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Final Report

# Cost/Benefit Study: Spring Load Restrictions

Research

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16. Abstract (Limit: 200 words)

Across the state of Minnesota, asphalt roads under the jurisdiction of counties, cities and townships have been controlled by restrictions that limit the total weight of each truck that uses those roads during the spring thaw period. During this time, the pavement weakens and the bearing capacity of the roadway is reduced. These policies vary from county to county and from road to road, depending on the capacity of the roads––typically, 5, 7 and 9 tons.

While spring load restrictions serve to extend the useful life of the road, they also add significant burdens to truckers who are forced to re–route their vehicles and/or increase the number of trips in order to adhere to the policies.

This study assesses the economic impact of lifting all vehicle restrictions during the spring thaw period.

Economic benefits of lifting the bans include reduced cost to carriers; potential cost includes reduced pavement life. Their research concludes that if the policy is changed, the costs of additional damage could be recovered from those who use the roads. Recovering those costs could take the form of annual fees, appropriate fuel taxes and/or user charges paid by vehicle operators.

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# Cost/Benefit Study of: Spring Load Restrictions

**Final Draft**

*Prepared by:*


**Principal Investigators**
David Levinson
Mihai Marasteanu
Vaughan Voller

**Graduate Research Assistants**
Ioana Margineau
Brian Smalkoski
Maryam Hashami
Ning Li
Mike Corbett

**Other Key Personnel**
Erland Lukanen

Department of Civil Engineering
University of Minnesota


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395 John Ireland Boulevard, MS 330
St. Paul, MN 55155

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# Preface

This report describes research conducted to determine the economic benefits and costs of spring load restrictions in Minnesota. The research study consisted of six tasks. Each chapter of this document presents a separate report addressing one of the six tasks. Because of this approach, each chapter is numbered separately and includes its own set of tables, figures and references. Each is also enhanced by its own set of appendices that present additional details. The conclusions are incorporated into the Executive Summary.

# Executive Summary

## Overview

The Local Road Research Board (LRRB) and the Minnesota Department of Transportation (Mn/DOT) funded this project to evaluate the continuing utility of the spring load restriction (SLR) policy (including both the legal framework and the administrative rules and informal procedures used to implement spring load restrictions) on county, city, and township roads, which collectively are the local roads analyzed in this study. The objective of this study is to determine the economic benefits and costs of spring load restrictions in Minnesota.

The strength of asphalt roads varies seasonally. During the winter, the layers of materials that make up the pavement structure harden when the temperature drops below the freezing point. When spring arrives, the frozen aggregate base and then the soil under the aggregate base, thaw, and are in a saturated condition. Under this condition, the pavement weakens and the bearing capacity of the roadway reduces. Heavy vehicles driving on the roadway under these conditions damage the roadway more than most other times of the year. To solve this problem, perhaps the most obvious technical solution is to improve the carrying capacity of all roads so that they can bear heavy loads (e.g. 10 tons/axle) even during the spring-thaw period. But this is expensive for the responsible agency. The spring load restriction policy was enacted in Minnesota in 1937 (Minnesota Statute 169.87) and has been periodically updated to protect the large public investment in county and municipal roadways by reducing pavement damage and extending the useful life of roads, which enables road authorities to save on infrastructure investment and maintenance of roads. The SLR policy (under various names, including spring (seasonal) weight restrictions, spring bands, or spring thaw load restrictions) is implemented in many cold climate countries, including the United States, Canada, France, Finland, and Sweden. The SLR policy regulates the axle load of trucks during the spring thaw. These restrictions impose costs on commercial vehicle operators while benefiting society by extending pavement life.

From the truck operator's point of view, the SLR policy is detrimental to business. Once the load limits are in place, most of the trucks must reroute and/or use more trucks or make more trips. Producers and retailers are also affected by the SLR policy because they might be forced to store commodities for a longer time. Other vehicles face the increasing number of trucks on the road network.

Estimating the impact of the SLR policy on the economy requires a careful analysis within a benefit/cost evaluation framework The benefits of lifting the SLR policy include reduced economic costs imposed on carriers and shippers (and ultimately consumers, workers, and businesses in Minnesota) associated with less additional distance traveled to avoid restricted roads, fewer truckloads to abide the restriction, and fewer deferred ship. The costs of lifting the SLR policy imposed on state and local government (and ultimately taxpayers in Minnesota) include reduced pavement life. Estimating the benefits requires an assessment of freight demand patterns and truck operating costs. Estimating the costs of changing the policy also requires knowing freight demand patterns, as well pavement performance and pavement construction costs. A flowchart of the procedure is given in Figure 1, and it is described briefly in the Methodology section below and in subsequent chapters.

## Findings

This study found that spring load restrictions extend the useful life of asphalt roads (which reduces costs to agencies and thus taxpayers). However they also impose significant economic costs on road users, particularly shippers and carriers and their customers. After careful evaluation of both the extended pavement life and the costs to the trucking industry, it was found that the benefits of lifting the existing SLR policy outweigh the additional costs. This means that although roads may receive additional damage and in some cases fail prematurely if the SLR policy were lifted, the cost to reconstruct or perform early resurfacing on these roads will in general be less than the savings to carriers and shippers. This finding assumes that roads can be replaced as they are; it does not account for the spending of additional funds to upgrade roads to modern standards after they are damaged.

Based on analysis of Lyon, Olmsted, and Clay counties at the time of the study, the research concludes that to improve overall economic efficiency, spring load restrictions be removed on roads operating year-round at 9-tons. A study of the City of Crystal, to investigate the effect of the SLR policy on residential streets, recommends removing the restrictions there as well, as failure due to mechanisms typically attributed to spring thaw loadings are not the dominant source of pavement failure. There may be other failure mechanisms that will be accelerated by spring thaw loads, but extensive further study would be required to identify them. Additional study is warranted on both 5-ton paved and 5-ton unpaved (gravel) roads. Additional study is also warranted on the few roads that have been posted at below 9-tons during the rest of the year. These roads are typically in worse condition than 9-ton roads (hence their posting), and may be more vulnerable during the spring thaw. The procedures for cost-effectively rating pavements should be determined by state and local engineers, and should be consistent with state standards.

The research concludes that if the SLR policy is changed, the costs of additional damage should be recovered from those who benefit from the change in policy. There are a number of forms this can take, ranging from an increase in the costs of annual fees to operate heavy vehicles to an increase in fuel and other user charges paid by the operators of those vehicles. The research recommends that a policy similar to the Oregon Weight-Distance tax be investigated when considering how to recover the additional costs. The revenue generated from this new tax or user fee should be allocated to maintain, repair, and upgrade roads that will be damaged or destroyed due to the change in policy. Based on the benefit/cost analysis, it is clear that some links should be upgraded, and some should not, but identifying the specific links that should be upgraded requires more detailed engineering analysis.

The research concludes that ongoing monitoring of real roads should take place to determine if roads are deteriorating faster or slower than predicted by the analytical models used to prepare this report. The consequences of any policy change should be evaluated after a suitable period of real-world experience, to inform future policy in this arena.

## Caveats

As with all forecasts, estimates, or analyses, the model results are sensitive to assumptions. To test the sensitivity of the model results, a number of alternative scenarios were tested. While there are a set of assumptions one can find that will change the general outcome (e.g. moving a benefit cost ratio from above 1.0 to below 1.0), reasonable variation of the model parameters does not lead to a change in the conclusions; in other words, the results are fairly robust to reasonable changes in the model assumptions.

All results in this study are based on models because recent real-world experience on Minnesota roads with and without the restrictions is lacking. Studies have been conducted in Norway, which has lifted its version of spring load restrictions, but these studies are insufficient to solely rely on, in part because of different climate and soil conditions as well as different structural designs. While the models have been calibrated with the available data, additional empirical evidence would provide more confidence about the consequences. In particular, additional calibration of MnPAVE to thin pavement conditions common on many local roads would be helpful for refining these results. Furthermore, additional performance data about the nature and condition of local roads, monitored over time, would be helpful in calibrating both Mechanistic-Empirical models such as MnPAVE, as well as Empirical models such as *Investigation 183* (which was used to validate the findings of the MnPAVE model vis-à-vis pavement performance using a completely different methodology and model). Whereas MnPAVE is deemed to provide reasonable average road life expectations, as verified by other studies, it is important to note that: a) outlier pavements that are in poor condition will most likely fail during the first non-restricted spring and b) MnPAVE alone is not sufficient for the calculation of the true costs of road damage.

This study utilized the limited available traffic data and, with the assistance of MnDOT, had additional truck classification counts collected in Lyon and Olmsted counties. However, there were not counts available on most roads, so freight demand model forecasts had to be used.

This study also focused on rural counties, with less analysis of roadway conditions in cities (only one city was examined). Roads are more expensive to reconstruct in cities (in part due to the more complex environment considering public utilities, and curb and gutters), so additional caution should be taken when applying these results in areas outside the domain of the study.

This study examined roads, not bridges. Bridges that are structurally deficient year round should still govern legal loads. The costs of repairing or replacing bridges to improve their rating to be consistent with the roads they serve was not taken into account in this study.

There are additional factors to be considered when making policy recommendations. In particular: do agencies enforce the policy and do users comply with it? Evidence on this is limited, but anecdote suggests that there is a large violation rate in some counties. A violated SLR policy will mean that the policy does not extend pavement life as much as predicted by the model. A violated SLR policy will also mean that the benefits of removing the policy for carriers and shippers are lower than predicted by the model, since the rerouting and additional truckloads predicted by the model do not take place. Lowering both the benefits and costs does not necessarily significantly change the ratio of benefits to costs. However, it is important for changes in the policy to reflect the costs of retaining un-enforced laws on the books, as it may undermine compliance with other laws.

Finally, there are permits available when the SLR policy is not in effect. This study did not examine the effects of permits during the spring-thaw period. Policy should carefully consider whether these permits should become available during the spring-thaw period.

## Methodology

The procedures for developing these recommendations are detailed in subsequent chapters of this report. In brief there are several models that need to be synchronized. First there is a pavement performance model (PPM). The PPM model estimates the expected life of pavement based on truck flows by type and load, pavement conditions, soil conditions, and other factors. The PPM model takes into account the seasonal variation of the mechanical properties of the materials used in all pavement layers. This model is coupled with a freight demand model (FDM). The freight demand model predicts truck flows by type and load on each link in the network being analyzed. A third model estimates the costs to the trucking industry (TCM), as function of distance traveled, load by type, and operating cost per distance or time traveled. The freight demand model thus feeds both the PPM and the TCM.

In the basic analysis, the FDM is run for two scenarios, the first assumes retaining the SLR policy (scenario 1), the second (scenario 2') assumes lifting the SLR policy on 7 and 9-ton roads (township, city, county, and state). The results of the PPM provide an expected life of the pavement with and without spring load restrictions. This life of pavement is translated into a net present value of expected costs. If the road lasts longer, expenditures are further in the future; and thus have a lower net present value of future expenses. The results of the TCM provide an expected cost to trucking firms with and without restrictions. The two results are combined in a benefit/cost analysis (BCA) framework to estimate the ratio of benefits to costs.

The data to estimate and apply the models has to the extent possible been developed for local (Minnesota) conditions. On the FDM and TCM, the models are estimated from a series of surveys and interviews with trucking firms. This includes local estimates of truck trip generation rates, use of local commodity profiles in each county studied, use of local road street networks, estimates of local truck operating costs and values of time. On the PPM side, the model results are derived from the MnPAVE software developed by Mn/DOT and the University of Minnesota, and calibrated to Minnesota trunk highway conditions. The seasonal variation analysis performed in Task 1 indicated that for the purpose of this project the seasonal material characteristics incorporated in MnPAVE computational algorithms were reasonable. It should be noted that the pavement design of the trunk highway system differs from the local road system. However, these results are corroborated using estimates from the *Investigation 183* work that empirically examined pavement performance up to 1980.

# Flowchart of SLR Benefit/Cost Analysis

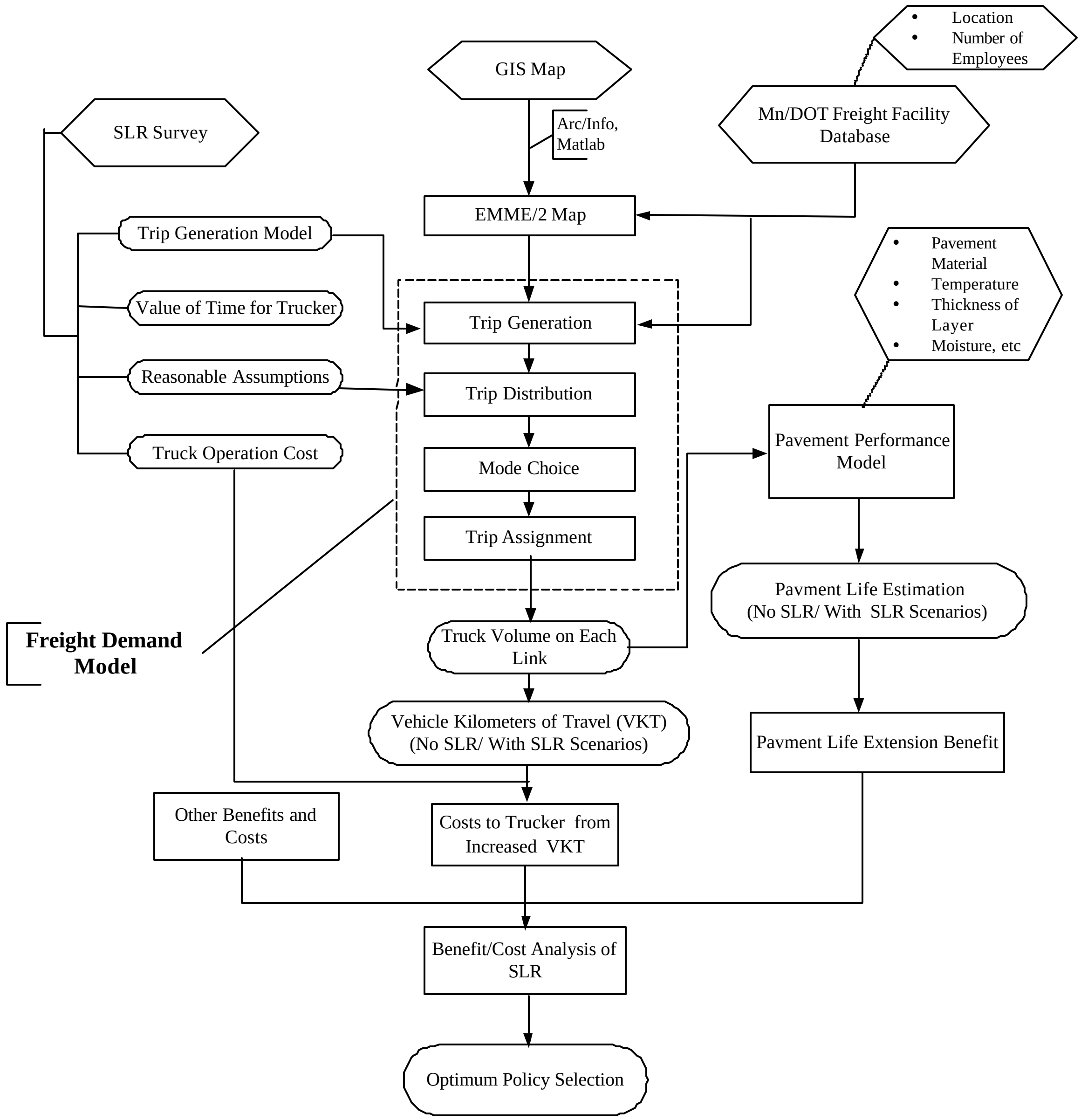


Figure 1: Flow chart of the SLR Benefit/Cost Analysis

# Chapter 1

### Task #1: Review and Prepare Existing Mechanistic Models

## 1.1 Introduction

### Background

In cold climates, at the beginning of spring, frozen pavement substructure starts to thaw. This uneven thaw pattern will result in water trapped in the base layer and will cause a dramatic loss of strength. Pavement strengths may be reduced in some cases, by as much as 50% of typical fall strength. The pavement will remain in a weakened state until the thaw is complete and the onset of strength recovery commences. The distresses that are mainly favored by the poor quality of the granular layers in the flexible pavements are rutting, fatigue cracking, depressions, corrugation, and frost heave.

Modern economic conditions and transportation practices have enabled the trucking industry to thrive. Spring thaw conditions combined with heavy truck traffic result in excessive damage. One alternative to avoid the excessive damage levels is to apply load limits for heavy trucks. These limits are commonly referred to as spring load restriction (SLR). Most of the states and countries in cold climates apply SLR to preserve the road investment for longer periods of time without substantial costs.

In order for SLR to be efficient, agencies must know when the weakening due to thaw begins and ends. This kind of information has been obtained by a number of methods. The depth of the frost penetration can be directly measured and the quality of the information obtained from the direct measurements is high; however, these types of measurements are expensive and data collection is time consuming. Thaw data may be obtained from visual observation of water seeping from cracks in the pavement as an alternative for monitoring the variation in frost depth. Unfortunately, once the seepage is observed the best time for placing restrictions has passed.

Relative indicators of pavement strength may be obtained from load tests such as the Benkleman Beam, or the Falling Weight Deflectometer (FWD). These tests provide deflection data, which can be used as an indicator of pavement strength, or the strength values can be calculated from the deflection data. However, these types of test also take time and effort to be performed and when the deflections begin to increase it is an indication that the thaw effect has already started.

Currently, the most efficient approach seems to be a restriction policy based on air temperatures. Many agencies, including Mn/DOT, have been interested in developing models that relate the start of spring thaw to the freezing and thawing index[i]. The models relate these indexes to the pavement surface temperature and other variables that predict thaw condition.

From the truck operator's point of view, the SLR policy is detrimental to business. The main source of income for truck carriers is delivering commodities on highways in an efficient and timely manner. Once the load limits are in place, most of the carriers must reroute and/or use more trucks or more trips. The producers and retailers are also influenced by SLR because they might be forced to store more commodities for a longer time. Last but not least, general traffic conditions are influenced because of the increasing of number of trucks on the road network. This change in the traffic flow makes car traveling more difficult and less safe, especially in congested urban areas.

The impact of the SLR on the economy imposes a careful analysis of the efficiency of this kind of programs using a cost-benefit evaluation. Such an analysis involves three major steps. First, an evaluation of the costs incurred by the restrictions on various industries must be performed. Secondly, an assessment of the amount of money saved as a result of preserving the road quality by using SLR is necessary. Finally, a comparison between the cumulative additional profits of all industries affected by SLR policy in the absence of such restrictions and the additional costs necessary to maintain and repair the road network to the required quality without the benefit of SLR must be done.

## Objectives and Research Approach

The objective of this research is to evaluate the reduction in damage on Minnesota roads subjected to the application of SLR. The focus is on County and State Aid paved roads mainly because of the available traffic data, a critical component of the analysis performed in this study[ii]. The research has been limited to paved roads for which maintenance, repair and rehabilitation activities are expensive.

The first part identifies the ways in which the SLR programs are designed and applied in the countries and states that deal with freeze/thaw problems. This part is followed by a detailed presentation of the structure and performance of Minnesota's local roads network. Next, a comprehensive review of the impact of the environment on the pavement behavior and the way in which this is considered in pavement design methods is presented. Based on the information presented in the first three parts, the evaluation of the impact of SLR on Minnesota restricted pavements is performed using MnPAVE mechanistic-empirical method.

## 1.2 Review of SLR Programs

### Introduction

The objective of implementing spring load restrictions is to reduce the damage on the roads that do not have the capacity to carry the expected truck loads during the spring time, as well as on roads in poor condition. Most of the countries that have the freeze/thaw phenomena impose it because they can assure that in this way the lifetime of the road is not reduced significantly.

A World Bank report from 1993 [1] indicated that during spring thaw paved roads with thin overlays on top of frost-susceptible soils may lose more than 50% of bearing capacity in spring while gravel roads can lose 70% of their bearing capacity. The strength variation during spring thaw may be smaller when the road is designed to frost-resistant standards and has sand/gravel sub-bases to limit capillary action. Frost-resistant designs are very expensive, and therefore agencies use spring load restrictions (SLR) as protective measures. Estimated benefits of SLR vary from one agency to another, ranging from 1.5 to 10 times, when annual road maintenance/ transport costs are compared with and without restrictions.

An article published in a Federal Highways Administration newsletter estimated the benefit of seasonal load restriction on US roads and concluded that more than 50% of the lifetime of the road is saved if spring load restrictions are applied, see Table 1.1.

Table 1.1 Benefit from seasonal load restriction in US in1990 [1]

| Pavement Load Reduction During Thaw (%) | Expected Pavement Life Increase (%) |
|---|---|
| 20 | 62 |
| 30 | 78 |
| 40 | 88 |
| 50 | 95 |

### Canada

All Canadian provinces impose spring load restrictions but they use different criteria to determine the period when spring load restrictions have to be imposed. Most of the agencies do not restrict their primary highway network during spring, but some of these are reclassified as secondary highways during spring, so that they are subjected to seasonal restriction. Percent reductions of 90, 75 or 50 of the basic allowable weights are typically imposed based on highway functional class and the reduction of bearing capacity. There are some agencies that allow tolerances on their basic allowable weights; these tolerances are removed during spring. Most of the agencies use deflection testing to establish the interval when restrictions are enforced. There are a few that use frost tubes. A summary of SLR policy in Canada is presented in Table 1.2. [3]

Most provinces allow exemptions to the restrictions for trucks carrying commodities such as milk, grain or forest products. Also, a large part of public utility and emergency vehicles are exempted.

**Europe**

The spring load restrictions are posted in several countries in Europe. A summary of these restrictions is presented in Table 1.3. Most of these countries try to have coherent SLR policies that tend to be comprehensible, enforceable and efficient.

Among the European countries, a particular case is represented by Norway, which ceased to enforce spring load restrictions in 1995. Norway has a main road network of 26,000 km and a secondary network of 27,000 km. Before lifting SLR, 89.4 percent of the main road network was posted as 10-ton roads during the summer and half of them were restricted during the spring. Table 1.4 presents the complete restriction system imposed on the main road network and secondary road network in Norway in 1994. The restrictions were imposed when the thaw was at a depth of 20 to 25 cm and lifted at a thaw depth of 100 to 125 cm. The length of the restriction period was approximately 8 weeks. The typical service lifetime for asphalt surfacing was 10 years for the main roads and 15 years for the secondary roads.[4]

Table 1.2 Summary of SLR in Canada [3]

| Province | Start of SLR | End of SLR | Restriction | Determination of restriction |
|---|---|---|---|---|
| **British Columbia** | mid-February | mid-June | no overloads, 70%, 50% of basic load | frost probes, deflections, historical data |
| **Alberta** | 30cm of thaw | from FWD testing | 90%, 75%, 50% of basic load | FWD |
| **Saskatchewan** | 2nd or 3rd week in March | maximum 6 weeks | 90%, 80% of basic load | Deflections |
| **Manitoba** | April 15 (Northern Zone) | May 31 | 95%, 90%, 65% of basic load | Deflections |
| **Ontario** | first Monday in March (S. Region) | mid-May | 5 ton per axle, 50% of basic load | n/a |
| **Quebec** | 30cm of thaw | 90cm of thaw below road surface | 85%, 80% of basic load | frost probes |

| | | | | |
|---|---|---|---|---|
| **New Brunswick** | 2nd or 3rd week in March | mid- or end of May | 90%, 80% of basic load | Dynaflect |
| **Prince Edward Island** | March 1 | April 30 | 75% of basic load | Dynaflect |
| **Nova Scotia** | March 2 (S. Region) | April 24 | 75%, 70% of basic load | Dynaflect |
| **Newfoundland** | February | April | as needed | n/a |

Table 1.3 SLR in Europe

| Country | Start of SLR | End of SLR | Restriction | Determination of restriction |
|---|---|---|---|---|
| **France** | n/a | n/a | 2.5-, 4-, 6-, 8-ton for single dual tire axles | frost depth measurements |
| **Finland** | April | May | gross weights: 4-, 8-, 12-, 18-ton; total shutdown | FWD, experience |
| **Iceland** | 30cm of thaw | n/a | depends on vehicle type and axle configuration | frost depth measurements |
| **Sweden** | April | May | 4-, 6-, 8-ton per axle | FWD, frost depth measurements, experience |
| **Norway** | old: 5-15cm of thaw | min. 90% of summer bearing capacity | changed yearly | FWD, frost depth measurements |
| | present: prediction that pavement will break down | 4-8 weeks after imposing | as needed | |

Table 1.4 Allowable axle loads (%) for summer and spring thaw on the Norwegian road network, January 1994 [4]

| **Allowable axle load summer/spring (t)** | **10/10** | **10/8** | **10/7** | **10/6** | **8/8** | **8/7** | **8/6** | **8/4** | **6/6** |
|---|---|---|---|---|---|---|---|---|---|
| Main road network (%) | 44.4 | 40.8 | 0.7 | 3.4 | 2.7 | 1.1 | 6.8 | 0 | 0 |
| Secondary road network (%) | 5.1 | 23.0 | 0.9 | 6.9 | 15.1 | 5.1 | 42.0 | 1.6 | 0.4 |

In 1990, the Norwegian Directorate of Public Roads initiated a project entitled "Better utilization of the bearing capacity of the road network". One of the main goals of this program was to investigate the bearing capacity cost implications for road owners and road users related to a general increase in the allowable axle load to 10 tons and lifting all axle load restriction during the spring. The project estimated that canceling of the spring load restrictions reduced the surface serving life from 10 to 8 years for the main road network and from 15 to 11 years for the secondary road network. It also predicted an increase in the maintenance and rehabilitation costs for the roads administrator in order to provide an acceptable serviceability level for the network. The conclusions of the project after the evaluation of road user and owner cost were that lifting of the spring restrictions would provide a social-economic profit of $24,700,000 resulting in a benefit/cost ratio of 2.3. On the other hand, the Norwegian report showed that without an increase of the maintenance budget a deterioration of surfacing quality would result, with a potential annual loss for the road user of $28,000,000. [4]

After 9 years without spring load restriction, Norwegian Public Roads Administration [5] has shown that the main performance parameters of the pavements (rutting and roughness) kept their normal trends. Based on field observations, they concluded that the change in policy did not significantly affect the road network, and this situation did not seem to be the result of a significant increase in the budget allocated for resurfacing. Among the possible explanations for this situation, they identified: "the slow, but steady increase in surfacing service life from 1985 to 2002 from approximately 10 to 15 years for the national roads and from 14 to 18 years for the county roads; and the reduced use of studded tires in winter (from approximately 80 percent in 1994 to 40 percent in 2002)" and "the general development in asphalt techniques and procedures, like thin surfacing". They have also indicated that even if they do not have any clear explanation for the performance of the network, they do not expect any significant changes in the quality of the network in the next years.

**United States**

In the US, 22 states are susceptible to freeze-thaw conditions, and most of them have imposed spring load restriction. The duration of this restriction is typically between 8 and 9 weeks. The methods used to determine when to place and remove the restrictions vary from state to state. In most of the cases, the restrictions are imposed at the same time in the entire state to eliminate the risk that transporters in one area have an unfair advantage over transporters in another area.

There are several methods [6] that are used in these states to determine the moment when spring load restrictions are imposed. The first is visual observations. The criteria that are used in this type of evaluation are: water seeping through cracks in the pavement from the subsurface layers as a result of traffic load applications, rapid deterioration of the surface layer, and soft shoulders. These states are: North Dakota, Idaho, Maine, Montana, New Hampshire, Oregon, New York, Iowa, Wisconsin and Michigan.

Washington, Alaska, Minnesota and South Dakota use analytical methods in addition to engineering judgment and experience to place and remove SLR. They used one of the following analytical methods: deflection tests to determine stiffness, various electrical sensors to measure frost depth and average daily air and pavement temperature to predict thawing.

Table 1.5 presents the main components of the SLR policy in Minnesota and in five adjacent states.

Table 1.5 SLR in Minnesota and five adjacent states [7]

| State | Start of SLR around | End of SLR around | Restriction | Determination of restriction |
|---|---|---|---|---|
| **North Dakota** | March 15 | June 1 | differs between trunk highways and county roads | deflection measurements and experience |
| **South Dakota** | February 28 | April 27 | 6-, 7-ton per axle | deflection measurements and experience |
| **Iowa** | March 1 | May 1 | no overloads | Road Rater and experience |
| **Wisconsin** | March 10 | May 10 | no overloads | deflection measurements and experience |
| **Michigan** | early March | late May | 70% of gross weight for HMA roads | experience |
| **Minnesota** | March | May | 5-, 7-, 9-ton per axle | design testing and experience |

The Minnesota Department of Transportation (Mn/DOT) became more concerned with SLR program in the mid 1980s, as a response to the increases in pavement damage noticed in successive springs. Three methods were used to determine when restrictions should be in place: observations of water movement and seepage near cracks were a primary focus, and the frost depth measured by frost tubes (installed in certain locations) and resistivity probes. Also, the weather conditions were collected in the spring. Even if the deflections proved to be a valid parameter in the evaluation of the seasonal variation, using deflections to analyze 62751 km (39,000 miles) of roadway is not a feasible approach [8].

When conditions warranted load restrictions, 7-day notices were given prior to the implementation. It was found that using this policy the SLR start dates were 7 to 10 days later than the critical point when the base starts to thaw. Thus, the system was found to be inefficient and in 1996 a study was done to improve the system by providing more protection for the roadways. An additional study was conducted in 2000 [6] producing a new method that provided a much more efficient and successful system, as described next.

Six frost zones (Figure 1.1) were used, in which analyses would be performed to determine separate starting dates for SLR. These were created based on general weather trends in spring and also on the traffic level, as indicated by the separate metro zone, which experiences a great deal of truck flow. The cumulative thaw index (CTI) was also considered as a primary tool to determine when SLR should be in place. Mn/DOT uses 3 to 7 days of weather forecasts to determine the CTI. The reference temperature has been determined by experiments, and varies linearly from -1.5°C (29 degrees F) on February 1 to -4.5°C (24 degrees F) on March 15. When the CTI exceeds -4°C-days (25 F degrees-days), a three-day notice is given to the public via internet and telephone. After the notice, restrictions are in place and remain so for approximately eight weeks. This time period is set for every zone, regardless of the SLR start date to ensure that the roadways have enough time to fully regain their strength. [6]

For pavements constructed with a 10-ton capacity, SLR is not necessary, since the structure is designed and constructed to handle standard loads. The Mn/DOT report “Improved Spring Load Restriction Guidelines Using Mechanistic Analysis” [6] estimates that “1,600 miles of state trunk highways, 23,600 miles of county state aid highways, 2,400 miles of municipal state aid city roads, and roughly 11,000 miles of other local roads” are subject to SLR. Based on the program in place in Minnesota, expected benefits are 10% in the pavement lifetime, which, based on an HMA overlay cost, save approximately $12,000,000 annually; these estimates were based on calculations performed with an earlier version of MnPAVE pavement design software.

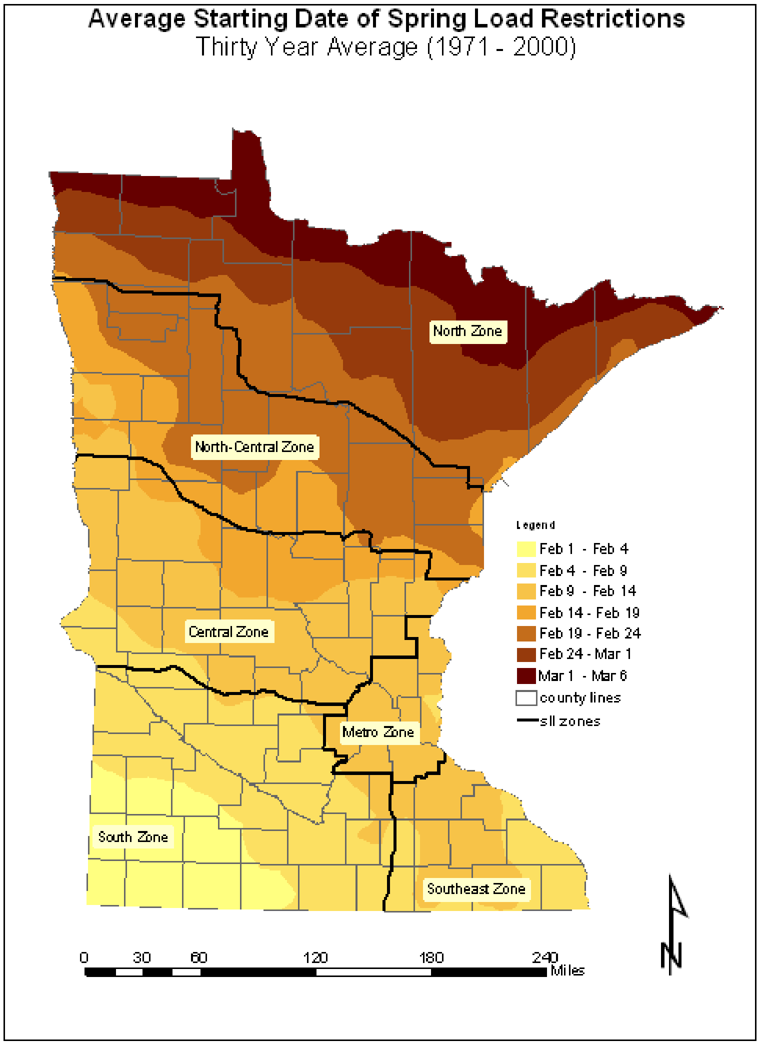


Figure 1.1 Minnesota frost zones [9]

The main conclusion of this review is that currently, there are different approaches in dealing with the consequences of the freeze-thaw phenomena on the pavement, but these phenomena concern all the countries and the US states located in cold-climate. It is very difficult to identify a general pattern for spring load restrictions around the world. The level of reduction of axle load varies from country to country, and the same diversity is encountered in the lengths of the restriction.

