in tackling rural road network problems of larger scale. It is important to note that the current model program embeds both heuristic and branch-and-cut solution algorithms to the knapsack (KS) sub-problem at each iteration. Although this slows model runs, it permits direct and immediate comparison of results across algorithmic strategies.

Each policy-specific model run occupied approximately 15 seconds of run-time on a Microsoft Windows-based desktop PC equipped with a 900 MHz AMD Athlon microprocessor and 512 Mb of PC-133 RAM. Although the entire algorithmic process
was permitted to iterate three times, stable (i.e., repeatable) solutions were reached within two to three iterations in all cases. This suggests superior performance would result if a comparative process were programmed into the main algorithm to interrupt redundant model iterations. Note that within the overall algorithmic process, certain algorithms iterated many times. For instance, to determine cost-minimizing traffic flows under each unique road structure and policy arrangement, the network simplex method iterated between 1,100 and 1,500 times.

In terms of total cost-savings, the performance of the heuristic algorithm compares favourably to the CPLEX branch-and-cut algorithm in reaching a solution to the KS sub-problem. In fact, in four of the eight model runs undertaken (i.e., one for each option), the heuristic algorithm produced results identical to the branch-and-cut procedure. Among the remaining model runs, the total cost-savings generated by the branch-and-cut and heuristic algorithms differed by no more than 1.65 percent. Hence, while the allocation of road structures to segments differed in half the model runs, the difference in total cost-savings proved negligible. Although the speed of computation in this case permits practicable application of the branch-and-cut procedure, the favourable performance of the heuristic algorithm may prove highly advantageous where larger networks are considered.

Although straight-forward, the pre-processing procedure applied to reduce the number of alternatives considered within the KS sub-problem proved highly successful. The RM of Cote network illustrated in Figure 7.2 contains 31 road segments under SHT jurisdiction (each subject to possible evaluation within the KS sub-problem). Since each road segment is a potential candidate for any one of five structural modifications
(i.e., extant road structure and four alternatives), the number of mutually exclusive allocations reaches approximately 4.66 septillion (i.e., \(5^{31}\)). At worst, the pre-processing procedure reduces this to 128 mutually exclusive allocations (i.e., \(2^7\), or three potentially advantageous road structure modifications across seven candidate segments). This explains, in large part, the advantageous computational speeds attained by the algorithmic strategies.

Overall, then, the algorithmic strategies perform reasonably well. The entire modeling process produces consistent results within two to three iterations and runs from start to finish within 15 seconds on a desktop PC. With regards the KS sub-problem, the heuristic algorithm produces results that compare favourably against the optimal results generated by the branch-and-cut procedure. Finally, the pre-processing procedure substantively reduces the number of mutually exclusive road structure allocations requiring consideration within the KS sub-problem. These observations suggest performance sufficient to tackle larger rural road networks in Saskatchewan within a practicable period of computation time.

### 7.3.2 Network Modeling Results

The results of the modeling naturally reflect the data inputs and algorithmic strategies applied. Hence, user and agency cost differentials across road and vehicle types, varying policy options and weight restrictions, and deterministic workings of each algorithmic strategy all conspire to generate alternative results within the modeling environment. Below, the results of the modeling exercise are summarized. First, a review of the road structure allocations corresponding to each policy option is provided. Second, cost and net benefit estimates pertinent to each policy option are examined.
Finally, to ensure predicted freight and passenger vehicle flows through the network comply with policy options and reasonable expectations, a sample of predicted edge flows and trip routings is analyzed.

7.3.2.1 Road Structure Allocations

In total, eight distinct policy options are analyzed within the modeling environment: base case (corresponding to HRMA option 1 and ubiquitous spring weight restrictions); five additional HRMA policies (all including spring weight restrictions); unlimited capital budget (under the base case and spring weight restrictions); and removal of all spring weight restrictions (labelled ‘no spring weights’ hereafter). Each policy option marks a separate model run that generates an attendant spatial allocation of road structure modifications over the Cote network. In this section, the road structure modifications corresponding to each policy option are compared.

Table 7.6 summarizes the road structure modifications corresponding to each policy option. Under the base case, upgrade from TMS to CIR structure is recommended for segments (12,15), (19,26), (33,34) and (34,35). Precisely the same result corresponds to HRMA options 5 and 7 as well as option ‘no spring weights’. Road structure allocations corresponding to HRMA option 2 suggest upgrade to CIR structure for segments (19,26), (33,34) and (34,35). Identical allocations are recommended under the terms of HRMA options 4 and 6. Where HRMA option 1 applies and budget constraints are lifted, model results suggest upgrade to CIR structure for segments (9,12), (12,15), (15,19), (19,26), (33,34) and (34,35).

Two key observations emerge from model results. First, regardless of policy option, upgrade to CIR is the recommended structural modification for all selected
segments. Second, the collection of network segments suggested for upgrade remain remarkably consistent across considered policy options.

Table 7.6. Recommended road structure modifications under each policy option.

<table>
<thead>
<tr>
<th>Policy regime</th>
<th>Segments included under HRMA policy</th>
<th>Segments modified (to CIR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRMA 1 (base case)</td>
<td>None</td>
<td>(12,15), (19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>HRMA 2</td>
<td>(26,27), (27,28), (4,9), (9,12), (12,15), (15,19), (17,21), (21,33)</td>
<td>(19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>HRMA 4</td>
<td>(4,9), (9,12), (12,15), (15,19)</td>
<td>(19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>HRMA 5</td>
<td>(26,27), (27,28)</td>
<td>(12,15), (19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>HRMA 6</td>
<td>(26,27), (27,28), (4,9), (9,12), (12,15), (15,19), (21,33)</td>
<td>(19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>HRMA 7</td>
<td>(26,27), (27,28), (8,14), (14,17), (17,21), (21,33)</td>
<td>(12,15), (19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>No spring weights / HRMA 1</td>
<td>None</td>
<td>(12,15), (19,26), (33,34), (34,35)</td>
</tr>
<tr>
<td>Unlimited budget / HRMA 1</td>
<td>None</td>
<td>(9,12), (12,15), (15,19), (19,26), (33,34), (34,35)</td>
</tr>
</tbody>
</table>

The ubiquitous choice of CIR as the preferred road structure modification reflects both performance and costing assumptions built into the modeling process.

Recall that the pre-processing procedure filters out all segment-upgrade combinations that fail to generate positive cost-savings under predetermined traffic volumes. For the RM of Cote network, this filter eliminates the majority of possible upgrades – leaving, in fact, only CIR and granular structures as potential upgrade alternatives for candidate segments. However, since model parameters infer that CIR structures embody – at lower cost – performance characteristics identical to granular structures, logic suggests its strict preference over granular structures in every case. Hence, granular structures are removed from further consideration within the pre-processing algorithm.
In practice, however, uncertainty regarding the long-term performance of CIR structures may well discourage such widespread adoption. As a comparatively new technology, the long-term performance of CIR is not well-known relative to ‘tried-and-true’ road structure options (including granular structures). Contrary to model recommendations, then, network managers may be reluctant to implement CIR on a widespread basis. For this reason it may prove prudent to incorporate – at a later date – a model constraint that limits, for instance, allowable expenditure on relatively new road structure technologies.

It is instructive to note that neither gravel (GHS) or AC pavement structures are recommended upgrades under any policy option. Despite potential preservation cost savings, the user cost penalty corresponding to GHS structures effectively ‘discourage’ application. Similarly, despite both annual maintenance and user cost savings, the initial capital and periodic resurfacing costs corresponding to AC pavement upgrades combine with modest traffic levels to effectively discourage application of this structural option as well. These results are not unexpected. Few users would welcome gravel reversion of even poorly performing TMS facilities – reflecting an intuitive appreciation of the user cost penalty involved. With regards AC pavement upgrades, internal SHT documents suggest traffic levels should reach at least 1,200 vehicles per day before implementation is worthy of consideration (SHT, 2000). Within the RM of Cote network, only Highway 57 and the east-west portions of Highway 5 – both extant AC pavement structures – meet this criteria. Hence, model results reflect reasonable expectations in this regards.
Consistency of segment upgrade recommendations across policy options is reflected in the incremental nature of model results. As shown in Table 7.6, segments (19,26), (33,34) and (34,35) are recommended for upgrade in every case. From this starting point, segments (12,15), (9,12) and (15,19) are added, incrementally, as policy options evolve. Not surprisingly, the greatest number of recommended segment upgrades corresponds to an unlimited budget.

Interestingly, the road structure allocations determined under HRMA policy options 2, 4 and 6 are not constrained by available budget monies. As shown in Table 7.6, only three segments – (19,26), (33,34) and (34,35) – are recommended for upgrade. Although this leaves sufficient budget monies to upgrade additional segments (e.g., (12,15)), the segment-specific weight restrictions corresponding to these policy options negate the usefulness of such upgrades. From the standpoint of SHT, this implies a capital budget savings of approximately 300,000 dollars over the base case, no spring weights, and HRMA options 5 and 7.

As mentioned above, the road structure allocations derived through application of the heuristic algorithm to the KS sub-problem sometimes vary from those generated by the branch-and-cut procedure. With regards the base case and HRMA options 5 and 7, for instance, the heuristic algorithm suggests an identical upgrade scheme excepting the substitution of segment (15,19) for segment (33,34). Similarly, where spring weight restrictions are removed, the heuristic algorithm suggests road structure upgrades that effectively substitute segments (1,4), (4,9) and (15,19) for segment (33,34). Despite these segment substitutions, however, the heuristic algorithm – like the branch-and-cut procedure – recommends upgrade to CIR structures in all cases. Furthermore, while the
segment-specific substitutions imply alternative structural allocations across the network, the total cost-savings generated varies by no more than 1.65 percent from the total cost-savings generated through implementation of the branch-and-cut procedure. Overall then, the performance of the heuristic algorithm compares favourably to the branch-and-cut procedure native to CPLEX.

7.3.2.2 Summary of Costs and Net Benefits

The results of the modeling exercise reflect both cost- and net benefit-based standards. Cost-based results summarize the network-wide use and provision costs corresponding to each policy option and associated arrangement of road structures. Net benefit-based results summarize the incremental cost savings attributable to each policy option and associated arrangement of road structures relative to the base case (prior to any road structure modification). As discussed below, the results corresponding to each standard nonetheless lead to identical rankings of road-related policy and investment arrangements.

Table 7.7 lists a range of cost estimates corresponding to each policy option. As can be seen, the top rows of Table 7.7 present flow and preservation cost estimates prior to any allocation of road structures through the network. The bottom rows, in contrast, provide upgrade, flow and preservation cost estimates following road structure allocations. In this way, the net savings attributable to road structure allocation alone can be compared for each policy option. Note that all results are presented in both annual worth (AW) and present worth (PW) terms. Conversion between the two measures presume a real discount rate of 10 percent and infinitely-lived road structures.
<table>
<thead>
<tr>
<th>HRMA 1</th>
<th>HRMA 2</th>
<th>HRMA 3</th>
<th>HRMA 4</th>
<th>HRMA 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>Present</td>
<td>Annual</td>
<td>Present</td>
<td>Annual</td>
</tr>
<tr>
<td>Worth</td>
<td>Worth</td>
<td>Worth</td>
<td>Worth</td>
<td>Worth</td>
</tr>
</tbody>
</table>

Results prior to road structure allocations:
- Total freight vehicle flow costs
- Total passenger vehicle flow costs
- Total flow costs
- Total preservation costs
- Total flow and preservation costs

Available Budget Monies

Results following road structure allocations:
- Total freight vehicle flow costs
- Total passenger vehicle flow costs
- Total flow cost
- Total capital costs of upgrades
- Total operational costs
- Total maintenance costs
- Total savings over original costs

Branch-and-Cut (B-and-C) cost savings

Percentage advantage of B-and-C results
Table 7.7. Cost-based results for policy options and corresponding road structure arrangements.