# 1.3 Factors that Affect Pavement Behavior

## Introduction

In order to quantify the SLR effects it is necessary to understand the factors that have a significant contribution to the damage of the pavement. These factors are: the traffic load, the pavement structure, and the environmental conditions.

Traffic load is frequently given in the format of the daily average traffic flow. From the pavement designer's perspective, another important characteristic is the traffic distribution by vehicle type and weight. Not all the vehicles have the same damage potential on the pavement; an increase in weight is commonly associated with an increase in the amount of damage received by the pavement. Almost all current design procedures consider the number and the type of heavy vehicles as an important parameter. Other important components associated with the traffic are the axle type and the load distribution per axle. For example, it has been shown that a super single axle induces more damage on the pavement than a dual axle with a similar load. [10] Other traffic parameters such as tire pressure and tire type influence the damage potential.

The pavement structure is represented by a layered system, with the highest quality materials on top and the lowest at the bottom, which is designed to transmit the traffic loads to the ground foundation. Similar to other structural designs, the load that is transmitted to the foundation should be less than the foundation bearing capacity, and as a consequence, based on the material properties and costs for these materials, an optimum thickness design is selected for the pavement structure. In the case of pavement design, the failure criteria are more related to the quantity of damage visible on the pavement surface; the current pavement design criteria are concerned with providing a safe and smooth ride during the whole lifetime of the road and are based on definite limits on the distresses that occur on the surface of the pavement.

One of the most important, however, very difficult to analyze and quantify factors is the environment. It can be considered as a load factor because it induces thermal loading in the pavement layer, but at the same time it is an important source of variation in the pavement layers' material properties. Temperature, rainfall, and water table level are components that have a significant influence on the pavement layers' properties. If a design procedure neglects these variations in properties, it is more likely to produce a pavement structure that either overestimates or underestimates the pavement capacity.

In order to evaluate the quality of the road and the impact of a particular factor on the road lifetime, the whole complex of inputs that affect it must be analyzed. For this purpose, a survey to evaluate the Minnesota road network was conducted and the results are presented next. In order to have a clear picture of the current condition of the local roads, a detailed review of the current design procedures and the traffic data is also presented. At the end of this section, considerations related to the material properties and environmental factors that influence the road performance are given.

## Minnesota Local Road Network

### Road network review

***Minnesota Network Size and Administrations***

Minnesota's public road system has about 217215 km (135,000 miles) spread out in 87 counties. From this system, only 9 percent is administrated by MnDOT. The large majority of the road network is under the jurisdiction of various other agencies. The size of the different road networks[iii] is presented in Table 1.6.

As can be seen in Table 1.6, the majority of the roads reside in townships. However, this is not the case for all counties. An analysis of the first two largest local road networks (St. Louis – 9068.536 km (5,636.136 miles) and Hennepin – 8009.636 km (4,978.021 miles)) indicates a significant difference between their structures. Figure 1.2 shows that county roads represent around 50 percent of the St. Louis network, but only 10 percent of the Hennepin network. These facts suggest that there are a large variety of roads and traffic distributions on the local roads network. A statistical analysis of the distribution of the roads by jurisdiction for all Minnesota counties indicates the same lack of uniformity. (Table 1.7)

Table 1.6 Minnesota road network (mileage from Mn/DOT, Transportation Information System - prepared by State Aid, 2004)

| All Roadway Systems | Kilometers (Miles) | % of Total System | Lane Kilometers (Miles) |
|---|---|---|---|
| Township & Other | 95,776.91 (59,525.74) | 43.9% | 191,574.69 (119,064.44) |
| Trunk Highway | 19,176.74 (11,918.42) | 8.8% | 46,779.81 (29,073.85) |
| County State Aid | 48,922.37 (30,405.45) | 22.4% | 99,445.69 (61,805.90) |
| County | 24,206.10 (15,044.19) | 11.1% | 48,453.42 (30,113.995) |
| Municipal State Aid | 4,568.61 (2,839.41) | 2.1% | 10,306.91 (6,405.78) |
| Municipal Streets | 25,474.39 (15,832.44) | 11.7% | 51,043.03 (31,723.45) |
| **Grand Total** | **218,125.15 (135565.64)** | **100.0%** | **447,603.56 (278187.42)** |

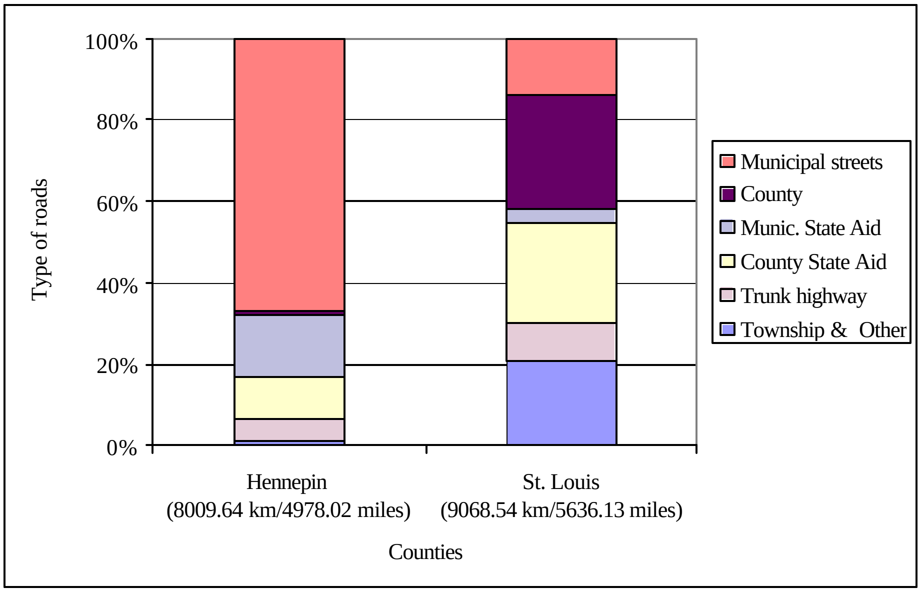


Figure 1.2 Distributions of roads by jurisdiction for the largest road networks in Minnesota

Table 1.7 Types of roads in the Counties' Networks [iv]

| Type of Roads | Average percent from the County Network | Minimum percentage | Maximum percentage | Median |
|---|---|---|---|---|
| Trunk Highway | 9.08% | 4.89% | 23.03% | 8.48% |
| State Aid Highway | 23.18% | 10.50% | 31.01% | 23.31% |
| County Roads | 11.56% | 0.00% | 33.92% | 10.84% |
| City Roads | 11.01% | 82.28% | 0.28% | 5.90% |
| Township & other | 45.17% | 1.11% | 62.94% | 47.76% |

In order to have up-to-date records of the county road networks, a survey was conducted in May 2003. This survey was addressed to the county engineers and contained questions related to the conditions of the local road network. Thirty-four out of eighty-seven counties (40%) responded to this questionnaire[v]. These counties were spread out all other the state as shown in Figure 1.3.

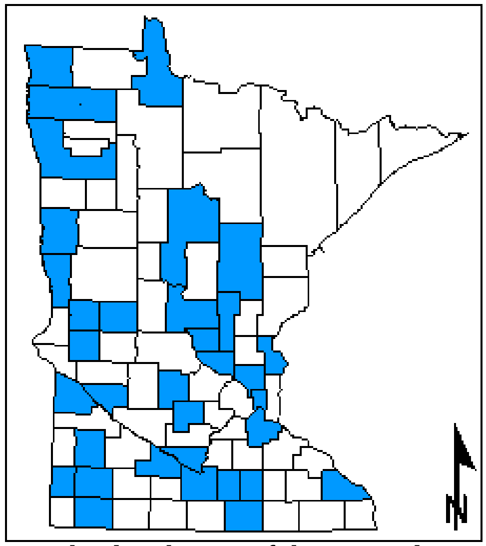


Figure 1.3 The distribution of the respondent counties

The road system of the counties and most cities are divided into 10-, 9-, 7-, and 5-ton roads during the spring season (Figure 1.4). The network administrators make this distribution based on the quality of the roads. Most of the local roads are 9-ton roads throughout the year except during SLR, when they are reduced to 7- or 5-ton [7]. Figures 1.5 and 1.6 depict the way in which the gravel and paved roads are restricted. Data for these figures are based on the information collected from 87 counties. Tables 1.8 and 1.9 provide a brief statistical analysis of road distribution in these counties.

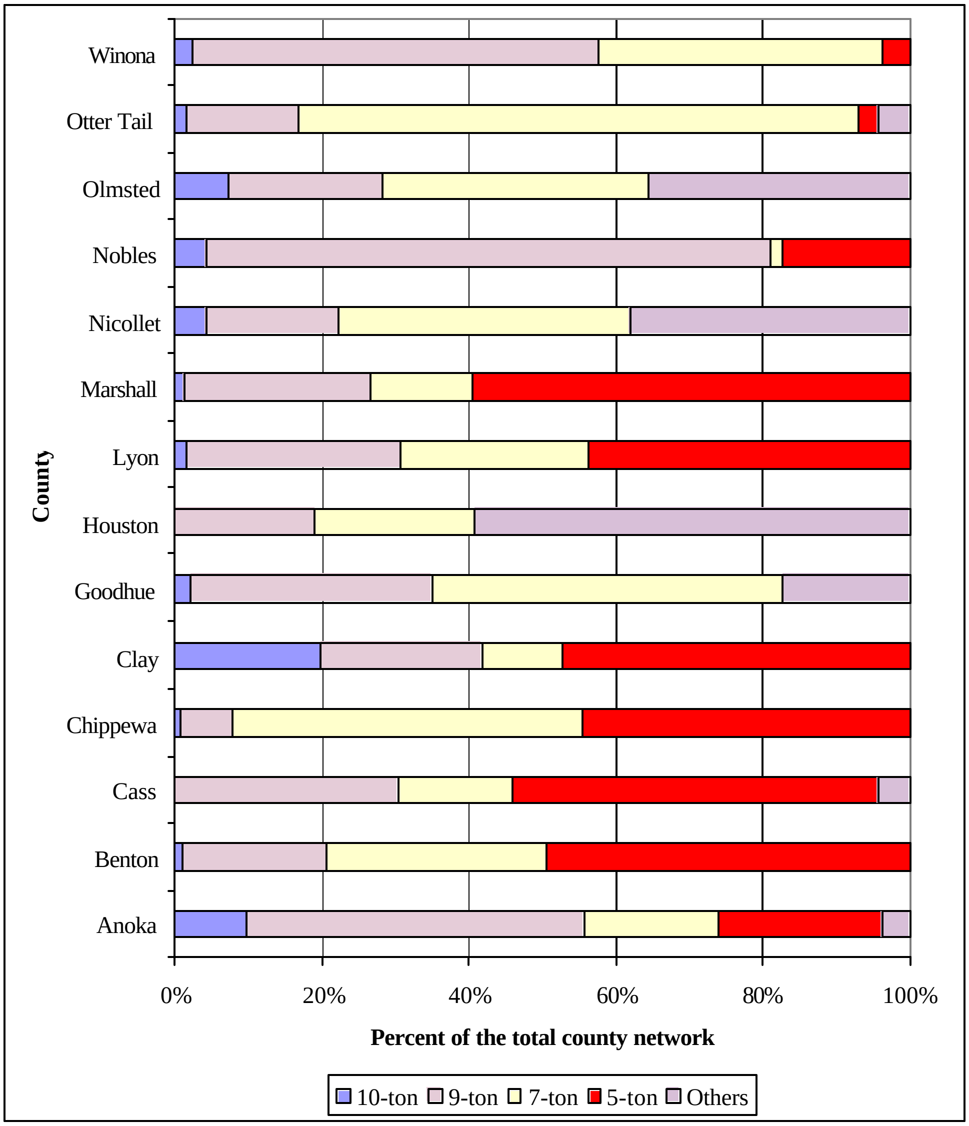


Figure 1.4 Road network compositions in some Minnesota counties during SLR

Table 1.8 Statistical analysis of the local gravel road network in 87 counties[vi]

| Statistics parameters | 10-ton | 9-ton | 7-ton | 5-ton | Others |
|---|---|---|---|---|---|
| | km (miles) | km (miles) | km (miles) | km (miles) | km (miles) |
| Average | 0.0 (0.0) | 1.3 (0.8) | 5.1 (3.2) | 269.9 (167.8) | 20.0 (12.4) |
| Std. Deviation | 0.2 (0.16) | 9.4 (5.8) | 21.3 (13.2) | 334.1 (207.6) | 66.7 (41.5) |
| Median | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 201.1 (125.0) | 0.0 (0.0) |
| Minimum | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| Maximum | 1.6 (1.0) | 86.9 (54.0) | 129.1 (80.2) | 2458.6 (1528.0) | 387.0 (240.5) |

Table 1.9 Statistical analysis of the local paved road network in 87 counties

| Statistics parameters | 10-ton | 9-ton | 7-ton | 5-ton | Others |
|---|---|---|---|---|---|
| | km (miles) | km (miles) | km (miles) | km (miles) | km (miles) |
| Average | 27.7 (17.2) | 211.3 (131.3) | 211.8 (131.6) | 50.9 (31.7) | 11.0 (6.8) |
| Std. Deviation | 54.1 (33.6) | 187.9 (116.8) | 173.7 (108.0) | 143.4 (89.2) | 28.5 (17.7) |
| Median | 9.8 (6.1) | 164.1 (102.0) | 170.6 (106.0) | 10.8 (6.7) | 0.0 (0.0) |
| Minimum | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| Maximum | 331.5 (206.0) | 999.2 (621.0) | 1245.8 (774.3) | 1208.4 (751.0) | 144.8 (90.0) |

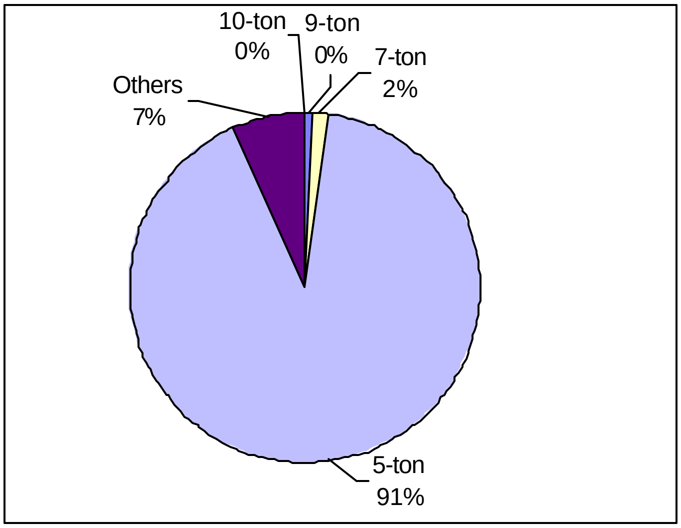


Figure 1.5 Gravel roads distribution on the Minnesota local network during SLR

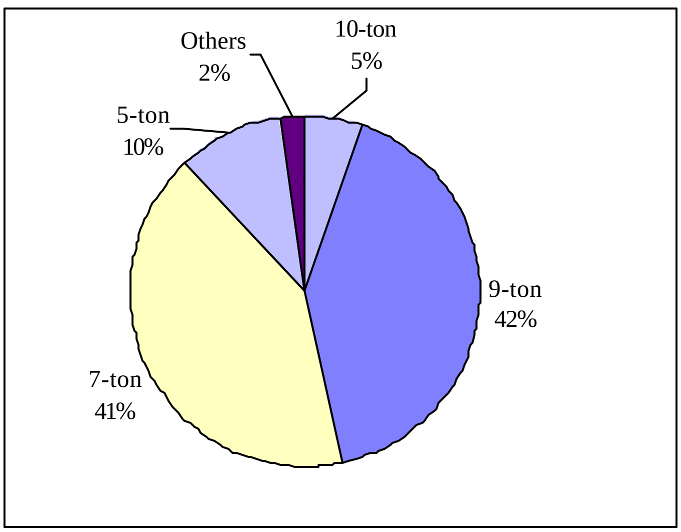


Figure 1.6 Paved roads distribution on the Minnesota local network during SLR

The 10-ton roads account for less than 10 percent of the county network. Only three counties, Nicollet, Redwood, and Watonwan have a large part of the network (around 35 percent) as 10-ton roads. These roads have a very good structural capacity and are not affected by a restriction program.

Another category of unrestricted roads during the SLR period is represented by 9-ton roads. All counties, except Clearwater, have 9-ton roads in their network. A typical 9-ton road has a cross section of 89 mm (3.5 in) to 254 mm (10 in) of bituminous surface on a granular base of 102 mm (4 in) to 381 mm (15 in). The largest 9-ton network is in Stearns County: 803 km (499 miles). Other counties in which 9-ton roads constitute a significant part of their network are Nobles (522 km / 324 miles), Polk (539 km / 335 miles), Morrison County (789 km - 485 miles), and Saint Louis ( 573 km / 356 miles).

The 7-ton roads are the prevalent type in the county road networks. The largest number of kilometers is registered in Otter Tail County (1245 km / 774 miles) and Blue Earth County (949 km / 590 miles), where 7-ton represents 76 percent and 82 percent of their networks, respectively. For this category of road, the typical cross sections have a bituminous surface ranging from 51 mm (2 in) to 153 mm (6 in) on an aggregate base of 153 mm (6 in) to 254 mm (10 in)

The 5-ton roads are either gravel roads or paved roads with 51 mm (2 in) of bituminous mixture. Four counties Cass, Marshall, Norman, and Roseau have more than 650 km (404 miles) of 5-ton gravel roads comprising more than half of their network.

The data indicate that in Minnesota, some roads are not included in any of the typical restricted categories. Usually, these roads are 6-ton roads and their proportion in the network is not significant (almost 4 percent). The largest number of kilometers can be found in Olmsted County where there are 296 km (184 miles) of 6-ton roads, and 242 km (151 miles) of them are gravel roads.

Based on State Aid data provided in 2004, Table 1.10 and Figure 1.7 present the distribution of roads for an "average" county, which could probably be representative for Minnesota.

Table 1.10 Distribution of roads for the average Minnesota county based on data from 87 counties

| **Type of road** | **10-ton** | **9-ton** | **7-ton** | **5-ton** | **Others** |
|---|---|---|---|---|---|
| | km (miles) | km (miles) | km (miles) | km (miles) | km (miles) |
| Gravel Roads | 0.04 (0.03) | 1.34 (0.83) | 5.11 (3.18) | 269.91 (167.75) | 20.00 (12.43) |
| Paved Roads | 27.65 (17.19) | 211.28 (131.31) | 211.77 (131.62) | 50.93 (31.65) | 10.97 (6.81) |
| Total Network | 27.70 (17.21) | 212.62 (132.1) | 216.88 (134.79) | 320.84 (199.40) | 30.97 (19.25) |

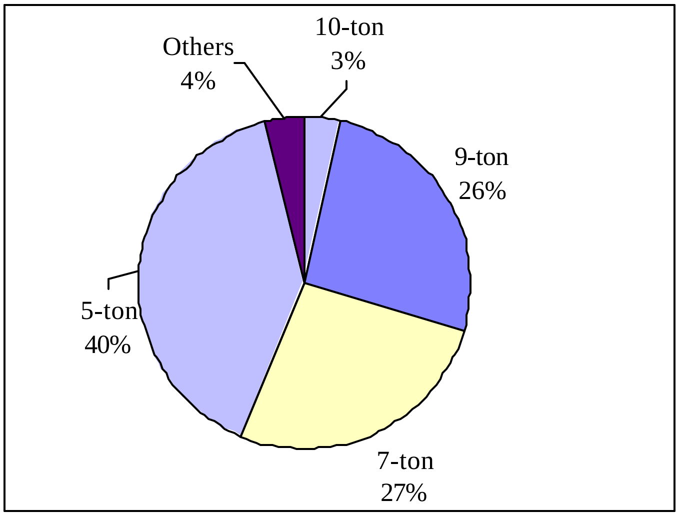


Figure 1.7 The network for the average county designed based from 87 counties

Another purpose of the survey was to evaluate the quality of the network. The first step in this process was to look at the quality of the soil because this parameter plays an important role in the way in which a road is designed and managed. Currently in Minnesota, two methods are frequently used to classify soils: the Soil Factor and the R-value. Because most of the respondents used the soil factor to express the quality of soil, this parameter was chosen to organize the data. Another fact that supports this approach is the availability of established relations between the Soil Factor and the R-value[vii].

Almost one quarter of the counties that responded to the survey have all the roads built on poor quality soil with a Soil Factor equal to 130. Another 20 percent of the respondent counties have more than 80 percent of the roads built on a similar type of soil (Figure 1.8). Only two counties do not have any soil with Soil Factor equal to 130 (Waseca County and Winona County). The survey seems to indicate that A7 is the most frequently encountered soil in Minnesota. However, Mn/DOT provides contrary information in its reports. [11] [12] [13] These reports show that A6 is the most frequent type of soil.

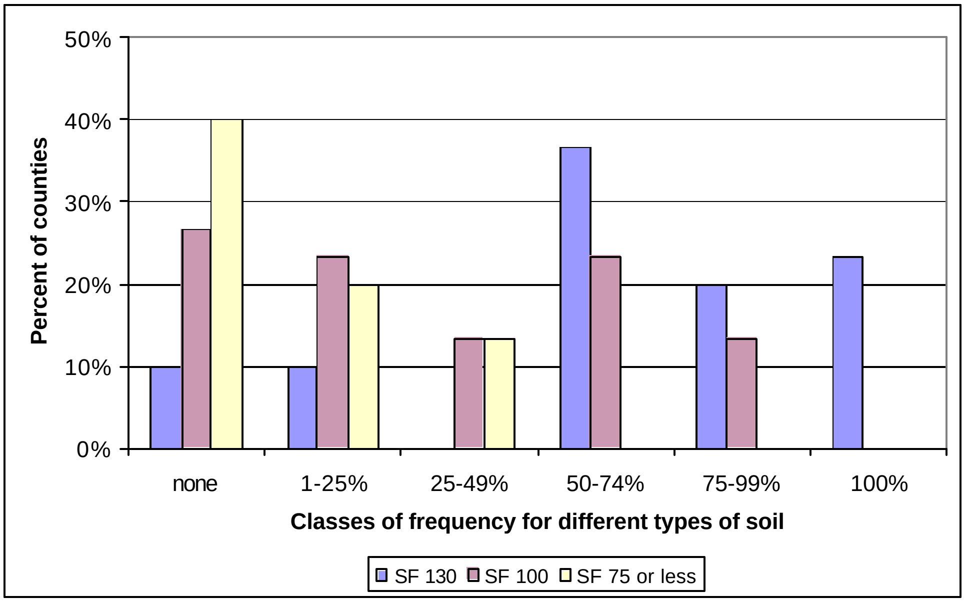

Figure 1.8 Frequency of different types of soil in Minnesota

High quality soil is not the predominant type of soil in Minnesota; 13 percent of counties have between 25 percent and 50 percent of roads in their network built on a soil with soil factor 75 or less. Conversely, 40 percent of respondent counties do not have any soil with soil factor equal to 75. Dakota County and Morrison County seem to have the best quality of soil. Dakota County reported 10 percent soil with SF=130, 50 percent soil with SF=100, 30 percent soil with SF=75, and 10 percent soil with SF=50. Morrison County reported 75 percent soil with SF=100, 10 percent soil with SF=75, and 15 percent soil with SF=130.

The survey also requested information about the design methods used today in Minnesota. The results indicate that there are only two methods: the Soil Factor method and the R-value method, and that there is no clear option for one of these methods (Figure 1.9).

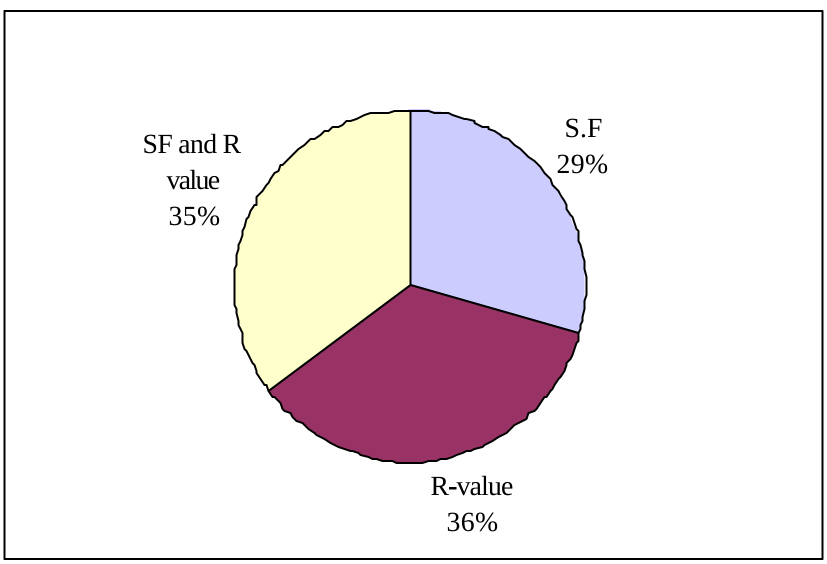

Figure 1.9 Current roads design methods used in Minnesota

The Soil Factor method is an old design procedure that has been used for more than 50 years and it is still used very often today. The R-value method was adopted in the early 1970s and many counties that use it have not given up completely the Soil Factor method. A few counties reported that they use the R-value method exclusively in the design of 10- and 9-ton roads.

Benton County seems to be one of the first counties that adopted R-Value for its road design in 1978. Currently in this county, 25 percent of roads are designed with the R-Value Method, 20 percent with the Soil Factor Method and 65 percent are designed using other design procedures. Because of this variety of methods used to design roads, it is very difficult to relate the effect of using R-value methods to the current quality of the Benton County's road network using only the answers from the survey.

The results show that 25 percent of counties have only used the Soil Factor method to design their roads and 90 percent of respondent counties have more than half of their road network designed based on the Soil Factor method. Only three counties: Nicollet, Dakota, and Chisago have more than 50 percent roads designed using R-Value method.

Design methods, other than the Soil Factor and R-Value are used in 15 percent of counties. No county indicated what other design methods they used. One of the methods seems to be the typical cross section method. [11]

For the traffic data used in pavement design, only 20 percent of counties used only ESAL to quantify traffic and another 20 percent used only Average Daily Traffic (ADT) (Figure 1.10). Almost half of the respondent counties considered traffic as a combination between HCDT and ESAL or ADT. All counties using the R-value method also consider ESAL for traffic quantification.

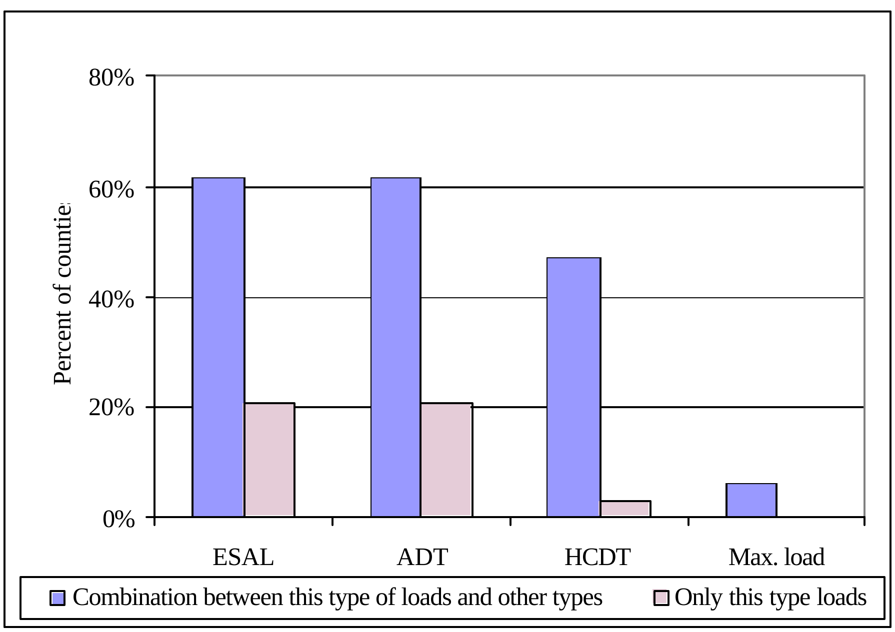


Figure 1.10 Types of traffic used in road design in Minnesota

Mn/DOT is the main traffic data provider for all counties. (Figure 1.11) However, 12 percent of counties combine the data from Mn/DOT with data from their own counts and 12 percent of that use only traffic data from their own counts. Counties using the R-value method tend to do traffic measurement by themselves. However, these data clearly indicate a significant lack of traffic measurements on local roads.

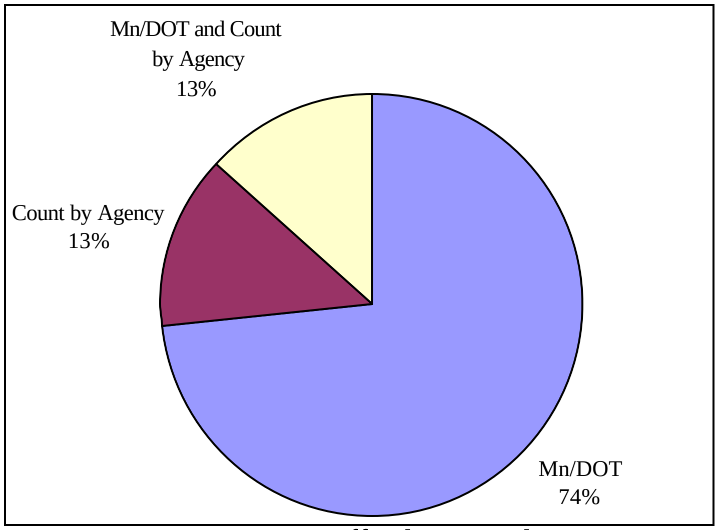

Figure 1.11 Traffic data providers

Almost all respondent counties evaluate the quality of their road networks. The most frequently used method to evaluate the performance of the local roads is the conditions survey. In some cases, however, the answers regarding the most frequent distresses were not relevant because it referred to the cause of the distress and not the distress. For nearly 20 percent of the counties, the heavy vehicles represent one of the major causes of distress, and for 15 percent of the counties, the age of the road is a major problem.

The county responses point out that cracks are the main pavement distress on the local network. From the 70 percent of counties that indicated this fact, nearly 20 percent identified thermal cracks as their main distress and another 17 percent identified transversal cracks. These data lead to the conclusion that the environment is a major cause of distress. Only 15 percent of the counties reported rutting as the main distress. Rutting is the distress typically caused by the variation of the quality of the granular materials due to an increase in the moisture content during springtime.

The repair and rehabilitation procedures are selected in correlation with the most frequent distresses. Thus, most counties seal the cracks. In terms of rehabilitation, the respondents have indicated that they overlay and try to increase the structural capacity at the same time.

The main conclusion of the survey is that it is very difficult to establish a structural pattern for the local road network. The length and the distribution of the roads in categories (10-, 9-, 7-, and 5-ton) can vary significantly from one county to another. Moreover, even when the same design procedures are employed, the results in terms of pavement structure are very different. There are counties that on their 5- ton road network have paved roads with 51 mm (2 in) of hot-mix asphalt on 102-153 mm (4-6 in) of granular base, and other counties that have a similar pavement structure on the 7-ton network. Also, there are counties with roads with thick granular base layer 254-305 mm (10-12 in) or thick asphalt layer of more than 153 mm (6 in), even for the 7-ton roads.

Evaluation of the network performance seems to indicate a more uniform outcome. All the respondent counties declared that they evaluated the quality of their network, most frequently using the condition survey. However, in many cases the data are not stored in an easy-to-use format for research purposes. The collected data indicate that environmental factors (low temperature and/or freeze-thaw phenomena) are the main causes of pavement damage.

## Design Methods Used for Pavement of the Local Roads

### *The Soil Factor Method*

One of the first methods used for pavement thickness design in Minnesota is the Soil Factor Design Method. This method was developed based on field observations and its main results were synthesized in a design table. It uses as input: 20 years projected two-way average daily traffic (ADT), heavy commercial average daily traffic (HCADT), maximum allowable spring axle load and type of soil.

*Principles of the method*

The method is based on the correlation between the pavement design thickness established for a road with an A6 embankment soil American Association of State Highway and Transportation Officials (AASHTO) Soil Class and the thicknesses of pavements built on different types of soil. In the first step of the development of this method, the design thicknesses of the pavements were established for the roads with an A6 soil as embankment and for various sets of traffic loads. An A6 soil was used as reference soil because it is the predominant soil in Minnesota. The pavement thickness is expressed in terms of Granular Equivalent (GE) because in this way it is independent of the material used for the pavement layers. In the second step, a relation between the pavements built on the A6 embankment soil and the pavements built on other types of soil, was determined. A soil factor was introduced to quantify this relationship. The factor expresses the variation of the thickness of the pavement built on another type of soil relative to the thickness of the pavement built on the A6 soil, under the hypothesis of the similar loads. In some cases (e.g. A4 soil), the soil factor is expressed as an interval because it has to quantify the frost susceptibility of soil. This implies that in cold regions it is recommended to assign a value of the soil factor that is larger than the minimum value of the soil factor interval.[13] [14] Table 1.11 is the design table that is currently recommended by the Mn/DOT State Aid Manual [14].

*Granular Equivalent (GE) and Granular Equivalent Factor*

Granular Equivalent (GE) is a quantification of pavement thickness based on the idea that the pavement is built entirely from a granular material. By comparing the strength properties of this standard granular material with the strength properties of all other materials used for pavement layers, a set of Granular Equivalent Factors (GE factor) has been established. These factors are used to transform the granular material in any other material and this transformation reflects the contribution of each layer to pavement performance.

Minnesota Specification 3139 assigns GE Factor equal to 1 for aggregates from Class 5 or 6 which characteristics are specified in Table 1.12.

Table 1.11 Table for flexible pavement design using Soil Factors from "State Aid Manual"

**FLEXIBLE PAVEMENT DESIGN USING SOIL FACTORS**

Required Gravel Equivalency (G.E.) for various Soil Factors (S.F.)

For new construction or reconstruction use projected ADT. For resurfacing or reconditioning use present ADT.

All units of G.E. are in inches with millimeters (mm) in parenthesis.

| 7 TON @ LESS THAN 400 ADT | | | 9 TON -150-300 HCADT | | | 9 TON - MORE THAN 1100 HCADT | | |
|---|---|---|---|---|---|---|---|---|
| S.F. | Minimum Bit. G.E. | Total G.E. | S.F. | Minimum Bit. G.E. | Total G.E. | S.F. | Minimum Bit. G.E. | Total G.E. |
| 50 | 3.0 (75) | 7.25 (180) | 50 | 7.0 (175) | 14.00 (350) | 50 | 8.0 (200) | 20.30 (510) |
| 75 | 3.0 (75) | 9.38 (235) | 75 | 7.0 (175) | 17.50 (440) | 75 | 8.0 (200) | 26.40 (660) |
| 100 | 3.0 (75) | 11.50 (290) | 100 | 7.0 (175) | 21.00 (525) | 100 | 8.0 (200) | 32.50 (815) |
| 110 | 3.0 (75) | 12.40 (310) | 110 | 7.0 (175) | 22.40 (560) | 110 | 8.0 (200) | 35.00 (875) |
| 120 | 3.0 (75) | 13.20 (330) | 120 | 7.0 (175) | 23.80 (595) | 120 | 8.0 (200) | 37.40 (935) |
| 130 | 3.0 (75) | 14.00 (350) | 130 | 7.0 (175) | 25.20 (630) | 130 | 8.0 (200) | 39.80 (995) |

| 7 TON @ 400 - 1000 ADT | | | 9 TON - 300-600 HCADT | | | MATERIAL | TYPE OF MATERIAL | G.E. FACTOR* |
|---|---|---|---|---|---|---|---|---|
| S.F. | Minimum Bit. G.E. | Total G.E. | S.F. | Minimum Bit. G.E. | Total G.E. | Superpave Hot Mix | Spec. 2360 | 2.25 |
| 50 | 3.0 (75) | 9.00 (225) | 50 | 7.0 (175) | 16.00 (400) | Plant Mix Asp Pave | Spec 2350 | 2.25/2.25/2.00 |
| 75 | 3.0 (75) | 12.00 (300) | 75 | 7.0 (175) | 20.50 (515) | Plant-Mix Bit. | Type 41,61 | 2.25 |
| 100 | 3.0 (75) | 15.00 (375) | 100 | 7.0 (175) | 25.00 (625) | Plant-Mix Bit. | Type 31 | 2 |
| 110 | 3.0 (75) | 16.20 (405) | 110 | 7.0 (175) | 26.80 (670) | Aggregate Base | (Class 5 & 6) 3138 | 1 |
| 120 | 3.0 (75) | 17.40 (435) | 120 | 7.0 (175) | 28.60 (715) | Aggregate Base | (Class 3 & 4) 3138 | 0.75 |
| 130 | 3.0 (75) | 18.60 (465) | 130 | 7.0 (175) | 30.40 (760) | Select Granular | Spec 3149.2B | 0.5 |

| 9 TON @ LESS THAN 150 HCADT | | | 9 TON - 600 @ 1100 HCADT | | | AASHTO SOIL CLASS | SOIL FACTOR (S.F.) % | ASSUMED R-VALUE |
|---|---|---|---|---|---|---|---|---|
| S.F. | Minimum Bit. G.E. | Total G.E. | S.F. | Minimum Bit. G.E. | Total G.E. | A-1 | 50 - 75 | 70 - 75 |
| | | | | | | A-2 | 50 - 75 | 30 - 70 |
| 50 | 7.0 (175) | 10.25 (255) | 50 | 8.0 (200) | 18.50 (465) | A-3 | 50 | 70 |
| 75 | 7.0 (175) | 13.90 (350) | 75 | 8.0 (200) | 23.70 (595) | A-4 | 100-130 | 20 |
| 100 | 7.0 (175) | 17.50 (440) | 100 | 8.0 (200) | 29.00 (725) | A-5 | 130 + | - |
| 110 | 7.0 (175) | 19.00 (475) | 110 | 8.0 (200) | 31.10 (780) | A-6 | 100 | 12 |
| 120 | 7.0 (175) | 20.50 (515) | 120 | 8.0 (200) | 33.20 (830) | A-7-5 | 120 | 12 |
| 130 | 7.0 (175) | 22.00 (550) | 130 | 8.0 (200) | 35.30 (885) | A-7-6 | 130 | 10 |

NOTE: If 10 ton (9.1 t) design is to be used, see Road Design Manual 7-3.
For full depth bituminous pavements, see Road Design Manual 7-3.
* Granular Equivalent Factor per MnDOT Technical Memorandum 98-02-MRR-01.

Table 1.12 Base and surfacing aggregate [16]

| Total Percent Passing Sieve Size | Class 5 | Class 6 |
|---|---|---|
| 75 mm | - | - |
| 50 mm | - | |
| 25.0 mm | 100 | 100 |
| 19.0 mm | 90-100 | 90-100 |
| 9.5 mm | 50-90 | 50-85 |
| 4.75 mm | (A) 35-80<br>(B) 35-70 | 35-70 |
| 2.00 mm | (A) 20-65<br>(B) 20-55 | 20-55 |
| 425 µm | 10-35 | 10-30 |
| 75 µm | 3-10 | (A) 3-7<br>(B) 4-8 |

Notes.
(A) Applies when the aggregate contains 60 percent or less of crushed quarry rock.
(B) Applies when the aggregate contains more than 60 percent crushed quarry rock

Equation (3.1) is used to establish the relation between the layer of standard granular material and the materials used in layers of the pavement.

$$GE = a_1 D_1 + a_2 D_2 + a_3 D_3 + \ldots\ldots.. \qquad (3.1)$$

where: GE – granular equivalent
$D_1$ – thickness of asphalt mix surface
$D_2$ – thickness of granular base course
$D_3$ – thickness of granular subbase course
$a_1$, $a_2$, $a_3$ – are GE factors for the materials of layers 1, 2 and 3

The values of GE factors and total GE in equation (3.1) are tabulated. (See Table 1.11). Also, a set of standard limits for assigning the minimum value of the thickness of asphalt mix layer ($D_1$) must be considered in the design process. Table 1.13 presents all the values that are assigned to the GE factors and the specifications that explain the way these values were determined.

Table 1.13 Values of GE factors used in Minnesota [12]

| **Material** | **Specification** | **G.E. Factor** |
|---|---|---|
| Hot-Mix Asphalt | 2360 | 2.25 |
| | 2350 | 2.25 |
| | 2331 | 2.00 |
| Road-mix Surface (base) | 2321 | 1.50 |
| Bituminous-treated Base | 2204 (rich) | 1.50 |
| | 2204 (lean) | 1.25 |
| Aggregate Base | Class 5 or 6, 3138 | 1.00 |
| Aggregate Base | Class 3, 4, 7, 3138 | 0.75 |
| Select Granular | 3149.2C | 0.50 |

If the traffic and the soil properties are known, the total granular equivalent can be determined from Table 1.12. Using total granular equivalent and equation (3.1), the thickness of each pavement layer can be determined.

Thus, the designer has the freedom to impose the thickness for all layers except one, which is determined from the design equation. However, care must be taken in the design process, as the load received by each individual layer ought not exceed its maximum allowable load. The minimum thickness for the bituminous layer is provided in Table 1.11 and the thickness for the subbase course can than determined.

*AASHTO Soil Classification System*

The AASHTO Soil Classification System is one of the first attempts to quantify the soil quality with applications in pavement design. It uses three basic characteristics of soil: gradation and Atterberg Limits - plastic limit and liquid limit. Washed sieve analysis (AASHTO T-27 Procedure) is used to determine gradation. The plastic limit is determined using the AASHTO Method T-90 and the liquid limit is established using AASHTO Method T-89. AASHTO Method T-90 requires establishing the moisture level of a set of small rolled samples of the soil of 3 mm diameter. Method T-89 requires determining the moisture level using the Casagrande Method. Based on these three characteristics, a parameter named Group Index is determined using equation (3.2). This parameter has a range between 0 and 20 and it represents the main criterion for soil classification. Table 1.14 shows AASHTO Soil Classification and the main characteristics of each soil type.

$$GI = 0.2a + 0.005ac + 0.01bd \qquad (3.2)$$

where: GI – Group Index

a – the portion of the percentage passing No. 200 sieve that is greater than 35 percent and less than 75 percent, expressed as a positive whole number (0 to 40)

b – the portion of the percentage passing No. 200 sieve that is greater than 15 percent and less than 55 percent, expressed as a positive whole number (0 to 40)

c – the portion of the numerical liquid limit that is between 40 and 60, expressed as a positive whole number (0 to 20)

d – the portion of the numerical plasticity index that is between 10 and 30, expressed as a positive whole number (0 to 20)

Table 1.14 AASHTO soil classification from "Mn//DOT Geotechnical and Pavement Manual" [16]

| Textural Class | Identification by Feel | Ribbon Length | AASHTO Group (H.R.B. Class) | Group Index | Rating For Upper Emb. |
|---|---|---|---|---|---|
| Gravel (G) | Stones: Pass 3" sieve, Retained on #10 | 0 | A-1-a | 0 | Excellent |
| Fine Gravel (FG) | Stones: Pass 3/8" sieve, Retained on #10 | 0 | A-1-a | 0 | Excellent |
| Sand (S) | 100% pass #10. Less than 10% silt & clay. | 0 | A-1-a | 0 | Excellent |
| Coarse Sand (CS) | Pass #10, Retained on #40 | 0 | A-1-a or A-1-b | 0 | Excellent |
| Fine Sand (FS) | Most will pass #40. Gritty - non plastic | 0 | A-1-b or A-3 | 0 | Excellent to Good |
| Loamy Sand (LS) | Grains can be felt, Forms a cast | 0 | A-2-4 or A-3-5 | 0 | Excellent to Good |
| Sandy Loam (SL) | | | | | |
| a. slightly plastic | 0-10% clay. Gritty | 0-1/2" | A-2-6 or A-2-7 | 0 | Excellent to Good |
| b. plastic | 10-20% clay. Gritty | 1/2"-1" | A-4 | 0-4 | Excellent to Good |
| Loam (L) | Gritty, but smoother than SL | 1/4"-1" | A-4 | 0-4 | Excellent to Good |
| Silt Loam (SiL) | Smooth, slippery or velvety. Little resistance | 0-1" | A-4 | 0-4 | Fair to Poor |
| Clay Loam (CL) | Smooth, Shiny, considerable resistance. | 1"-2" | A-6 | 0-16 | Good to Fair |
| Silty Clay Loam (SiCL) | Dull appearance, slippery, less resistance. | 1"-2" | A-6 or A-5 | 0-16 | Fair to Poor |
| Sandy Clay Loam (SCL) | Somewhat gritty. Considerable resistance. | 1"-2" | A-6 or A-5 | 0-16 | Good to Fair |
| Clay (C) | Smooth, shiny, long thin ribbon. | 2"+ | A-7 | 0-20 | Fair to Poor |
| Silty Clay (SiC) | Buttery, smooth, slippery. | 2"+ | A-7 or A-7-5 | 0-20 | Poor |
| Sandy Clay (SC) | Very plastic but gritty. Long thin ribbon. | 2"+ | A-7 or A-7-6 | 0-20 | Fair to Poor |

Note: Where the group index is expressed as a range, such as 0-16, the lower values are the better foundation soils.

The AASHTO classification of soil does not illustrate the mechanical characteristics of the soil because it was not developed directly on a stiffness or strength test. In Investigation No 183 [13], M. Kersten and E. Skok showed that for a given type of soil the strength characteristics can vary significantly. For example, they noticed that for an A4 soil the R-value has a range from 10 to 68, CBR has a range from 2 to 40 and E modulus from 23.2 and 48.8 MPa (3370 and 7080 psi). Moreover, the stiffness and strength of the soil varies with the density and moisture content.

Because of the inability of the soil factor to quantify the quality of the soil more precisely and because of the impossibility to use the soil factor in any mechanistic analysis, the researchers tried to find another parameter to accurately characterize the mechanical properties of the soil. In order to define this parameter, E. Skok and M. Kersten analyzed the following tests: CBR, Stabilometer R-Value test and plate test. The CBR and Stabilometer R-Value test are laboratory tests frequently used to establish the strength of soil. On the other hand, the plate bearing test was often used to evaluate the E modulus in field. Performing a statistical analysis of the data obtained from the laboratory tests and the data resulted from the field tests, the researchers have established that the E value measured in the field is best correlated to R-values obtained at exudation pressure of either 1.38 or 1.65 MPa (200 or 240 psi). Moreover, practice has demonstrated that the R-value test is easier to run than the CBR test. Based on these observations, a design method with the R-value as an input was developed in the late 60's.

*STABILOMETER R-VALUE*

Currently, the Stabilometer R-Value Method is another method used to design low-volume roads in Minnesota. This method was developed from the research conducted to apply the results from the AASHO Road Test to Minnesota conditions [13].

R-value is a measure of the resistance (stiffness) of embankment soil. It can be determined from a standard laboratory test (ASTM D-2844) or estimated based on the soil type. In the laboratory, the R-value is determined in a device called stabilometer. A sample compacted using a standardized kneading foot compactor is placed in the stabilometer, and the horizontal pressure for a given vertical pressure (1.103 MPa) is measured. Equation (3.3) is used to calculate the R-value as a function of the parameters from the stabilometer test. [18] The R-value used in Minnesota is based on a 1.65 MPa (240 psi) exudation pressure. [16]

$$R = 100\left[1 - \frac{1}{\frac{2.5}{D}\left(\frac{p_v}{p_h} - 1\right) + 1}\right] \qquad (3.3)$$

where: D – displacement of stabilometer fluid;
$p_v$ – vertical pressure ($p_v$=1103 kPa);
$p_h$ – horizontal pressure;

The early research related to this method was done in California and equation 3.4 shows the first form of the design equation. [14]

$$GE=0.0032(TI)(100-R) \qquad (3.4)$$

where: GE – granular equivalent;
TI – traffic index;
R – stabilometer R-value;

Based on equation (3.4) the granular equivalent is determined for each layer. Then, the values are subsequently divided by the Granular Equivalent Factor to establish the true thickness of each layer. The Traffic Index is a parameter that quantifies the effect of load on the road and it is determined as a function of traffic loads and admissible deflections. Because of this characteristic of TI, the R-Value design method has the possibility of limiting the deflection of pavement.

Investigation No 183 [13] had as its main objective correlating the performance of flexible pavement to traffic load, pavement structure and quality of the materials used. One of the first conclusions of this research was that the most efficient and complete parameter to quantify traffic load is the number of ESAL. In establishing the effect of the loads on the pavement structure, E. Skok and M. Kersten made a comparison between the total predicted lifetimes of the road, which were determined using four methods: Soil Factor, AASHTO, Asphalt Institute and Benkelman Beam Deflection. The results showed that the deflection method provided the most conservative estimate. The same observation showed that the thickness of the asphalt layer had a significant influence on the value of the deflection.

The researchers also wanted to find a method to quantify the thaw effects on the roads. They found that the spring deflection is the best parameter to indicate the degree to which thaw affects the strength of granular layers. The determined allowable values of deflections are presented in Table 1.15. Based on these deflections, traffic load in ESAL, and the R-value, a new design chart for 9-ton roads has been developed and a new design method has been established. The current format of the design chart for the R-value method is presented in Figure 1.12.

Table 1.15 Summary of recommended allowable spring deflection [13]

| Traffic | | | | | |
|---|---|---|---|---|---|
| Traffic | One-way Daily N18 | <25 | 25 - 50 | 50 -150 | >150 |
| | Two-way ADT | <500 | 500 - 1000 | 1000 - 3000 | >3000 |
| | Two-way HCDT | <50 | 50-100 | 100 -150 | >150 |
| Surface Thickness (in) | | Allowable deflection (in) | | | |
| less than 3 in | | 0.075 | 0.070 | 0.060 | 0.045 |
| 3 to 6 in | | 0.065 | 0.060 | 0.050 | 0.040 |
| greater than 6 in | | 0.055 | 0.050 | 0.040 | 0.035 |

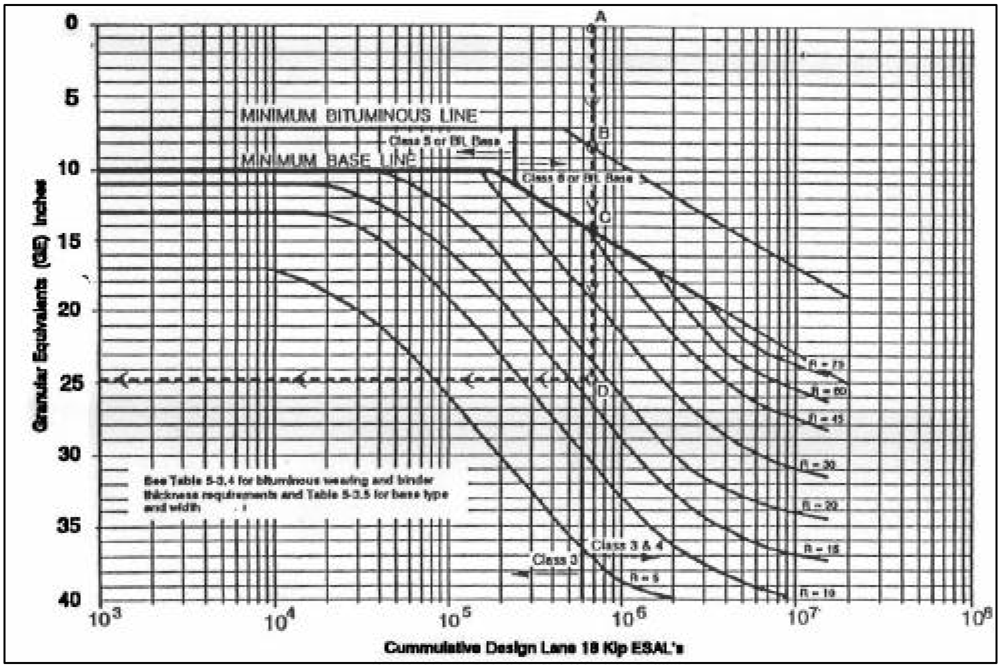


Figure 1.12 Bituminous pavement design chart (aggregate base) [16]

Currently, Stabilometer R-Value Method is the design method for flexible pavement used by Mn/DOT and it is fully presented in Mn/DOT Geotechnical and Pavement Manual [16].

The R-Value method is based on limiting the spring deflections for a 9-ton design axle load for a given level of traffic. The method's input is the R-value and the cumulative design lane ESAL. The output is the Granular Equivalent and the minimum thickness of bituminous and base layers. The main data necessary for design are extracted from a design chart (Figure 1.12). To determine the thickness of each layer, the output values from design chart and equation (3.1) are used.

Both design methods used in Minnesota for local roads are empirical methods. The Soil Factor method is based on soil classification, traffic, and material properties. However, large variations exist in pavement materials strength caused by the environmental factors and by the materials themselves not being quantified in these methods. Moreover, the design of 7-ton roads is not affected by heavy traffic, because only average daily traffic is governing this design. The minimum thickness of the bituminous layer for 7-ton roads is around 38.1 mm (1.5 in), independent of soil type, which is questionable for the current traffic conditions.

Trying to minimize the drawbacks of the Soil Factor methods, the R-value method proposes an approach that is based on a value that quantifies more properly the strength of the soil (R-value). The minimum design thickness for the asphalt layer is 76.2 mm (3 in). The traffic is quantified using the equivalent single axle load (ESAL), which makes the procedure more sensitive to the traffic composition. However, this procedure uses the granular equivalent factor, which is a parameter that does not fully consider all seasonal variations in material proprieties.

The conclusion is that both methods are not very sensitive to the environmental effect. They also seem to be inadequate to reflect small variations in traffic loading and material properties.

**Traffic and Traffic Loading**

As previously discussed, the three main parameters that quantify traffic are average daily traffic (ADT), heavy commercial average daily traffic (HCADT), and equivalent single axle load (ESAL). The average daily traffic is the result of a continuous traffic count for 24 hours. The annual average traffic (AADT) is often based on ADT, which is adjusted for season and day of the week. Heavy commercial average daily traffic counts only the vehicles with at least six tires that pass in one day through a road section in each direction. Currently, Mn/DOT performs traffic counts on most of the Minnesota's trunk and interstate highways, and provides the results in a flow map format. However, there are only a few traffic counts conducted on the restricted roads that represent the focus of this study.

ESAL is a traffic quantification developed based on the AASHO Roads Test, which associates a quantity of damage induced in a standard pavement with one pass of a standard load. This load is a single axle with dual tires. The axle load is 80 kN (18 kips), the wheel load is 20 kN (4.5 kips), and tire pressure is 552 kPa (80 psi).

The predicted number of ESALS during the lifetime of the road is the traffic parameter in many current design procedures. In Minnesota, it is used as input in R-Value design method and is one of the inputs that can be used in the mechanistic empirical design software Mn/PAVE, which will be described in detail in section 5. Each axle expected to pass on a road is made equivalent to a number of ESAL passes, based on the hypothesis that the same amount of damage has to occur in both cases. To simplify the computational process, the axles are grouped according to vehicle type, and a load equivalent factor that transforms the effect of the real load (vehicle load) in a number of equivalent load (ESAL), is assigned to each type. The load equivalent factors used in Minnesota design procedures are presented in Table 1.16. The factor is intended to represent the mix of fully loaded, partially loaded and empty vehicles in the traffic stream.

Table 1.16 Average ESAL factors by vehicle type [16]

| Vehicle Type | ESAL Factor |
|---|---|
| Cars and Pickups | 0.0007 |
| 2 Axle, 6 Tire - Single Unit | 0.25 |
| 3+ Axle - Single Unit | 0.58 |
| 3 Axle Semi | 0.39 |
| 4 Axle Semi | 0.51 |
| 5+ Axle Semi | 1.13 |
| Bus/Truck Trailers | 0.57 |
| Twin Trailers | 2.40 |

Equation (3.5) is used to compute the number of ESAL for the design lifetime of Minnesota local roads:

$$ESAL=\left(\sum_{i=1}^{m} p_i F_i\right) \cdot (AADT) \cdot G \cdot L \cdot 365 \cdot Y \qquad (3.5)$$

where:
- ESAL - number of equivalent single axle loads predicted for the pavement design lifetime
- AADT - annual average daily traffic
- m - types of vehicles (m=8, and the types of vehicles are presented in Table 1.16, 1.17)
- $p_i$ - the percent of vehicles of type i in the traffic stream (Table 1.17)
- $F_i$ - equivalent axle load factor (Table 1.16)
- G - growth factor
- L - lane distribution factor (Table 1.18)
- 365 - days/year
- Y - number of years (the lifetime of the road)

Table 1.17 Vehicle classification percentages – rural CSAH or county road

| Vehicle Type | Percentage in Traffic Stream |
|---|---|
| Cars and Pickups | 94.1 |
| 2 Axle, 6 Tire - Single Unit | 2.6 |
| 3+ Axle - Single Unit | 1.7 |
| 3 Axle Semi | 0.0 |
| 4 Axle Semi | 0.1 |
| 5+ Axle Semi | 0.5 |
| Bus/Truck Trailers | 1.0 |
| Twin Trailers | 0.0 |

Table 1.18 Lane distribution factors [16]

| Number of Lanes in One Direction | Lane Distribution Factor | |
|---|---|---|
| | Single-Direction Traffic Data | Two-Direction Traffic Data |
| 1 1 | 2 1 | 3 0.5 |
| 4 2 | 5 0.9 | 6 0.45 |
| 7 3 | 8 0.7 | 9 0.35 |

Because the traffic distribution proposed by Mn/DOT Geotechnical Manual was determined some time ago, E Skok et al. conducted a set of traffic counts on 29 local roads from three Minnesota counties: Douglas, Kandiyohi, and Olmsted. The data were collected in two consecutive years (1998 and 1999) during the summer, by the Mn/DOT Office of Management Data Services, Traffic Forecasts and Analysis Section. The final report of this research [19] revealed significant differences between the distributions measured and the distribution assumed by the Geotechnical Manual. Moreover, these distributions are not uniform. For example, in Kandiyohi County section 3013 (Farm-to-Market County Roads) the count indicated 19.25 percent HCDT (ADT=575 vehicles) in 1998 and indicated 7.85 percent HCDT (ADT=650 vehicles) in 1999. By contrast, in the same county, for the same category of road, section 3021 had 3.15 percent HCDT (ADT=1000) in 1998 and 4 percent HCDT (ADT=850) in 1999. This study showed that there is a large variation in traffic distribution on county roads, and in many cases, the traffic estimation specified in the "Geotechnical Manual" underestimate the real traffic distribution. The authors also noticed that the errors increased if the data measured and estimated was transformed into ESALS and compared after transformation.

The available data indicates that quantifying traffic into ESALS is not suitable for the scope of this analysis. Its computational process may introduce new approximations in the model, with effects that are difficult to estimate. In addition, it is more complicated to compute ESAL considering seasonal variations in traffic. Thus, the load spectrum seems to be a much better approach. In the load spectrum method, the effect of each axle load on the pavement is taken into account making this method more adequate for studying the axle weight impact.

**Environmental Effects**

The most important environmental parameters affecting the pavement behavior (mechanic properties respectively) are: temperature, water table level, and rainfall. The degree to which the material characteristics vary with the change in these parameters is related to the material type and the range of variation. For example: the stiffness of a concrete slab is not influenced by the temperature variation, but the stiffness of an asphalt layer is a function of temperature. Also, an aggregate base is less sensitive to the variation of the moisture content than a fine grained soil.

**Models of the climatic factors**

The pavement is modeled as a multi-layer system subject to heat flow. The boundary where this phenomenon is initiated is the top of the pavement, where heat is transferred into convection and radiation processes. However, the other layers of the system frequently become very important in the thermal energy transfer, since they are porous materials that have significant variations in moisture content and thermal characteristics.

The most frequent way to describe the interaction between the pavement and environment is to model them as thermodynamic systems and to use the energy balance condition at the surface of the pavement. Equation 3.6 (Berg [20]) gives the typical model for a heat transfer, with the provision that for a paved surface $Q_u = Q_m = Q_i = 0$

$$Q_s - Q_r + Q_w - Q_p \pm Q_c \pm Q_l \pm Q_u \pm Q_m \pm Q_i \pm Q_g = 0 \qquad (3.6)$$

where: $Q_s$ - incident shortwave radiation
$Q_r$ - reflected short wave radiation
$Q_w$ - long wave radiation emitted by the atmosphere
$Q_p$ - long wave radiation emitted by the pavement
$Q_c$ - convective heat transfer.
$Q_l$ - effects of condensation, evaporation, sublimation, and transpiration
$Q_u$ - conduction into air

$Q_g$ - conduction into the ground
$Q_m$ - mass flow to surface
$Q_i$ - infiltration of moisture into ground

The quantities in equation (3.6) can be evaluated using quasi-theoretical considerations, measurements or empirical considerations. However, to solve this equation, iterative numerical methods are proposed. [21] In order to reduce the complexity of these algorithms a more efficient approach has been advanced by CRREL's researchers. [20] Here the problem is cast in terms of determining the temperature at the surface of the pavement, which represents the key parameter in the computation of the heat flow in the pavement and implicitly in the frost/thaw depth prediction.

A simple approach to predict the temperature at the surface of pavement is suggested by Berg [20], [22] and adopted by the US Army Corps of Engineers. (Eq 3.7). The "n" factor is an empirical parameter that varies with wind speed, rainfall, and evaporation. The CRREL's recommendation is that the "n factor" be computed using regression analysis for a particular geographical region.

$$T_u = n_0 T_0 \quad (3.7)$$

where: $T_u$ - soil/pavement surface temperature (ºC)
$T_0$ - air temperature (ºC)
$n_0$ - empirical factor

Another equation that predicts the temperature at the surface of the asphalt layer is SHRP's equation. (Eq. 3.8) [23] This is adjusted by Ovik et al. [23] to predict the average daily temperature at the pavement surface. (Eq. 3.9)

$$T_{surf} = 0.859 T_{min\ air} + 1.7 \qquad (3.8)$$

where $T_{min\ air}$ - one day minimum air temperature (ºC)

$$T_{mean} = 0.859 T_{air} + 7.7 \qquad (3.9)$$

where $T_{air}$ – mean daily air temperature (ºC)

The next step in the evaluation of the climatic impact on pavement is to predict the temperature variation in pavement and the freeze-thaw depth. Equation (3.9) presents a simple formula used to estimate the temperature in the soil. [25] The prediction depends on the air temperature and the thermal properties of the material (thermal diffusivity). This equation is suitable for temperature prediction in a uniform material.

$$T(x,t) = T_{mean} + A e^{-x\sqrt{\frac{2\pi}{P\alpha}}} \sin\left(\frac{2\pi}{P}(t) - x\sqrt{\frac{2\pi}{P\alpha}}\right) \qquad (3.10)$$

where: $T(x,t)$ - soil temperature as function of depth and time (ºC)
$x$ - depth (m)
$t$ - time measured from the moment when temperature increase more than $T_{mean}$ (days)
$T_{mean}$ - mean temperature at the surface (ºC)
$A$ - maximum temperature amplitude ($T_{max} - T_{mean}$) (ºC)
$\alpha$ - thermal diffusivity ($m^2$/days)

$P$ - period or recurrence cycle (days) and $\omega = \frac{2\pi}{P} = \frac{2\pi}{365}$

Another simple equation (Eq. 3.11) to predict temperature variation in pavement layer is proposed by Witczak [26] and adopted in the MnPAVE model [27]. This equation is designed to compute the temperature in asphalt pavement at 1/3 of the thickness of the asphalt layer.

$$T_p = T_A\left(1+\frac{1}{z+4}\right)-\frac{34}{z+4}+6 \qquad (3.11)$$

where: $T$ - temperature in asphalt pavement;
$T_p$ - average seasonal pavement temperature (°F)
$T_A$ – average seasonal air temperature (°F)
$z$ – the depth at which the temperature is predicted (in) - The default value of z is 1/3 of the HMA thickness.

More complex models for temperature variation in space-time coordinates are associated with solving numerically the parabolic equations of the heat transfer problems. PaveCool [28] proposes a one dimensional model for evaluation of the heat transfer through the depth of the lift. Figure 1.13 depicts the main elements of the model. Thermal properties of the granular base are functions of temperature, while thermal properties of the lift are functions of temperature and compaction level. The equations of the model are presented in Table 1.19 and a temperature variation profile that represents the results obtained based on PaveCool model, is shown in Figure 1.14.

The PaveCool model is a simplified model compared to a real climatic model, because it does not deal with the moisture variation or with a large time and temperature domain.