<table>
<thead>
<tr>
<th>HRMA 6:</th>
<th>HRMA 7:</th>
<th>No Spring Weights:</th>
<th>Unlimited Budget:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>Present</td>
<td>Annual</td>
</tr>
<tr>
<td></td>
<td>Worth</td>
<td>Worth</td>
<td>Worth</td>
</tr>
<tr>
<td>Results prior to road structure allocations:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total freight vehicle flow costs</td>
<td>2,639,630</td>
<td>2,513,440</td>
<td>2,860,060</td>
</tr>
<tr>
<td>Total passenger vehicle flow costs</td>
<td>11,922,800</td>
<td>12,065,000</td>
<td>12,270,000</td>
</tr>
<tr>
<td>Total flow costs</td>
<td>14,562,400</td>
<td>14,578,400</td>
<td>15,130,100</td>
</tr>
<tr>
<td>Total preservation costs</td>
<td>658,769</td>
<td>658,769</td>
<td>658,769</td>
</tr>
<tr>
<td>Total flow and preservation costs (1)</td>
<td>15,221,200</td>
<td>15,237,200</td>
<td>15,788,900</td>
</tr>
</tbody>
</table>

Results following road structure allocations:

<table>
<thead>
<tr>
<th>Available Budget Monies</th>
<th>Annual Worth</th>
<th>Present Worth</th>
<th>Annual Worth</th>
<th>Present Worth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>n/a</td>
</tr>
<tr>
<td>Total freight vehicle flow costs</td>
<td>2,536,340</td>
<td>2,392,960</td>
<td>2,695,330</td>
<td>2,330,520</td>
</tr>
<tr>
<td>Total passenger vehicle flow costs</td>
<td>11,505,000</td>
<td>11,597,800</td>
<td>11,795,000</td>
<td>11,593,400</td>
</tr>
<tr>
<td>Total flow cost</td>
<td>14,041,400</td>
<td>13,990,760</td>
<td>14,490,300</td>
<td>13,924,000</td>
</tr>
<tr>
<td>Total capital costs of upgrades</td>
<td>262,060</td>
<td>293,529</td>
<td>293,529</td>
<td>383,894</td>
</tr>
<tr>
<td>Total preservation costs</td>
<td>677,402</td>
<td>679,640</td>
<td>679,640</td>
<td>686,065</td>
</tr>
<tr>
<td>Total flow, upgrade and preservation costs (2)</td>
<td>14,980,800</td>
<td>14,963,900</td>
<td>15,463,500</td>
<td>14,993,900</td>
</tr>
<tr>
<td>Total savings over original costs (1 - 2)</td>
<td>240,316</td>
<td>273,300</td>
<td>325,380</td>
<td>307,945</td>
</tr>
<tr>
<td>Branch-and-Cut (B-and-C) cost savings</td>
<td>240,316</td>
<td>273,300</td>
<td>360,463</td>
<td>310,773</td>
</tr>
<tr>
<td>Heuristic cost savings</td>
<td>240,316</td>
<td>271,871</td>
<td>357,763</td>
<td>310,773</td>
</tr>
<tr>
<td>Percentage advantage of B-and-C results</td>
<td>0.00%</td>
<td>0.52%</td>
<td>0.75%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>
Beginning with the base case (HRMA option 1), the AW and PW of total flow costs predicted by the model reach approximately 14.6 and 146.4 million dollars, respectively, prior to any road structure allocations. Of the total AW flow costs, approximately 2.5 and 12.2 million dollars may be attributed, respectively, to freight and passenger vehicle trips. Freight traffic flow costs therefore represent slightly less than 20 percent of total flow costs over the Cote network.

Predicted, annualized preservation costs – including periodic resurfacing costs – corresponding to the base case reach approximately 659 thousand dollars prior to any structural modification of extant network segments. As might well be expected, this amount is dwarfed by the trip costs incurred by users – representing only about 4.5 percent of total flow costs. Adding this amount to predicted flow costs results in total AW flow and preservation costs of approximately 15.3 million dollars (or 153.0 million dollars in PW terms).

Following road structure allocations, total AW flow, upgrade and preservation costs predicted by the model reach approximately 15.0 million dollars for the base case. As shown in Table 7.7 – and illustrated graphically in Figure 7.4 – this represents a net annualized cost savings of about 274 thousand dollars. The savings enjoyed, however, rest entirely with freight and passenger vehicle users. Annualized flow costs for passenger and freight vehicle users fall by about 470 and 120 thousand dollars, respectively. In contrast, annualized capital and preservation costs incurred by SHT are expected to rise, respectively, by about 294 and 21 thousand dollars. Hence, as Figure 7.4 clearly shows, the savings enjoyed by users is ‘purchased’ through incremental capital and preservation costs incurred by SHT. Note from Table 7.7 that predicted PW
capital upgrade expenditures undercut the three-million dollar budget constraint by only about 65 thousand dollars.

Figure 7.4. Change in base case annualized costs following road structure modification (in thousands of dollars).

Interestingly, predicted cost savings corresponding to the branch-and-cut procedure, in this case, exceed the cost savings achieved through the heuristic procedure by only about 1.65 percent. As shown in Table 7.7, the AW cost savings generated by the branch-and-cut algorithm of the KS sub-model reach almost 277 thousand dollars for the base case. In contrast, the AW cost savings generated by the heuristic algorithm reach approximately 272 thousand dollars. This attests to the relatively good performance of the heuristic greedy algorithm outlined in Chapter 6.
Note that both the branch-and-cut and heuristic cost saving estimates differ from the savings ultimately derived within the model program (approximately 274 thousand dollars in AW terms for the base case). This slight divergence is due to the workings of the overall algorithmic procedure. More particularly, it involves the iterative application of the SP sub-model to derive stable traffic flows following the allocation of road structures determined within the KS sub-model (as discussed in Chapter 6). The implication of flow stabilization is marginal changes in freight and passenger trip-making costs that influence final model results.

Independent observations of the remaining options (including the base case) reflect, in principle, those involving the base case. Proportionally speaking, flow costs dominate agency (i.e., SHT) costs and passenger vehicle trip costs far outstrip trip costs attributable to freight vehicles. Annualized cost savings attributable to road structure allocations lie in the range of 240 to 325 thousand dollars. The PW of initial capital and preservation costs lie in the neighbourhood of 2.6 to 3.8 million dollars and 6.8 to 6.9 million dollars, respectively — where the higher costs correspond, not surprisingly, to an unconstrained capital budget. The proportional advantage of the branch-and-cut procedure over the heuristic algorithm ranges from zero to 1.65 percent.

Comparison across policy options leads to some interesting observations. Compare, for instance, the results corresponding to the base case against HRMA options 2, 4, 5, 6 and 7. Prior to any road structure modifications, the implementation of weight restrictions under each unique HRMA holds important implications for flow costs. Excepting HRMA option 5, for example, freight vehicle trip costs rise while passenger vehicle trip costs fall. This result mirrors reasonable expectations regarding the
influence of the weight restrictions: getting payloads off vulnerable roads leads to road performance gains that reduce the cost of travel for passenger vehicle users. Since freight truck users are prevented from using these roads, however, they are forced to choose sub-optimal routes from origin to intended destination – leading to a concomitant rise in freight costs. Under HRMA option 5, however, both freight and passenger trip costs fall. Although seemingly impossible, this result reflects a straight-forward logic discussed later in this section. Note, additionally, that the total flow and preservation costs under each policy option are fairly consistent. While all HRMA options (including the base case) generate substantively lower total flow and preservation costs than ‘no spring weights’, total costs across alternative HRMA options vary at most by 1.2 million dollars in PW terms.

Following road structure allocations determined within the KS sub-model, comparison across the base case and HRMA options 2, 4, 5, 6 and 7 leads to some interesting observations as well. Again, excepting HRMA option 5, trip cost reductions experienced by passenger vehicle users are ‘purchased’ through a rise in trip costs incurred by freight vehicle users. This trend is clearly illustrated in Figure 7.5. The vertical bars of Figure 7.5 depict the incremental change in freight, passenger and total vehicle flow costs across all HRMA policy options considered in this study (relative to the base case). Excepting HRMA policy option 4 – discussed in greater detail below – all policy options reduce total vehicle flow costs incurred. Yet, apart from HRMA option 5, the net reduction in total flow costs observed reflect a rise in freight vehicle costs more than offset by concomitant reductions in passenger vehicle costs. Again, then, despite road structure modifications the re-routing of freight trucks off vulnerable
road segments improves the overall performance of the Cote road network and therefore reduces trip costs for passenger vehicle users.

\[\text{Figure 7.5.} \quad \text{Change in annualized flow costs following road structure modification (in thousands of dollars).}\]

Notice that the consistency of total cost results across HRMA options (including the base case) actually improves following road structure modification across the network. As shown in Table 7.7, the PW total of flow, upgrade and preservation costs across HRMA options vary by no more than 500 thousand dollars. It appears, then, that road structure modification reduces the relative effectiveness of alternative HRMA policies. For each HRMA option, the net cost savings generated through road structure modification appear rather consistent as well. Table 7.7 shows that net PW cost savings corresponding to each HRMA option vary between a narrow range of about 2.4 to 2.7
million dollars. Note as well that – despite alternative road structure modifications across HRMA options – PW preservation costs estimates remain virtually constant at approximately 6.8 million dollars.

As mentioned above, both prior to and following road structure allocations across the Cote network, both freight and passenger vehicle trip costs fall under HRMA option 5 (i.e., passenger vehicle trip cost savings are not ‘purchased’ by a concomitant rise in freight vehicle trip costs). The logic of this counter-intuitive result is, however, consistent. Recall that under HRMA option 5 segments (26,27) and (27,28) of Figure 7.2 fall under attendant weight restrictions. Since freight vehicles are effectively prevented from traveling those segments (excepting captive freight trips originating from node 20), the segments cannot suffer performance deterioration due to excessive freight vehicle traffic. From the standpoint of passenger vehicle users, this implies lower trip costs across segments (26,27) and (27,28). For freight vehicle users – all of whom are destined for node 41 – this implies diversion off (26,27) and (27,28) to substitute segments (including segment (26,35)). Under the base case, this diversion occurs as well. However, it only occurs after flows stabilize and segments (26,27) and (27,28) have been damaged by freight truck traffic. For freight vehicle users captive to these segments (i.e., those originating from node 20), this implies higher trip costs than under HRMA policy option 5 (where freight traffic emanating from node 20 alone are insufficient to damage segments (26,27) and (27,28)). All these factors combine to reduce, albeit marginally, total freight flow costs through the network due to implementation of HRMA policy option 5.
Both prior to and following road structure allocations, it is worth noting that total flow and preservation costs corresponding to HRMA option 4 exceed those of the base case. As shown in Table 7.5, HRMA option 4 places weight restrictions on segments (4,9), (9,12), (12,15) and (15,19). Although this arrangement reduces total passenger vehicle trip costs (as expected), the concomitant rise in freight vehicle trip costs more than outweighs this savings. Prior to road structure allocations, net increase in flow cost is approximately 200 thousand PW dollars. Following road structure allocations, this figure rises to almost a million dollars in PW terms. This suggests that implementation of HRMA option 4 might prove counter-productive. More generally, it suggests HRMA policies are not ubiquitously ‘good’.

Comparing the base case to ‘no spring weights’ under extant road structures provides some support for the efficacy of spring weight policies and the ‘neighbourly pressure’ implied. In this case, both freight and passenger vehicle trip costs rise. Overall in fact, predicted PW flow and preservation costs under the base case exceed predicted PW flow and preservation costs under the base case by approximately 4.9 million dollars (157.9 versus 153.0 million dollars, respectively). Following road structure allocations determined within the modeling environment, the relative efficacy of spring weight restrictions falls. As shown in Table 7.7, total flow, upgrade and preservation costs under the base case exceed the total costs of the base case by only about 4.3 million dollars in PW terms (154.6 versus 150.3 million dollars, respectively). This result mirrors logical expectations. The allocation of road upgrades to particularly vulnerable TMS segments within the network should reduce the overall usefulness of
spring weight restrictions. Hence, while a spring weight policy still appears beneficial, the relative advantages fall as network road structures improve.

Prior to any road structure modifications, an unlimited capital budget (given the terms of HRMA option 1) produces results identical to the base case – which is subject to a three-million dollar capital budget. This reflects the fact that the amount of budget monies made available is irrelevant to existing road structure arrangements and attendant flow and preservation costs. However, since an unlimited capital budget permits upgrade of any road segment that posts potential cost-savings, the unlimited budget option generates total flow, upgrade and preservation costs lower than those generated under the base case. As shown in Table 7.7, following road structure allocations the total PW costs corresponding to the base case exceed the total PW costs corresponding to the unlimited budget option by approximately 440 thousand dollars. As can be seen, under the cost-savings criteria embedded in the KS sub-model, the unlimited budget option justifies approximately 3.8 million dollars in expenditures (exceeding the constrained budget by a little over 800 thousand dollars). The rise in capital (and preservation) expenditures incurred by the SHT, however, is more than offset by a concomitant fall in both freight and passenger vehicle traffic flow costs – a fall of approximately 1.3 million dollars in PW terms.

The results of the unlimited budget option deserve some additional comment particularly relevant to rural road investment in Saskatchewan. Among citizens of rural regions in Saskatchewan there exists the perception that rural road networks are grossly under-funded. This is reflected in Clifton (2000, 34) where stakeholders in the Gardiner Dam Transportation Area felt that all damaged TMS roadways in the region should be
upgraded to primary highways (i.e., full-depth AC pavement structures) – an expenditure clearly incommensurate with local traffic volumes. Yet the results of this study suggest, first, that rural traffic volumes justify upgrade to only modestly-priced road structures for a strict subset of TMS roadways and, second, that the maximum extent of defensible upgrades reach a cost of only 25 percent above existing capital budget levels. Additionally, recall that the net benefit standard embodied in the KS sub-model reflects a benefit-cost ratio of 1.0. If this ratio were raised to reflect competing investment, policy and program opportunities in Saskatchewan, the ‘optimal’ capital expenditure levels reached within the modeling environment could easily fall below the three million dollar mark. Clearly, such insights counter the perception that rural roadways in the Province are under-funded.

An overall ranking of road-related policy and investment arrangements according to the cost-based standard is illustrated graphically in Figure 7.6. Note that Figure 7.6: (i) includes total AW costs both prior to and following recommended road structure allocations across the RM of Cote network, and (ii) ranks policy options according to costs following attendant road structure allocations. As can be seen, HRMA option 5 is ranked ‘best’ according to total annualized cost. This is followed by: HRMA options 7, 2 and 6; unlimited budget (mated to HRMA option 1); the base case and HRMA option 4; and ‘no spring weights’. Although relatively consistent, notice that rankings change in the absence of recommended road structure modifications. Specifically, HRMA option 7 posts higher costs than HRMA options 2 and 6 prior to attendant road structure allocations across the network. In general, this suggests that
road policy and investment options are interrelated: the 'best' policy is subject to corresponding road structure modifications (and vice-versa).

![Graph](image)

**Figure 7.6.** Total annualized costs prior to and following road structure modification (in millions of dollars).

The summary results of Figure 7.6 also illustrate the relative influence of policy and road structure allocations. While marginal differences in total costs do distinguish the considered haul policy and other options, the magnitude of impact is far less than that attributable to road structure modifications. Hence, while policy options do influence the costs incurred by users and road agencies, the bulk of cost reductions correspond to investments involving roadway upgrades (to CIR, in this case).

Table 7.8 presents incremental reductions in cost across policy and road investment arrangements relative to the base case (absent any road structure modifications). This provides an immediate comparison of various policy options and structural allocations against the presumed base case and leads to a number of pertinent
Table 7.8. Net benefit (cost savings) incremental to base case.

<table>
<thead>
<tr>
<th></th>
<th>HRMA 1 (Base Case):</th>
<th>HRMA 2:</th>
<th>HRMA 4:</th>
<th>HRMA 5:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Worth</td>
<td>Present Worth</td>
<td>Annual Worth</td>
<td>Present Worth</td>
</tr>
<tr>
<td>Results prior to road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>0</td>
<td>0</td>
<td>-156,430</td>
<td>-1,564,300</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>0</td>
<td>0</td>
<td>237,100</td>
<td>2,371,000</td>
</tr>
<tr>
<td>- Total flow costs</td>
<td>0</td>
<td>0</td>
<td>80,700</td>
<td>807,000</td>
</tr>
<tr>
<td>- Total preservation costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- Total flow and preservation costs</td>
<td>0</td>
<td>0</td>
<td>80,700</td>
<td>807,000</td>
</tr>
<tr>
<td>Results following road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available Budget Monies</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>121,090</td>
<td>1,210,900</td>
<td>-53,140</td>
<td>-531,400</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>467,200</td>
<td>4,672,000</td>
<td>654,900</td>
<td>6,549,000</td>
</tr>
<tr>
<td>- Total flow cost</td>
<td>588,300</td>
<td>5,883,000</td>
<td>601,700</td>
<td>6,017,000</td>
</tr>
<tr>
<td>- Total capital costs of upgrades</td>
<td>-293,529</td>
<td>-2,935,290</td>
<td>-262,060</td>
<td>-2,620,600</td>
</tr>
<tr>
<td>- Total flow, upgrade and preservation costs</td>
<td>273,900</td>
<td>2,739,000</td>
<td>321,007</td>
<td>3,210,070</td>
</tr>
</tbody>
</table>
Table 7.8. Net benefit (cost savings) incremental to base case.

<table>
<thead>
<tr>
<th></th>
<th>HRMA 6:</th>
<th>HRMA 7:</th>
<th>No Spring Weights:</th>
<th>Unlimited Budget:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Worth</td>
<td>Present Worth</td>
<td>Annual Worth</td>
<td>Present Worth</td>
</tr>
<tr>
<td>Results prior to road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>-156,430</td>
<td>-1,564,300</td>
<td>-30,240</td>
<td>-302,400</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>237,100</td>
<td>2,371,000</td>
<td>94,900</td>
<td>949,000</td>
</tr>
<tr>
<td>- Total flow costs</td>
<td>80,700</td>
<td>807,000</td>
<td>64,700</td>
<td>647,000</td>
</tr>
<tr>
<td>- Total preservation costs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>- Total flow and preservation costs</td>
<td>80,700</td>
<td>807,000</td>
<td>64,700</td>
<td>647,000</td>
</tr>
<tr>
<td>Results following road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available Budget Monies</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>-53,140</td>
<td>-531,400</td>
<td>90,240</td>
<td>902,400</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>654,900</td>
<td>6,549,000</td>
<td>562,100</td>
<td>5,621,000</td>
</tr>
<tr>
<td>- Total flow cost</td>
<td>681,700</td>
<td>6,017,000</td>
<td>652,400</td>
<td>6,524,000</td>
</tr>
<tr>
<td>- Total capital costs of upgrades</td>
<td>-262,060</td>
<td>-2,620,600</td>
<td>-293,529</td>
<td>-2,935,290</td>
</tr>
<tr>
<td>- Total flow, upgrade and preservation costs</td>
<td>321,007</td>
<td>3,210,070</td>
<td>338,000</td>
<td>3,380,000</td>
</tr>
</tbody>
</table>
observations. First, as noted above, immediate savings may be attributed to spring weight restrictions should substantive freight trip reductions occur over the spring period when TMS and gravel road structures are most vulnerable. Comparing the base case against 'no spring weights', it can be seen that savings enjoyed by network users reach approximately 4.9 million dollars in PW terms. Second, beyond spring weight restrictions, the bulk of incremental cost savings enjoyed are attributable to road structure allocations across the network. Although HRMA policy options can contribute to cost savings, the concomitant savings for passenger vehicle users are offset to some degree by a rise in freight trucking costs. For instance, while HRMA option 5 posts approximately 1.0 million dollars in incremental PW cost savings over the base case, the incremental PW cost savings attributable to road structure allocations alone ranges between 2.0 and 2.7 million dollars across HRMA options. Finally, excepting 'no spring weights', the net benefits (cost savings) estimated within the modeling exercise are remarkably consistent across policy options – varying from approximately 2.2 to 3.7 million dollars in PW terms.

Figure 7.7 illustrates the rankings among all options and the base case according to the net benefit-based standard. As can be seen, the results identically mirror those of Figure 7.6. The 'best' alternative remains HRMA option 5. This is followed by: HRMA options 7, 2 and 6; unlimited budget; the base case and HRMA option 4; and 'no spring weights'. Again, notice that rankings change in the absence of recommended road structure modifications. Specifically, HRMA option 7 posts lower net benefits than HRMA options 2 and 6 prior to attendant road structure allocations across the network.
This supports the general conclusion reached above: the ‘best’ policy is subject to corresponding road structure modifications (and vice-versa).

![Graph showing annualized net benefits incremental to base case (in thousands of dollars).]

**Figure 7.7.** Annualized net benefits incremental to base case (in thousands of dollars).

To summarize, given a capital budget commitment of 3.0 million dollars, both cost- and net benefit-based standards suggest that HRMA option 5 is best – both prior and subsequent to road structure modifications. Of HRMA options 2, 4, 5, 6 and 7, only option 4 is predicted to generate total costs higher than total costs assigned the base case (where no HRMA weight restrictions are imposed). This result suggests that some element of caution should be exercised with regards the implementation of HRMA policies; net cost savings need not accompany each considered HRMA alternative. Presuming spring weight restrictions and attendant ‘neighbourly pressure’ function adequately within the RM, model results suggest their elimination would only increase the total costs of network use and provision (both prior and subsequent to road structure
modifications). If SHT policy mandated upgrade for every segment demonstrating non-negligible cost-savings, model results under the unlimited budget option suggest capital expenditures of approximately 3.8 million dollars would suffice for the RM of Cote network.

7.3.2.3 Edge Flows and Trip Routings

Computed flows and routings of vehicle traffic through the RM of Cote network reflect presumed origin-destination (O-D) pairings, variable unit vehicle costs, road structure allocations across the network, and policy options restricting freight truck movements. Since the O-D pairings reflect a certain degree of guess-work, however, the flows and routings derived may sometimes fail to mirror observed traffic volumes among network segments. For this reason the flow assignment results generated and summarized in this section must be met with some scepticism. Despite this obvious shortcoming the results still serve a useful purpose: they illustrate the potential effects policy and road investment arrangements hold for trip-making behaviour. As discussed previously, such effects may in turn influence the allocation of road structures among network segments under reigning budget constraints. Review of flow results, then, can provide useful insights for subsequent investigations incorporating more accurate data.

Table 7.9 summarizes average daily traffic flows for a subset of network edges and policy options across season (non-spring and spring periods), vehicle class (freight, passenger and total), and road structure allocation scheme (existing, E, and modified, M). For each policy option, the difference in total traffic flows due solely to road structure modifications is denoted D. The last six columns of Table 7.9 compare differences in total traffic flows across policy options for both existing and modified
### Table 7.9: Sample road segment (edge) traffic flows.

<table>
<thead>
<tr>
<th>Edge</th>
<th>No Spring</th>
<th>Base Case (HRMA Option 1)</th>
<th>HRMA Option 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Freight</td>
<td>Pax</td>
</tr>
<tr>
<td>EDGE(8,14)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-spring</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EDG(9,12)</td>
<td>51</td>
<td>51</td>
<td>255</td>
</tr>
<tr>
<td>Non-spring</td>
<td>51</td>
<td>51</td>
<td>255</td>
</tr>
<tr>
<td>EDG(12,15)</td>
<td>74</td>
<td>74</td>
<td>391</td>
</tr>
<tr>
<td>Non-spring</td>
<td>74</td>
<td>74</td>
<td>391</td>
</tr>
<tr>
<td>EDG(14,17)</td>
<td>12</td>
<td>12</td>
<td>58</td>
</tr>
<tr>
<td>Non-spring</td>
<td>12</td>
<td>12</td>
<td>58</td>
</tr>
<tr>
<td>EDG(15,19)</td>
<td>83</td>
<td>83</td>
<td>446</td>
</tr>
<tr>
<td>Non-spring</td>
<td>83</td>
<td>83</td>
<td>446</td>
</tr>
<tr>
<td>EDG(17,18)</td>
<td>12</td>
<td>12</td>
<td>58</td>
</tr>
<tr>
<td>Non-spring</td>
<td>12</td>
<td>12</td>
<td>58</td>
</tr>
<tr>
<td>EDG(17,21)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-spring</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EDG(18,19)</td>
<td>20</td>
<td>20</td>
<td>109</td>
</tr>
<tr>
<td>Non-spring</td>
<td>20</td>
<td>20</td>
<td>109</td>
</tr>
<tr>
<td>EDG(19,26)</td>
<td>103</td>
<td>103</td>
<td>555</td>
</tr>
<tr>
<td>Non-spring</td>
<td>103</td>
<td>103</td>
<td>555</td>
</tr>
<tr>
<td>EDG(21,33)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No Spring Weights:</td>
<td>Base Case (HRMA Option 1):</td>
<td>HRMA Option 2:</td>
<td>No Spring - HRMA 1</td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------------------</td>
<td>---------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Freight</td>
<td>Pax</td>
<td>Total</td>
<td>Freight</td>
</tr>
<tr>
<td>- Spring</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EDGE(26,27):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>0</td>
<td>0</td>
<td>555</td>
</tr>
<tr>
<td>- Spring</td>
<td>0</td>
<td>0</td>
<td>555</td>
</tr>
<tr>
<td>EDGE(26,35):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>103</td>
<td>103</td>
<td>0</td>
</tr>
<tr>
<td>- Spring</td>
<td>103</td>
<td>103</td>
<td>0</td>
</tr>
<tr>
<td>EDGE(27,28):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>7</td>
<td>7</td>
<td>602</td>
</tr>
<tr>
<td>- Spring</td>
<td>7</td>
<td>7</td>
<td>602</td>
</tr>
<tr>
<td>EDGE(33,34):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>37</td>
<td>37</td>
<td>300</td>
</tr>
<tr>
<td>- Spring</td>
<td>37</td>
<td>37</td>
<td>300</td>
</tr>
<tr>
<td>EDGE(34,35):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>39</td>
<td>49</td>
<td>313</td>
</tr>
<tr>
<td>- Spring</td>
<td>39</td>
<td>49</td>
<td>313</td>
</tr>
<tr>
<td>EDGE(34,42):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>- Spring</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>EDGE(35,41):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>142</td>
<td>152</td>
<td>313</td>
</tr>
<tr>
<td>- Spring</td>
<td>142</td>
<td>152</td>
<td>313</td>
</tr>
<tr>
<td>EDGE(41,44):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>186</td>
<td>176</td>
<td>1106</td>
</tr>
<tr>
<td>- Spring</td>
<td>186</td>
<td>176</td>
<td>1106</td>
</tr>
<tr>
<td>EDGE(42,43):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>10</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td>- Spring</td>
<td>10</td>
<td>0</td>
<td>64</td>
</tr>
</tbody>
</table>
Table 7.9. Sample road segment (edge) traffic flows.

<table>
<thead>
<tr>
<th>No Spring</th>
<th>Weights:</th>
<th>Base Case (HRMA Option 1):</th>
<th>HRMA Option 2:</th>
<th>No Spring - HRMA 1</th>
<th>No Spring - HRMA 2</th>
<th>HRMA 1 - HRMA 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freight</td>
<td>Pax</td>
<td>Total</td>
<td>Freight</td>
<td>Pax</td>
<td>Total</td>
</tr>
<tr>
<td>- Non-spring</td>
<td>13</td>
<td>3</td>
<td>81</td>
<td>17</td>
<td>94</td>
<td>20</td>
</tr>
<tr>
<td>- Spring</td>
<td>13</td>
<td>3</td>
<td>81</td>
<td>17</td>
<td>94</td>
<td>20</td>
</tr>
<tr>
<td>EDGE(47,48)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>7</td>
<td>7</td>
<td>80</td>
<td>80</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>- Spring</td>
<td>7</td>
<td>7</td>
<td>80</td>
<td>80</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>EDGE(47,52)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>7</td>
<td>7</td>
<td>80</td>
<td>80</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>- Spring</td>
<td>7</td>
<td>7</td>
<td>80</td>
<td>80</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>EDGE(48,49)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>11</td>
<td>11</td>
<td>101</td>
<td>101</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>- Spring</td>
<td>11</td>
<td>11</td>
<td>101</td>
<td>101</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>EDGE(52,54)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>0</td>
<td>0</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>- Spring</td>
<td>0</td>
<td>0</td>
<td>42</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>EDGE(54,55)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>- Spring</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>EDGE(55,56)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Non-spring</td>
<td>12</td>
<td>12</td>
<td>25</td>
<td>25</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>- Spring</td>
<td>12</td>
<td>12</td>
<td>25</td>
<td>25</td>
<td>37</td>
<td>37</td>
</tr>
</tbody>
</table>
road structure allocation schemes. Below, a number of important observations related to Table 7.9 are discussed.