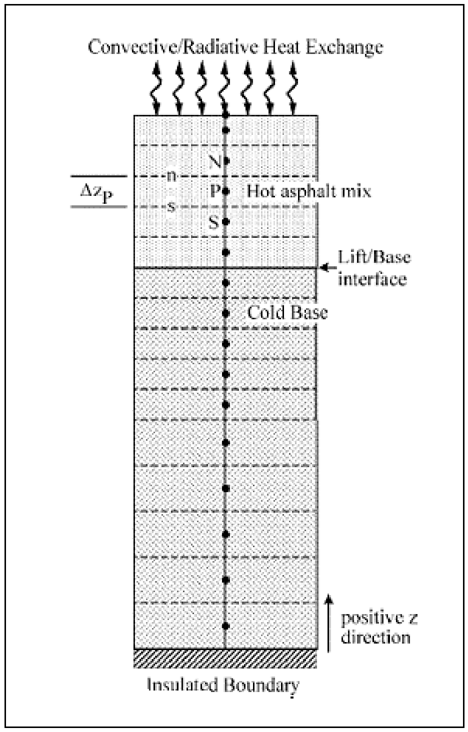

Figure 1.13 Solution domain for asphalt cooling [28]

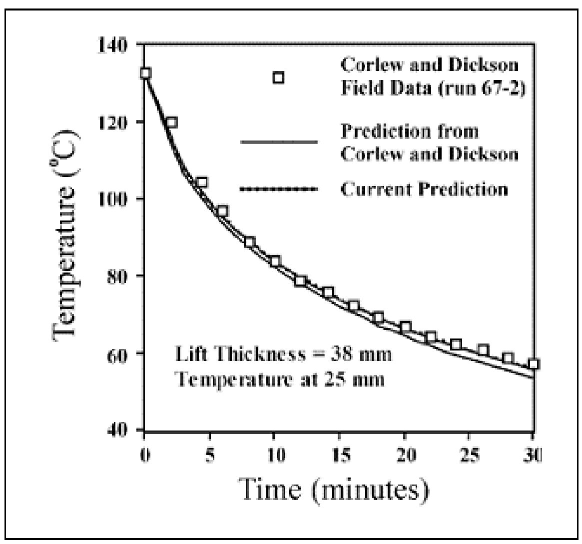

Figure 1.14 Temperature history versus time [28]

Table 1.19 PaveCool model equations

| I. Heat flow equations | |
|---|---|
| Asphalt Layer | Base Layer |
| $\rho_{HMA} c_{HMA} \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[k_{HMA} \frac{\partial T}{\partial z}\right]$ | $\rho_B c_B \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left[k_B \frac{\partial T}{\partial z}\right]$ |
| $\rho_{HMA}$ – density of the lift (kg/m $^3$)<br>$c_{HMA}$ – specific heat of the lift (J/kg K)<br>$k_{HMA}$ – thermal conductivity base layer (W/m · K) | $\rho_B$ – density of the base layer (kg/m $^3$)<br>$c_B$ – specific heat of the base layer (J/kg K)<br>$k_B$ – thermal conductivity of the base layer (W/m · K) |
| **II. Boundary Conditions** | |
| 1**. z=0 (no flux)** – lower boundary condition: $k_B \frac{\partial T}{\partial z} = 0$ | |
| 2. **z=Z $_{base}$ (Continuity of flux)** – interface boundary condition : $k_B \frac{\partial T}{\partial z} = k_{HMA} \frac{\partial T}{\partial z}$ | |
| 3**. z=Z$_{top}$ (Non-linear convection with non-linear convection with convection, radiation and solar input)** – upper boundary condition:<br>$k_{HMA} \frac{\partial T}{\partial z} = h_c (T - T_{amb}) + \varepsilon\sigma(T^4 - T_{sky}^4) - \alpha H_s$<br>$\varepsilon$ – the total emissivity of the asphalt surface<br>$\sigma$ – the Stephan-Boltzman constant (5.67 10-8 W/m$^2$ · K$^4$)<br>$\alpha$ – the total absorbance of asphalt<br>$T_{amb}$ - the ambient temperature (K)<br>$T_{sky}$ - the effective sky temperature (K)<br>$H_s$ - the incident solar radiation (W/m$^2$)<br>$h_c$ - convective heat transfer coefficient (W/m$^2$.K) | |

A starting point in the prediction of the moisture content of the soil can be a rainfall model. The amount of rainfall seems impossible to be computed via a deterministic model, thus the few models currently developed are based on the probabilistic approach. One of these models is proposed by Liang and Lytton [29] Using Monte Carlo simulations, the authors developed an algorithm to predict the amount of rainfall based on the rainfall history and freeze-thaw period. A large amount of rainfall can significantly reduce the pavement material' strength and increase the damage potential.

One of the most complex models that attempt to provide a complete simulation of the environmental effect in the cold climate is the CRREL Model. [22] It is a one-dimensional model that computes the variation of heat flow through the pavement layers considering the variation in humidity, freeze effect, and material parameters. It proposes an approach based on a combination of probabilistic and deterministic models. The heat transfer model and the material properties typical for a set of standard conditions represent the deterministic part of the model. The problems associated with the variation of the parameters of the porous media with moisture content and ice presence are solved probabilistically. After the researchers proved that a stochastic analysis based on the Monte Carlo method is too time consuming to solve their complex dynamic problem, a method based on Rosenbloueth's point is proposed. [30] [31] The final product of this work is a numerical code to predict frost heave, thaw depth and frost depth range within a confidence interval.

In order to find an easy-to-implement method to evaluate the effects of temperature on the pavement using real-time climatic data, Departments of Transportation from US northern states frequently use freezing index (FI) and thaw index (TI). Their research indicated that the depth of frost and thaw depend in part on the magnitude and duration of the temperature differential below or above the freezing index.

The FI (Eq. 3. 12) is defined as the positive cumulative deviation between a reference freezing temperature and the mean daily air temperature for successive days. [32]

$$FI=?\ (0°C - T_{mean}) \qquad (3.12)$$

where: $T_{mean}$ - mean daily temperature, ($T_{mean} = 1/2(T_1 + T_2)$ °C

$T_1$ - maximum daily air temperature (°C)

$T_2$ - minimum daily air temperature (°C)

The TI (Eq. 3.13) is the positive cumulative deviation between the mean daily air temperature and a reference thawing temperature for successive days.

$$TI = ?\ (T_{mean} - T_{ref}) \qquad (3.13)$$

where $T_{ref}$= reference freezing temperature that varies as pavement thaws (°C)

One of the most frequent ways to compute the maximum frost penetration depth is by using the modified Berggren's equation (MBE - (Eq.3.14)). [33]

$$x = h\sqrt{(48knFI)/L} \qquad (3.14)$$

where : x - maximum frost depth (ft)

k - thermal conductivity (Btu/ft hr °F)

n - factor to convert an air freezing index to a surface freezing index (dimensionless)

FI - air freezing index (°F-days)

L - volumetric latent heat of fusion (Btu/ft3)

h – a dimensionless factor to account for the effects of the initial temperature conditions not being isothermal at 32°F.

Chisholm and Phang [34] proposed for Ontario an equation that considers only air FI to compute the maximum frost depth (P) based on air FI. (Eq. 3.15)

$$P = -0.328 + 0.0578\sqrt{FI} \qquad (3.15)$$

The research conducted by Wa/DOT [35], developed a regression equation that relates the freeze index and thaw index to the duration of the thaw period. (Eq. 3.16) This equation has been deduced based on heat-flow simulation for a fine-grained subgrade soils and a FI range from about 200 to 1000°C-days.

$$D = 25 + 0.018(FI) \qquad (3.16)$$

where: D - thaw duration (days)

FI - Freezing Index (°C –days)

Moreover, correlating the data obtained from the theoretical approach (heat flow simulation) with the field data, the research indicated that thaw penetrated the base to a depth of about 150 mm (6 in.) at a TI of 15°C-days (TI Thawing Index defined as a function of reference temperature equal to -1.7°C). Because of this observation, it is recommended that SLR be placed when the TI reaches 15°C-days. However, Yesiller et al. [36] Wi/DOT) and Van Deusen[37] Mn/DOT), analyzing the field observations, showed that Washington State overestimates the length of the thaw period. They noticed that Washington's method for predicting the beginning of the thaw period skips the moment when the thaw occurs in the base layer.

Based on the data from MnROAD,Van Deusen proposed equation (3.17) to predict the duration of the thaw base on freeze index. He noticed that for the location where the frost depth is unknown, equation (3.15) can be used to compute it. However, this model has a standard error of estimation of 8 days and a correlation coefficient (R-square value) of 0.5.

$$D = 0.15 + 0.010\,FI + 19.1P - 12090\,\frac{P}{FI} \qquad (3.17)$$

where: D - thaw duration (days)

FI - Freezing Index (°C –days)

P – frost depth

Two major categories of data should be collected in order to estimate the effect of the environment in a cold climate: the air temperature and data related to temperature and moisture in the soil. Data related to air temperature and rainfall is available from US Weather Bureau and the local Climate Station. For measuring the temperature in the pavement layers thermocouples are frequently used. The degree of saturation in the pavement layer is measured with time domain reflectometry waveguides (TDR). The resistivity probes (TDRs) are used to estimate the frozen depth in the granular material. [23]

Many attempts have been directed to predict the variation of temperature and moisture content in the pavement structure. A combination between the probabilistic and analytical models seems to be the more successful approach. However, the development of the analytical part requires a large amount of data related to thermal properties and permeability of the materials.

On the other hand, the prediction of the beginning of the thaw as a function of thaw index seems to be a very efficient approach, especially since it is well correlated with field data. [6] [35]

**Variation in materials properties caused by the climatic factors**

Two important material parameters are used in pavement design to quantify the mechanistic behavior: Poisson ratio and modulus. As will be shown in the following paragraphs, the values of these parameters are affected by temperature, density, moisture content and gradation, thus they are influenced by climatic conditions.

*Poisson Ratio*

Poisson ratio ($\nu$) is defined as the ratio of lateral strain ($\varepsilon_t$) to axial strain ($\varepsilon_a$) caused by a load parallel to the axis. It is determined using equation (3.18) in which the values measured in the triaxial test are input parameters.

$$n = \frac{1}{2}\left(1 - \frac{1}{e_a}\frac{\Delta V}{V_0}\right) \qquad (3.18)$$

where $V_0$ is original volume and $\Delta V$ is change in volume.

Poisson's ratio ranges between 0.0 and 0.5 (Table 3.15). However, Huang [18] among many others, noticed that Poisson's ratio has little effect on the pavement's response, in other words a typical value can be successfully assumed for this parameter. The same observation is used in AASHTO design method [38]

*Modulus*

The modulus of elasticity quantifies the linear range of stress-strain behavior of a material, under the hypothesis of the perfect elastic material and is calculated using the following expression:

$$E = \frac{\sigma}{\varepsilon} \qquad (3.19)$$

Table 3.15 Poisson Ratios for different materials [18]

| **Material Description** | **Poisson Ratio Range** | **Typical Value** |
|---|---|---|
| Hot Mix Asphalt | 0.3 - 0.4 | 0.35 |
| PCC | 0.15 - 0.2 | 0.15 |
| Untreated Granular Base | 0.3 - 0.4 | 0.35 |
| Clay (saturated) | 0.4 - 0.5 | 0.45 |
| Clay (unsaturated) | 0.1 - 0.3 | 0.2 |
| Sandy clay | 0.2 - 0.3 | 0.25 |
| Silt | 0.3 - 0.35 | 0.325 |
| Dense sand | 0.2 - 0.4 | 0.3 |
| Coarse-grained sand | 0.15 | 0.15 |
| Fine-grained sand | 0.25 | 0.25 |
| Bedrock | 0.1-0.4 | 0.25 |

It characterizes the ability of a material to return to its original shape and size immediately after deformation and is part of the constitutive law in the elastic theory.

The elastic modulus is often determined in the laboratory using repetitive loads tests and recoverable strain, and in this case, it is referred to as resilient modulus ($M_r$). (Eq. 3.20)

$$M_R = \frac{\sigma_d}{\varepsilon_r} \qquad (3.20)$$

where $\sigma_d$ - the deviator stress ($\sigma_d$=$\sigma_1$-$\sigma_3$)
$\varepsilon_r$ – recoverable strain

The deviator stress is the axial stress in an unconfined compression test or the axial stress in excess of the confining pressure in a triaxial compression test.
Resilient modulus is the standard value recommended by AASHTO for the modulus of elasticity for pavement materials because it is determined based on stress and strain measurements from rapidly applied loads similar to those experienced from wheel loads. The typical range for the resilient modulus of HMA is between 150 MPa (at 49°C), 3,500 MPa (at 21°C) and 14,000 MPa (at 0°C). Crushed stone modulus values range between 150 and 300 MPa, silty soil modulus values range between 35 and 150 MPa, and clayey soil modulus values range between 35 and 100 MPa. [39]

The change in HMA resilient modulus depends significantly on temperature fluctuations and mixture characteristics. To determine HMA resilient modulus in the laboratory, the repeated load diametral test and the indirect tensile test are frequently used. [18] Equation (3.21) presents the formula used to determine this value.

$$M_R = \frac{P(\nu + 0.2734)}{\delta t} \qquad (3.21)$$

where: $M_r$ - resident modulus of asphalt mixture
$P$ - magnitude of the dynamic load
$\nu$ - Poisson's Ratio
$\delta$ - total recoverable deformation
$t$ - specimen thickness

Current design procedures use the dynamic modulus to quantify the properties of the asphalt mixture. This value can be determined empirically based on the characteristics of aggregate and binder, using equation (3.22):[40]

$$\log E = a_0 + a_1 p_{200} + a_3 (p_{200})^2 + a_3 p_4 + a_4 V_a + a_5 \frac{V_{beff}}{V_{beff} + V_a} + \\ + \frac{a_6 + a_7 p_4 + a_8 p_{3/8} + a_9 (p_{3/8})^2 + a_{10} p_{3/4}}{1 + e^{a_{11} + a_{12} \log f + a_{13} \log \eta}} \qquad (3.22)$$

where: $E$ – asphalt mix dynamic modulus, in $10^5$ psi
$\eta$ – bitumen viscosity ($10^6$ poise)
$f$ – load frequency (Hz)
$V_a$ – expected in-place air voids in the mix ( percent by volume)
$V_{b\,eff}$ – effective bitumen content, ( percent by volume)
$p_{200}$ – percentage passing the No. 200 sieve, by total aggregate weight ( percent);
$p_{3/8}$ – cumulative percentage of material retained on the No. 3/8 sieve, by total aggregate weight ( percent)
$p_{3/4}$ – - cumulative percentage retained on the No. 4 sieve, by total aggregate weight ( percent)
$a_i$ – regression coefficients i=1…10

The resilient modulus of aggregate and soil materials depends on the material type, sample preparation, deviator stress ($\sigma_d$), confining pressure ($\sigma_3$), density and the moisture content used in the test. The resilient modulus of a granular material is increasing if the density, the confining pressure and the angularity of the granular particles are increasing. On the other hand, it decreases with increases in the moisture content of the granular material. For the fine-grained soil, the resilient modulus typically decreases with an increase of the deviator stress, but it also depends upon the soil type, moisture content and density. All these observations lead to the conclusion that cohesion is the main factor influencing the resilient modulus of an unbound material.

One of the most frequently used models for characterizing the resilient response of the unbound material is K-θ model (Eq 3.23). It was developed by Hicks and Monismith [41] in the early 1970s. In the 1980s May and Witczak [41] and Uzan [43] showed that the K-θ model neglects the effect of shear stress, which seems to play an important role in the resilient modulus calculation.

$$M_R = K_1 \sigma_\theta^{K_2} \qquad (3.23)$$

where: $\sigma_\theta$ - bulk stress $\sigma_\theta = \sigma_1 + 2\sigma_3$

$\sigma_1$ - vertical pressure

$\sigma_3$ - confining pressure

$K_1$, $K_2$ – material regression constants

In order to eliminate the drawback of the K- θ model, Uzan [43] proposed the model shown in equation (3.24).

$$M_R = K_3 \sigma_\theta^{K_4} \sigma_d^{K_5} \qquad (3.24)$$

where: $\sigma_\theta$ - bulk stress $\sigma_\theta = \sigma_1 + 2\sigma_3$

$\sigma_d$ - deviator stress $\sigma_d = \sigma_1 - \sigma_3$

$\sigma_1$ - vertical pressure

$\sigma_3$ - confining pressure

$K_3$, $K_4$, $K_5$ – material regression constants

This model was later updated (Eq. 3.25) to consider the dilatation effect caused by the large principal stresses ratio. The model is also known as the octahedral shear stress model [44]. Unlike the previous model, this one can approximate relatively well the fine granular soil behavior.

$$M_R = K_6 p_a \left(\frac{\sigma_\theta}{p_a}\right)^{K_7} \left(\frac{\tau_{oct}}{p_a}\right)^{K_8} \qquad (3.25)$$

where: $\sigma_\theta$ - bulk stress $\sigma_\theta = \sigma_1 + 2\sigma_3$

$\tau_d$ – octahedral shear stress ($t_{oct} = \frac{1}{3}\sqrt{(s_1 - s_2)^2 + (s_1 - s_3)^2 + (s_2 - s_3)^2}$ )

$p_a$ – atmospheric pressure

$K_6$, $K_7$, $K_8$ – material regression constants

Attempts to simplify the process of determining the resilient modulus of the soil are related to the development of empirical relations between the resilient modulus of a type of soil and the value of a strength parameter (CBR or R-value). (Eq. 3.26 [44], 3.27 [46], 3.28[38]). The values of the coefficients in the equations (3.27) and (3.28) vary with the bulk stress. [38]

$$M_R\,(MPa) = 10CBR \qquad (3.26)$$

$$M_R\,(psi) = 1155 + 555CBR \qquad (3.27)$$

$$M_R\,(MPa) = 17.6(CBR)^{0.64} \qquad (3.28)$$

Typically, the triaxial test is used to determine the resilient modulus for fine granular material. Based on the results of this test, a bilinear model (Eq. 3.29) is used to describe their behavior rather than the bulk strain model (Eq. 3.23) [47]. On the other hand, Thompson and Elliot [47] noticed that the values where the slopes are changing can be used in soil classification.

$$\begin{cases} M_r = K_1 + K_2(K_3 - \sigma_d) & \text{when} \quad \sigma_d < K_3 \\ M_r = K_1 - K_4(\sigma_d - K_3) & \text{when} \quad \sigma_d > K_3 \end{cases} \qquad (3.29)$$

where: $\sigma_d$ - deviator stress $\sigma_d = \sigma_1 - \sigma_3$

$K_1, K_2, K_3, K_4$ – material constants obtained from laboratory test

Johnson et al. [49] proposed equation (3.31) in order to calculate the resilient modulus for an unbound material. They developed this model based on their research related to seasonal variations in materials properties in the cold climate. They showed that the resilient modulus is strongly dependent on temperature and moisture content.

$$M_r = K_5\left(\frac{J_2}{\tau_{oct}}\right)^{K_6} \qquad (3.30)$$

where: $J_2$ - second stress invariant ($J_2 = \sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3$)

$\tau_{oct}$ – octahedral shear stress ($t_{oct} = \frac{1}{3}\sqrt{(s_1 - s_2)^2 + (s_1 - s_3)^2 + (s_2 - s_3)^2}$)

$K_5, K_6$ – material regression constants

Currently, there are two categories of tests used to determine the resilient modulus of the pavement materials: laboratory tests and in situ tests.

A triaxial test is the way in which the resilient modulus is determined in the laboratory. Almost all models for the unbound material reflecting their non-linear behavior were developed based on triaxial results. ([41], [41], [44], [44], [47], [49], [51]) The study performed for the unbound material from the LTTP sections, using repeated load tests [50], shows that in most of the cases the values of the resilient modulus are significantly influenced by the moisture content. On the other hand, the same Federal Highway Administration (FHWA) report indicates that equation (3.31), a statistical adaptation of the octahedral shear stress model (Eq. 3.25), seems to best fit the results obtained from the laboratory test.

$$M_R = K_1 p_a\left(\frac{\sigma_\theta - 3K_4}{p_a}\right)^{K_3}\left(\frac{\tau_{oct}}{p_a} + 1\right)^{K_4} \qquad (3.31)$$

Over the last sixty years, many methods have also been developed to evaluate the strength of the soil material in the field. These methods include: the plate load test, the California Bearing Ratio (CBR) test, and the Dynamic Cone Penetrometer (DCP). However, most of the research conducted in the last fifteen years related to field evaluation of the material characteristics has used Falling Weight Deflectometer [viii] (FWD) (Figure 1.15) measurements. This device measures the deflections at a few points (4-9) on the surface of the pavement system (deflection basin) caused by an impulse load. These values are input in software based on linear elastic theory that computes the moduli of the pavement layer. Table 1.20 provides a brief description of some of the deflection basin parameters [37][39] and the way in which they are related to the strength of the pavement.

All these models show that the temperature and moisture content have a significant impact on the value of the modulus. However, most of the models require a large number of tests to determine the coefficients of the models. On the other hand, the field determinations indicate how the moduli of the flexible pavement materials vary with the change in temperature and moisture, but there are issues related to their ability to provide exact values for this parameter. [41][41] [44] [47][49]

Figure 1.15 FWD Load Plate

Table 1.20 Deflection basin parameters

| Parameter | Formula | Significance |
|---|---|---|
| Deflection under the load | $D_1$ | total deflection of the pavement that provides information about the overall pavement strength |
| Surface Curvature Index | $SCI = D_1 - D_3$ | may be related to the relative stiffness of the upper layers of the pavement |
| Base Damage Index | $BDI = D_3 - D_5$ | may be related to the relative stiffness of the base layer of the pavement |
| Area of the basin deflection | | general condition of the pavement |
| Deflection towards the end of the basin | $D_6$ | tend to indicate the condition of the subgrade layer |

## 1.4 Consideration of the Environmental Effect in the Design Procedures

### Introduction

One of the most important issues in the design of a pavement is how well a design procedure considers the environmental influence on the pavement. This question arises more often when the pavement is designed in a cold climate because, as shown previously, the freeze-thaw phenomena induce a large variation in material properties. Neither the approaches that consider the poorest quality for the pavement material, nor the ones that completely neglect the variations in material properties caused by environment impact, are completely efficient approaches in pavement design.

Two categories of design methods exist today: empirical methods and mechanistic-empirical methods.

An empirical method is based on field observations. In many cases the local experience is the main factor on which an empirical model is developed. Frequently, it is based on a regression model whose dependent variable is an indicator of pavement performance (e.g. riding quality, condition index, roughness, rutting, cracking, etc), and the independent variables are pavement structural strength, traffic loading, and sometimes environmental conditions.

A mechanistic-empirical method is based on a model for pavement behavior that considers the most important mechanical characteristics of all the layers of the pavement. It uses a physical model to establish the reaction of the pavement structure under the traffic loads, and connects the results with the performance of the pavement structure. This type of model combines the advantages of both empirical and theoretical models, while minimizing most of their disadvantages. A mechanistic model is based on using the material behavior and pavement response functions, which are believed to represent the actual behavior of the pavement structure under the combined actions of traffic and environment.

Because of this complex structure, a design method based on a mechanistic empirical model has two major phases. In the first phase, the stresses, strains, and displacements of the road are calculated using theoretical models that are solved with an analytical or numerical method. In the second phase, the empirical models are used to relate the physical parameters determined in the first phase with the performance of the pavement structure. For example, one can use a theoretical model to determine the strain of the asphalt layer in correlation with the pavement lifetime, and then use an empirical model to evaluate the expected performance of the road at any moment of its lifetime.

Basically, the development of a mechanistic - empirical model requires two main steps:

- Obtaining the response (structural response) of the pavement against certain load conditions, taking into consideration the material properties;
- Relating the structural response to a certain structural damage.

The first step consists of setting up a mechanical model that appropriately reproduces the structural behavior of the pavement under the given climatic condition in time. Many different models are available, addressing different types of material behaviors and particularities of the wheel-pavement system. The main issues of these models are quantifying the climatic effect and modeling different types of loads. The second step is related to determining one or more failure criteria and to relate them to the mechanistic response of the pavement. This involves the development and calibration of the performance functions. The flexible pavement failure criteria considered in most mechanistic-empirical design methods are traffic-induced fatigue and traffic-induced rutting.

**Quantification of the Environmental Effects in the Pavement Design Methods**

Even though it is an empirical design procedure, AASHTO method [38] considers the seasonal variations in material properties. It requires estimating the loss of serviceability caused by swell clay and frost heave over the pavement lifetime, and adds this to the cumulative traffic loads. The serviceability loss due to frost heave depends on the frost heave rate, the maximum potential serviceability loss and the frost heave probability.

Equation (4.1) is the design equation of AASHTO Design procedure for flexible pavement. It considers explicitly the ability of the structural layer to drain water, but the decision related to choosing of the "m" coefficients should be made based on engineering experience. The structural number (SN) value is determined from a design chart as a function of reliability, number of ESAL for the design lifetime, design serviceability loss, and effective resilient modulus of roadbed soil.

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \qquad (4.1)$$

where:
- SN - structural number
- $D_1, D_2, D_3$ -thickness of surface, base and subbase layers
- $a_1, a_2, a_3$ - layers coefficient for surface, base and subbase layers
- $m_2, m_3$ - drainage coefficient for base and subbase layers

In order to consider the seasonal variations in the soil resilient modus, the relative damage factor $u_f$ is introduced. Using equation (4.2), a damage factor can be computed for each period of time (maximum 24 periods per year) when the resilient modulus has a significant variation. Taking the arithmetic mean of all these values, an average damage factor is computed and then an effective resilient modulus is determined. With this new value, which considers the environmental effects, the designer uses the design chart and determines the structural number that is further used in the calculation of the thickness layers.

$$u_{fi} = 1.18 \times 10^8 M_{ri}^{-2.322} \qquad (4.2)$$

where:
- $u_{fi}$ - relative damage factor for the period i
- $M_{ri}$ - resilient modulus determined for the period i
- i - time period for which we assign a characteristic resilient modulus (i can be between 2 and 24)

The AASHTO design procedure uses the physical characteristics of the material and a set of design plots to determine the thickness of the pavement layer. However, the method only considers the variation in the soil resilient modulus, while it completely neglects the variation of the elastic properties in the other layers of the pavement structure.

Idaho has developed a mechanistic-empirical procedure for overlay design. [52] The method is based on multi-layer system theory and Asphalt Institute failure criteria. It considers the climatic effect on pavement material characteristics.

In order to consider the influence of the environment as accurately as possible, the state is divided into six regions with freeze periods ranging between 126 and 82 days and the thaw periods between 15 and 38 days. For these regions, the "normal period" (the period when the characteristics of the material are close to reference values) represents between 71 percent and 53 percent of the year.

Based on field observations, four periods that have a significant influence of the material properties were identified: summer, winter, spring thaw and spring wet. According to this climatic distribution, four resilient moduli for each unbound layer should be determined to model their behavior in the multi-layer system. The moduli are computed as functions of the summer modulus, using a set of adjustment factors ($R_f$, $R_t$, $R_w$) determined for each region. (Eq 4.3) The HMA modulus variation is computed using equation (3.11) and (3.22) [ix].

$$M_i = M_{summer} R_i \qquad (4.3)$$

where: $M_i$ – resilient modulus in season i
- i - season (winter, spring thaw and spring wet)
- $M_{summer}$ – summer resilient modulus
- $R_i$ - adjustment factors that correspond for the i period

A similar mechanistic-design approach for overlay design was proposed in Ontario. [53] They consider in their design procedure five seasons: January and February season 1- frozen pavement condition; March and April season 2 – spring subgrade reduction; May to August season 3 – low asphalt modulus; September and October season 4 – reference values for the pavement layers elastic characteristics; November and December season 5 - beginning of the freeze. Based on the FWD measurements, they have developed a set of adjustment factors for the pavement materials that give them the possibility to consider the climate effects on the material characteristics. In the next step, they proposed an evaluation of the admissible number to failure for each season, a computation of the damage coefficient for each season, and finally an evaluation of the overlay thickness.

Washington Department of Transportation [54] has developed a mechanistic-empiric design procedure that considers the climate effect on material characteristics. Their method is integrated in the "Everseries Pavement Programs" software package. They consider in their computation the adjusted pavement layers moduli that are determined based on the FWD results and the climatic maps of the Washington State. Moreover, their approach can assume a non-linear behavior for granular material. The failure criteria are fatigue, rutting and maximum spring deflection. In order to mitigate the frost penetration they recommend increasing the thickness of the base.

Another mechanistic-empirical approach was developed by Illinois in the form of Climatic-Material-Structural (CMS) pavement analysis software. [55] It proposes a combination between a model that predicts the variation of climate factors during the year, and consequently the variation in material properties, and a model that performs structural analysis. The climatic model is based on the heat transfer model described by the one-dimensional Fourier heat-transfer equation. In order to simulate the temperature profile through different layers of the pavement, the method considers the thermal properties of the pavement materials. The moisture model is designed as an equilibrium model of the pore water.

Based on the results of the climatic model the CMS predicts the strength variations in pavement layers. The stiffness of the asphalt layer is a function of temperature, binder properties and percent of aggregate in the mixture. For the unbound materials (except fine-grained materials), the values of frozen and unfrozen resilient moduli should be declared and these values are used in correlation with temperature in these layers. For the fine-grained material, the software uses the bilinear model correlated with the moisture model and state of stress, and predicts the variation of the resilient modulus during the year.

The structural analysis is performed based on layer elastic theory, using a finite-element code. The model considers failure criteria for granular and fine grained soil, and fatigue and rutting criteria for computing the lifetime of the pavement.

**Rutting Models**

Because this research is mainly dealing with the effect of the thaw on the properties of the materials, most of the review process has focused on models that are related to the permanent deformation - rutting. Typically, this distress is caused by densification and plastic flow in the pavement layers. These two components make the development of a predictive model for the variation of the permanent deformation very difficult because of the large number of parameters that vary with time and applied load. Among the difficulties that arise in the design of a mechanistic model for rutting, Uzan [56] identified: nonlinearity and the complexity of the constitutive relation of the material under the repeated loads, the time dependency of the asphalt concrete material and the high variability of the material characteristics with temperature and moisture.

In Figure 1.16 [57] two possible models for the increase in the depth of the rut are presented. Curve A represents a uniform monotonic curve and depicts the case in which the properties of the material do not vary significantly over time. Curve B is a non-uniform one and it is typical for the case in which the materials are frequently affected by the variations in their properties.

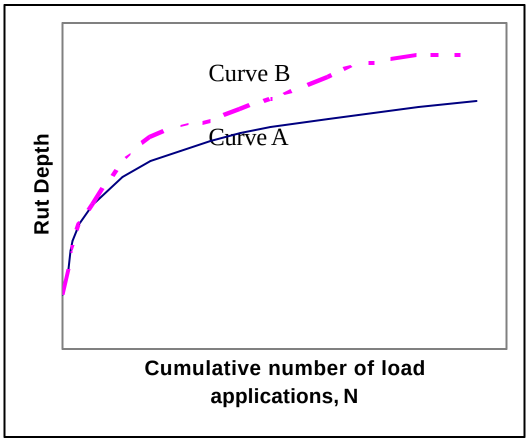


Figure 1.16 Variation of the rut depth with the traffic load

Currently, there are two major categories of mechanistic empirical models for rutting. The first category includes models that relate the maximum admissible rutting to the vertical strain on the top of the subgrade. The second category compounds models that compute rutting as a permanent deformation of the flexible pavement.

The first category of models was developed as part of the Asphalt Institute and Shell design methods. [18] These assume that when the vertical strain on the top of the subgrade is controlled, the depth of the rut in the pavement can be limited. (Eq. 4.4) In order to achieve this limitation, the coefficients $f_4$ and $f_5$ have to be calibrated to the local conditions. The limits imposed for the rut depth range between 10 mm (0.4 in) and 13 mm (0.5in).

$$N_d = f_4 (\varepsilon_c)^{-f_5} \qquad (4.4)$$

where: $N_d$ - allowable number of repetitions to limit rutting from one axle
$\varepsilon_c$ - compressive strain on the top of the subgrade
$f_4, f_5$ - model coefficients.

Equation 4.4 gives one of the most frequently used rutting models in the mechanistic-empirical design methods for the flexible pavements. The advantage of this type of model is that it does not require a large number of laboratory tests for the materials from the pavement system. If the model is calibrated for a region, it can be used for any type of flexible pavement and traffic load. The main drawback of this model is that it does not properly account for the permanent deformation in the pavement layers. Because of this, the model can cause error in the estimation of the lifetime of pavement when large seasonal variations occur in the material properties.

The second category of models addresses the problem of the first category, but these new models involve a large number of parameters that ought to be determined a priori. Currently, there are two major tendencies in the evaluation of rutting considering the contribution of all pavement layers. There are models that compute the permanent deformation in different locations in the pavement and accumulate these deformations and there are models that consider the rate of loading under each load application and integrate this over the lifetime of the pavement.