Although the effect is not generally dramatic, road structure modifications do appear to influence traffic flows through the network. The magnitude and spatial location of traffic flow differences, however, vary by policy option. For instance, under 'no spring weights' annual average daily traffic (AADT) flows across segments (34,35), (34,42), (35,41), (41,44), (42,43), and (43,44) change by 74 over both spring and non-spring periods due to attendant road structure modifications. This reflects an apparent 'attraction' to a newly modified road segment, (34,35), by freight and passenger vehicle trip-makers formerly traveling on parallel gravel RM roads (see Figure 7.2). Similar though less dramatic effects occur under the base case. As shown in Table 7.9, non-spring and spring traffic flows change by 12 and 4, respectively, across a number of network segments. In this case, however, the change in routing decisions motivating these model predictions are attributable solely to freight truck trip-makers – regardless of attendant road structure modifications, passenger vehicle trip-makers maintain a consistent route (path) choice. Although not presented in Table 7.9, it is interesting to note that the traffic flow results corresponding to HRMA option 5 and 'unlimited budget' identically mirror the base case. Under HRMA option 2, it appears road structure modification alone has no influence on predicted traffic flows and attendant routings through the network. As can be seen in Table 7.9, the difference in flows attributable to road structure modification is identically zero for every segment (an observation that extends to all segments in the RM of Cote network). Although absent from Table 7.9, the same results correspond to HRMA options 4, 6 and 7.
While the magnitude and scope of traffic flow differentials is modest, it can be said that road structure modifications alone can influence the path choice reached by freight and passenger vehicle users and therefore the segment-specific traffic volumes observed across the network. However, the results also suggest that the nature of such changes vary by policy environment. This supports the claim that decisions governing road-related policy and investment are indeed interrelated.

As hoped, predicted freight traffic flows across policy options realistically emulate the effect of HRMA weight restrictions. For example, only ‘captive’ freight traffic flows are predicted to traverse segments (9,12), (12,15) and (15,19) under HRMA option 2 (an observation that extends to HRMA options 4 and 6 as well). Comparing against the base case, it can be seen that much of the freight truck trips formerly conducted over segments (9,12), (12,15) and (15,19) have diverted to segments (8,14), (14,17), (17,18) and (18,19) to avoid the weight restrictions under HRMA option 2 (see Figure 7.2 for clarification). The magnitude of this change is evident in the last two columns of Table 7.9 (under the heading ‘Base Case – HRMA 2’). As the calculations demonstrate, both prior to and following attendant road structure modifications, approximately 80 non-spring and 25 spring freight truck trips are predicted to alter travel paths through the network due to the impact of HRMA option 2.

Other relative comparisons between the base case, ‘no spring weights’, and HRMA option 2 reveal similar trends of varying magnitude. Although, not surprisingly, the bulk of underlying trip path changes correspond to freight truck journeys, it is interesting to note that passenger vehicle users may change network routings due to the effect of freight traffic on road performance before and after road structure
modifications. Compare, for instance, model results corresponding to edges (47,48), (47,52), (48,49), and (52,54) against edges (54,55) and (55,56). As Table 7.9 suggests, the overall shift in traffic volumes over these 'competing' road segments are almost entirely attributable to changes in trip routings reached by passenger vehicle users.

Clearly, then, the road damage patterns corresponding to various policy options can alter the path choice reached by both freight and passenger vehicle users. This matches, in general, intuitive expectations.

Not all results necessarily appeal immediately to intuitive expectations. For example, note that freight traffic flow predictions on segments (26,27) and (27,28) under HRMA option 2 appear anomalous – implementation of corresponding weight restrictions actually increase predicted freight traffic flows relative to the base case and 'no spring weights'. This reflects the fact that captive trip-makers (freight trips originating from nodes 16 and 20, in this case) choose to use segments (26,27) and (27,28) to conduct their respective journeys. Since the number of freight trips generated by captive trip-makers is insufficient to damage (26,27) and (27,28), these segments are included within the optimal routing joining nodes 16 and 20 to node 41. In contrast, under the base case and 'no spring weights', segments (26,27) and (27,28) are damaged by excessive freight traffic – effectively 'discouraging' freight trips over subsequent and necessary iterations of the SP sub-model.

General trends in traffic flows predicted within the model for the RM of Cote network reflect O-D assumptions underlying the analysis that, in turn, reflect observed traffic flows. As freight and passenger vehicles 'approach' Kamsack, traffic flows consolidate over network segments. For instance, as Table 7.9 shows the volume of
traffic predicted for segments (19,26), (26,27), (27,28), (34,35), (35,41) and, most noticeably, (41,44) attest to the sheer volumes that secondary highways under SHT jurisdiction can 'collect' as freight and passenger trip-makers approach a main centre within a RM. Hence, while the O-D data is admittedly less-than-ideal, the results generated within the model appear reasonable given observed traffic volumes within the region.

While a number of results generated within the model appear reasonable, it should be noted that the model fails to emulate reality in certain instances. For example, under existing road structure allocations and the base case – the option most closely resembling the current policy regime within the RM of Cote – Highway 357 is predicted to carry almost no traffic. As shown in Table 7.9, segments (8,14), (17,21) and (21,33) carry no freight or passenger vehicle traffic whatsoever. Segment (14,17) is an exception to this rule as it ‘bridges’ both freight and passenger traffic traveling through segments (13,14) and (17,18). These results contradict traffic counts collected by SHT in 1999 and 2000 which suggest that average daily volumes across Highway 357 vary from 95 to 205 vehicles per day. Again, more accurate knowledge regarding O-D pairings in the region may serve to correct such anomalies.

Careful examination of each trip commodity reveals the individual route choices underlying the cumulative edge flows presented in Table 7.9. While an exhaustive review would prove both tedious and overwhelming, a representative sample of individual trip routings does provide some useful insights regarding flow determination within the SP sub-model across policy options.
Table 7.10 presents detailed path choices (and corresponding daily trip volumes) for a subset of non-spring freight trip commodities across the base case and HRMA options 5 and 7—a subset illustrating the manner in which policy options influence individual trip routings. As can be seen, route choices reached by trip commodities traversing O-D pairs (2,41) and (13,41) can vary strongly across policy options. For instance, while trip routing for O-D pair (2,41) remains consistent under the base case and HRMA option 7, it is quite different under HRMA option 2. Under the base case and HRMA option 7, the 18 daily trips conducted between O-D pair (2,41) are linked via (2,11), (11,12), (12,15), (15,19), (19,26), (26,35) and (35,41). In contrast, under HRMA option 2, these trips are linked via (2,11), (11,10), (10,9), (9,8), (8,14), (14,17), (17,18), (18,19), (19,26), (26,35) and (35,41). Similarly, the path choice revealed by non-spring freight trip routings from node 5 to node 41 suggest the influence of HRMA option 2. Although the first three and last three segments coincide across policy options, the four segments comprising the middle of the 13 journeys conducted change from (8,9), (9,12), (12,15) and (15,19) to (8,14), (14,17), (17,18) and (18,19). Under the base case and HRMA option 2, the 12 daily trips conducted between O-D pair (13,41) are linked via (13,14), (14,17), (17,18), (18,19), (19,26), (26,35) and (35,41). Under HRMA option 7, however, this routing changes to (13,7), (7,8), (8,9), (9,12), (12,15), (15,19), (19,26), (26,35) and (35,41). While the influence of policy options on trip routings is widespread, it should be noted that most trips conducted over the RM of Cote network are, as expected, consistent over all policy options. This is particularly true of passenger vehicle trips not directly influenced by seasonal or HRMA weight restrictions.
Table 7.10. Sample non-spring freight flow assignments across policy options (following road structure modification).

<table>
<thead>
<tr>
<th>BASE CASE (HRMA OPTION 1)</th>
<th>HRMA OPTION 2</th>
<th>HRMA OPTION 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flows on path (2,41) are:</td>
<td>Flows on path (2,41) are:</td>
<td>Flows on path (2,41) are:</td>
</tr>
<tr>
<td>- Flow on (2,11) 18</td>
<td>- Flow on (2,11) 18</td>
<td>- Flow on (2,11) 18</td>
</tr>
<tr>
<td>- Flow on (11,12) 18</td>
<td>- Flow on (9,8) 18</td>
<td>- Flow on (11,12) 18</td>
</tr>
<tr>
<td>- Flow on (12,15) 18</td>
<td>- Flow on (8,14) 18</td>
<td>- Flow on (12,15) 18</td>
</tr>
<tr>
<td>- Flow on (15,19) 18</td>
<td>- Flow on (10,9) 18</td>
<td>- Flow on (15,19) 18</td>
</tr>
<tr>
<td>- Flow on (19,26) 18</td>
<td>- Flow on (11,10) 18</td>
<td>- Flow on (19,26) 18</td>
</tr>
<tr>
<td>- Flow on (26,35) 18</td>
<td>- Flow on (14,17) 18</td>
<td>- Flow on (26,35) 18</td>
</tr>
<tr>
<td>- Flow on (35,41) 18</td>
<td>- Flow on (17,18) 18</td>
<td>- Flow on (35,41) 18</td>
</tr>
<tr>
<td></td>
<td>- Flow on (18,19) 18</td>
<td>- Flow on (35,41) 18</td>
</tr>
<tr>
<td></td>
<td>- Flow on (19,26) 18</td>
<td>- Flow on (19,26) 18</td>
</tr>
<tr>
<td></td>
<td>- Flow on (26,35) 18</td>
<td>- Flow on (26,35) 18</td>
</tr>
<tr>
<td></td>
<td>- Flow on (35,41) 18</td>
<td>- Flow on (35,41) 18</td>
</tr>
<tr>
<td>Flows on path (5,41) are:</td>
<td>Flows on path (5,41) are:</td>
<td>Flows on path (5,41) are:</td>
</tr>
<tr>
<td>- Flow on (5,6) 13</td>
<td>- Flow on (5,6) 13</td>
<td>- Flow on (5,6) 13</td>
</tr>
<tr>
<td>- Flow on (6,7) 13</td>
<td>- Flow on (6,7) 13</td>
<td>- Flow on (6,7) 13</td>
</tr>
<tr>
<td>- Flow on (7,8) 13</td>
<td>- Flow on (7,8) 13</td>
<td>- Flow on (7,8) 13</td>
</tr>
<tr>
<td>- Flow on (8,9) 13</td>
<td>- Flow on (8,14) 13</td>
<td>- Flow on (8,9) 13</td>
</tr>
<tr>
<td>- Flow on (9,12) 13</td>
<td>- Flow on (14,17) 13</td>
<td>- Flow on (9,12) 13</td>
</tr>
<tr>
<td>- Flow on (12,15) 13</td>
<td>- Flow on (17,18) 13</td>
<td>- Flow on (12,15) 13</td>
</tr>
<tr>
<td>- Flow on (15,19) 13</td>
<td>- Flow on (18,19) 13</td>
<td>- Flow on (15,19) 13</td>
</tr>
<tr>
<td>- Flow on (19,26) 13</td>
<td>- Flow on (19,26) 13</td>
<td>- Flow on (19,26) 13</td>
</tr>
<tr>
<td>- Flow on (26,35) 13</td>
<td>- Flow on (26,35) 13</td>
<td>- Flow on (26,35) 13</td>
</tr>
<tr>
<td>- Flow on (35,41) 13</td>
<td>- Flow on (35,41) 13</td>
<td>- Flow on (35,41) 13</td>
</tr>
<tr>
<td>Flows on path (13,41) are:</td>
<td>Flows on path (13,41) are:</td>
<td>Flows on path (13,41) are:</td>
</tr>
<tr>
<td>- Flow on (13,14) 12</td>
<td>- Flow on (13,14) 12</td>
<td>- Flow on (13,14) 12</td>
</tr>
<tr>
<td>- Flow on (14,17) 12</td>
<td>- Flow on (14,17) 12</td>
<td>- Flow on (13,7) 12</td>
</tr>
<tr>
<td>- Flow on (17,21) 12</td>
<td>- Flow on (17,18) 12</td>
<td>- Flow on (8,9) 12</td>
</tr>
<tr>
<td>- Flow on (21,33) 12</td>
<td>- Flow on (18,19) 12</td>
<td>- Flow on (9,12) 12</td>
</tr>
<tr>
<td>- Flow on (33,34) 12</td>
<td>- Flow on (19,26) 12</td>
<td>- Flow on (12,15) 12</td>
</tr>
<tr>
<td>- Flow on (34,35) 12</td>
<td>- Flow on (26,35) 12</td>
<td>- Flow on (15,19) 12</td>
</tr>
<tr>
<td>- Flow on (35,41) 12</td>
<td>- Flow on (35,41) 12</td>
<td>- Flow on (19,26) 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Flow on (26,35) 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Flow on (35,41) 12</td>
</tr>
</tbody>
</table>

160
To summarize, while inaccuracies of presumed O-D assignments are acknowledged, the results produced by the SP sub-model appear generally reasonable and illustrate the potential impact that both road structure allocations and policy options can exert on selected paths through a rural road network. Since the rerouting of flows may hold important implications for subsequent structural allocations – which may hold reciprocal impacts for traffic flow routings – no model or method of road structure allocation across a network can function adequately absent a flow component.