One of the most recent models developed using the summation of the permanent deformations of the pavement layers for computing the rut depth is proposed by 2002 Design Guide (NCHRP 1999b) [58]. (Eq. 4.5)

$$PD_{Total} = PD_{AC} + PD_{Base} + PD_{Subgarde} \qquad (4.5)$$

where: $PD_{total}$ - depth of the rut in the pavement system
$PD_{AC}$ - permanent deformation of the asphalt layer
$PD_{Base}$ - permanent deformation of the granular base layer
$PD_{Subgarde}$ - permanent deformation of the subgarde

The permanent deformation is defined as a function of the plastic strain and the thickness of the layer/sublayer in which this deformation occurred. (Eq 4.6)

$$PD = \sum_{i=1}^{n\_sublayers} \varepsilon_p^i h^i \qquad (4.6)$$

For the asphalt layer, the plastic strain is determined as a function of the resilient strain of the asphalt material, temperature, the number of load repetitions, regression coefficients computed based on laboratory tests, and field calibration coefficients (Eq 4.7). This model for plastic strain was developed based on the research [59], [60], [61] conducted during the past two decades.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} a_1 T^{a_2 \beta_{r2}} N^{a_3 \beta_{r3}} \qquad (4.7)$$

where:
$\varepsilon_p$ - accumulated plastic strain at *N* repetitions of load
$\varepsilon_\rho$ - resilient strain of the asphalt material as a function of mix properties, temperature and time rate of loading
N - number of load repetitions
T - temperature
$a_i$ - non-linear regression coefficients

Equation (4.8) presents the model for permanent deformation occurred in granular material (aggregate base and subgrade).

$$PD_{UM}(N) = \varepsilon_p h = \beta_1 \left( \frac{\varepsilon_0}{\varepsilon_r} \right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_v h \qquad (4.8)$$

where:
$PD_{UM}(N)$ - permanent deformation in the unbound layer/sublayer after N loads
$\beta$ - material characteristic determined as a function of material, water content in granular material and resilient modulus of the material
$\rho$ - material characteristic depending on *b* and the resilient modulus of the material
$\varepsilon_r/\varepsilon_0$ - material characteristic depending on the resilient modulus, *b*, and *r*
$\varepsilon_v$ - average vertical resilient strain in the layer/sublayer obtained from the primary response model
N - number of load repetitions
h - thickness of the layer/sublayer
$\beta_1$ - calibration factor

One of the well-known methods that takes into account the plastic deformation in the evaluation of rutting is the VESYS method [18], [62], [63]. In this method, the rut depth increment caused by each passing of the load is computed, and the total depth is calculated using an integration over the lifetime of the road. To determine the rut depth increment, the model assumes that the plastic strain is proportional to the resilient strain.(Eq 4.9, 4.10)

$$\varepsilon_p(N) = \mu \varepsilon N^{-\alpha} \qquad (4.9)$$

$$\varepsilon_p = \int_0^N \varepsilon_p(N)dN = \mu\varepsilon\frac{N^{1-\alpha}}{1-\alpha} \qquad (4.10)$$

where: $\varepsilon_p(N)$ - plastic strain due to the application of the $N^{th}$ single load
$N$ - number of load applications
$\varepsilon_p$ - permanent deformation after N load applications
$\varepsilon$ - resilient (elastic) strain at the $200^{th}$ repetition
$\mu, \alpha$ - permanent deformation parameter

Equation (4.10) gives the value of the permanent strain only for one material. In order to obtain the permanent deformation for a multi-layer system, permanent deformation parameters must be determined. This is done under the assumption that the condition described by equation (4.11) is valid for each load application. Starting from this assumption, the model defines two elastic moduli, one for unloading ($E_r$) and one for loading conditions (E) for each layer. (Eq. 4.13)

$$\varepsilon = \varepsilon_p(N) + \varepsilon_r(N) = ct \qquad (4.11)$$

$$\varepsilon_r(N) = \varepsilon(1-\mu N^{-\alpha}) \qquad (4.12)$$

where: $\varepsilon_p(N)$ - plastic strain due to application of the $N^{th}$ single load
$N$ - number of load applications
$\varepsilon_r(N)$ - recoverable strain due to each load application
$\varepsilon$ - resilient (elastic) strain at the $200^{th}$ repetition
$\mu, \alpha$ - permanent deformation parameters (To determine the values of the plastic parameters $(\alpha, \mu)$, the VESYS manual [63] recommends to perform a set of triaxial tests.)

$$E_r(N) = \frac{E}{1-\mu N^{-\alpha}} \qquad (4.13)$$

Using these values, the plastic deformation is computed as the difference between the elastic and recoverable deformation. An approach similar to the one used to determine the plastic strain for one layer is employed to get the plastic deformation for the pavement system. (Eq. 4.14)

$$w_p(N) = w - w_r(N) = \mu_{sys} w N^{-\alpha_{sys}} \qquad (4.14)$$

where: $w_p(N)$ - plastic deformation due to application of the $N^{th}$ single load
$N$ - number of load applications
$w_r(N)$ - recoverable deformation after $N^{th}$ load application
$w$ - elastic deformation due to loading
$\mu_{sys}, \alpha_{sys}$ - permanent deformation parameters of the multi-layer system computed as functions of the permanent deformation parameters of each layer of the system

Uzan and Lytton [64] developed a model for the computation of the increment of the rut depth based on the primary response of a four-layer system and the plastic characteristics of the pavement materials. This model is presented in equation (4.15).

$$\Delta RD_j = \frac{pa}{E_{sg}} \cdot \frac{a_1}{1+a_2} (n_j^{1+a_2} + n_{j-1}^{1+a_2}) \qquad (4.15)$$

$$\log(a_1+1)=f(\alpha_1, \alpha_2, \alpha_2, \alpha_4, \mu_1, \mu_2, \mu_3, \mu_4, W)$$
$$\log(a_2+1)=g(\alpha_1, \alpha_2, \alpha_2, \alpha_4, \mu_1, \mu_2, \mu_3, W)$$

where $\Delta RD_j$ - increment of the rut depth caused by a given load during a period j
$p$ - contact pressure of the dual wheel
$a$ - contact radius of each wheel
$E_{sg}$ - the subgrade modulus
$a_1, a_2$ - regression coefficients determined for canalized and non-canalized traffic
$W$ - non - dimensional deflection defined as a function of pavement layer system primary response. (Eq 4.16)
$\alpha_1, \alpha_2, \alpha_2, \alpha_4, \mu_1, \mu_2, \mu_3, \mu_4,$ - plastic parameters of the material determined based on the laboratory tests

$$\log W = 0.2847 - 0.2361\log\left(\frac{T_1}{a}\right) - 0.0898\log\left(\frac{T_2}{a}\right) - 0.2441\log\left(\frac{E_1}{E_4}\right) - 0.1830\log\left(\frac{E_2}{E_4}\right) -$$
$$- 0.0460\log\left(\frac{E_3}{E_4}\right) + \log\left(\frac{T_1}{a}\right)\left[-0.2075\log\left(\frac{T_1}{a}\right) + 0.2015\log\left(\frac{T_2}{a}\right) + 0.0986\log\left(\frac{1+T_3}{a}\right) -\right.$$
$$\left. - 0.2191\log\left(\frac{E_1}{E_4}\right) + 0.1246\log\left(\frac{E_2}{E_4}\right) + 0.1020\log\left(\frac{E_3}{E_4}\right)\right] + \log\left(\frac{T_2}{a}\right)\left[-0.1720\log\left(\frac{T_2}{a}\right) +\right.$$
$$\left. + 0.1143\log\left(\frac{1+T_3}{a}\right) + 0.0118\log\left(\frac{E_1}{E_4}\right) - 0.1919\log\left(\frac{E_2}{E_4}\right) - 0.0965\log\left(\frac{E_3}{E_4}\right)\right] +$$
$$+ \log\left(\frac{T_3+1}{a}\right)\left[-0.0474\log\left(\frac{E_1}{E_4}\right) + 0.0220\log\left(\frac{E_2}{E_4}\right) + 0.0220\log\left(\frac{E_3}{E_4}\right)\right] +$$
$$+ \log\left(\frac{E_1}{E_4}\right)\left[-0.3315\log\left(\frac{E_1}{E_4}\right) + 0.0145\log\left(\frac{E_2}{E_4}\right) + 0.0095\log\left(\frac{E_3}{E_4}\right)\right] +$$
$$+ \log\left(\frac{E_2}{E_4}\right)\left[0.0216\log\left(\frac{E_2}{E_4}\right) + 0.0074\log\left(\frac{E_3}{E_4}\right)\right] + +0.0300\left[\log\left(\frac{E_3}{E_4}\right)\right]^2 \qquad (4.16)$$

where: $W$ - Non dimensional deflection
$T_1, T_2, T_3$ - the thicknesses of the pavement layer
$E_1, E_2, E_3$ - the moduli of the pavement layers
$a$ - the radius of the load
$E_4=E_{sg}$ - the subgarde modulus

Archilla et al. [57], [65] propose a particular perspective on the evaluation of the depth of the rut. They developed an empirical incremental model that tends to be very sensitive to the variations of the material properties. To this end, they conducted a statistical analysis of the parameters that influenced the rut depth, and designed an incremental function for the increase in rut depth. (Eq 4.17) Their model is based on the observation that the effect of the plastic flow is typically more significant in the bituminous layers and densification is more related the granular layer. As can be seen from equation (4.18), they considered separately the rut that occurred in the asphalt layer and the rut that occurred in the granular material.

$$RD_{it} = c_i + \sum_{s=1}^{t} \Delta RD_{is} \qquad (4.17)$$

where:
- $i$ - an index that quantifies the section ("section i")
- $RD_{it}$ - the rut depth at time t
- $\Delta RD_{is}$ - the increment of rut depth during the time steps
- $c_i$ - a term that indicates the rut depth immediately after construction

$$\Delta RD_{it} = \Delta RD_{it}^{AC} + \Delta RD_{it}^{U} = m_{it} e^{b' N'_{it}} \Delta N'_{it} + a_{it} e^{b N_{it}} \Delta N_{it} \qquad (4.18)$$

where:
- $i$ - a index that quantifies the section ("section i")
- $\Delta RD_{it}$ - the increment of the rut depth during the time step t
- $\Delta RD_{it}^{AC}$ - the increment of the rut depth during the time step t originated in the asphalt concrete layers
- $\Delta RD_{it}^{U}$ - the increment of the rut depth during the time step t originated in the unbound layers
- b'and b - model parameters (negative values)
- $m_{it}$ - a coefficient that is a function of mix characteristics, air temperature, and loading
- $a_{it}$ - a coefficient that is a function of pavement layer thicknesses and length of freeze-thaw period
- $\Delta N_{it}$ - a parameter that quantifies the traffic loads in the step t that influenced the rut occurred in the unbound layers
- $\Delta N'_{it}$ - a parameter that quantifies the traffic loads in the step t that influenced the rut occurred in the asphalt concrete layers
- $N_{it}$ - a parameter that quantifies the load from the traffic that caused the rut in unbound layers (the traffic is counted from the beginning of the lifetime of the road until the time t)
- $N'_{it}$ - a parameter that quantifies the load from traffic that caused the rut in the asphalt layer (the traffic is counted from the beginning of the lifetime of the road until the time t)

As shown above, a number of models have been developed to predict rutting in flexible pavement. The more complex models are more adequate for a reasonable estimation of the evolution of this distress. The main problem with this type of models is that they require a large number of laboratory tests to be performed, because they have to deal with the plastic behavior of the materials. These models seem to work properly if they are associated with a model that can predict the variations in the moisture content in the pavement layers.

Unlike the first category, the models that consider only the rutting that occurred in the subgrade are less accurate but they require considerably less data to be developed. The models depend only on the elastic properties of the materials.

**The Mechanistic Empirical Design Procedure Used in Minnesota - MnPAVE**[x]

MnPAVE is software for flexible pavement design, developed by Mn/DOT and the University of Minnesota. It is based on a mechanistic-empirical design procedure calibrated for the climatic conditions, pavement structures, and materials used in Minnesota. To perform the mechanistic part (linear elastic analysis of a multi-layer pavement structure), MnPAVE has integrated "WESLEA", a software developed at the Waterways Experimental Station of the Army Corps of Engineers.

As with any other structural design program, it requires a set of data that provide information about the main characteristics of the structure, loading conditions, and the main properties of the materials that are used. These data form the input parameters. The input information is analyzed using software algorithms and a set of data is delivered to the user as output. MnPAVE needs three major categories of input: structural input, climate input and traffic input. The current version of MnPAVE provides as output the following quantities: the lifetime of the pavement, damage factor for asphalt fatigue and subgrade rutting, the percentage of damage that occurs in each season, the maximum stress on the top of the base, and most of the values for stresses and strains determined using the elastic analysis.

*The structural input* includes the number of layers of the pavement structure, the thickness of each layer, and the elastic properties of the material from each layer. All these characteristics are necessary to construct the mechanistic model. MnPAVE has a set of options that allow the user to choose the parameter that defines the elastic characteristics of the material. For a complex project, the designer can obtain the values of the resilient modulus for each season and for each material used. In most cases, the user determines the typical elastic characteristics for the optimal conditions. Based on these values, MnPAVE computes the value of the elastic parameter for each season using seasonal modulus multipliers. These multipliers were determined based on the research done in Minnesota to evaluate the seasonal effects on the material properties.[23]

The HMA layer can be divided into three lifts and for each lift the user can specify the binder types and aggregate gradations. (MnPAVE is calibrated only for PG 58-28 binder, because this binder has been used for most of the flexible pavements built in Minnesota.) The values of the elastic moduli are determined based on the characteristics of aggregate and binder, using equation (4.19).

$$\log E = a_0 + a_1 p_{200} + a_3 (p_{200})^2 + a_3 p_4 + a_4 V_a + a_5 \frac{V_{beff}}{V_{beff} + V_a} + \\ + \frac{a_6 + a_7 p_4 + a_8 p_{3/8} + a_9 (p_{3/8})^2 + a_{10} p_{3/4}}{1 + e^{a_{11} + a_{12} \log f + a_{13} \log \eta}} \qquad (4.19)$$

where:

- $E$ - asphalt mix dynamic modulus, in $10^5$ psi
- $\eta$ - bitumen viscosity ($10^6$ poise)
- $f$ - load frequency (Hz)
- $V_a$ - expected in-place air voids in the mix ( percent of volume)
- $V_{b\,eff}$ - effective bitumen content ( percent of volume)
- $p_{200}$ - percentage passing the No. 200 sieve, of total aggregate weight ( percent)

$p_{3/8}$ - cumulative percentage of material retained on the No 3/8 of total aggregate weight ( percent)

$p_{3/4}$ - cumulative percentage retained on the No. 4 sieve, by total aggregate weight ( percent)

$a_i$ - regression coefficients i=1..10

The value of Poisson's Ratio is determined based on equation (4.20)

$$m = 0.15 + \frac{0.35}{1 + e^{b_0 + b_1 E}} \qquad (4.20)$$

where $b_1$ and $b_2$ – the regression coefficients

*The climate input* was designed to provide the user the possibility of considering the variation in material properties caused by the environment. Based on the research done in Minnesota, a year is divided into 5 seasons. The criteria used for this distribution are related to air temperature and moisture, the parameters that have a major influence on the road material characteristics. The typical lengths of seasons and their influence on elastic moduli of the material are presented in Table 1.21.

Table 1.21 Seasonal distribution of a typical year for the design purpose [23]

| Parameter | **Season I**<br>***Winter***<br>Layers are frozen | **Season II**<br>***Early Spring***<br>Base Thaws<br>SG is frozen | **Season III**<br>***Late Spring***<br>Base Recovers<br>SG Thaws | **Season IV**<br>***Summer***<br>HMA Low<br>SG Recovers | **Season V**<br>***Fall***<br>Layers are standard |
|---|---|---|---|---|---|
| *Estimated duration of each season* | | | | | |
| Beginning | FI>90°C-day | TI>15°C-day | End of Season II | 3-day $T_{avg}$>17°C | 3-day $T_{avg}$<17°C |
| Ending | TI>15°C-day | Approx 28 days later | 3-day $T_{avg}$>17°C | 3-day $T_{avg}$<17°C | FI>90°C-day |
| *Pavement layer moduli relative to fall values* | | | | | |
| $E_{HMA}$ | High | High | Standard | Low | Standard |
| $E_{AB}$ | High | Low | Low | Standard | Standard |
| $E_{SG}$ | High | High | Low | Low | Standard |

In MnPAVE, the lengths of the seasons are either suggested by the software in correlation with the geographical location of the roads or declared by the user based on experience. The pavement temperature based on air temperature is determined using Witczak equation (4.21)

$$T_p = T_A\left(1 + \frac{1}{z+4}\right) - \frac{34}{z+4} + 6 \qquad (4.21)$$

where: $T_p$ - average seasonal pavement temperature (°F)

$T_A$ - average seasonal air temperature (°F)

z - the depth at which the temperature is predicted (in) - The default value of z is at one third of the HMA thickness.

*Traffic input* is the section where the loads during the pavement lifetime are defined. There are two ways to define these loads: using ESAL or using traffic spectrum.

If ESAL is used, the maximum anticipated axle load and the total number of ESAL during the design period have to be specified. The maximum load value is used to check whether the aggregate base can carry this load under the hypothesis that the materials characteristics are the worst possible.

The load spectrum is used to quantify more precisely the variety of traffic loads, but in order to obtain good results using this method, it is necessary to be able to input an accurate traffic distribution. On the other hand, a good evaluation of traffic distribution requires a complete set of traffic measurements (including weigh-in-motion) whose determination is typically expensive and time consuming. Because of the limitations on accurate traffic data, the load spectrum method cannot be employed for most of the local roads.

In MnPAVE, the load spectrum can be declared using two methods. The first one requires declaring the number of axles enclosed in a given load range, which are expected to pass on pavement during its lifetime. The second one is less complex and requires that the user declares only the first year AADT, design life, annual growth rate, and the distribution of traffic on Mn/DOT or FHWA traffic categories. Based on this information, the software generates a complete load spectrum that is used in the design. The default distribution for the traffic spectrum generation was developed based only on the measurements done on highways and it assumed a uniform distribution of the traffic for all year long.

In order to quantify the effect of traffic load on pavement, MnPAVE considers a circular footprint with an area that varies with the loads. Software provides a default tire pressure equal to 689 kPa (100 psi) and the wheel spacing for each type of axle. These values are considered as average values for the vehicles that traveled in Minnesota. It is recommendable not to modify these values since the transfer functions used in the software are calibrated for these default values.

*The basic output* of MnPAVE consists of the damage and lifetime of the pavement. Nevertheless, these values represent only the main part of the output of the program. In addition, the values of stresses strains and damages under various loads can be obtained.

Before determining the lifetime of the roads, MnPAVE checks the maximum allowable stress criterion. This criterion, based on Mohr-Coulomb law (Eq. 4.22), is used to prevent the failure of the aggregate base caused by an excessive load.

$$\sigma_1 < \sigma_{1critical} = \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right) + 2c\tan\left(45 + \frac{\phi}{2}\right) \qquad (4.22)$$

where:

- $\sigma_{1critical}$ - maximum allowable stress at the middle of the aggregate base
- $\sigma_1, \sigma_3$ - principal stresses due to maximum axial load
- $c$ - cohesion
- $\phi$ - friction angle

MnPAVE is calibrated to perform the verification of the failure criterion only for Mn/DOT class 5 aggregate. The research done related to this criterion showed that the critical stress occurred at the middle of the aggregate base. The Mn/DOT Office of Materials and Road Research determined the values of c and $\varphi$ for the Class 5 aggregate based on the triaxial test. Because not enough triaxial tests were run for various moisture contents, the coefficients obtained from laboratory tests are reduced by 30 percent. Consequently, MnPAVE has as default input the characteristic values for Class 5 Aggregate: cohesion (c) equals to 41.37kPa (6 psi) and friction angle ($\phi$) equals to 24°. Based on these values, the maximum admissible stress is limited to 395.4 kPa (57.34 psi).

The damage analysis involves the investigation of the pavement using fatigue criterion and rutting criterion under the hypothesis that Miner's law (Eq. 4.23) is valid. For the declared pavement structure, the computational algorithms determine the value of admissible traffic using one of these two criteria and compare this value to the traffic input. From this comparison, it is established whether the designed pavement can carry the predicted loads during its lifetime.

$$\text{Damage} = \sum_{j=1}^{J}\sum_{i=1}^{I}\frac{n_{ij}}{N_{ij}} \qquad (4.23)$$

where:
- i - axle types
- j - seasons (periods for which there are no variations in material)
- $n_{ij}$ - the estimated number of repetitions of the axle i in the season j
- $N_{ij}$ - the allowable number of repetitions of the axle i in the season j

It is considered that a pavement has failed when it exhibits fatigue/alligator cracks on more than 20 percent of the total lane area (fatigue failure) or when it has 13 mm (0.5 inch) rut (rutting failure). Equations (4.24) and (4.25) represent the fatigue law and the rutting law respectively.

$$\boldsymbol{N_f} = \boldsymbol{f_1}(\boldsymbol{e_t})^{\boldsymbol{f_2}}(\boldsymbol{E})^{\boldsymbol{f_3}} \qquad (4.24)$$

where:
- $N_f$ - number of repetitions to fatigue failure
- $\varepsilon_t$ - horizontal tensile stress at the bottom of the HMA layer
- E - HMA dynamic modulus
- $f_1$, $f_2$, $f_3$ - constants determined from the laboratory fatigue tests;

The coefficient $f_1$ is adjusted in order to provide a correlation with the observed field performance. Equation (4.25) is the most common way to compute $f_1$.

$$f_1 = H \cdot C \cdot S \cdot f_L \qquad (4.25)$$

where:
- H - height adjustment
- C - correction factor related to the quality of HMA

$$C = 10^M \quad \text{and} \quad M = C_{F1}\left(\frac{V_b}{V_a + V_b} + C_{F2}\right)$$

$V_b$ (percent) – volume of asphalt
$V_a$ (percent) – volume of air voids (in MnPave $V_a$=8.0 percent at the bottom of HMA)
$C_{f1}$ = 4.84
$C_{f2}$ = -0.69

$f_L$ - coefficient determined from the laboratory fatigue test
S - calibration coefficient (S=278 for MnPAVE)

$$N_r = f_4(e_v)^{f_5} \quad (4.26)$$

where: $N_r$ - number of repetitions to rutting failure
$\varepsilon_v$ - vertical strain at the top of the subgrade
$f_4$, $f_5$ - constants determined from road tests or field performance.

Both models involve a set of coefficients related to material characteristics and local conditions. MnPAVE allows the user to choose the values of these coefficients, but only the default coefficients are calibrated for the Minnesota local conditions. The values of the coefficients of damage models that can be used in MnPAVE are presented in Table 1.22 and 1.23.

Table 1.22 Rutting models used in MnPAVE

| **Rutting models** $N_r = f_4(e_v)^{f_5}$ | | |
|---|---|---|
| **MnPave** | $f_4$ | = 0.0199 |
| | $f_5$ | = -2.35 |
| **Roadent** | $f_4$ | =1.11-e008 |
| | $f_5$ | = -3.949 |
| **Asphalt Institute** | $f_4$ | =-1.365-e009 |
| | $f_5$ | = -4.4477 |
| **Chevron** | $f_4$ | =-1.388-e009 |
| | $f_5$ | = -4.4843 |
| **CRREL-A4** | $f_4$ | =0.0025 |
| | $f_5$ | = -3.138 |

Table 1.23 Fatigue models used in MnPAVE

| **Fatigue models** $N_f = CK_{F1}(e_t)^{f_2}(E)^{f_3}$ | | |
|---|---|---|
| **MnPave** | $f_2$ | = -3.291 |
| | $f_3$ | = -0.854 |
| | $K_{F1}$ [xi] | = 1.2 for $H_{HMA} \geq$ 114.75 mm (4.5in)<br>= 0.342 for $H_{HMA}$ <114.75 |
| | C | =0.314 |
| **Roadent** | $f_2$ | =-3.20596 |
| | $f_3$ | = 0 |
| | $K_{f1}$ | = 2.83e-006 |
| | C | =1 |

| | | |
|---|---|---|
| **Asphalt Institute** | $f_2$ | = -3.291 |
| | $f_3$ | = -0.854 |
| | $K_{f1}$ | = 0.07949 |
| | C | = 0.314 |
| **Illinois** | $f_2$ | =-3.16 |
| | $f_3$ | = -1.4 |
| | $K_{f1}$ | = 259.2 |
| | C | = 1 |

Most of the models used in MnPAVE are calibrated to local conditions. In order to reflect the seasonal variations in material properties, it considers 5 seasons in which significant variations in the elastic properties of the materials occur. The elastic parameters of the materials frequently used in pavement layers, were determined and set as default values. The effect of different traffic loads and material properties are combined using Miner's law, in order to determine the damage of the pavement structure.

# 1.5 Mechanistic – Empirical Analysis for Evaluation of the SLR Impact on the Lifetime of the Minnesota Local Roads

## Introduction

Based on the traffic and pavement information available for local roads and on the review of available mechanistic-empirical models it was decided to use MnPAVE software to evaluate the effect of spring load restriction on the restricted roads in Minnesota. The reasons that sustained this decision were:

- MnPAVE has a climatic model developed for Minnesota
- The failure criteria are calibrated to match the predictions for the local conditions using the R-value and the SF methods
- Most of the pavement materials parameters used in the calculations are known for each season based on research performed at MnROAD facility.
- The traffic input options and the capability of running large numbers of scenarios in a short time makes MnPAVE ideal for use in performing a detailed economic analysis of the costs incurred by hauling companies during SLR.

Similar to all the other models used for pavement design or performance prediction, this approach has a number of limitations that can affect the results of this analysis:

- The calibration factors currently used in MnPAVE were developed for well-maintained asphalt pavements with thickness greater than 4 inches, while many county roads have thinner and less maintained structures. The historical performance data needed for the calibration of the model for typical county roads does not exist and obtaining it would require millions of dollars and many years of well documented pavement condition surveys. The research team believes that the performance of pavements does not change abruptly when the thickness of the asphalt layer drops under 4" considering that the traffic is lower on these pavements than on the thicker ones (thinner pavements are designed thinner to address less traffic than a thicker pavements, unless the pavement was under designed). In addition, the thinner layers affect the behavior of the pavement over the entire year, not only in spring, and therefore the ratio of the damage accumulated in spring over year-long damage most likely is not significantly (one order of magnitude) affected when changing from a thicker pavement to a thinner pavement. With respect to the pavement age effect on performance, currently there is no data available to document the age of local roads in Minnesota and therefore this analysis cannot be performed even if a model to take this into account was available.
- MnROAD rutting model neglects the non-linear behavior of the unbound materials and assumes that rutting occurs only in the subgrade. This assumption underestimates the damage that occurs in early spring, however, this damage is underestimated for both restricted and unrestricted scenarios and therefore it is expected that the ratio between the two, which is used in the economic calculations, is not considerably affected. In addition, this damage is accounted for in the calibration factors used in the transfer functions of the model. The development of a model that accounts for these limitations would require extensive laboratory material characterization and the development of a different distress

model. One option to check the reasonableness of the MnPAVE results is to use the distress model proposed in the new Design Guide once this becomes available. However, this approach has its own limitations as the calibration factors are not based on typical Minnesota conditions.

- Many pavements fail due to the combined effects of traffic and environmental loads. For example a pavement may crack initially due to low temperature thermal stresses followed by water infiltration and failure in rutting or fatigue. At this time there is no well documented model available in the area of asphalt pavement research, including the newly released AASHTO Design Guide, that addresses this issue.

Taking into consideration that the development of a more robust model would require substantially more time and funding to acquire the required field and traffic data and that the main focus of the project was the economic analysis of the costs associated with spring load restrictions, it was decided to pursue the pavement damage analysis using MnPAVE design software.

### The Analysis Input Parameters

The Minnesota climatic model has five seasons. The lengths of these seasons can be found in Table 1.24, and the variation of material properties during these seasons is presented in Table 1.25.

Table 1.24[xii] Climatic parameters

| Season | Fall | Winter | Early Spring | Later Spring | Summer |
|---|---|---|---|---|---|
| Length (Days) | 88 | 98 | 14 | 56 | 109 |
| Tair (°C) | 5 | -7 | 0 | 10 | 22 |
| Tpave (°C) | 9 | -6 | 4 | 15 | 29 |

Table 1.25[xiii] The variations of the elastic properties with seasons

| Material | Elastic Modulus (MPa) | | | | |
|---|---|---|---|---|---|
| | Fall | Winter | Early Spring | Later Spring | Summer |
| HMA (PG 58-28) | 7009 | 18640 | 10490 | 4258 | 1328 |
| Agg Class 5 | 151.70 | 344.70 | 45.51 | 106.20 | 128.90 |
| Soil - A-7-6 | 31.72 | 317.20 | 317.20 | 22.20 | 26.96 |
| Soil - A-6 | 44.13 | 344.70 | 344.70 | 30.89 | 37.51 |

The values of the elastic moduli for fall are considered the reference values. In early spring the aggregate base is only 30 percent of the fall value; this low value is assumed only for two weeks. As thawing progresses during late spring, the fall elastic modulus of the soil reduces by 30 percent. The most significant reduction, however, occurs in the asphalt mixture modulus, which in summer reduces to 18 percent of the fall modulus.

The asphalt layer is defined as a hot-mix asphalt layer with a binder PG 58-28. This is the only type of mixture for which software has default values. The aggregate class 5 is the most frequently used type of material for the base layer. A6 is the soil considered in this model because it is the most frequent type of soil in Minnesota.

The typical cross-section on the restricted local roads has a bituminous layer with the thickness ranging from 51 mm (2 in) to 153 mm (6 in) on a base layer of minimum 253 mm (6 in).

The information about the composition of traffic flow on the local road network in Minnesota [19] shows that 2-, 3- and 5-axle trucks are the most frequent types of vehicles. In order to model this traffic, a representative truck from each category is chosen. The main parameters of these representative trucks are presented in Table 1.26. The axle parameters (distance between wheels and tire pressure) have been considered similar to the MnPAVE values.

Table 1.26 Truck fleet parameters [66]

| Truck Type | Gross Weight (t) | Tarred Weight (t) | Front Axle Type | Middle Axle Type | Rear Axle Type | Weight Distribution per axle (empty truck) | Weight Distribution per axle (full truck) |
|---|---|---|---|---|---|---|---|
| 2-axle | 12 | 3.4 | Steer | - | Dual Wheels | 1.00:1.15 | 1.00:1.65 |
| 3-axle | 21 | 8.0 | Steer | - | Dual Tandem | 1.00:1:36 | 1.00:1.98 |
| 5-axle | 39 | 14.4 | Steer | Dual Tandem | Dual Tandem | 1.00:1.50 :1.00 | 1.00:3.09:3.07 |

In order to evaluate the effect of SLR, these trucks are assumed loaded with the maximum admissible load. The weight distribution under different scenarios is presented in Table 1.27.

Table 1.27 Axle weight distribution

| Truck Type | Restrictions | Weight (t) | Front Axle (t) | Middle Axle (t) | Rear Axle (t) |
|---|---|---|---|---|---|
| 2 Axles | Empty | 3.400 | 1.581 | - | 1.819 |
| | 5 ton road | 7.276 | 2.746 | - | 4.530 |
| | 7 ton road | 10.186 | 3.844 | - | 6.342 |
| | 9 ton road | 12.000 | 4.528 | - | 7.472 |
| 3 Axles | Empty | 8.000 | 3.387 | - | 4.613 |
| | 5 ton road | 12.922 | 4.366 | - | 8.557 |
| | 7 ton road | 18.091 | 6.112 | - | 11.979 |
| | 9 ton road | 21.000 | 7.095 | - | 13.905 |
| 5 Axles | Empty | 14.400 | 4.114 | 6.171 | 4.114 |
| | 5 ton road | 19.968 | 2.797 | 8.613 | 8.558 |
| | 7 ton road | 27.870 | 3.885 | 12.006 | 11.979 |
| | 9 ton road | 35.833 | 4.995 | 15.402 | 15.436 |

To separate the effects of different types of traffic during the non restricted period of time and the SLR period of time, different indices were used for the daily traffic for each of the 3 types of trucks considered in the analysis, as shown in Table 1.28.

Table 1.28 Traffic indices

| Truck Type | No of trucks | Restrictions | Weight (t) |
|---|---|---|---|
| 2 axles | $N_1^5$, $N_1^{5-7}$, $N_1^{5-9}$ | 5 ton road | 7.276 |
| | $N_1^7$, $N_1^{7-9}$ | 7 ton road | 10.186 |
| | $N_1$, $N_1^9$ | 9 ton road | 12.000 |
| 3 axles | $N_2^5$, $N_2^{5-7}$, $N_2^{5-9}$ | 5 ton road | 12.922 |
| | $N_2^7$, $N_2^{7-9}$ | 7 ton road | 18.091 |
| | $N_2$, $N_2^9$ | 9 ton road | 21.000 |
| 5 axles | $N_3^5$, $N_3^{5-7}$, $N_3^{5-9}$ | 5 ton road | 19.968 |
| | $N_3^7$, $N_3^{7-9}$ | 7 ton road | 27.870 |
| | $N_3$, $N_3^9$ | 9 ton road | 35.833 |

The meaning of each index[xiv] is provided below.

- **$N_1$, $N_2$, $N_3$** – the number of trucks per day for each type of truck during the unrestricted time of the year (44 weeks).
- **$N_1^9$, $N_2^9$, $N_3^9$** –the number of trucks per day on a 9-ton road during SLR (8 weeks).
- **$N_1^7$, $N_2^7$, $N_3^7$** – the number of trucks per day on a 7-ton road during SLR (8 weeks).
- **$N_1^5$, $N_2^5$, $N_3^5$** – the number of trucks per day on a 5-ton road during SLR (8 weeks).
- **$N_1^{7-9}$, $N_2^{7-9}$, $N_3^{7-9}$** – the number of trucks per day traveling from the 7-ton roads to a 9 ton road during the SLR (8 weeks).
- **$N_1^{5-9}$, $N_2^{5-9}$, $N_3^{5-9}$** – the number of trucks per day traveling from the 5-ton roads to a 9-ton road during SLR (8 weeks).
- **$N_1^{5-7}$, $N_2^{5-7}$, $N_3^{5-7}$** – the number of trucks per day traveling from the 5-ton roads to a 7-ton road during SLR (8 weeks).

The model assumed that half of the vehicles are empty and half of them are full, and the load per axle is the lowest of the maximum admissible load for the road category or the maximum load admissible by the reference truck capacity. This seems a reasonable assumption since most of the heavy vehicles that travel on the local roads are operated by various industries and not by the transportation companies. Moreover, in this way the effect of the increase in the number of trucks can be better quantified.

**A Model which Evaluates the SLR Effect on the Lifetime of the Roads**

The first step in this analysis was to establish the relevant failure criteria. For this, MnPAVE was run for a few particular pavement structures and loads[xv]. The results are presented in Tables 1.29 and 1.30 and show that rutting is the critical failure criterion that determines the lifetime of a pavement in the local road network.

Table 1.29 Relevant failure criteria analysis for an HCDT =20 heavy vehicles

| **Criterion** | **Pavement Structure** | | |
|---|---|---|---|
| | **51 mm (2") HMA 153 mm (6") agg base** | **51 mm (2") HMA 204 mm (8") agg base** | **102 mm (4") HMA 153 mm (6") agg base** |
| Fatigue lifetime (years) | 19 | 23 | 50 |
| Rutting lifetime (years) | 4 | 7 | 19 |

Table 1.30 Relevant failure criteria analysis for an HCDT =200 heavy vehicles

| **Criterion** | **Pavement Structure** | | |
|---|---|---|---|
| | **51 mm (2") HMA 153 mm (6") agg base** | **51 mm (2") HMA 204 mm (8") agg base** | **102 mm (4") HMA 153 mm (6") agg base** |
| Fatigue lifetime (years) | 1 | 2 | 9 |
| Rutting lifetime (years) | 0 | 0 | 1 |

These preliminary MnPAVE runs also indicate that during spring the largest amount of rutting occurs during later spring. Thus, the efforts related to determining the impact of the heavy traffic focused on this period. Note that MnPAVE also indicates that a large part of the damage occurs in summer due to the substantial reduction in the asphalt modulus, which reduces the effect of SLR damage compared to the year long pavement damage.

The main purpose of the model developed in this chapter is to provide a tool that can evaluate the lifetime of the roads for a traffic flow with heavy trucks similar to the trucks presented in Table 1.28 and variable heavy traffic distributions. The model is based on a linear accumulation of the damage (Miner's Law, Eq. 4.23). When Damage = 1, the service life of the road is reached.

The following procedures were used to determine the lifetime of the roads with and without SLR:

1. Based on the weights per axle showed in Table 1.27 and the type of axle, the traffic was distributed according to MnPAVE weight classes from the traffic spectrum section, which resulted into 11 types of weight classes. The range of each class is 9 kN (2 kips) and the computation uses the mark value for each class.
2. Each passing of an axle causes damage to the pavement. The amount of damage depends on the season (the material characteristics) and on the load. Using MnPAVE, the number of cycles to failure for rutting was determined. Assuming that each pass results in the same amount of damage regardless of the time in the pavement life when it is applied, the values of damage caused by one passing of each of the axle types in each season were calculated.
3. Next, the value of damage caused by each type of truck (full + empty) in one pass, in each season was calculated. This was done by adding up the damage caused by each axle corresponding to the particular type of truck and the particular type of loading (restricted for 5-tons, restricted for 7-tons or unrestricted) for that truck.
4. Knowing the length of each season and assuming that in each day of the year a full truck and an empty truck from one category are passing, the damage caused by this pair in each season was calculated.

5. Next, the damage values calculated for each season were added up and the damage caused by a pair of trucks in one year was calculated for each truck type - load restriction combination. These values were divided by 2, to obtain the damage per one truck, represented by the $a_i$ and $a_i^j$ coefficients.
6. The damage per year from the total number of passes for a particular type of truck is simply calculated by multiplying the "N" coefficients with the corresponding "a" coefficients.
7. The summation of all "aN" products for a particular traffic - road combination give the total damage accumulated during one year.
8. Considering that the pavement fails when the accumulated damage is 1, the lifetime of the road, in years, is calculated as the inverse of the yearly damage.
9. The ratio or the difference between the lifetimes determined with SLR in place and without SLR can quantify the savings of the SLR policy.

The results of the procedure are the functions given in Table 1.31. The meaning of the N and "a" coefficients was explained in the previous paragraphs.

Table 1.31 Equations for calculation of the pavement lifetime in years for various scenarios

| |
|---|
| *9-ton road – no restriction on the network*<br>Lifetime (pavement structure, $N_1$, $N_2$, $N_3$) = $\left(a_1N_1 + a_2N_2 + a_3N_3\right)^{-1}$ |
| *9-ton road –SLR on the network*<br>Lifetime (pavement structure, $N_1$, $N_2$, $N_3$, $N_1^9$, $N_2^9$, $N_3^9$, $N_1^{7\text{-}9}$, $N_2^{7\text{-}9}$, $N_3^{7\text{-}9}$, $N_1^{5\text{-}9}$, $N_2^{5\text{-}9}$, $N_2^{5\text{-}9}$) $=(a_1N_1 + a_2N_2 + a_3N_3 + a_1^9N_1^9 + a_2^9N_2^9 + a_3^9N_3^9 + a_1^{5-9}N_1^{5-9} + a_2^{5-9}N_2^{5-9} + a_3^{5-9}N_3^{5-9} + a_1^{7-9}N_1^{7-9} + a_2^{7-9}N_2^{7-9} + a_3^{7-9}N_3^{7-9})^{-1}$ |
| *7-ton road - SLR on the network*<br>Lifetime (pavement, $N_1$, $N_2$, $N_3$, $N_1^7$, $N_2^7$, $N_3^7$, $N_1^{5\text{-}7}$, $N_2^{5\text{-}7}$, $N_2^{5\text{-}7}$) =<br>$= \left(a_1N_1 + a_2N_2 + a_3N_3 + a_1^7N_1^7 + a_2^7N_2^7 + a_3^7N_3^7 + a_1^{5-7}N_1^{5-7} + a_2^{5-7}N_2^{5-7} + a_3^{5-7}N_3^{5-7}\right)^{-1}$ |
| *5-ton road - SLR on the network*<br>Lifetime (pavement, $N_1$, $N_2$, $N_3$, $N_1^5$, $N_2^5$, $N_3^5$) =<br>$= \left(a_1N_1 + a_2N_2 + a_3N_3 + a_1^5N_1^5 + a_2^5N_2^5 + a_3^5N_3^5\right)^{-1}$ |

**The Seasonal Variations in the Damage Caused by Heavy Trucks**

Table 1.32 and 1.33 present the damage caused by heavy trucks [xvi] assumed on different types of roads. The daily damage during SLR to a road with 51 mm (2") HMA layer and 153 mm (6") is plotted in Figure 1.17. The plot clearly indicates a significant reduction in the amount of damage induced in the pavement when the load of the trucks is reduced. If the road is posted as a 7-ton road, the amount of daily damage accumulated in the pavement during late spring is reduced by 20 to 36 percent. If the same road is posted as a 5-ton road, the reduction of daily damage during later spring is between 51 and 59 percent. These values become much smaller if a similar analysis is performed for the annual damage[xvii], as shown in Figure 1.18. The annual reduction in damage is between 5 to 9 percent if the road is posted as a 7-ton road and between 13 to 14 percent if the road is posted as a 5-ton road.

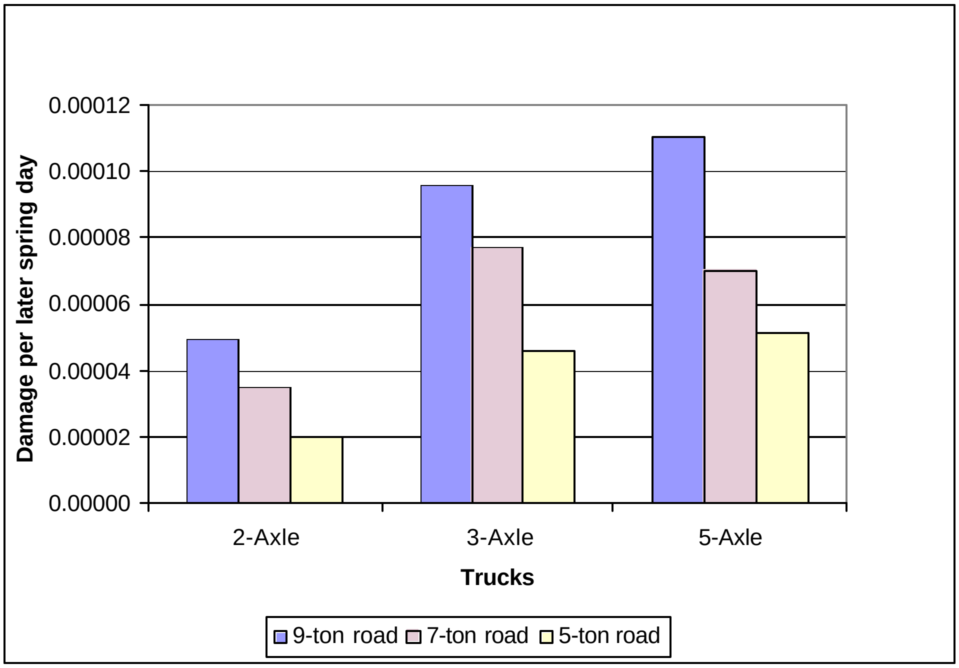


Figure 1.17 Load restriction effect on the daily damage in later spring for a road with 51 mm (2 in) HMA layer and 153 mm (6 in) base layer

Table 1.32 The distribution of damage per seasons (SLR=later spring) for one pair of trucks (1 empty and 1 full with admissible loads)

| **Pavement Structure** | **Seasons** | **9 ton roads** | | | **7 ton roads** | | | **5 ton roads** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **2 Axle Trucks** | **3 Axle Trucks** | **5 Axle Trucks** | **2Axle Trucks** | **3Axle Trucks** | **5 Axle Trucks** | **2 Axle Trucks** | **3 Axle Trucks** | **5 Axle Trucks** |
| 51 mm (2") HMA 153 mm (6") agg base Soil A6 | Fall | 15.38% | 15.48% | 15.52% | 16.53% | 16.26% | 17.04% | 17.98% | 17.71% | 17.84% |
| | Winter | 0.22% | 0.22% | 0.22% | 0.23% | 0.23% | 0.24% | 0.25% | 0.25% | 0.25% |
| | Early Spring | 0.33% | 0.31% | 0.33% | 0.35% | 0.32% | 0.36% | 0.38% | 0.35% | 0.38% |
| | Later Spring | **24.31%** | **24.49%** | **24.50%** | **18.62%** | **20.70%** | **17.10%** | **11.52%** | **13.62%** | **13.20%** |
| | Summer | 59.77% | 59.50% | 59.44% | 64.26% | 62.49% | 65.26% | 69.87% | 68.07% | 68.33% |
| 51 mm (2") HMA 204 mm (8") agg base Soil A6 | Fall | 17.37% | 17.11% | 17.49% | 18.87% | 18.10% | 19.50% | 20.79% | 19.94% | 20.57% |
| | Winter | 0.20% | 0.20% | 0.20% | 0.22% | 0.21% | 0.22% | 0.24% | 0.24% | 0.24% |
| | Early Spring | 0.31% | 0.29% | 0.32% | 0.34% | 0.31% | 0.36% | 0.38% | 0.34% | 0.38% |
| | Later Spring | **26.87%** | **26.61%** | **27.03%** | **20.55%** | **22.33%** | **18.63%** | **12.46%** | **14.45%** | **14.20%** |
| | Summer | 55.25% | 55.79% | 54.96% | 60.02% | 59.04% | 61.29% | 66.13% | 65.03% | 64.62% |
| 102 mm (4") HMA 153 mm (6") agg base Soil A6 | Fall | 11.75% | 11.17% | 11.79% | 12.45% | 11.63% | 12.75% | 13.33% | 12.42% | 13.24% |
| | Winter | 0.25% | 0.26% | 0.25% | 0.27% | 0.27% | 0.27% | 0.29% | 0.28% | 0.28% |
| | Early Spring | 0.57% | 0.53% | 0.58% | 0.60% | 0.56% | 0.63% | 0.65% | 0.59% | 0.65% |
| | Later Spring | **19.08%** | **18.21%** | **19.13%** | **14.28%** | **14.82%** | **12.56%** | **8.18%** | **9.03%** | **9.18%** |
| | Summer | 68.35% | 69.83% | 68.25% | 72.40% | 72.73% | 73.80% | 77.55% | 77.67% | 76.64% |

Table 1.33 Total damage per years (SLR=later spring) caused by one pair of trucks (1 empty and 1 full with admissible loads)

| **Pavement Layers Thickness** | | | **9 ton roads** | | | **7 ton roads** | | | **5 ton roads** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil** | **HMA** | **Base** | **2 Axle Trucks** | **3 Axle Trucks** | **5 Axle Trucks** | **2 Axle Trucks** | **3 Axle Trucks** | **5 Axle Trucks** | **2 Axle Trucks** | **3 Axle Trucks** | **5 Axle Trucks** |
| A6 | 51 mm (2”) | 153 mm (6”) | 1.14E-02 | 2.18-02 | 2.52E-02 | 1.06E-02 | 2.08E-02 | 2.30E-02 | 9.74E-03 | 1.91E-02 | 2.20E-02 |
| | 51 mm (2”) | 204 mm (8”) | 6.30E-03 | 1.21E-02 | 1.41E-02 | 5.78E-03 | 1.14E-02 | 12.6E-02 | 5.26E-03 | 1.04E-02 | 1.20-02 |
| | 102 mm (4”) | 153 mm (6”) | 2.42E-03 | 4.44E-03 | 5.44E-03 | 2.28E-03 | 4.28E-03 | 5.04E-03 | 2.12E-03 | 4.00E-03 | 4.84E-03 |

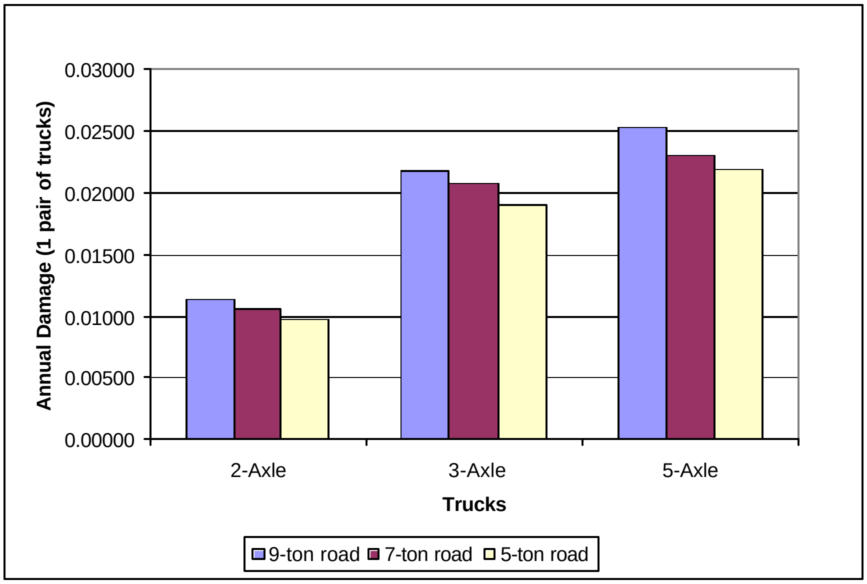

Figure 1.18 Load restriction effect on the annual damage for a road with 51 mm (2 in) HMA layer and 153 mm (6 in) base layer

The difference between the percent savings occurring in one later spring day and the percent savings occurring in one year can be explained by the large amount of daily damage that occurred in summer, as shown in figure 1.19, combined with the longer duration of summer time (109 days) compared to the later spring (56 days).

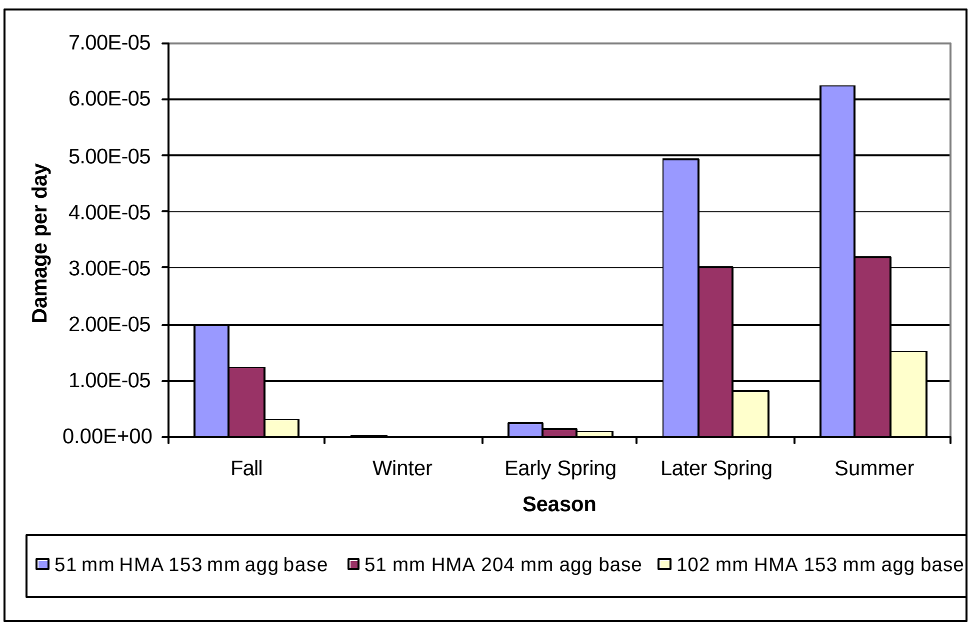

Figure 1.19 Variation of daily damage per season for a 2-axle truck

Figure 1.19 also indicates that based on the rutting criterion used in MnPAVE an increase of the quantity of freight transported during the summer time to offset the reduced operations of the carrier during the SLR season on the three types of roads analyzed can cause more damage than if no load restriction were imposed.

The results presented in Table 1.33 and Figure 1.18 indicate that a 5-axle truck induces the largest amount of damage in the pavement structure. However, if the problem is posed in terms of the damage caused by one ton transported, the order is changed. When the freight is carried with a 5-axle truck, the amount of damage caused by one ton transported is approximately 30 percent smaller than when the transportation is provided by a 2- or 3-axle truck, as shown in Figures 1.20 and 1.21. This observation is independent of the road category.

The results also indicate that any increase in the quality of the materials or the thickness of the pavement layers decreases the damage. An increase of the thickness of the asphalt layer has the most significant reduction in the damage caused by heavy vehicles during spring. A comparison between a pavement structure with 51 mm (2 in) and 153 mm (6 in) granular base and a structure with 102 mm (4 in) and 153 mm (6 in) granular base shows that 51 mm more in the thickness of the asphalt layer reduces the annual damage by 80 percent and the value of the daily later spring damage by 84 percent.

The analysis presented in this chapter illustrates the effects of the three most representative types of heavy trucks on local roads under different SLR scenarios. Note that the yearly and seasonal damage results were based on the assumption of a uniform traffic during the year and did not take into account the variation in the numbers of trucks during SLR period and the truck distribution during the seasons. The economic calculations, however, do take into account these variations based on the traffic counts collected from the counties included in the analysis.

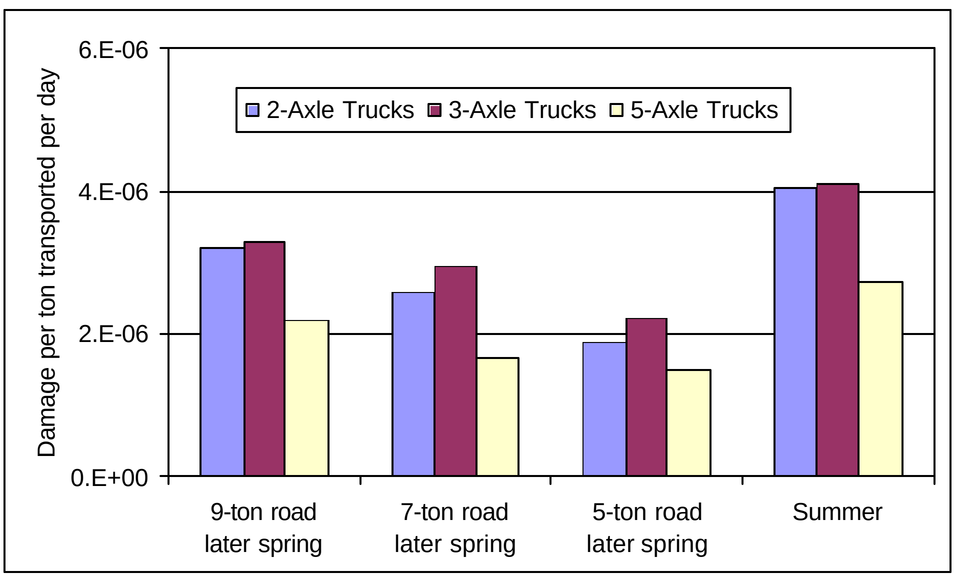


Figure 1.20 Damage per transported ton for a pavement with 51 mm (2 in) HMA layer and 153 mm (6 in) base layer

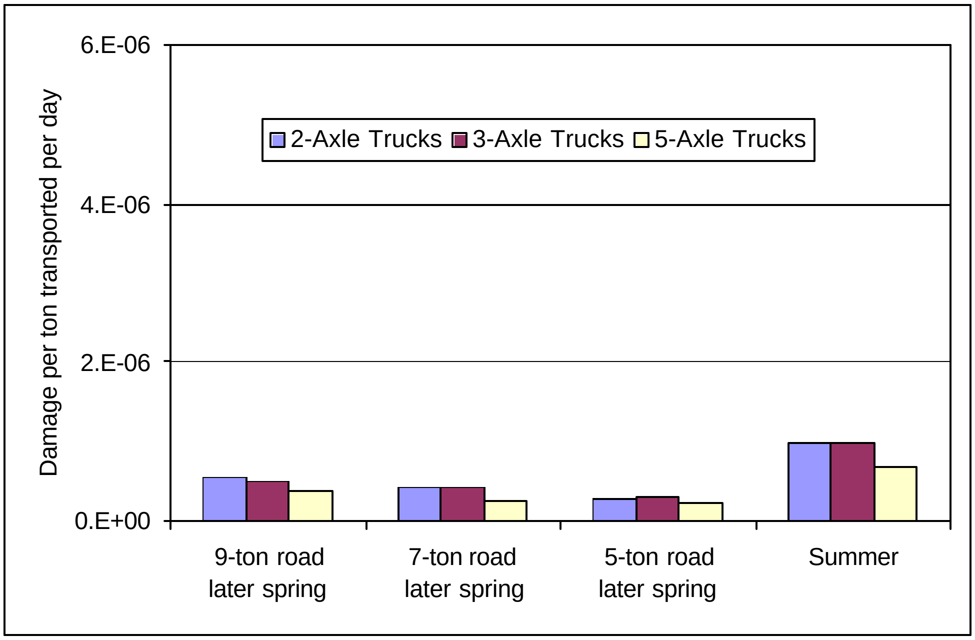


Figure 1.21 Damage per transported ton for a pavement with 102 mm (4 in) HMA layer and 153 mm (6 in) base layer

# 1.6 Conclusions

## Observations

This research quantifies the effects of the spring load restriction on local roads in Minnesota. The data collected from the State Aid Office and the counties indicated that local roads in Minnesota are designed based on various empirical design methods. Currently, there is a large diversity of pavement structures on the local roads network; in many instances the same pavement structure was posted as 9-ton, 7-ton, and 5-ton depending on the location of the road.

The research showed that, given the lack of traffic and pavement condition data for local roads and the large degree of empiricism associated with pavement design and performance in general, a reasonably approximate model for the evaluation of the SLR impact on the lifetime of the roads can be developed based on a mechanistic-empirical approach calibrated on trunk highway pavements, for which traffic and pavement condition data is less scarce. Unlike the empirical design methods, this approach is sensitive to the variation of truck loads caused by the restriction program and to the seasonal variation of the traffic flow and can be easily integrated in the more complex economics analysis required to evaluate the cost-benefit of SLR.

## Conclusions

The analysis performed in this task led to a number of important conclusions. However, these conclusions should be interpreted with caution due to the inherent limitations associated with any type of pavement evaluation analysis, as described in chapter 5:

- The pavement structures that are posted as 5-, 7-, and 9-ton roads vary from county to county. In many cases the decision concerning the roads classification is made by considering the performance indicators (distresses and deflections) measured at different times during the pavement life
- Based on the mechanistic-empirical analysis performed using MnPAVE software, rutting represents the most frequent cause of failure of the local roads. However, the survey performed as part of this task indicates low temperature thermal cracking as the primary distress (similar to trunk highways in Minnesota). This distress can be significantly reduced by a better selection of the asphalt binder grade used in the asphalt pavement. The effect of traffic or of spring thaw on thermal cracking is unknown and has not been researched so far.
- MnPAVE rutting model indicates a significant reduction in the damage accumulated during spring when load restrictions are imposed. For a road with a 51 mm (2”) asphalt layer and 153 mm (6”) aggregate base posted as a 7-ton road, the amount of daily damage accumulated in the pavement during later spring is reduced by 20 to 36 percent. If the same road is posted as a 5-ton road, the reduction of daily damage during later spring is between 51 and 59 percent. However, these numbers drop to less than one third if the analysis considers the damage accumulated in one full year due to the large amount of damage that accumulates in summer as a result of the substantial decrease in the asphalt mixture modulus. The annual reduction in damage

is between 5 to 9 percent if the road is posted as a 7-ton road and between 13 to 14 percent if the road is posted as a 5-ton road. This is in agreement with data published for Quebec flexible pavements, which indicates an increase of between 6 to 14 percent in the average life expectancy of pavements due to SLR. [67]

- The amount of damage induced in the flexible pavement by trucks increases with the number of axles. In terms of transported tons, a ton transported with a 5-axle truck induces 30 percent less annual damage than a ton transported with a 2- or 3-axle truck. This observation is independent of the assumed SLR scenario. An increase in the quantity of freight transported on the road during the summer as a consequence of the reduced operations of the carrier during the SLR season most likely can cause more damage to the pavement than the case when no load restriction would be imposed.
- An increase in the thickness of the asphalt layer significantly decreases the values of the annual damage. A comparison between a pavement structure with 51 mm (2 in) and 153 mm (6 in) granular base and structure with 102 mm (6 in) and 153 mm (6 in) granular base shows that addition of 51 mm in the thickness of the asphalt layer reduces the annual damage by 80 percent and the value of the daily later spring damage by 84 percent.

**Recommendations**

The research performed to evaluate the effect of the spring load restrictions program on local roads resulted in the following recommendations:

- The input data required to design and evaluate local roads in Minnesota is very scarce. This includes traffic distribution and axle load information as well as pavement condition information, such as cross section, age, and distresses. It is therefore recommended that this data is collected and stored periodically; traffic and distress data need to be collected during the different critical seasons of the year to better evaluate the damage level that occurs during spring load restriction.
- The SLR damage evaluation can be improved if a rutting model based on the accumulation of permanent deformation in all layers is developed and calibrated. As a first step, MnPAVE results should be compared to the new Design Guide software. In the near future, as more performance data becomes available for typical local roads, MnPAVE should be calibrated for pavements with thinner asphalt layers.

The most direct and reliable approach to investigate the effect of spring load restrictions is to perform a simple field experiment as follows:

- Build two test sections with cells that are representatives of the cross sections characteristic of typical local pavements.
- Load the first section with unrestricted traffic loads during SLR and load the second one with restricted traffic loads during SLR.
- Monitor their performance in time and determine the pavement life savings due to the application of SLR.

Until such an experiment is performed and completed it is recommended that the conclusions of this analysis should be used in policy making only after consultations with experienced state, county and city engineers.

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## Endnotes

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[i] A detailed explanation of these indices is given in Part 3 of Task 1.
[ii] From this point on, restricted roads refer to County and State Aid paved roads for which traffic and information was available.
[iii] An excerpt from State Aid Manual with the definition of the main type of roads is given in Appendix 1.
[iv] In this table, city roads embed municipal streets and municipal state aid system.
[v] A table with the responses of the county engineers at the survey can be found in Appendix 2.
[vi] The data used for the computation are presented in Appendix 2. The data count only state aid highways and county highways.
[vii] The explanation of the Soil Factor and the R-value is provided in Section 3.2.2. "Design Methods Used for Pavement of the Local Roads".
[viii] There are other devices to measure the deflection but FWD is the most frequently used. Moreover, a large part of the research done is based on the results obtained using FWD device.
[ix] Equations 3.11 and 3.22 have been presented and explained in Chapter 3.
[x] The description of the MnPAVE software is based on [27], on personal experience using this program and discussions with Bruce Chadbourne – Research Project Engineering Mn/DOT.
[xi] The increase in the value of the coefficient $K_{F1}$ when the thickness is less than 114.75 mm (4.5 in) is not calibrated and it is recommended that it be used in design of the new pavement when MnPAVE runs in standard mode.
[xii] The climate parameters are typical for Lyon County.
[xiii] The values from the table are the default values in MnPAVE.
[xiv] Note that the superscript index indicates traffic during the SLR period time, while an unsuperscripted index indicates traffic during unrestricted period of time.
[xv] The load distribution assumed for heavy commercial traffic is: 24.4% 2-axle trucks (half empty half fully loaded), 11% 3-axle trucks (half empty, half fully loaded), and 64.5% 5-axle trucks (half empty, half fully loaded).
xvi The results were obtained for one pair of trucks, one empty and one loaded with admissible load.

[xvii] The annual damage is the damage caused to the pavement by a pair of trucks traveling daily, all year long.

# Chapter 2

Task #2: Conduct surveys of shippers and carriers.

## 2.1 Introduction

To determine the economic impacts of SLR, surveys of commercial road users were performed. The cost of SLR on commercial vehicle operators is the consequence of alternate behavior resulting from the imposition of the restrictions. This alternate behavior can be summarized as any combination of the following options: shift the seasonal timing of shipments, reduce load size per vehicle (resulting in more trips), change vehicle type, or change routes (to longer but less restricted roadways). All these behaviors add costs to the operation of commercial vehicles.

This research describes the study and calculates the average and marginal truck operating cost in Minnesota by using models estimated from data collected from a large sample of different trucking companies. Using more detailed adaptive stated preference surveys, the research also calculates value of time. Truck operating cost per km were used, along with data from the freight demand model, to determine the cost of the SLR on the freight industry.

This report consists of several parts. Section 2 discusses the framework and process of the mail-out/mail-back survey. Section 3 estimates a cost model from the survey data. Section 4 provides an overview of the theory that was used as a building block for the stated preference analysis to estimate value of time. It details the methodology used in the interview and surveying process. Section 5 presents the results of the interviews and explains the variation in results. Finally, the conclusion summarizes the findings and their relation to the benefit/cost study, and discusses further analysis.

## 2.2 Mail-Out/Mail-Back Survey

The objective of the mail-out/mail-back survey was to obtain values to enable the estimation of truck operating costs, appraise the effect of SLR on freight transportation among different sectors of the freight industry and collect general information about their operation, and willingness to participate in an in-depth interview. The survey collected data which was believed to affect value of time and operating cost, such as size of company, type of trucks and company strategy.