7.4 Concluding Remarks

In this chapter, the algorithmic strategies developed in Chapter 6 were applied to a real-world rural road network captured within the boundaries of the RM of Cote, Saskatchewan. The cost- and net benefit-based standards embedded in the algorithmic strategies were used to rank various arrangements of policy and road structure options pertinent to network managers. The results generated through this process include: road structure allocations corresponding to each considered policy option; network-wide user and agency cost estimates required to compute total costs and net benefits for purposes of ranking alternative policy-road structure arrangements; and a sample of edge- and path-specific traffic flow predictions needed to evaluate the influence of policy and road structure arrangements on path choice.

A number of important observations emerged through this analysis. First, as expected, road structure and policy arrangements do appear to influence the path choices reached by both freight and passenger vehicle trip-makers. Second, cost- and net benefit-based rankings are consistent and suggest that policy and road structure modification are indeed interrelated decisions – road structure allocations reached by the
model were sensitive to the policy environment in place. Third, while spring weight and HRMA policy restrictions appear generally beneficial, there are exceptions — suggesting caution and appropriate analysis accompany policy design. Fourth, all recommended road structure modifications suggest upgrade to CIR. Excepting upgrade to CIR or granular structures, in fact, no road structure modifications generate benefits sufficient to outweigh attendant user and/or agency (SHT) costs. Finally, net benefits attributable to road structure allocations across the RM of Cote network appear exhausted at a capital budget of approximately 3.8 million dollars. Expenditure beyond this point is unwarranted according to the cost- and net benefit-based standards used in this study — a result counter to arguments that rural road networks in Saskatchewan are grossly under-funded.

Analysis of a real-world case study tested the veracity of the models and associated algorithms designed to tackle the rural road network problem that is the subject of this study. Variations in model parameters corresponding to alternative policy regimes led to results that met logical expectations and produced certain valuable insights. However, to genuinely test and verify model capabilities across a range of circumstances, it is useful to explore variations in other model parameters that reflect potential shifts in the rural economic landscape and uncertainty surrounding road-related costs and performance estimates pertinent to model results. The sensitivity analysis conducted and summarized in the next chapter addresses this issue.
CHAPTER 8

SENSITIVITY ANALYSIS

8.1 Introduction

Sensitivity analysis achieves two goals: (i) determines the comparative responsiveness of model outcome to changes in model parameters, and (ii) in doing so furnishes an opportunity to compare model output against expectations. Of course, while the specific output (e.g., spatial road structure allocations) of any modeling exercise is difficult to forecast due to the complexity of the rural road network problem at-hand, the general trend of results should match reasoned expectations. For example, a presumed reduction in the capital costs of a competitive road structure option should – all else constant – encourage its application across some range of network segments. Should model output fail to mirror this logical if general expectation, closer scrutiny of modeling results and/or algorithms is warranted.

To some degree, the analytical investigation conducted in the last chapter addressed the two goals of sensitivity analysis. To emulate alternative policy options it was necessary to modify model parameters. The results of the corresponding analyses were then compared against implicit expectations to determine whether or not model output appeared realistic. Where output appeared perverse (e.g., reduction of freight
vehicle flow costs under HRMA option 5), detailed modeling results were carefully traced to verify model logic and ultimately demonstrate the sensibility of model output.

Yet while the results derived in Chapter 7 appeared reasonable, the implied sensitivity analysis was limited to a narrow range of parameters used to emulate the policy options considered. In this chapter, the range of parameters subjected to variation is greatly expanded. This provides a better opportunity to investigate model capabilities and veracity across a number of likely (and not so likely) circumstances.

Since parameter adjustments within sensitivity analysis often reflect a reasoned appraisal of uncertainty in the real-world, the set of circumstances emulated are often termed ‘what-if’ scenarios. In this case, three ‘what-if’ scenarios emerged naturally from the sensitivity analysis undertaken. The discussion to follow summarizes: the scenarios examined; the parameter adjustments necessary to emulate these scenarios; and the results of the corresponding sensitivity analysis.

8.2 ‘What-if’ Scenarios and Parameter Adjustments

Three ‘what-if’ scenarios guide the application of sensitivity analysis summarized in this chapter. Although an infinite variety of scenarios and attendant parameter adjustments is available for analysis, the three chosen emulate uncertainty in many important directions within the model environment and therefore affect a broad range of parameter categories. These include road user costs, road performance parameters, agency (SHT) costs, freight truck traffic volumes, and the number of road segments eligible for structural modification. In this section, the scenarios and attendant parameter adjustments are described. Note that all scenarios implicitly presume HRMA option 1
describes the reigning policy environment (i.e., ‘do nothing’ excepting ubiquitous spring weight restrictions).

8.2.1 Scenario 1: Road Use Costs

As the results of Chapter 7 demonstrate, the primary justification for road structure modification involves trip cost savings enjoyed by freight and passenger vehicle users. This raises an interesting question. How might an alternative set of user cost estimates influence road structure allocations reached by the model? For this scenario, the differences in freight and passenger vehicle unit user costs across road structure type are changed and narrowed to investigate the potential impact on road structure allocations and attendant cost estimates reached by the model.

Table 8.1 is the counterpart of Table 7.3. In Table 7.3, user cost estimates across road structures range from 10 to 60 percent higher than the user cost estimates corresponding to an asphaltic concrete (AC) pavement structure (the ‘best’ of road structures from a user’s standpoint). In Table 8.1, user cost estimates across road structures range from only 5 to 25 percent higher than user cost estimates corresponding to an AC pavement structure. In addition, user costs corresponding to granular structures are presumed marginally lower than for either cold in-place recycled (CIR) or ‘good’ thin membrane surfaced (TMS) road structures. This is a purposeful attempt to sway road structure allocations towards granular structures where traffic volumes are sufficiently high. Note as well that the user cost differentials between TMS and gravel highway standard (GHS) road structures have been adjusted. As Table 8.1 shows, a good GHS road structure posts user costs only marginally higher than a good TMS road structure, and the user costs corresponding to a poorly performing (‘bad’) GHS road
structure is presumed equal to user costs for a bad TMS road structure. Note that while a range of user costs are modified for purposes of sensitivity analysis, the absolute unit user costs corresponding to an AC pavement remain at 0.273 and 0.496 dollars per kilometer for passenger and freight vehicles, respectively.

Table 8.1. Unit user costs for sensitivity analysis.

<table>
<thead>
<tr>
<th>Variable cost estimates ($/km)</th>
<th>Cars and pickups</th>
<th>Freight vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Pavements</td>
<td>0.273</td>
<td>0.496</td>
</tr>
<tr>
<td>Granular</td>
<td>0.287</td>
<td>0.520</td>
</tr>
<tr>
<td>CIR</td>
<td>0.292</td>
<td>0.530</td>
</tr>
<tr>
<td>TMS – good</td>
<td>0.300</td>
<td>0.545</td>
</tr>
<tr>
<td>TMS - bad</td>
<td>0.341</td>
<td>0.620</td>
</tr>
<tr>
<td>Gravel (GHS) – good</td>
<td>0.314</td>
<td>0.570</td>
</tr>
<tr>
<td>Gravel (GHS) – bad</td>
<td>0.341</td>
<td>0.620</td>
</tr>
</tbody>
</table>

Due to the presumed changes in user costs, it is logical to expect: (i) a fall in freight and passenger vehicle traffic flow costs, (ii) a drop in cost-savings corresponding to road structure modification, and (iii) a possible reduction in the number of segments recommended for upgrade. Since granular structures now compare favourably to CIR structures in terms of user costs, it is reasonable to presume a narrowing of the cost-savings differential between the structures. Whether or not this is sufficient to sway substitution of CIR for granular structures is conditional on traffic volumes. The change in user costs between GHS and TMS road structures is unlikely to sway adoption of GHS road structures within the model since the corresponding capital costs and performance characteristics of GHS roadways must compete against the similar capital
costs and vastly superior performance of CIR road structures. However, under alternative assumptions regarding GHS costs and performance, the adoption of GHS road structures in certain instances may prove advantageous.

### 8.2.2 Scenario 2: Gravel Highway Standard Performance and Costs

The performance and capital costs of GHS road structures is highly variable.\(^1\) Since ongoing preservation costs are already low, any additional capital cost savings attributable to GHS structures make them an attractive alternative for SHT managers. This is particularly true where the performance of GHS structures is adequate for the traffic levels sustained. The question is, do additional savings enjoyed by SHT outweigh the clear ‘penalty’ paid by road users even where the performance of GHS structures is adequate?

To answer this question, the capital costs assigned GHS structures are lowered from 100,000 to 15,000 dollars per kilometer (the lower bound on the capital costs of gravel reversion). To emulate superior performance, the critical (daily) freight traffic volumes corresponding to the non-spring and spring periods were raised from 35 and 8 to 45 and 15, respectively. Together, the reduction in cost and improvement in performance should render GHS a relatively more attractive road structure option. However, to overcome the significant user cost barrier separating GHS from superior road structures (e.g., CIR), the capital cost reduction and performance improvements were mated to the user costs listed in Table 8.1. Combined, the influence of user costs, capital costs and performance levels may prove sufficient to encourage the adoption of GHS road structures in certain cases.

---

\(^1\) Personal communication with Mr. Ron Gerbrandt (Preservation Director, SHT).
8.2.3 Scenario 3: Freight Truck Traffic Volumes and Roadway Candidates

Freight truck traffic volumes used in the model reflect traffic counts of the recent past among road segments within the RM of Cote. Future economic developments may, however, influence observed volumes. For instance, a strawboard plant is expected to open just outside Kamsack. As the only manufacturer of its kind in the region, the strawboard plant is likely to attract additional freight truck traffic to the area. Hence, one would expect freight truck traffic volumes to increase along at least some network road segments.

To emulate such changes, all freight truck volume estimates for the region are arbitrarily increased by a factor of five times.\(^2\) Although a somewhat unrealistic estimate, an increase of this magnitude is likely to generate a significant number of segment candidates for road structure modification and therefore better test model capabilities. To complicate matters further, a number of road segments under the jurisdiction of the RM were added to the set of SHT road segments eligible for structural modification. The RM road segments added to the eligible set include: (17,18), (18,19), (23,24), (24,25), (29,30), (30,31), (42,43), (43,44), (47,48), (47,52), (48,49), (52,54), (54,55), (55,56), and (56,60). All road segment references correspond to the network graph illustrated in Figure 7.2.

Higher freight truck traffic volumes and a significant rise in the number of road segments eligible for structural modification should increase the set of segment-road structure combinations considered within the KS sub-model and therefore increase the

\(^2\) Note that a factor of two was originally tried. However, this made no difference to model results relative to HRMA policy option 1 alone. Only factors of four or higher generated any significant change in model results.
computational effort and time required to reach a good solution. The dramatic rise in truck traffic within the modeled network should increase overall flow costs for two reasons. First, all else constant higher traffic volumes translate to higher costs. Second, more truck trips should translate to a fall in overall road performance levels that should, in turn, increase the cost of freight and passenger vehicle trips alike.

8.3 Results of Sensitivity Analysis

In Chapter 7, three categories of model results were reviewed: (i) road structure allocations, (ii) costs and net benefits, and (iii) traffic flows and routings. The primary reason underlying the investigation of traffic flows and routings involved the veracity of model predictions – did the flows and routings reached by the model appear reasonable in the context of governing policy and investment arrangements. Since the flow and routing results reached by the model did indeed appear reasonable, there is little to be gained by repeating that investigation in this chapter. Hence, unless directly pertinent to discussions, the review of results provided below are limited to the road structure allocations and costs corresponding to each ‘what-if’ scenario.

8.3.1 Road Structure Allocations

Road structure allocations corresponding to each ‘what-if’ scenario (labelled SA1, SA2 and SA3, respectively) are provided in Table 8.2. Since HRMA option 1 is the policy environment common to all scenarios, the results corresponding to HRMA option 1 (the base case of Chapter 7) is included for purposes of comparison. Unlike Table 7.6, note that Table 8.2 accommodates GHS as a likely structural modification.
Table 8.2. Recommended road structure modifications pertinent to sensitivity analysis.