Data were collected for different trucking companies in Minnesota. The target was the decision maker in each company, who was thought to be able to give accurate information of how their trucks operate. Contact information was obtained from different sources: Minnesota Department of Transportation (Mn/DOT) Freight Facilities Database, Minnesota Trucking Association (MTA) board of directors, Mn/DOT overweight permit list, Mn/DOT filed insurance list, and a list of significant local trucking companies in Minnesota identified by city and county engineers. The surveys were mailed during the spring of 2003 in three waves: before SLR, during SLR, and after SLR. Table 2.1 displays our response rates.

The mail-out/mail-back survey comprised two different types of questionnaires: about half of the firms received a long form consisting of 19 questions, the others received a short form consisting of 7 of those same 19 questions. It was estimated to take twenty minutes for a person to complete the long-form questionnaire. The two different forms were used to test the loss in responses due to survey fatigue, as some respondents might be unwilling to spend significant time answering the questionnaire.

Results show there is a difference between the response rates for these two forms, (Table 2.2), the long form resulted in an 18% response rate (both overall and for the subjects obtained from the freight facility database), while the short form had a 25% rate. No follow-up contacts with potential respondents were made to increase the response rate.

As previously stated, the survey questionnaires were mailed in three different waves, pre-SLR, during SLR and post-SLR, to study the difference between responses. Results show the response rate is higher before SLR (26%) than during (18%) or after (20%) the period of SLR, while controlling for subjects from the same source database.

Respondents were asked if they would be willing to participate in future interviews for more information, of which, 50.9% said they were willing to be interviewed. Interviews were conducted later to estimate value of time from a stated preference survey, as described in later sections of this report.

Important information was obtained from the survey, including: type of trucks and number of axles, overall distance traveled by a firm's trucks, number of employees, type of products that a firm hauls, if the company is assessed financial penalties for late or missed delivery, who chooses the route, total truckloads per year, operating cost per unit distance, if they impose a fuel surcharge, and how do they pay their drivers. These descriptive results from the survey are summarized in Appendix 2-3.

**Table 2.1** Response Rates For Mail-Out/Mail-Back Survey

| Sample | Count Response Rate By Survey Group | Total Returned | Return Rate | Bad Addresses | Bad Address Rate | Actual Responses | Actual Response Rate | Actual Response Rate (Adjusted) |
|---|---|---|---|---|---|---|---|---|
| MTA February 2003 - Pre SLR, Long Form | 34 | 12 | 35.3% | 0 | 0.0% | 12 | 35.3% | 35.3% |
| FF March 3 2003 - Pre SLR, Long Form | 165 | 45 | 27.3% | 27 | 16.4% | 18 | 10.9% | 13.0% |
| FF March 3 2003 - Pre SLR, Short Form | 200 | 76 | 38.0% | 31 | 15.5% | 45 | 22.5% | 26.6% |
| FF March 6 2003 - Pre SLR, Long Form | 51 | 24 | 47.1% | 12 | 23.5% | 12 | 23.5% | 30.8% |
| FF March 6 2003 - Pre SLR, Short Form | 50 | 27 | 54.0% | 4 | 8.0% | 23 | 46.0% | 50.0% |
| FF March 10 2003 - Pre SLR, Long Form | 50 | 24 | 48.0% | 6 | 12.0% | 18 | 36.0% | 40.9% |
| FF March 10 2003 - Pre SLR, Short Form | 50 | 23 | 46.0% | 11 | 22.0% | 12 | 24.0% | 30.8% |
| FF March 21 2003 - SLR, Long Form | 300 | 79 | 26.3% | 39 | 13.0% | 40 | 13.3% | 15.3% |
| FF March 21 2003 - SLR, Short Form | 300 | 103 | 34.3% | 51 | 17.0% | 52 | 17.3% | 20.9% |
| MnDOT April 4 2003 - SLR, Long Form | 459 | 104 | 22.7% | 53 | 11.5% | 51 | 11.1% | 12.6% |
| FF May 23 2003 - Post SLR, Long Form | 300 | 98 | 32.7% | 56 | 18.7% | 42 | 14.0% | 17.2% |
| FF May 23 2003 - Post SLR, Short Form | 300 | 96 | 32.0% | 39 | 13.0% | 57 | 19.0% | 21.8% |
| CC June 5 2003 - Post SLR, Long Form | 264 | 77 | 29.2% | 18 | 6.8% | 59 | 22.3% | 24.0% |
| | 2523 | 788 | 31.2% | 347 | 13.8% | 441 | 17.5% | 20.3% |

Note: MTA refers to Minnesota Trucking Association as the mailing list source, FF refers to the Mn/DOT Freight Facilities database as the source, Mn/DOT refers to the filed insurance and overweight permit lists as the source, and CC refers to the city/county engineer surveys as the source.

**Table 2.2** Summary Response Rates For 1st Cut Survey

| | Count | Total Returned | Return Rate | Bad Addresses | Bad Address Rate | Actual Responses | Actual Response Rate | Actual Response Rate (Adjusted) |
|---|---|---|---|---|---|---|---|---|
| Response Rate By Form Type | | | | | | | | |
| Long Form | 1623 | 463 | 28.5% | 211 | 13.0% | 252 | 15.5% | 17.8% |
| Short Form | 900 | 325 | 36.1% | 136 | 15.1% | 189 | 21.0% | 24.7% |
| Response Rate By Wave | | | | | | | | |
| Pre SLR (MTA, FF) | 600 | 231 | 38.5% | 91 | 15.2% | 140 | 23.3% | 27.5% |
| SLR (FF & MnDOT) | 1059 | 286 | 27.2% | 143 | 13.5% | 143 | 13.5% | 15.6% |
| Post SLR (FF, CC) | 864 | 271 | 31.4% | 113 | 13.1% | 158 | 18.3% | 21.0% |

Table 2.3 summarizes the results of average trip length per truckload by industry. Truck loads are assumed to be round trips. Results show food products have the most km per truckload compared to other industries. Table 2.3 also summarizes the percent of trip length that a firm's trucks spend on roads subject to SLR (Based on Question 15 of the Long Form). One can see that the rubbish industry is most affected by the imposition of SLR. It should be noted that there were only three respondents in this industry.

The average cost from data collected was $0.69/km ($1.11/mile). This was for a sample of 186 different trucking companies. The answers ranged between $0.087/km and $2.98/km ($0.14 - $4.79/mi), which shows the diversity of cost per km by industry and size of company (see Figure 1). Typical labor cost for commercial trucks is around $0.22/km ($0.35/mi). Values below $0.31/km ($0.50/mi) may exclude or undervalue labor cost. The data around $0.69/km ($1.11/mi) more accurately represents the total cost of operating a truck per km, such that the respondents correctly interpreted the question as total cost including labor. A follow up study was conducted to get a better result for cost per km. All respondents who reported operating cost per km less than $0.31/km were re-contacted by phone to verify survey answers. There were total of 26 responses less than $0.31/km. Of these respondents, seven of them re-verified their operating costs while five respondents revised them. The remaining 14 respondents could not be reached. None of the responses were removed from the data, since it is uncertain as to whether the responses were incorrect.

**Table 2.3** Responses by Industry Type

| | Km/Truckload | Miles/Truckload | % of Trip Length Affected by SLR | Response Count |
|---|---|---|---|---|
| Ag Chem | 151 | 242 | 38.5% | 14 |
| Aggregate | 66 | 106 | 20.6% | 23 |
| Agricultural | 312 | 499 | 28.7% | 61 |
| Beverages | 259 | 414 | 15.0% | 3 |
| Construction | 392 | 627 | 12.6% | 10 |
| Dairy | 635 | 1016 | 1.8% | 3 |
| Food Products | 1446 | 2314 | 9.7% | 15 |
| General Products | 989 | 1582 | 6.3% | 23 |
| Industrial Supplies | 1058 | 1693 | 5.6% | 16 |
| Paper | 354 | 566 | 1.7% | 4 |
| Petroleum | 235 | 376 | 35.1% | 12 |
| Rubbish | 161 | 258 | 100.0% | 3 |
| Timber | 379 | 606 | 45.8% | 10 |
| **Average** | 503 | 805 | 22.2% | 198 |

Note: % Of Trip Affected by SLR from Long-Form respondents only.

Owner/operators have higher operating cost compared to non owner/operators, as shown in Table 2.4, perhaps a result of having fewer trucks to distribute their fixed operating costs. If economies of scale exist, it makes sense that smaller firms have higher operating cost. Figure 2.1 displays a histogram of costs.

**Table 2.4** Operating Costs

| **Table 4a Cost/km** | Response Count | Average | Mode | Median | Standard Deviation |
|---|---|---|---|---|---|
| Overall | 186 | $0.69 | $0.62 | $0.60 | $0.44 |
| | | | | | |
| By Industry | | | | | |
| Rubbish | 2 | $1.54 | | $1.54 | $1.30 |
| Dairy | 3 | $1.03 | | $0.84 | $0.47 |
| Food Products | 18 | $0.90 | $0.60 | $0.64 | $0.66 |
| Paper | 4 | $0.85 | | $0.86 | $0.29 |
| Petroleum | 11 | $0.81 | $1.86 | $0.78 | $0.62 |
| Timber | 5 | $0.76 | | $0.56 | $0.40 |
| Aggregate | 22 | $0.70 | $0.30 | $0.61 | $0.37 |
| Industrial Supplies | 12 | $0.68 | $0.56 | $0.59 | $0.43 |
| Construction | 13 | $0.67 | $0.40 | $0.59 | $0.35 |
| Ag Chem | 15 | $0.62 | $0.80 | $0.48 | $0.67 |
| Agricultural | 55 | $0.61 | $0.50 | $0.55 | $0.32 |
| General Products | 24 | $0.60 | $0.78 | $0.65 | $0.29 |
| Beverages | 2 | $0.50 | | $0.50 | $0.54 |
| | | | | | |
| Ownership | | | | | |
| Owner/Operator | 21 | $0.84 | $0.93 | $0.50 | $0.69 |
| Non Owner/Operator | 165 | $0.67 | $0.80 | $0.61 | $0.39 |

| Table 4b<br>Cost /Mile | Response<br>Count | Average | Mode | Median | Standard<br>Deviation |
|---|---|---|---|---|---|
| Overall | 186 | $1.10 | $0.99 | $0.96 | $0.70 |
| | | | | | |
| By Industry | | | | | |
| Rubbish | 2 | $2.46 | | $2.46 | $2.08 |
| Dairy | 3 | $1.65 | | $1.34 | $0.75 |
| Food Products | 18 | $1.44 | $0.96 | $1.02 | $1.06 |
| Paper | 4 | $1.36 | | $1.38 | $0.46 |
| Petroleum | 11 | $1.30 | $2.98 | $1.25 | $0.99 |
| Timber | 5 | $1.22 | | $0.90 | $0.64 |
| Aggregate | 22 | $1.12 | $0.48 | $0.98 | $0.59 |
| Industrial Supplies | 12 | $1.09 | | $0.94 | $0.69 |
| Construction | 13 | $1.07 | $0.64 | $0.94 | $0.56 |
| Ag Chem | 15 | $0.99 | $1.28 | $0.77 | $1.07 |
| Agricultural | 55 | $0.98 | $0.80 | $0.88 | $0.51 |
| General Products | 24 | $0.96 | $1.25 | $1.04 | $0.46 |
| Beverages | 2 | $0.80 | | $0.80 | $0.86 |
| | | | | | |
| Ownership | | | | | |
| Owner/Operator | 21 | $1.34 | $1.49 | $0.80 | $1.10 |
| Non Owner/Operator | 165 | $1.07 | $1.28 | $0.98 | $0.62 |

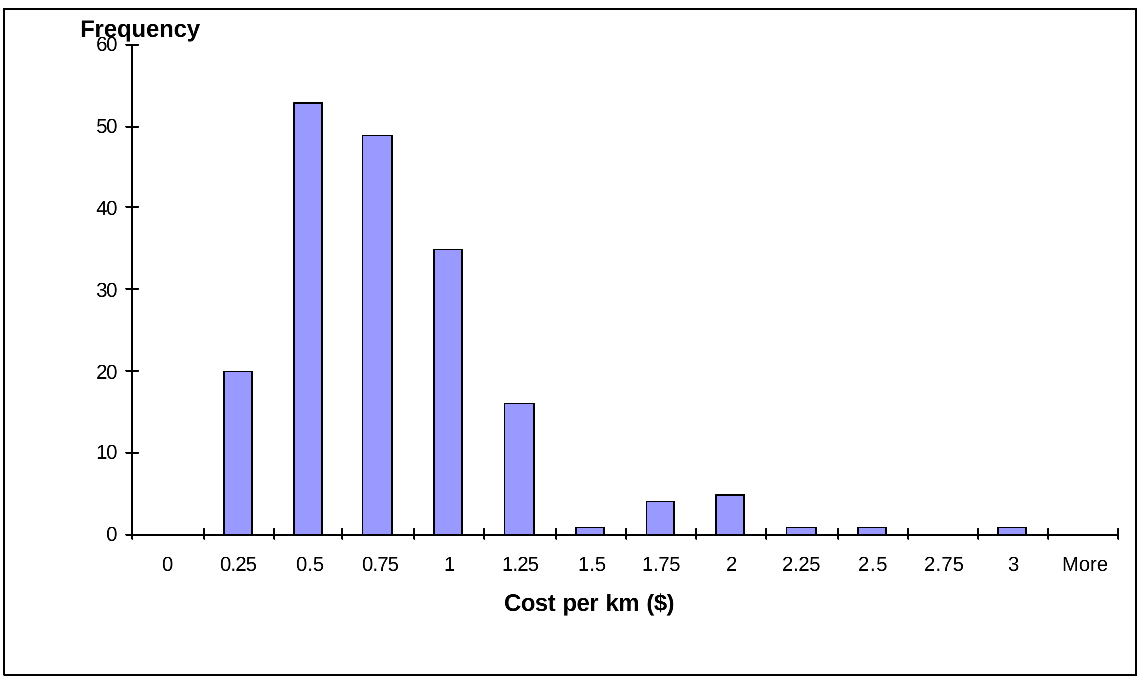


**Figure 2.1 Histogram of Reported Operating Cost Per Km**

## 2.3 Operating Cost Models

There are many approaches to estimate the operating cost for trucks. Each of them employs a different methodology and models to calculate the variable costs of operating trucks. Fuel, repair and maintenance, tire, depreciation, and labor cost are the most important costs that are considered to estimate operating cost.

Daniels divided vehicle operating cost into two different categories, running costs and standing cost [1]. Running cost includes fuel consumption, engine oil consumption, tire costs, and maintenance cost. Standing cost includes license, insurance, and interest charges. Speed was reported as the most important factor in fuel consumption and maintenance costs rise with increasing speed. If fuel consumption and maintenance cost change, operating cost will change as well. Vehicle size is another factor that affects fuel consumption and it will change operating cost. Vehicle size was included in the model by using average axle number for each firm.

Watanatada divided the variables that affect the truck operating cost to the following categories [2]:

1) Truck characteristics (e.g., weight, engine power, maintenance)
2) Local factors (e.g., speed limit, fuel price, labor cost, drivers attitude)
3) Road characteristics (e.g., pavement roughness, road width)

Operating cost is considered a function of road characteristics and so is policy sensitive.

Barnes estimated operating cost for commercial trucks based on fuel, repair, maintenance, tires and depreciation costs [3]. He also considered adjustment factors for cost, based on pavement roughness, driving conditions and fuel price changes. He estimated an average of truck operating cost at $0.27/km ($0.43/mile), not including labor cost. If one assumes labor costs are around $0.22/km ($0.35/mile), total operating cost using Barnes model will be around $0.49/km ($0.78/mile). This number can be used as a check for operating cost per km data obtained from the survey.

Firms seek to minimize their cost including truck operating cost. Truck operating cost for each firm can be divided into fixed and variable costs. Fixed costs are not sensitive to the volume of output, but variable costs change with the level of output.

Waters has explained different costing methods that are useful to estimate the relationship between outputs and costs [4]. One of the methods that has been used in transportation studies is the statistical costing method. In this method the relationship between outputs and costs are estimated using statistical techniques across observations. Multiple regression analysis shows how cost changes by changing any of the variables. In this study this statistical method will be used to estimate the effect of different variables on operating cost. The primary factors which are posited to be important in estimating total operating cost for different firms include firm size, strategy, type, and if economies of scope are present.

**Size of firm:**

Transportation cost, including the question of economy of scale, has been of interest to decision makers in different transportation sectors for many years. Managers need to have enough information about their costs to make the right decision about the type of services to provide and the prices to charge [5]. There are many factors that can be used to determine the presence of economies of scale for firms in the transportation industry. In railroads, economy of scale can be estimated for traffic density, length of haul, size of firm, and number of products. The studies that were conducted to estimate economies of scale for railroad industry during the 1950s and 1960s showed there was no economy of size or traffic density. Later studies in 1970s showed increasing returns and economies of traffic density for large railroads [6]. Results show that to reduce railroad cost, the flow of traffic over existing lines should increase or the lines with light traffic need to be eliminated. In the airline industry, cost studies have found the unit cost of service within any city-pair market decreases quickly, there are roughly constant returns to scale exist for U.S. trunk carriers, and there are economies of scale for smaller airlines [6]. Economies of density in the airline industry exist because average costs decline as a plane filled and because larger planes can move more passengers at a lower average cost. Most of the studies for motor carriers, for example Winston *et al.* (1990) and Allen and Liu (1995), show that they operate subject to constant returns to scale, however smaller carriers may operate with some increasing returns to scale [5].

Economies of scale in larger firms would reduce operating cost. This means larger companies should have a lower cost per unit distance. In this case two factors give us size of firm: km per truckload and number of truckloads. These factors are considered important and are expected to be significant in the model. *Km/Truckload* (*K/T*) is calculated by dividing the total kilometers traveled by firm's truck in a year by total annual truckloads. It measures average length of haul for each firm. This variable is expected to be statistically significant in the model as total cost should increase by increasing km/load. The *Number of Truckloads* (*T*) was asked directly from each firm and is another indicator of the size of the firm. The expectation is that it will be statistically significant and the total cost increases with number of truckloads.

**Firm Strategy:**

Each firm develops its own strategy based on management policy, which may lead to differences in operating costs for firms. In this study firms were asked if they were assessed financial penalties by clients for late or missed delivery. Firms were also asked how they determined driver compensation and if compensation is linked to on-time delivery, and if they have a fuel surcharge. All these policies could be used as variables in the model. *Financial Penalty* (*P*) indicates the company was assessed a financial penalty by clients for late or missed deliveries. By paying a financial penalty to the client, operating costs should increase, so it is expected it will be positive and significant.

**Type of Firm:**

Different industries have different lengths of haul for their products. *Owner/operator* (*O*) indicates the company owns and operates its own trucks. Survey results reveal the difference in operating cost for owner/operators versus non owner/operators. Owner/operators have larger cost per km. The reason for this may be the absence of economies of scale and that they have fewer trucks over which to distribute their firm's fixed costs. The models are estimated separately for each type of firm.

**Economy of Scope:**

A firm is said to operate with economy of scope if for outputs $y_1$ and $y_2$

$$C(y_1, y_2) < C(0, y_2) + C(y_1, 0) \tag{1}$$

That means the cost of producing two outputs with one firm is less than the cost of producing each output with two different firms. In this case economy of scope has been tested by considering the number of goods that a firm hauls as an output. An indicator for multi-product firms (*H*) indicates if a firm hauls more than one good. Using *H* as a categorical variable in the model allows testing to see if economies of scope exist in the trucking industry.

**Total Cost Model**

To measure the effects of the hypothesized independent variables, statistical models with total operating costs as the dependent variable are estimated. Total operating cost (*C*) is calculated by using the following formula:

$$C = K * (C / K) \tag{2}$$

Where: $C$ is cost, $K$ is overall kilometers, and $C / K$ is cost per kilometer.

Both overall kilometers and operating cost per km have been asked directly of each firm.

**Linear Regression model**

First a linear model is tested with Ordinary Least Squares (OLS) regression. The following model has been generated using total cost as a dependent variable and kilometers, the number of truckloads, financial penalties, owner/operator status, and whether or not the firm hauls more than one good as independent variables.

$$C = b_0 + b_1(K / T) + b_2T + b_3P + b_4O + b_5H \tag{3}$$

Where:
*C* is Total Annual Cost
*K* is kilometers
*T* is number of truckloads
*P* is 1 if firm is assessed a financial penalty for late delivery, 0 otherwise
*O* is 1 if the firm is owner/operator, 0 otherwise
*H* is 1 if the firm hauls more than one product, 0 otherwise

From the correlation matrix (Table 2.5), one can see number of truckloads (*T*) is highly correlated with number of drivers (*D*) and overall kilometers (*K*); because all of them represent size of firm, just one of them is used in the model.

**Table 2.5** Correlation Matrix

| | *T* | *D* | *K* | *P* | *O* | *(K/T)* | *H* |
|---|---|---|---|---|---|---|---|
| *T* | 1.0000 | | | | | | |
| *D* | 0.7441 | 1.0000 | | | | | |
| *K* | 0.3867 | 0.7418 | 1.0000 | | | | |
| *P* | 0.3108 | 0.3088 | 0.2520 | 1.0000 | | | |
| *O* | -0.1207 | -0.1289 | -0.0748 | -0.1710 | 1.0000 | | |
| *K/T* | -0.0417 | -0.0185 | 0.0076 | -0.0245 | -0.0116 | 1.0000 | |
| *H* | -0.0134 | 0.0254 | 0.0324 | -0.0634 | -0.1447 | -0.1877 | 1.0000 |

**Cobb-Douglas Model**

Cobb-Douglas models are often used to estimate cost functions and may provide a better fit than the linear model.

The form of the Cobb-Douglas model used in this model is:

$$C = e^{b_0}(K/T)^{b_1} T^{b_2} (e^P)^{b_3} (e^O)^{b_4} (e^H)^{b_5} \quad (4)$$

The coefficient $b$ on the independent variable is the elasticity of cost with respect to that independent variable such as output. It shows the percentage change in total cost resulting from a 1 percent increase in the level of output.

Using a Cobb-Douglas model produces the following:

$$Ln(C) = b_0 + b_1 Ln(K/T) + b_2 Ln(T) + b_3 Ln(e^P) + b_4 Ln(e^O) + b_5 Ln(e^H) \quad (5)$$

The results from fitted models are shown in Table 2.6. The linear model is not a good fit for our data. Just two of the independent variables are significant and the R-squared is 0.180. In the Cobb-Douglas model three independent variables are statistically significant with p-value less than 0.05, R-squared is about 0.95.

Results show the elasticity of total cost with respect to the km/load and truckload is close to 1, (the coefficient on $Ln(K/T)$) and $Ln(T)$), which means that as the km/load rate or truckload rate increase by 1 percent, the total cost will increase roughly by 1 percent as well, which is expected. However coefficients are slightly greater than 1, indicating overall diseconomies. The coefficients on $Ln(e^P)$ and $Ln(e^O)$ show the elasticity of total cost with respect to the two categorical variables: *O* and *P*. Total cost increases with both variables. Because the coefficients are smaller than 1 (both are around 0.3), it means if the variables increase by 1 percent, cost increases by 0.3 percent. The coefficient on $Ln(e^H)$ is statistically insignificant and indicates no economies of scope.

**Table 2.6** Estimated Models of Total Operating Cost

| Variable | | Linear Model | Cobb-Douglas Model |
|---|---|---|---|
| **K/T** | ß | 45.27 | 1.015 |
| | Std-Error | 117.130 | 0.033 |
| | T-stat | 0.390 | 30.620 |
| | p-value | 0.700 | 0.000 |
| *T* | ß | 117.34 | 1.043 |
| | Std-Error | 28.8 | 0.029 |
| | T-stat | 4.07 | 35.87 |
| | p-value | 0.000 | 0.000 |
| *P* | ß | 3973163 | 0.297 |
| | Std-Error | 1791364 | 0.118 |
| | T-stat | 2.22 | 2.52 |
| | p-value | 0.028 | 0.013 |
| *O* | ß | -43952 | 0.312 |
| | Std-Error | 2597629 | 0.172 |
| | T-stat | -0.02 | 1.81 |
| | p-value | 0.987 | 0.072 |
| *H* | ß | 1095115 | -0.012 |
| | Std-Error | 2100002 | 0.13 |
| | T-stat | 0.52 | -0.09 |
| | p-value | 0.603 | 0.927 |
| *Constant* | ß | -948570 | -1.037 |
| | Std-Error | 2111996 | 0.328 |
| | T-stat | -0.45 | -3.16 |
| | p-value | 0.645 | 0.002 |
| R-Squared | | 0.180 | 0.945 |
| N | | 145 | 145 |

To determine if the Cobb-Douglas is a good fit for our data, one can look at the summary graph of the final model. Figure 2.2 shows the actual values versus predicted values. Results show the predicted total cost by using the Cobb-Douglas model is close to the actual values.

To determine if economies of scale exist in the trucking industry, each industry type can be looked at individually. Models 3-6 (Table 2.7) show the results of the Cobb-Douglas model for four industry types that had a relatively large number of observations. It is important to note that translog models were also employed, but since they provided no improvement in explanatory power, their results were not included.

**Table 2.7** Cobb-Douglas estimate of total cost for different industry

| | | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|
| Variable | | Agriculture | General Product | Aggregate | Food Product |
| **K/T** | ß | 1.047 | 1.023 | 0.718 | 0.509 |
| | Std-Error | 0.50 | 0.145 | 0.120 | 0.227 |
| | T-stat | 20.910 | 7.070 | 5.960 | 20240 |
| | p-value | 0.000 | 0.000 | 0.000 | 0.055 |
| *T* | ß | 1.102 | 1.125 | 0.809 | 0.905 |
| | Std-Error | 0.043 | 0.083 | 0.119 | 0.182 |
| | T-stat | 25.630 | 13.500 | 6.800 | 4.980 |
| | p-value | 0.000 | 0.000 | 0.000 | 0.001 |
| *P* | ß | 0.214 | 0.335 | 0.712 | 0.128 |
| | Std-Error | 0.161 | 0.440 | 0.354 | 0.446 |
| | T-stat | 1.330 | 0.810 | 2.100 | 0.290 |
| | p-value | 0.191 | 0.433 | 0.075 | 0.782 |
| *O* | ß | 0.659 | 0.179 | -0.317 | 0.364 |
| | Std-Error | 0.227 | 0.353 | 0.626 | 0.657 |
| | T-stat | 2.910 | 0.510 | -0.510 | 0.550 |
| | p-value | 0.006 | 0.622 | 0.625 | 0.595 |
| *H* | ß | -0.339 | -0.498 | 0.250 | 0.807 |
| | Std-Error | 0.191 | 0.302 | 0.428 | 0.470 |
| | T-stat | -1.780 | -1.650 | 0.580 | 1.720 |
| | p-value | 0.084 | 0.124 | 0.574 | 0.124 |
| *Constant* | ß | -1.414 | -1.390 | 2.016 | 3.026 |
| | Std-Error | 0.441 | 10171 | 1.299 | 2.481 |
| | T-stat | -3.180 | -1.650 | 1.550 | 1.220 |
| | p-value | 0.003 | 0.124 | 0.155 | 0.257 |

| | | | | |
|---|---|---|---|---|
| R-Squared | 0.970 | 0.967 | 0.917 | 0.944 |
| N | 45 | 19 | 15 | 14 |

The coefficients of km/truckload and number of truckload for Agriculture and General Products are greater than 1, this shows there are diseconomies of scale in Agriculture and General Products. Diseconomies of scale in Agriculture and General Products may be the result of smaller firms, more owner/operators or having shorter hauls. However there are economies of scale in Food Products and Aggregate which may be a result of larger firm size and longer hauls (Table 2.3).

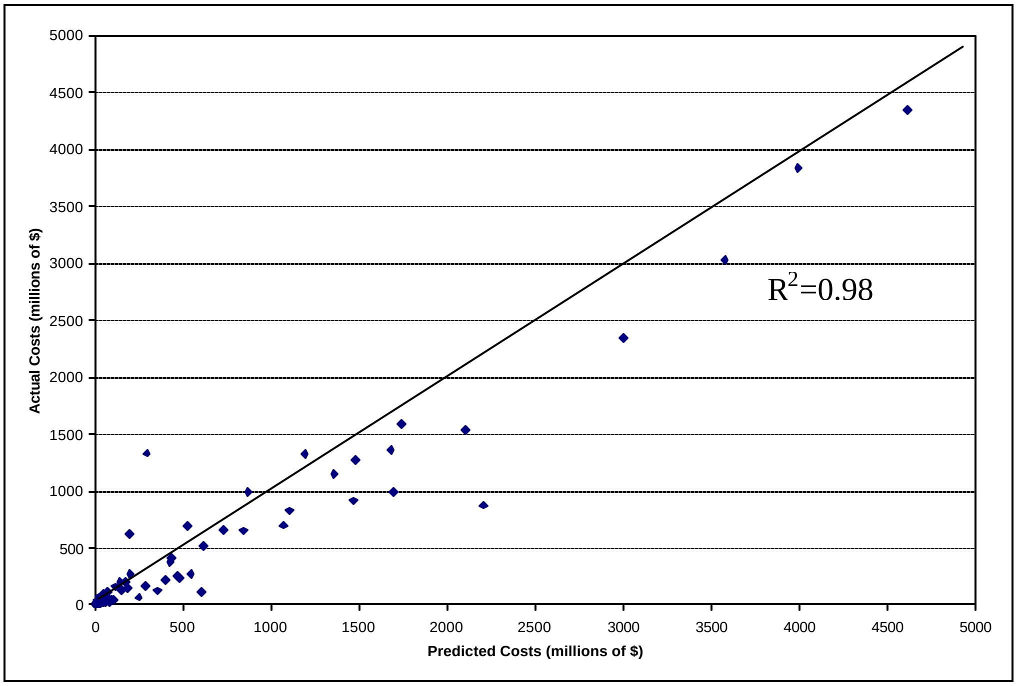


**Figure 2.2 Actual total costs versus predicted total costs from model**

## Average Cost Function

The average cost function is found by computing total costs per unit of output. Assuming total truckloads is the output of each firm, the average cost function for each firm can be calculated as following:

Average cost = (total cost) / (total truckload)

Average cost: $C/T = (e^{b_0}(K/T)^{b_1}T^{b_2}e^{b_3P}e^{b_4O}e^{b_5H})/T$ (6)

Average cost: $= e^{b_0}K^{b_1}T^{b_2-b_1-1}e^{b_3P}e^{b_4O}e^{b_5H}$ (7)

$= e^{-1.037}K^{1.015}T^{-0.972}e^{0.297P}e^{0.312O}e^{-0.012H}$ (8)

Using the mean of each variable in equation (8), gives an average cost of $232 per truckload.

To compare this value with the average cost from survey data, the mean of cost per km and the mean of overall kilometers can be used to calculate the average total cost. Average cost can be calculated by dividing average total cost by average truckload (output). This gives an average cost of $249 per truckload. One can see the average cost calculated from model is less than the average cost that was obtained from the data.

Assuming total kilometers is the output of each firm, the average cost function for each firm can be calculated as following:

Average cost = (total cost) / (total kilometers)

Average cost: $C / K = (e^{b_0} (K / T)^{b_1} T^{b_2} e^{b_3 P} e^{b_4 O} e^{b_5 H}) / K$ (9)

Average cost: $= e^{b_0} K^{b_1 - 1} T^{b_2 - b_1} e^{b_3 P} e^{b_4 O} e^{b_5 H}$ (10)

$= e^{-1.037} K^{0.015} T^{0.028} e^{0.297P} e^{0.312O} e^{-0.012H}$ (11)

Using the mean of each variable in equation (11), gives an average cost of $0.64 per km.

**Marginal cost function**

The marginal cost function is found by computing the change in total costs for a change in output. If output is total truckloads then:

Marginal cost = (change in total cost) / (change in truckloads)

The marginal cost function is

$$\partial C / \partial T = (b_2 - b_1) e^{b_0} K^{b_1} T^{b_2 - b_1 - 1} e^{b_3 P} e^{b_4 O} e^{b_5 H} \quad (12)$$

Using coefficients from Table 2.6, the marginal cost function will be

$$MC = (1.043 - 1.015) e^{-1.037} K^{1.015} T^{-0.972} e^{0.297P} e^{0.312O} e^{-0.012H} \quad (13)$$

Using the mean of each variable in equation (13), gives an overall marginal cost per truckload of $6.51. The average cost per truckload is much higher than the marginal cost, indicating economies of scale in truckloads.

Assuming total kilometers is the output of each firm, the marginal cost function for each firm can be calculated as following:

The marginal cost = (change in total cost) / (change in kilometers)

The marginal cost function is

$$\partial C / \partial K = b_1 e^{b_0} K^{b_1 - 1} T^{b_2 - b_1} e^{b_3 P} e^{b_4 O} e^{b_5 H} \quad (14)$$

Using coefficients from Table 2.5 the marginal cost function will be

$$MC = 1.015 e^{-1.037} K^{0.015} T^{0.028} e^{0.297P} e^{0.312O} e^{-0.012H} \quad (15)$$

Using the mean of each variable in equation (15), gives an overall marginal cost per km of $0.65. The marginal cost is slightly higher than the average cost, indicating slight diseconomies of scale per km. Table 2.8 summarizes economies of scale by variable and industry classification.