<table>
<thead>
<tr>
<th>'What if' scenario</th>
<th>Policy regime</th>
<th>Segments modified to CIR structure</th>
<th>Segments modified to GHS structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/a</td>
<td>Base case (HRMA 1)</td>
<td>(12,15), (19,26), (33,34), (34,35)</td>
<td>n/a</td>
</tr>
<tr>
<td>SA1</td>
<td>Modify user costs</td>
<td>(12,15), (15,19), (19,26)</td>
<td>n/a</td>
</tr>
<tr>
<td>SA2</td>
<td>SA1 and modify GHS costs / critical values</td>
<td>(12,15), (15,19), (19,26)</td>
<td>(1,4), (4,9), (33,34), (34,35)</td>
</tr>
<tr>
<td>SA3</td>
<td>Increase truck traffic and segments eligible for modification</td>
<td>(12,15), (15,19), (19,26), (27,28), (34,35)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The results corresponding scenario 1 (SA1) match reasoned expectations. A lowering and narrowing of differences in user costs should reduce the number of road segments recommended for upgrade. As Table 8.2 shows, only three segments are recommended for upgrade to CIR: (12,15), (15,19) and (19,26). A more detailed examination of model results reveal that only CIR and granular road structures are predicted to generate positive cost savings for each of these three segments. However, despite the slight user cost advantage accorded the granular option, the CIR option posted marginally superior cost-savings in all cases. Since the CIR option also posts lower initial capital costs, it is only logical that CIR was selected in preference to the granular option for each of the three segments.

Comparing the results of SA1 against HRMA option 1 leads to some interesting insights. First, note that neither (33,34) or (34,35) are offered as potential candidates for road structure modification under SA1. As it turns out, the general reduction in freight and passenger vehicle user costs corresponding to SA1 eliminate any cost-savings these segments posted previously under HRMA option 1. Second, (15,19) is a recommended
upgrade candidate under SA1 but not under HRMA option 1. Although (15,19) did indeed post positive cost-savings under HRMA option 1, the three million dollar budget constraint prevented its adoption given cost-savings corresponding to other competing road segments. In other words, had additional budget monies been made available under HRMA option 1, segment (15,19) would have been included among segments recommended for structural modification (in fact, segment (15,19) is included among recommended segments under the 'unlimited budget' option of Table 7.6).

Where the change in user costs is accompanied by a reduction in capital costs and improved performance for GHS structures, recommended road structure allocations alter dramatically. As show in Table 8.2, the results corresponding to SA2 suggest a number of segments undergo structural modification. In this case, however, both CIR and GHS are included among recommended road structure allocations across the RM of Cote network. Identical to SA1, CIR is the preferred upgrade for segments (12,15), (15,19) and (19,26) despite the fact both CIR and granular options post positive cost savings. Segments (1,4), (4,9), (33,34) and (34,35), in contrast, are assigned a GHS structure within the modeling environment.

Closer scrutiny of model results reveal the reasons underlying the allocation of GHS structures to certain segments. The daily volumes of non-spring and spring freight traffic flows corresponding to segments (1,4), (4,9), (33,34) and (34,35) fall conveniently between the critical values assigned to TMS and GHS road structures. Hence, where the TMS roadways are expected to fail under predicted freight traffic volumes, the GHS substitutes are expected to succeed (i.e., maintain good performance). Since the user costs assigned to good GHS roads are lower than the user costs assigned
to bad TMS roads, the substitution actually lowers overall trip costs for users traveling over these four segments. Moreover, since the capital costs of gravel reversion in this case are slight and the corresponding preservation costs are lower than for any other road structure, the annualized costs incurred by the road agency (SHT) differ negligibly between TMS and GHS road structures. Overall then, the ‘price’ of road structure modification is more than outweighed by the cost savings enjoyed by freight and passenger vehicle users alike.

Comparing the results of SA2 against HRMA option 1 and SA1 raises some interesting points. First, like SA1, segment (15,19) substitutes for segments (33,34) and (34,35) where CIR road structure modifications are concerned. Second, under SA2 segments (33,34) and (34,35) are assigned GHS rather than CIR road structure modifications. This does not counter intuitive expectations. Since neither (33,34) or (34,35) benefit from CIR upgrade under SA1, one would not expect their inclusion under SA2. As discussed above, the only reason (33,34) and (34,35) are included among structural modifications at all is due to the assigned capital costs and performance attributes of GHS in this case.

The road structure allocations corresponding to scenario SA3 are quite different from the other scenarios. Like HRMA option 1 and scenario SA1, scenario SA3 includes only CIR upgrades. However, the set of segments advocated for upgrade under SA3 does differ. In this case, segments (27,28) and (34,35) are added incrementally to segments (12,15), (15,19) and (19,26) advocated within SA1.

Closer scrutiny of model results explains some of the differences observed in Table 8.2. Under the traffic and segment eligibility assumptions governing SA3, 31
segment-road structure combinations post positive cost savings. The road structure modifications included among these combinations consist of CIR, granular and even AC pavement. Since freight traffic volumes are presumed to increase by a factor of five, a number of segments qualify for all three road structure modifications. In all cases, however, CIR out-competes both granular and AC pavement structures since attendant cost savings are higher and capital upgrade costs are lower. Hence, for these segments granular and AC pavement options are eliminated from further consideration within the pre-processing procedure applied during model computations.

Compared against upgrade recommendations reached under HRMA option 1, SA3 substitutes road segments (15,19) and (27,28) for segment (33,34). Although investigation of model results reveal that upgrade of segment (33,34) to a CIR structure is likely to generate positive cost savings, the cost savings posted are lower than the cost savings corresponding to the upgrade of either (15,19) or (27,28). This is due, in large measure, to differences in freight truck traffic volumes between the two scenarios and sets of road segments. Comparing segments (15,19) and (27,28) against segment (33,34), the multiplicative influence of truck traffic volumes on cost-savings is relatively greater under SA3 than under HRMA option 1. Hence, segments (15,19) and (27,28) simply out-compete segment (33,34) under the higher freight truck traffic presumed under SA3.

Interestingly, AC pavement is the only recommended upgrade for segments (37,38), (38,39) and (39,40). Currently, these segments are granular structures supporting approximately 180 daily freight truck trips and 1,450 daily passenger vehicle trips. Multiplying the number of freight truck trips by five therefore increases total daily
traffic volumes to approximately 2,400. Hence, while the difference in user costs between granular and AC pavement structures is in the neighbourhood of only three to five cents per kilometer (for passenger and freight vehicles, respectively), the sheer volume of traffic in this case justifies upgrade to AC pavement. Nonetheless, given a budget of only three million dollars, the model assigns only the CIR upgrades listed in Table 8.2.

Overall, the results posted in Table 8.2 match reasonable expectations. Relative to HRMA option 1, a general lowering of user costs and narrowing of differences among user costs across alternative road structure options leads to fewer defensible road structure allocations. Combining changes to user costs with improvements in the cost-competitiveness and performance of GHS road structures leads to the recommended allocation of GHS road structures across several segments. Finally, an increase in both truck traffic and the number of segments eligible for structural modification generates a greater number of segment-road structure combinations posting positive cost-savings and alters the list of segments recommended for upgrade to CIR.

8.3.2 Cost Results

As demonstrated in Chapter 7, both cost-based and net benefit-based standards lead to identical rankings and comparative insights. For this reason, the results reviewed in this section focus on cost-based results alone. In the discussion to follow, the cost estimates corresponding to each scenario are examined in some detail. All cost estimates reached through the modeling exercise are summarized in Table 8.3. As can be seen, equivalent annual and present worth results are categorized by scenario (including HRMA option 1) and nature of costs incurred (flow costs, preservation costs, etc.).
Table 8.3. Cost-based results for ‘what-if’ scenarios and corresponding road structure arrangements.

<table>
<thead>
<tr>
<th></th>
<th>HRMA Option 1:</th>
<th>SA 1 (user costs):</th>
<th>SA 2 (GHS &amp; user):</th>
<th>SA 3 (strawboard):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual Worth</td>
<td>Present Worth</td>
<td>Annual Worth</td>
<td>Present Worth</td>
</tr>
<tr>
<td>Results prior to road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>2,463,200</td>
<td>24,832,000</td>
<td>2,248,690</td>
<td>22,486,900</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>12,159,900</td>
<td>121,599,000</td>
<td>11,423,500</td>
<td>114,235,000</td>
</tr>
<tr>
<td>- Total flow costs</td>
<td>14,643,100</td>
<td>146,431,000</td>
<td>13,672,200</td>
<td>136,722,000</td>
</tr>
<tr>
<td>- Total preservation costs</td>
<td>658,769</td>
<td>6,587,690</td>
<td>658,769</td>
<td>6,587,690</td>
</tr>
<tr>
<td>- Total flow and preservation costs (1)</td>
<td>15,301,900</td>
<td>153,019,000</td>
<td>14,331,000</td>
<td>143,310,000</td>
</tr>
<tr>
<td>Results following road structure allocations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Available Budget Monies</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
<td>3,000,000</td>
</tr>
<tr>
<td>- Total freight vehicle flow costs</td>
<td>2,362,110</td>
<td>23,621,100</td>
<td>2,207,210</td>
<td>21,207,210</td>
</tr>
<tr>
<td>- Total passenger vehicle flow costs</td>
<td>11,692,700</td>
<td>116,927,000</td>
<td>11,258,100</td>
<td>112,581,000</td>
</tr>
<tr>
<td>- Total flow cost</td>
<td>14,054,800</td>
<td>140,548,000</td>
<td>13,465,300</td>
<td>134,653,000</td>
</tr>
<tr>
<td>- Total capital costs of upgrades</td>
<td>293,529</td>
<td>2,935,290</td>
<td>131,934</td>
<td>1,319,340</td>
</tr>
<tr>
<td>- Total preservation costs</td>
<td>679,640</td>
<td>6,796,400</td>
<td>668,150</td>
<td>6,681,500</td>
</tr>
<tr>
<td>- Total flow, upgrade and preservation costs (2)</td>
<td>15,028,000</td>
<td>150,280,000</td>
<td>14,265,400</td>
<td>142,654,000</td>
</tr>
<tr>
<td>- Total savings over original costs (1 - 2)</td>
<td>273,911</td>
<td>2,739,110</td>
<td>65,593</td>
<td>655,930</td>
</tr>
<tr>
<td>Branch-and-Cut (B-and-C) cost savings</td>
<td>276,739</td>
<td>2,767,390</td>
<td>65,593</td>
<td>655,930</td>
</tr>
<tr>
<td>Heuristic cost savings</td>
<td>272,177</td>
<td>2,721,770</td>
<td>65,593</td>
<td>655,930</td>
</tr>
<tr>
<td>Percentage advantage of B-and-C results</td>
<td>1.65%</td>
<td>0.08%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
</tbody>
</table>
As discussed earlier in this chapter, the freight and passenger vehicle user costs assigned under scenario SA1 are quite different from the user costs assigned under HRMA option 1. Relative to the anchored costs of trip-making over AC pavements, user costs across alternative road structures under SA1 are lower and moderately biased towards granular and GHS structures. Compared against HRMA option 1, then, the freight and passenger vehicle flow costs corresponding to scenario SA1 should be lower. Also, since user costs are generally less sensitive to road structure modifications, it is logical to expect a reduction in attendant cost-savings relative to HRMA option 1.

Clearly, the results posted in Table 8.3 support reasoned expectations. The annual worth (AW) of freight and passenger vehicle flow costs under SA1 are approximately 240 and 730 thousand dollars lower than the flow costs predicted under HRMA option 1. Since user costs under SA1 are less sensitive to road structure modifications, total cost savings reach only about 66 thousand dollars – over 200 thousand dollars less than the cost savings predicted under HRMA option 1.

Note that predicted capital expenditure under SA1 falls well short of the available budget. In PW terms, capital expenditures reach only about 1.3 million dollars – approximately 1.7 million dollars less than available budget monies. This stands in stark contrast to HRMA option 1 where only the inherent ‘lumpiness’ of road structure upgrades prevents use of the entire 3.0 million dollar budget. This observation is further reflected in the comparative cost-savings reached under the heuristic and branch-and-cut algorithms used to solve the KS sub-model. As can be seen, both algorithms reach predicted savings of approximately 66 thousand dollars. Since the ‘volume’ of the knapsack (3.0 million dollar budget) exceeds the ‘volume’ of eligible artefacts
(expenditure on road segment upgrades), any segment-road structure combinations surviving the pre-processing algorithm are immediately added to the knapsack.

Under scenario SA2, the user costs corresponding to SA1 are combined with lower capital costs and improved performance of GHS road structures. Relative to HRMA option 1, this should reduce flow costs and potential cost savings. However, since GHS road structures emerge as a viable road structure alternative for certain segments within the Cote network, total cost savings under SA2 should exceed those predicted for SA1. From an agency (SHT) standpoint, the application of GHS road structures should reduce preservation costs incurred since gravel roadways are typically the least expensive road structures to maintain on an on-going basis.

The results listed in Table 8.3 support these expectations. Prior to any road structure modifications, freight and passenger vehicle flow costs under SA2 are identical to those posted under scenario SA1 and therefore less than predicted flow costs under HRMA option 1. Following road structure allocations over the network, however, flow costs fall below those predicted for both SA1 and HRMA option 1. Moreover, since GHS road structures are indeed assigned across a number of segments, the cost-savings attributable to structural modification reach approximately 1.5 million dollars in PW terms – over twice the cost-savings reached under SA1. Although the bulk of these savings are due to a reduction in freight and passenger trip costs, some portion of the savings are attributable to a fall in preservation costs. Since GHS road structures are allocated to four segments within the network, overall preservation costs fall by about 25 thousand dollars annually. Note again that capital expenditure on road structure
modification lie resolutely below available budget monies. The cost savings reached by
the heuristic and branch-and-cut algorithms are therefore identical.

While user costs under scenario SA3 equal those of HRMA option 1, both
freight truck traffic volumes and the number of road segments eligible for structural
modification increase. Logically, this should lead to higher freight and passenger
vehicle flow costs and therefore an increase in predicted cost savings following
attendant road structure modifications.

The results of Table 8.3 support expectations. Due to higher truck volumes, both
freight and passenger vehicle flow costs rise relative to HRMA option 1. Prior to road
structure allocations reached by the model, passenger vehicle flow costs are predicted to
rise by approximately 120 thousand dollars on an annual basis. The dramatic increase
freight truck volumes, however, lead to a predicted rise of over 10 million dollars on an
annual basis – exceeding, not surprisingly, freight vehicle flow costs under HRMA
option 1 by a factor of five. Following road structure allocations determined within the
modeling environment, annual freight and passenger vehicle flow costs fall by
approximately 600 and 500 thousand dollars, respectively. Despite corresponding
capital upgrade expenditures and a marginal increase in preservation costs, the AW of
net savings attributable to road structure modification alone reach almost 800 thousand
dollars. The relative magnitude of savings under SA3 are not surprising – all else
constant, a rise in traffic (and therefore flow costs) should increase the potential benefits
attributable to road structure modifications that improve road performance from the
standpoint of all trip-makers.
Note the relatively poor performance of the heuristic algorithm under SA3. In this case, the proportional advantage of branch-and-cut algorithm is over seven percent. As always, this is due to the 'lumpiness' of road structure modifications and corresponding capital expenditures. Under SA3, however, this problem is magnified since the branch-and-cut algorithm determines a combination of road structure upgrades (all to CIR) that virtually exhausts the entire budget. As shown in Table 8.3, capital expenditures on road upgrades are within 5,200 dollars of available budget monies. Closer scrutiny of model results reveals, however, that the gap between capital upgrade expenditures and available budget monies grows to over 25,000 dollars where the heuristic algorithm is applied to solve the KS sub-problem. Moreover, the collection of segments selected by the heuristic algorithm misses some key substitutions that result in greater overall cost savings. For these reasons, the heuristic algorithm fares poorly relative to the branch-and-cut algorithm. Of course, finer segmentation of roadways within the network would likely lead to better performance of the greedy heuristic applied in this study.

In Table 8.3, note the significant gap in cost savings attributable to the application of the heuristic and branch-and-cut algorithms relative to the actual cost savings enjoyed under scenario SA3 (a gap of approximately 740 thousand dollars in PW terms). Recall the overall algorithmic procedure used to solve the rural road network problem at-hand. Following recommended road structure allocations across the network, the model iteratively runs the shortest path (SP) sub-model until stable traffic flows are reached. Given the magnitude of freight traffic flows under this scenario, the number of road segments damaged by re-assigned traffic flows under each iteration of
the SP sub-model can dramatically influence the total trip-making costs incurred by freight and passenger vehicle users alike.

As mentioned previously, the number of possible segment-road structure combinations posting positive cost-savings under scenario SA3 reaches 31. However, application of the remaining features of the pre-processing algorithm reduces this to a set of 15 possible combinations. In this case, the corresponding number of mutually exclusive road structure arrangements across segments within the network reach 32,768 \(2^{15}\). Since this exceeds the number of mutually exclusive arrangements available under any other scenario or option analyzed in this study, it is logical to expect an increase in the computation time required to complete each model run. Indeed this is the case. Excepting SA3, all model runs completed within 10 to 15 seconds. Computation time corresponding to SA3, however, increases to approximately 20 seconds. Although a relatively mild increase, the exponential influence of additional segment-road structure combinations does clearly affect model run times.

In sum, the cost results detailed in Table 8.3 support reasoned expectations. Presumed changes in user costs alone (scenario SA1) did reduce the magnitude of cost savings available through road structure modifications. Combined with improved performance and lower capital costs for GHS road structures (SA2), the presumed changes in user costs lead to the allocation of GHS road structures to certain segments within the network and increase overall cost savings available. Finally, all else constant, an increase in freight traffic volumes and the number of road segments eligible for structural modification (SA3) leads to greater opportunities for cost-saving allocations of road structure modifications across the network. Although greater opportunities
translate to greater combinatorial difficulties, the pre-processing procedure still substantively reduces the set of segment-road structure combinations requiring consideration within the branch-and-cut and heuristic algorithms used to solve the KS sub-model.

8.4 Concluding Remarks

The process and results of the sensitivity analysis summarized in this chapter conform to three ‘what-if’ scenarios – each expressing a unique appraisal of uncertainty surrounding real-world circumstances emulated within the modeling environment. Although limited in number, the scenarios permitted the adjustment of many important model parameters including: road user costs; capital cost of road structure modifications; road performance parameters; freight traffic volumes; and number of segments eligible for road structure modification. The results of the sensitivity analysis generate a number of interesting insights and further verify the intuitive sensibility of results reached by the model.

A number of important observations emerged through the sensitivity analysis. First, as the relative influence of road structure improvements on user costs fall, the number of road segments advocated as candidates for structural modification fall as well. Second, if user costs are less sensitive to gravel reversion (i.e., substitution of GHS for existing TMS road structures) and the performance of GHS structures is arbitrarily improved, then the adoption of GHS road structures across a network increase as the corresponding capital costs fall. Third, increasing both the number of road segments eligible for structural modification and the volume of freight truck traffic traveling through a rural road network leads to greater opportunities for cost saving road
structure modifications. Not only does the number of candidate segment-road structure combinations rise, but the magnitude of potential cost savings corresponding to each segment-road structure combination increases as well. Fourth, despite the efficacy of the pre-processing procedure, an increase in the number of segment-road structure combinations posting positive cost savings increases the computation time of model runs. However, the results do suggest that a relatively large rural road network characterized by modest traffic volumes can be analyzed within the model developed in this study.
CHAPTER 9

STUDY SUMMARY, LIMITATIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

9.1 Summary of Study

Investment and policy decisions reached by managers of mature rural road networks may be influenced by many factors, including: the performance of roadways within networks; evident travel patterns and traffic volumes among freight truck and passenger vehicle trip-makers; and changes in the rural economic landscape. Reciprocally, the investment and policy decisions reached may influence road performance, road use and, in time, the shape of the rural economic landscape. To reach sound decisions, then, rural road network managers must be cognizant of these complex interrelationships.

Complicating the decision-making environment further is the reality of limited budget monies and the combinatorial challenge posed by network structure. Mature road networks are composed of many linked road segments. Each of these segments may be a candidate for costly investment (e.g., road structure modification) or inclusion within a considered policy regime (e.g., subject to truck weight restrictions under the terms of a haul road management agreement). The question is, given limited budget monies what arrangement of road-related policy and investment across a network might prove ‘best’? To answer this question in a quantitative way, two needs must be
addressed: (i) a defensible standard of measure used to rank available policy-investment combinations, and (ii) a practicable computation method to rank demonstrably good combinations for road networks of non-trivial size and configuration.

The principal objective of this study was to develop a credible standard and computational method necessary to answer the question posed above for road-related policy and investment alternatives pertinent to managers of rural road networks in Saskatchewan. In this case, a cost-based standard – founded on long-standing economic principles – is incorporated within a modified network design problem (NDP) model. The resulting NDP-based model seeks a cost-minimizing spatial arrangement of available road structure modifications (e.g., upgrade to granular structure, reversion to gravel structure) across segments of a road network governed by a predefined policy regime (e.g., predefined terms of a haul road management agreement). To solve the model, computer-based algorithmic strategies were designed to determine a spatial allocation of road structure modifications posting net cost savings relative to a predefined base case (representing extant road structure arrangements of a given network). Run once for each mutually exclusive policy regime under consideration, the cost savings predicted by the model can be used to subsequently rank corresponding policy-road structure combinations.

Since policy and investment decisions reached by managers of rural road networks in Saskatchewan may influence – and may be influenced by – road performance, road use, and features of the surrounding rural economy, the complex interrelationships involved required some level of representation within the model environment. Figure 9.1 illustrates components of the decision-making environment
Figure 9.1. Components endogenous to modeling environment.

endogenous and exogenous to the NDP-based model. As shown, components endogenous to the model include the allocation of considered road-related investments across the network, interrelated road performance and road use effects, and potential consequences for costly network preservation efforts. Exogenous to the model are considered policy regimes and features of the rural economic landscape pertinent to road use in the region. Note that only a subset of components – policy, investment and
preservation decisions – lie under the direct control of road network managers.

Although the decisions reached may influence road performance, road use and the local economy, the modeling environment implicitly presumes that network managers in Saskatchewan do not exercise direct control over the shape of rural economies or the self-interested trip-making behaviour of freight and passenger vehicle users that affect road performance within the network. Nonetheless, the road-related impacts of decisions reached by trip-makers and those shaping rural communities may well influence the efficacy of decisions reached by network managers. To support sound policy and investment decisions within road agencies, then, it was necessary to consider all facets of the decision-making environment in some way within the corresponding model process.

The proposed model and associated algorithmic strategies were applied to a case study in order to evaluate the efficacy and performance of the modeling environment. The case study chosen is the road network bounded within the rural municipality (RM) of Cote, Saskatchewan. Segment-specific road structure modifications considered within the modeling environment include: upgrades to cold in-place recycled (CIR), granular, and AC pavement structures; reversion to gravel highway standard (GHS); and ‘do nothing’ (i.e., maintain current road structure). Considered policy regimes include spring weight restrictions, a range of haul road management agreements (HRMAs), and ‘do nothing’. Based on data regarding road use (traffic volumes, origin-destination patterns, vehicle types and trip-making costs), road performance (freight truck volumes ‘triggering’ structural failure of certain road structure types during spring and non-spring periods), agency costs (capital, preservation and resurfacing costs corresponding
to considered road structure modifications), and existing network configuration (descriptive spatial ‘map’ of the RM of Cote network), the modeling environment was used to determine a demonstrably good spatial arrangement of road structure modifications for each considered policy regime. The net cost savings (net benefits) predicted by the model were then used to rank corresponding policy-road structure arrangements. Subsequent analysis of predicted freight and passenger trip routings through the Cote network verified the model’s ability to logically ‘re-route’ traffic flows based on the terms of policy regimes and the predicted allocation of road structure modifications across the network.

Despite certain shortcomings in the data (e.g., lack of reliable origin-destination data), a number of important insights emerged through the analysis of the RM of Cote road network. First, decisions regarding road structure arrangements and policy do appear to influence the route choices reached by freight and passenger vehicle users. In turn, the trip routing decisions reached by road users can affect the performance of road segments within the network (and vice-versa). Second, ‘good’ road structure arrangements reached by the model were sensitive to the policy regime in place. This suggests that policy and road structure modification are best viewed as interrelated decisions. Third, while spring weight and HRMA policies appear generally beneficial, exceptions do occur. This suggests caution and careful analyses should accompany policy design for any rural road network. Finally, road structure modifications are not ubiquitously ‘good’. The analysis demonstrates, in fact, that only a handful of segment-road structure combinations within the Cote network generate net cost savings — suggesting a definitive and modest limit on ‘good’ road structure modifications and
attendant expenditures involving rural road networks (an important insight from the standpoint of establishing defensible budgets for rural road networks). Note that in all cases, the cost savings (benefits) of road structure modifications accrued to road users. The road agency (Saskatchewan Highways and Transportation in this case) absorbed the concomitant rise in capital and on-going road preservation costs.

To further test and verify model capabilities, a sensitivity analysis was conducted. A number of model parameters used to describe the case study were perturbed to determine the responsiveness of model results and whether or not the results reached matched reasonable expectations. In this case, the sensitivity analysis led naturally to the development of three 'what-if' scenarios. In the first scenario (SA1), road user costs across alternative road structures and vehicle types (freight trucks and automobiles) were adjusted to effectively dampen the beneficial influence of road structure improvements from the trip-maker's standpoint. The changes to road user costs under SA1 also improved the relative beneficial impact of granular and gravel (GHS) road structures – effectively biasing decisions towards these options. In the second scenario (SA2), the road user costs of SA1 were combined with lower capital costs and improved performance of GHS road structures – further biasing decisions towards the GHS option. The final scenario (SA3) maintains the original user cost parameters, but dramatically increases freight truck traffic volumes through the Cote network while increasing the number of road segments eligible for road structure modification (up to this point, only segments under SHT jurisdiction were labelled 'eligible' within the modeling environment).
The parameter adjustments corresponding to each scenario were applied as inputs to the modeling environment to generate corresponding results. A number of interesting and intuitively reasonable observations emerged through subsequent investigation of model results. First, as the relative trip-related benefits (user cost savings) of road structure modification shrinks, the number of road structure modifications recommended by the model falls. Second, where user costs are less sensitive to gravel (GHS) reversion, the capital costs of GHS structures are low, and the performance of GHS structures is adequate, the model tends to favour the adoption of GHS road structure modifications for certain segments within the RM of Cote network. In general, this result suggests that road structure alternatives exhibiting relatively favourable performance and cost characteristics are more readily adopted than competing alternatives. Third, increasing both freight truck traffic volumes and the number of road segments eligible for structural modification concomitantly increases the number of beneficial segment-road structure combinations identified by the model. Finally, due to combinatorial implications, a rise in the number of potentially beneficial road structure modifications across a network increases the computation time required to reach a demonstrably good road structure allocation scheme within the modeling environment. However, the favourable computation times reached by the model suggest road networks larger than that bounded by the RM of Cote can be analyzed within the proposed modeling environment.

Overall, the results of the case study and corresponding sensitivity analysis suggest the principal objective of the study is satisfied. The modified network design problem (NDP) model embeds a defensible standard and method capable of ranking
alternative road-related policy and investment arrangements in the context of broader issues involving rural economies, road use, road performance, and preservation activities. The computer-based algorithmic strategies employed to solve the model ensure that any policy and investment arrangements advocated are 'demonstrably good' (i.e., predicted user cost savings exceed predicted agency costs) and adequately capture pertinent impacts involving road use, road performance, and related preservation efforts and costs. Although successful, insights gained during the course of this study suggest both limitations of the study and concomitant opportunities for future research.

9.2 Study Limitations and Opportunities for Future Research

The key limitations of this study can be organized, broadly, in two categories: (i) limitations related to the selected model application, and (ii) limitations related fundamentally to current model design. Of course, any set of limitations suggest promising avenues of investigation for researchers. For this reason, opportunities for future research are discussed alongside noted study limitations.

9.2.1 Limitations and Opportunities Related to Model Application

Figure 9.1 stands as a succinct summary of the decision-making environment facing managers of mature rural road networks and the division of this environment into components endogenous and exogenous to the NDP-based model developed during the course of this study. An obvious feature of Figure 9.1 is its emphasis on challenges relevant to Saskatchewan and, more particularly, road-related policy and investment options directly pertinent to the RM of Cote – the case study analyzed and reviewed in
this dissertation. It is this particular focus that suggests the first of notable study limitations and concomitant directions for further research.

While a reasonable case study for modeling and testing purposes, the RM of Cote road network is but one component of an entire transportation area relevant to planning activities within SHT. Hence, although the case study demonstrates the usefulness of the model for policy and investment planning as well as budget determination (based on defensible economic standards), truly relevant results are contingent on modeling networks encompassed within or beyond the level of transportation area (West Central Municipal Government Committee, 1997; Clifton, 2000). A straight-forward implication for future research, then, is simply to expand model application to larger networks within Saskatchewan.

A number of other study limitations and research opportunities are immediately related to the selected model application suggested by Figure 9.1. These include:

- **Options for study:** The range of policy and investment options analyzed herein are limited to the select number included in the case study. Should model application expand to include other regions of the Province, the list of relevant policy and investment options may also expand. For example, to concomitantly reduce freight vehicle and agency costs, current vehicle weight and dimension policy may be overhauled to encourage the use of more benign heavy vehicle configurations (personal communication, Dr. Curtis Berthelot). Although model parameters can be adjusted to emulate and examine the potential impacts of this considered policy initiative, the effective spatial implications of such change lies well beyond the borders of a mere Rural Municipality. Hence, a productive area for future research
involves the incorporation of policy and/or investment options of more widespread relevance within the Province.

- **Seasonal road performance characteristics:** As discussed earlier in this dissertation, the performance of thin membrane surfaced (TMS) and gravel highway standard (GHS) road structures varies by season. Currently, the model environment encompasses only ‘spring’ and ‘non-spring’ seasonal characteristics. Where this categorization is insufficient to address investment and policy issues in various regions of the Province, it will prove necessary to segregate traffic flows into finer categorizations within the modeling environment. For example, the performance of roadways in Saskatchewan is known to increase during winter months. For this reason, a ‘winter weights’ policy exists – permitting higher loads on certain provincial highways during winter months. A useful direction for further research therefore involves the further segregation of traffic flows and related performance parameters according to seasonal categories.

- **Budget determination:** Recall that the KS sub-problem employed within the algorithmic strategies implicitly presumes a benefit-cost ratio of 1.0. Hence, potential benefits arising through incremental additions to proposed road structure modifications need only exceed concomitant costs by a factor of one to earn recommendation within the modeling environment. For this reason, results surrounding ‘optimal’ budget forecasts may not reflect the reality of competing public investments, policies and programs within Saskatchewan. An important avenue for further research, then, involves comparison of budget forecasts across a
defensible range of benefit-cost ratios (for any rural road network captured within relevant transportation areas in the Province).

- **Risk management:** Since experience and field verification is limited, new road-related technologies (e.g., CIR road structures) may prove a relatively risky investment. For this reason, prudence would temper immediate and widespread application across rural road networks. Recall, however, that results pertaining to the RM of Cote network advocated the ‘immediate and widespread’ application of CIR road structures under all policy options investigated. Since this result seemingly violates prudent judgement, a productive direction for future research might involve the introduction of constraints to control the application of new technologies within the modeling environment. For instance, the capital budget (B) might be partitioned to limit expenditures on ‘risky’ road structure investments and thereby encourage a diversified road structure ‘portfolio’ across the network in question.

- **Economic planning:** Excepting the inclusion of an imminent strawboard plant in Kamsack during the course of sensitivity analysis, the model was not employed to forecast the impacts of potential changes to the rural economic landscape of the Cote region. Yet the capabilities of the model can be exploited as an economic planning tool for any region of the Province. Suppose, for example, a given region of Saskatchewan was weighing the costs and benefits of varying hog barn proposals. As part of a broader economic analysis, an important question would involve the influence of hog barn distribution on the costs of road use and provision in the region. Since an answer to this question is predicated on related traffic flow
implications as well as considered haul policy and road investment arrangements, the model – as it stands – could provide important information in the economic planning process. Particularly for those involved in rural economic planning, addressing this challenge in the context of the existing modeling environment might prove a highly productive area of research.

- **Competing modes of transport**: Road-based hauls are not the only means of transporting goods within and beyond Saskatchewan’s borders. Rail-bound movements, in particular, are a competing alternative to heavy trucks where longer hauls are involved. In this regards, changes to transport regulations that improve access privileges for the competitive short-line rail industry could well resuscitate abandoned rail lines in the Province. This has clear implications for heavy truck hauls and road-related investment and policy arrangements. While the current model configuration does not capture rail lines in any way, the scope of change required is minimal since the corresponding mathematics and algorithms are insensitive to segment characteristics (whether road- or rail-based). Extending the existing model to tackle this challenge therefore seems a useful direction for future research.

- **Retrospective analysis**: The case study chosen for analysis involves forecasting – based on knowledge regarding traffic flows in the region, it projects a reasoned arrangements of available policy and road structure modification options. An interesting application not examined involves retrospective analysis – modeling a region already ‘modified’ to compare actual policy and investment arrangements to those the model might recommend. Insights reached through such an exercise
would help evaluate the efficacy of current decision-making standards within SHT and, potentially, shape current haul policy to better exploit road structure modifications already undertaken. Hence, this also appears to be a productive area for research in future.

- **Other jurisdictions**: Saskatchewan is not the only jurisdiction in Canada, North America or the world facing policy and investment questions involving rural road networks. Yet while the focus of investigations in this study furnished a range of apparently generic insights (e.g., the interrelated nature of policy and investment decisions), no other jurisdiction was modeled for comparative purposes and further insight. For instance, districts of rural India face decisions regarding the costly upgrade of earth, gravel and water-bound macadam to all-weather standards to stimulate economic growth (Liu, 2000). Despite the conceptual equivalence of this challenge and the lessons learned during the course of investigations herein, it is difficult to forecast any meaningful outcome in the absence of explicit modeling and comparison. In the case of India, for example, radical changes in road structure arrangements within extant networks would likely stimulate substantive changes in the rural economic landscape – an issue of negligible import within the RM of Cote case study. To build on insights reached to-date – and to tackle specific issues in differing jurisdictions – an obvious avenue for future research involves the application (and, potentially, modification) of the existing model to rural road networks in other parts of the world.

In addition to the foregoing are two key limitations and opportunities related to the technical implementation of model as it stands. As discussed in Chapter 7, origin-
destination (O-D) data was not available for the RM of Cote network – necessitating extrapolation from historical traffic count data. Given the important interrelationships between road use and other endogenous model components noted in Figure 9.1, a useful direction for future research involves collection and application of reliable O-D data.

A second technical limitation involves the solution method (algorithmic strategies) developed and employed in this study to determine policy-road structure arrangements for a predefined rural road network. While the model can produce demonstrably good results – ranking policy-road structure combinations according to defensible economic standards – there exists no clear way to verify the corresponding ‘level of goodness’. Often, mixed-integer programs (MIP) – such as the NDP-based model applied here – permit linear relaxations that generate ‘super-optimal’ yet infeasible results that nonetheless provide a yardstick against which to measure the relative goodness of feasible results determined by the corresponding model. The intrinsic complexity of the rural road network problem addressed in this study, however, suggests no obvious means of developing a useful yardstick. Hence, it is not possible to confidently appraise the true goodness of the results generated within the modeling environment. Tackling this issue stands, therefore, as another valuable opportunity for future research.

9.2.2 Limitations and Opportunities Related to Model Design

From the standpoint of rural road managers, an important limitation of the current study involves policy determination. As Figure 9.1 shows, road-related policy decisions are exogenous to the current model design. Where policy schemes are ubiquitous across a network (e.g., spring weight restrictions), this poses little difficulty for model
application across even large rural road networks. However, where the possible arrangement of policy schemes increases rapidly with network size (e.g., haul road management restrictions), endogenous policy determination would prove highly advantageous. To address this challenge, it is of course necessary to modify the current model design. The means by which this might be accomplished, however, has important and widespread implications for model use and therefore future research opportunities.

Recall that rural road networks are generally uncapatitated – traffic volumes are insufficient to generate congestion. Hence, a principal objective of road structure modification is to increase strength and therefore mitigate the damaging impact of heavy vehicles. Similarly, a principal objective of haul policies is to control the weight, dimensions, routing, et cetera, of heavy vehicles to again mitigate damage among vulnerable road segments. So it is that policy and investment decisions involve implicit trade-offs between user costs (both freight and passenger) and agency costs (capital and on-going preservation) – a suspicion supported by analyses conducted over the course of this study. The question is, at what point is this trade-off ideally balanced?

From the standpoint of shippers, any policy permitting higher haul weights (e.g., winter weights policies in Saskatchewan) is beneficial since it ultimately lowers freight prices within the highly competitive trucking business. From the standpoint of rural road managers, however, the concomitant impacts on other users through deteriorating road performance can be effectively addressed only through related haul policy changes (e.g., haul road management agreements) and/or road structure modification. This suggests a possible combination of road structure allocations and haul policies that effectively establishes a heavy haul sub-network within an extant rural road network –
permitting quasi-monopolistic control over the routings and weights of at least some subset of heavy truck hauls.

The challenge of shaping a heavy haul sub-network through policy is directly akin to the root challenge of the network design problem (NDP) discussed in Chapter 2. In essence, within an overall computational strategy it would prove necessary to employ algorithms that effectively 'construct' the linkages of a cost-minimizing heavy haul sub-network among all segments contained within the rural road network in question. Ultimately, the solution reached within the modeling environment would combine haul route restrictions and expressly tailored road structure modifications across the network.

Shippers and trucking companies wishing to exploit the cost-savings of higher haul weights would be restricted to the heavy haul sub-network. To ensure incentives are properly aligned, any 'cheaters' (i.e., truckers hauling heavy loads on non-designated road segments) would be subject to severe penalties.

Currently, SHT has heavy haul partnership agreements in place with a few key shippers in Saskatchewan (Berthelot et al, 2000). In exchange for heavy haul permits, the shippers agree to restrict truck haul movements to certain designated corridors and 'share' a proportion of their cost savings with SHT. The penalty for cheating is the withdrawal of the permit (with obvious consequences for shipping costs). Due to combinatorial implications, however, expanding this concept across an entire network of spatially disparate shipping origins and destinations in an efficient way would require modeling of the sort suggested above.

Tackling the heavy haul problem through endogenous policy formation suggests a range of opportunities for researchers. First and foremost, the existing model would
have to be modified to permit endogenous haul policy formation. This would involve the explicit determination of road segments included within, or excluded from, the heavy haul sub-network. Second, researchers would have to establish efficient trade-offs among weight restrictions, haul route restrictions and road structure modifications such that total use and provision costs are truly minimized. Third, since bridge structures are subject to load restrictions, strengthening and haul policy options pertinent to roadways would have to be translated to equivalent options pertinent to bridges. Finally, to maximize the economic efficiency of policy and investment arrangements, it would prove necessary to develop defensible pricing schemes for participation in the heavy haul program (i.e., a form of pricing related to marginal damage costs).

Beyond endogenous policy formation, the suggested modification of the existing model design naturally permits the consideration of new, expanding or contracting rural road networks. Since ‘constructing’ a heavy haul sub-network within an existing road network is equivalent to ‘constructing’ a new network, adding new links within an existing network, or eliminating links from an existing network, each of these tasks could be addressed within the updated model design. Hence, the implications for extant rural road networks extend, for instance, to: (i) the construction of new rural road networks in developing countries, (ii) the expansion of extant networks in developed and developing countries, and (iii) elimination of road segments within networks in contracting rural economies (Hamlett and Baumel, 1990). Clearly, each of these areas of investigation furnishes myriad opportunities for future research.
REFERENCES


Bonsor, N., Competition, Regulation, and Efficiency in the Canadian Railway and Highway Industries, Chapter 2 in *Essays in Canadian Surface Transportation*, F. Palda (Editor), The Fraser Institute, Vancouver, BC, 1995.


204