**Table 2.8** Economies of scale by variable and industry classification

| Industry | Agriculture | General Product | Aggregate | Food Product |
|---|---|---|---|---|
| Variable | | | | |
| AC per truckloads | 188 | 597 | 20 | 588 |
| MC per truckloads | 9.94 | 60.93 | 1.80 | 233.18 |
| Economies of Scale | 18.90 | 9.79 | 11.11 | 2.52 |
| | | | | |
| AC per km | 0.67 | 0.76 | 0.54 | 0.66 |
| MC per km | 0.70 | 0.78 | 0.37 | 0.33 |
| Economies of scale | 0.95 | 0.97 | 1.46 | 2.00 |

AC = Average Cost
MC = Marginal Cost

## 2.4 Value of Time Theory and Methodology

The value of time for vehicles has been evaluated for over 40 years, since it was noted to be an important part of economic analysis in transport planning [7] Haning and McFarland published one of the first reports estimating the value of time for commercial vehicles [8]. They evaluated time savings through the *net operating profit* approach. This approach makes the assumption that business oriented travel time saved is used for productive purposes, whereas personal travel time saved may be used for productive purposes or leisure activity. Thus commercial vehicle value of time should be greater even when no cargo is being carried. Their methodology fixed most vehicle and labor costs so that with improved speeds, a vehicle will be able to travel farther in the same time and contribute more profit. The difference was the value of time savings.

Adkins, Ward, and McFarland used a *cost savings model* to estimate the value of time for commercial vehicles, which is "based on a reduction of those costs that are not variable with miles of operation." [9] They also reviewed two additional methods of estimation: the *cost-of-time* method in which the value of time is "derived by determining the cost of providing time savings" for a specific project, and the *willingness to pay* method in which "individuals are faced with a decision between time savings and other benefits." A summary of some previous results is provided in Table 2.9, adapted from Kawamura [10]. The Consumer Price Index was used to adjust the figures to reflect 2003 prices.

**Table 2.9** Summary of Previous Value of Time Studies

| Authors | Year of Publication | Focus | Adjusted to 2003 | Average |
|---|---|---|---|---|
| Haning and McFarland | 1963 | Truck Operators | $19.57 to $25.42 | $22.50 |
| Waters et al. | 1995 | Truck Operators | $6.86 to $38.92 | $22.89 |
| Kawamura | 1998 | Truck Operators | $30.14 | $30.14 |
| Brownstone et al. | 2002 | Autombiles | $30.58 | $30.58 |
| Small and Yan | 2001 | Autombiles | $21.36 | $21.36 |
| Adkins et al. | 1967 | Cargo Vehicles | $25.81 | $25.81 |
| | | | Overall Average | $25.55 |
| | | | Standard Deviation | $4.01 |

Over the past decade, several European papers have used willingness to pay methods [11][12][13]. They used both revealed and stated preference methods to derive choice data. Revealed preference (RP) refers to preferences observed in actual market situations. Stated preference (SP) refers to preferences recorded in hypothetical situations. While economists typically are reluctant to rely on stated consumer preference compared with observing actual consumer behavior, in many situations the choice for researchers is to take consumers at their word or do nothing [14].

SP methods have several advantages over RP methods. Louviere, *et al.* [14] show how SP surveys can be designed to control for outside influences whereas data from RP methods sometimes cannot satisfy model assumptions, thus observed relationships cannot provide reliable and valid inferences. SP data are often less expensive to collect and such methods are used widely in marketing studies to explain preference for items that are not in the actual marketplace. SP can introduce variability in explanatory variables to estimate preference where little variation exists in the marketplace.

In the case of this cost-benefit analysis of SLR, we have very little available market choice data in instances where we could derive proper demand equations and estimate a value of time. We are limited to the use of SP methods, from which one can apply econometric models to estimate the value of time from the stated choices of commercial truckers.

A sample of commercial vehicle operators is necessary to conduct an analysis on their value of time. An interview was chosen for the SP component rather than telephone and mailed methods because the interviewer can be available for clarifying and follow-up questions, allowing the subject to gain a clearer grasp of the scenarios presented and their trade-offs [10].

As previously noted, of the 441 good responses from the mail-out/mail-back survey, 50.9 percent were willing to be interviewed. It was decided for the benefit/cost analysis of SLR that four Minnesota counties would be modeled: Olmsted, Lyon, St. Louis, and Clay; which were chosen based on available data and geographic location. These four counties are located at different extremes in the state and represent a different mix of commodity flows representative of their respective locations. (Due to time constraints and the addition of the city of Crystal, St. Louis County was excluded from this study). To remain consistent, the interviews were to be conducted in these same counties. Only 40 candidates were willing to be interviewed from these four counties, so the sample area was increased to include neighboring counties. A pilot study was conducted in Hennepin County because of its close proximity to the University of Minnesota and to include some metropolitan data. In all, 50 interviews were conducted throughout twelve different counties during July and August of 2003 (see Figure 2.3).

Several options are available in designing an SP survey. Preferences can be reported as rankings, or choices between two or more options, or as ratings of each individual option. Stated choice was chosen for this experiment because ranking and rating of alternatives seems to be an unusual activity in transportation [10]. Also, discrete choice data has been shown to be less sensitive to bias when compared with other methods such as rating and ranking [13]. The options are described by attributes set to particular levels. "It is usual, because it provides useful data, to choose attribute levels such that alternatives do not dominate each other, i.e. are not better in all respects. Instead, trade-offs are built into the experiment, where respondents are given more of one good (or less of a bad) in return for less of another good (or more of a bad)" [15].

The chosen design for our analysis employed adaptive stated preference (ASP) methodology. ASP surveys differ from conventional SP surveys in four major ways: options presented in subsequent games depend on the answers recorded in previous games, fewer alternatives and attributes are presented in individual games, the subject is often presented with more games, and it is possible to obtain estimates of parameters at the individual level [16]. The last reason is the most important reason this methodology was chosen, value of time is estimated at the disaggregate level.

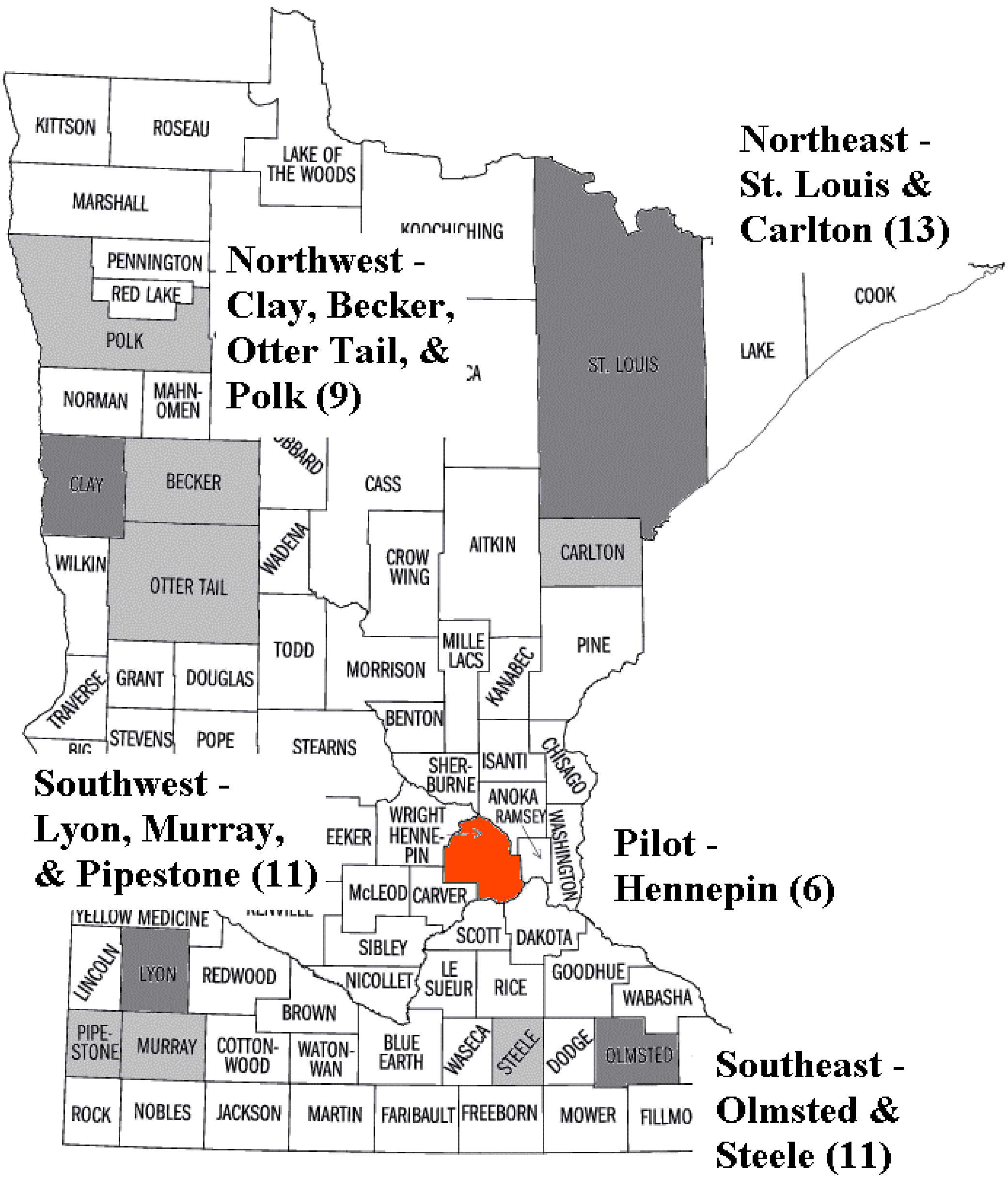


**Figure 2.3** Interview Locations

The design of the commercial vehicle survey included the often utilized permit schemes of Mn/DOT and several municipalities as an attribute, in addition to time per truckload, total truck loads, and the expected value of the fine. The permit would allow the truck to travel on an otherwise restricted route to save travel time for a fee. Two options of permits were presented, a seasonal permit that would allow a truck to travel at the legal load limit imposed during the non-restricted period for the entire duration of SLR, and a single use permit that would allow this type of travel only once. The expected value of a fine is the product of the fine and the probability of getting caught. Fines for overweight trucks are on the order of hundreds of dollars, but the probability of getting caught is low. The expected value of fine displays the product of full fine value and the probability, one figure for simplicity.

The adaptive technique presented one no cost option and one cost option in exchange for time or reducing number of truckloads. There were five scenarios (each with six games):

- trading a reduction in time per truck load for a single use permit
- trading a reduction in total truck loads for a single use permit
- trading a reduction in total truck loads for a seasonal permit
- trading a reduction in time per truck load for an expected value of fine
- trading a reduction in total truck loads for an expected value of fine

The interviews were conducted in person and the survey was administered on a laptop computer. A computer program running through a Microsoft Access database was used to alter values in the separate presentations. The computer program used bisection techniques to focus on each subject's maximum willingness to pay. It started at a midpoint of an appropriate range and increased or decreased the cost attribute by half depending on the alternative chosen by the subject. This process continued until a reasonable amount of precision was reached; in this case we were looking for values to the nearest \$1 or \$2. A reasonable starting point should be two to three times the final mean [16]. The average values in previous studies indicated that the starting point should be around \$50/h, but instead \$40/h was chosen for its meaningful integer values when bisected up to the $4^{th}$ iteration. This makes the range of possible values of time from \$1.25/h up to \$77.75/h for the six iterations. The full range is \$0 to \$80, but these values represent the limits to which infinite iterations would be bound.

A screenshot of the database displays the instructions and layout of presentation two, the first tradeoff scenario (see Figure 2.4). The question would repeat a total of six times with a different value for option B after each response. The subsequent values would depend on the previous choice for each scenario, with the program resetting at \$40 for each of the other scenarios. The complete list of questions is given in Appendix 2-2.

The range was tested for validity in a pilot study, along with the language of the instructions, SP and interview questions, as well as SP format and database functionality. The average value given was \$19.74/h, the minimum was \$0/h, the maximum was \$45.00/h, and the average of the maximums was \$33.33/h. These values confirmed that the chosen anchor and maximum points were sufficient, and all bugs in the operation of the database and all misinterpretations of instructions were eliminated prior to travel to the four study areas.

Extraction of value of time estimates from SP data can be obtained with two different methods, switching point analysis and statistical analysis. Switching point analysis estimates the value of time from the level of trade-off where the choices switch from the cost option to the free option [20]. An example would be a traveler who chooses to pay a toll for a given amount of time savings on all options up to $5, but then chooses the alternate route without a toll for all tolls presented over $5. The switching point for this individual is $5, and this would be an estimate of that traveler's value of time. The second method, statistical analysis, employs a logit model to estimate the value of time from discrete choice data. It assumes that the error terms are Gumbel distributed. Using the logit model for aggregate estimation yields utility coefficients that reflect average behavior. If the objective of the analysis is to measure differences in coefficient values across individuals, aggregate estimation is contradictory [10]. Various suggestions have been presented to handle this problem including introducing socioeconomic variables, relaxing assumptions, or segmenting the data. Fowkes suggests fitting individual models for each respondent [15]. Further analysis can be conducted by aggregating the fitted disaggregate models.

In cases of truncated data, data that has lower and/or upper limiting values, there may be a number of responses that take on the limiting value. In this situation, logit analysis would be inappropriate. Probit analysis would provide a suitable model of the probability of responses taking on the limiting value, and regression analysis would be appropriate for the non-limited values. Tobin proposed a model that is a hybrid of these two techniques for cases of truncated data [17].

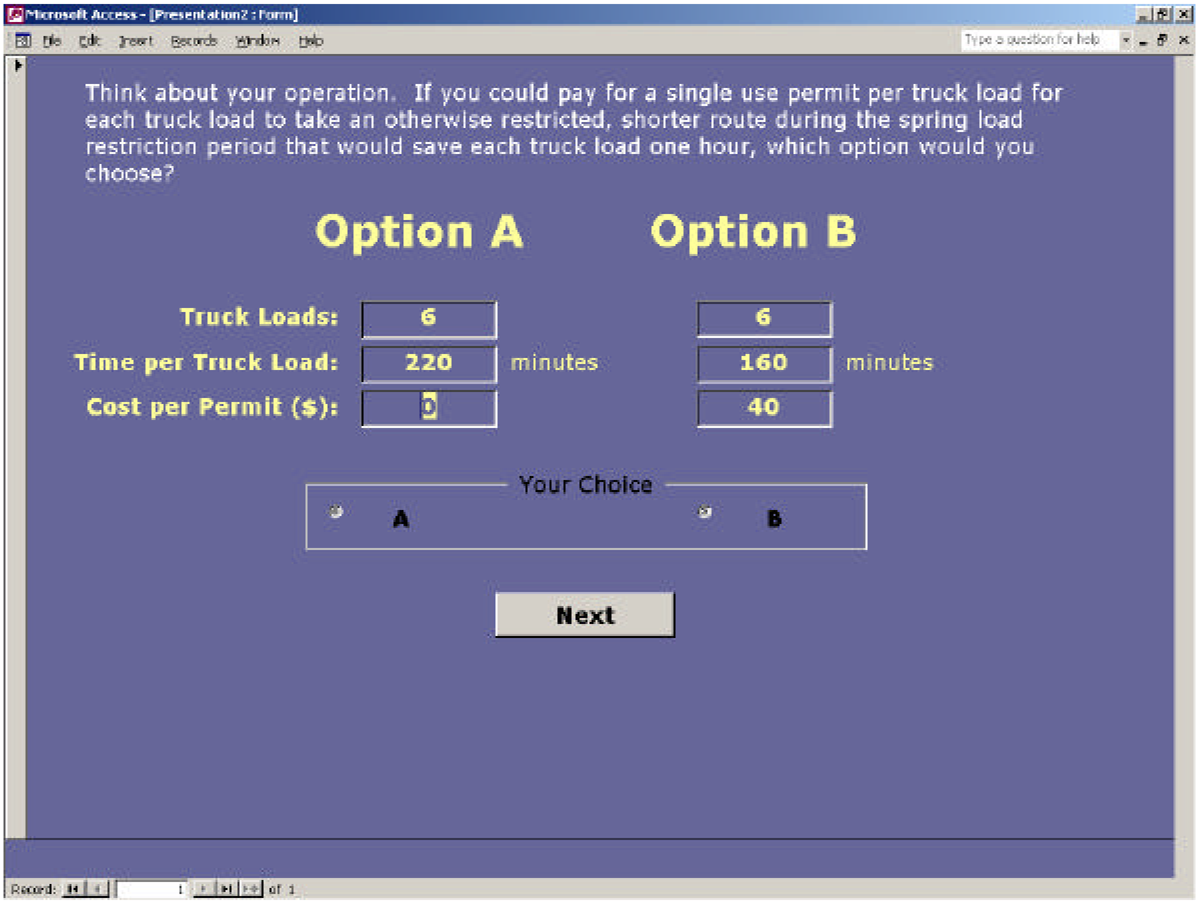


**Figure 2.4** Scenario 1 – A tradeoff of a reduction in time per truck load for a single use permit

## 2.5 Value of Time Results

The first presentation measured the preference for saving truckloads for a particular shipment versus time per truckload for that same shipment. The mean final value of truck loads and time per truckload were near the midpoint of the analysis, thus no clear indication of preference for time savings or truckload savings was indicated. For the value of time analysis, the estimates from the two scenarios of truck load savings and time per truck load savings will be based on the product of the two, the total time savings.

The results of the switching point analysis yielded an overall mean of $24.10/h (see Table 2.10). The values presented are descriptive statistics based on the greatest value of the non-free alternative that the respondent chose in the ASP survey.

**Table 2.10** Switching Point Analysis

| | P1: Trucks | P1: Time (min.) | P2: Permit, Time Savings Per Truck Load ($) | P3: Permit, Total Truck Load Savings ($) | P4: Seasonal Permit, Total Truck Load Savings ($) | P4/40: Seasonal Adjusted to Single Savings ($) | P5: Fine, Time Savings Per Truck Load ($) | P6: Fine, Total Truck Load Savings ($) | Mean ($) | Max P ($) |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 5.82 | 176.61 | 36.70 | 30.23 | 653.41 | 16.34 | 19.50 | 17.35 | 24.10 | 46.78 |
| Median | 5.00 | 176.00 | 38.75 | 13.75 | 300.00 | 7.50 | 3.75 | 1.88 | 10.00 | 48.75 |
| Mode | 4.00 | 120.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | |
| Max | 8.00 | 240.00 | 78.75 | 78.75 | 3,150.00 | 78.75 | 78.75 | 78.75 | | |
| Min | 4.00 | 120.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | | |
| Standard Deviation | 1.85 | 55.44 | 28.10 | 30.34 | 857.82 | 21.45 | 27.86 | 25.88 | 27.98 | 27.07 |

*Notes:*

- *P refers to presentation*
- *P2 is a scenario where there is a trade-off between an hour of time savings for each truck with a single-use permit versus no time savings for zero cost.*
- *P3 is a scenario where there is a trade-off between a savings of one truck load with a single-use permit versus no truck load savings for zero cost.*
- *P4 is a scenario where there is a trade-off of having to run fewer truck loads over the SLR period for the cost of a seasonal permit, or more truck loads for the same amount of product for zero cost.*
- *P4/40 adjusts the 40 hours of time savings to one hour.*
- *P5 is similar to the second presentation except in this case, fines are used instead of single-use permits.*
- *P6 is the same as P3, except that fines were used in the place of single-use permits. The second set of data presented in this table averages the two single-use permit scenarios and the two fine scenarios.*

The second presentation, time savings in exchange for a single-use permit, has the greatest switching point mean of $36.70/h. The lowest mean corresponds to the seasonal permit scenario, followed closely by the fine scenarios. The mean of all the presentations for all 50 survey participants is \$24.10/h. This is in line with the past studies' estimates of the value of time (see Table 2.9).

Typically in value of time analysis, the mean of the switching points is referred to as the estimate of the value of time. Most SP surveys have a similar structure as was used in presentation two where time is saved as a result of paying a fee, in most cases a toll, but in this case, a single-use permit. Brownstone *et al.* have noted that SP studies generally yield lower values than RP studies [18]. Avoidance of paying additional fees for a public good that people believe they already pay enough for in the form of taxes may be the reason behind this underestimate. Some respondents noted that they would not purchase permits, but were more willing to pay fines to save time. Using only permits to estimate value of time would not capture this group of respondents' actual willingness to pay. The maximum switching points for each respondent would take into account those who are unwilling to pay additional fees, but still have a willingness to pay using other means (e.g. fines) in other scenarios; similarly it would account for those who would not be willing to break the law and receive fines, but would pay extra for permits. The mean of those maximum switching points is \$46.78/h (see Table 2.10). The use of this value is likely to represent a varied samples' maximum willingness to pay and therefore more accurately estimate the value of time.

One problem that was encountered in this analysis is that some cases were bounded by the survey instrument's computer program that adaptively adjusted the values of the fines and permits based on previous answers. The program was bounded at \$0 so that no one would receive payment for time savings. The expectation was that no individual value of time would exceed \$78.75/h throughout the experiment; this was corroborated by the pilot study. However, eight subjects reached the maximum willingness to pay during at least one presentation. Two options are available when working with bounded data: either throw out the bounded cases due to the fact that they violate the homogeneity assumption for the data, or use all the data with a model that accounts for limited cases. A tobit model accounts for limited cases; this model will be fit to the data in a later section.

The estimate for value of time with the bounded cases eliminated reduced the previous estimate by \$4.06 to \$42.72 (see Table 2.11). In Table 2.11, the two lower bounded cases and the eight upper bounded cases were eliminated, leaving 40 for the analysis.

The results for the logit model when analyzed at the extreme disaggregate level of each presentation for each subject are equivalent to the switching point analysis.

$$Utility = b_0 + b_1(\Delta Cost) + b_2(\Delta Time) \tag{12}$$

If the data are aggregated to the individual level, the results of the logit analysis are roughly equivalent to the mean over presentations for the switching point analysis as shown in Table 2.12. One difference is that the mean increases by eliminating the bounding cases, whereas the mean decreases in the switching point analysis. These results should not be given much consideration because only three out of 40 individuals had significant coefficients for time and cost at the 95 percent confidence interval. This is consistent with previous research [14][19]. Aggregating the data at the presentation level will result in large differences in value of time estimates (see Table 2.13). Logit analysis must be done at the disaggregate level, and in this case the results are equivalent to those presented in the switching point analysis section.

**Table 2.11** Switching Point Analysis - Bounded Cases Eliminated

| | P1: Trucks | P1: Time (min.) | P2: Permit, Time Savings Per Truck Load ($) | P3: Permit, Total Truck Load Savings ($) | P4: Seasonal Permit, Total Truck Load Savings ($) | P4/40: Seasonal Adjusted to Single Savings ($) | P5: Fine, Time Savings Per Truck Load ($) | P6: Fine, Total Truck Load Savings ($) | Mean ($) | Max P ($) |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 5.50 | 184.09 | $34.81 | $26.44 | $605.88 | $15.15 | $15.44 | $13.56 | $21.22 | $42.72 |
| Median | 4.50 | 192.00 | $36.25 | $10.63 | $325.00 | $8.13 | $2.50 | $1.88 | $10.00 | $48.75 |
| Mode | 4.00 | 240.00 | $5.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | | |
| Max | 8.00 | 240.00 | $77.50 | $77.50 | $2,800.00 | $70.00 | $70.00 | $70.00 | | |
| Min | 4.00 | 120.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | $0.00 | | |
| Standard Deviation | 1.76 | 54.93 | $25.85 | $26.89 | $792.75 | $19.82 | $23.31 | $20.00 | $24.67 | $24.12 |

*Notes:*

- *P refers to presentation*
- *P2 is a scenario where there is a trade-off between an hour of time savings for each truck with a single-use permit versus no time savings for zero cost.*
- *P3 is a scenario where there is a trade-off between a savings of one truck load with a single-use permit versus no truck load savings for zero cost.*
- *P4 is a scenario where there is a trade-off of having to run fewer truck loads over the SLR period for the cost of a seasonal permit, or more truck loads for the same amount of product for zero cost.*
- *P4/40 adjusts the 40 hours of time savings to one hour.*
- *P5 is similar to the second presentation except in this case, fines are used instead of single-use permits.*

*P6 is the same as P3, except that fines were used in the place of single-use permits. The second set of data presented in this table averages the two single-use permit scenarios and the two fine scenarios.*

**Table 2.12** Logit Results – Individual

| | All Cases ($) | Bounded Cases Eliminated ($) |
|---|---|---|
| Mean | 24.92 | 26.58 |
| Median | 14.70 | 14.80 |
| Mode | | |
| Max | 85.33 | 85.33 |
| Min | 0.46 | 1.89 |
| Standard Deviation | 23.60 | 24.19 |

**Table 2.13** Logit Results - By Presentation - Bounded Cases Eliminated

| Presentation | ?T | ?C | ?T/?C | VOT ($) | Significant |
|---|---|---|---|---|---|
| 2 | 1 | 0.0106 | 93.9 | 93.92 | |
| 3 | 1 | 0.0116 | 86.3 | 86.34 | |
| 4 | 1 | -0.0002 | -115.7 | 115.74 | |
| 5 | 1 | 0.0177 | 56.5 | 56.48 | * |
| 6 | 1 | 0.0148 | 67.7 | 67.69 | |
| Mean | 84.04 | | | | |
| Median | 86.34 | | | | |
| Max | 115.74 | | | | |
| Min | 56.48 | | | | |
| Standard Deviation | 23.10 | | | | |

The main problem with the previous analysis is the limited cases. The tobit model can be fitted to truncated data without eliminating cases. It provides additional information, and thus will provide a better estimate of the value of time in this analysis. The tobit model used in this analysis uses the maximum switching point as the dependent variable with a constant as the independent variable and an upper limit of $78.75/h. The estimate for the independent variable parameter is $49.42/h using all 50 cases. The estimate is statistically significant with a *t*-statistic of 11.07.

The best result from these data to be used as an estimate of the commercial vehicle operator's value of time is $49.42/h. It accounts for people's aversion to paying for something that they feel they have already paid for by including fine scenarios and choosing the maximum from all presentations. It also uses all data collected in the derivation of the estimate.

A check for this estimate of value of time would be to take the stated cost per kilometer reported by the subjects and multiply that by a reasonable estimate of kilometers per hour. The average stated cost for these subjects is $0.65/km ($1.05/mi). From the interviews, 80 km/h (50 mi/h) was considered a reasonable expectation for the speed of trucks. The product comes out to be $52.36/h, which is in line with the estimate from the tobit analysis.

One aim of this study was not only to provide an accurate estimate for commercial vehicle operator's value of time in Minnesota, but also to account for the variation in value of time. The recorded values of time comprise a very flat distribution with variance exceeding the mean exponentially. The mailed survey recorded many operational and economic details of each firm so that they could be used in further analysis as independent variables to test for a statistically significant relationship.

Kawamura showed that the value of time varies at a significant level based on the operation of the trucking firm, whether it is has a private or for-hire truck fleet [20]. Using the tobit model, this hypothesis is tested. The indicator variable for firms with private fleets was significant at the 90 percent level. The results are consistent with Kawamura's findings that firms with private fleets have a considerably lower value of time (see Table 2.14). This can be explained by for-hire firms having a better idea of their operating costs, and the greater flexibility to pass most of the additional cost on to the consumer.

**Table 2.14** Tobit Model - Private vs. For-Hire

| | Estimate | Standard Error | t-statistic | P-value | 95% Interval | Confidence |
|---|---|---|---|---|---|---|
| Constant | 59.5962 | 6.715904 | 8.87 | 0 | 46.10009 | 73.09232 |
| Private | -17.23666 | 8.641082 | -1.99 | 0.052 | -34.60156 | 0.1282455 |

The freight facility database has records organized by facility type (see Table 2.15). The hypothesis that for-hire fleets have a higher value of time is tested, and the results are consistent with previous studies. Three facility types are significant at the 90 percent level, with two more being almost significant.

**Table 2.15** Tobit Model - By Freight Facility Type

| | Estimate | Standard Error | t-statistic | P-value | 95% Interval | Confidence |
|---|---|---|---|---|---|---|
| Constant | 78.09 | 16.04 | 4.87 | 0 | 45.77 | 110.42 |
| Ag Chem | -56.43 | 21.98 | -2.57 | 0.014 | -100.72 | -12.13 |
| Grain | -34.80 | 20.03 | -1.74 | 0.089 | -75.18 | 5.57 |
| Manufacturing | -34.34 | 20.65 | -1.66 | 0.103 | -75.97 | 7.28 |
| For-Hire Trucking | -19.79 | 16.82 | -1.18 | 0.246 | -53.68 | 14.11 |
| Waste | -50.59 | 30.57 | -1.65 | 0.105 | -112.21 | 11.02 |
| Wholesale | -54.52 | 18.81 | -2.9 | 0.006 | -92.44 | -16.60 |

*Note: Ag Chem refers to Agriculture Chemical Distribution Centers*

Most variables, especially continuous variables, failed to account for the variation in value of time estimates across individuals. This is consistent with the literature; only Kawamura's study has postulated and provided evidence for an explanatory variable or variables [20].

## 2.6 Conclusions

During SLR periods, trucking companies report changes in their operating behavior mostly by changing routes and reducing load size, which imposes additional cost on their operation. The average cost for commercial trucks in Minnesota is \$0.69/km (\$1.11/mi). This number is the result of using data collected from 186 different firms in Minnesota. Owner/operators have a higher cost as a result of having less output to distribute their fixed cost over.

A Cobb-Douglas model gives the best fit to estimate the total cost from the survey data. Total truckloads represent the size of firm in the total cost model. From the model one can see roughly constant returns to scale. If output (total truckloads) increases by 1%, total cost will increase by 1.04%. Results from the model for each industry type show there are economies of scale in food product and aggregate industry. It may be result of having longer length of hauls or larger firms.

Average cost for trucks obtained from the model is \$0.64/km (\$1.02/mi) and \$250/truckload (for an average truckload size). That is very close to the average cost from the survey data. Marginal cost is \$6.51/truckload and \$0.65/km (\$1.04/mile). Therefore there are economies of scale in additional truckloads but diseconomies in additional trip distance.

A caveat on the analysis is that some of the respondents may have misunderstood the survey questionnaire. There is a possibility that the number of respondents (26 of 186) who reported operating cost less than \$0.31/km (\$0.50/mi) may not have included labor cost in their answers. This may cause the estimated value to be somewhat lower than the actual number.

The total operating cost model estimation also does not show the impact of road quality on operating cost. It may be an important factor in operating cost as low quality roads can reduce the life of tires, increase fuel consumption and also increase the maintenance cost. It may also reduce speed which increases labor cost.

This research study used six scenarios of Adaptive Stated Preference (ASP) to estimate the value of time for commercial vehicle operators in Minnesota. The games within each scenario were bounded by reasonable estimates of the value of time, and during the course of the analysis several subjects reached the upper limit of the survey. The best model for truncated data of this type is the tobit model. The tobit model provided an estimate for the average commercial vehicle value of time in Minnesota of \$49.42/h. This result is very similar to the median of the maximum of presentations of \$48.75/h using switching point analysis with bounded cases eliminated. Comparisons between for-hire firms and those with private fleets indicated that for-hire firms have a considerably higher value of time.

The primary limitation in the analysis of the value of time is the lack of RP data, which led to the use of SP methods. In the absence of economic data derived from observed behavior, researchers are left with taking consumers at their word. While it has previously been shown that SP methods routinely underestimate value of time, most of the underestimate should be accounted for by using many different scenarios and taking the maximum of the presentations as the maximum willingness to pay for each subject.

The truncation of the data provided some limitations in the modeling that could be done in order to extract the estimate for the value of time. The truncation could account for the data not following the expected log-normal distribution.

The small sample size limited the number of variables that could be used to explain the variance in value of time. The budget and time horizon for the study limited the sample size when interviews were used to conduct the analysis, but it was felt that the quality of the data from interviews overcame this limitation.

Previous SP surveys estimate the value of time using trade-offs that involve fee scenarios. Many respondents in this analysis indicated preferences to avoid them. Considering the maximum of fines versus fees provides a new way of looking at the question. Further research is needed to corroborate SP estimates with existing RP data. Little RP value of time data exist in the field of commercial trucking, but the analysis should be done where both sets of data are obtainable.

Future freight value of time analysis using the ASP technique should increase the upper bound to eliminate the truncation problem that was encountered. A reasonable upper limit would be $160/h; this would still possess all the attractive properties that $80/h had for meaningful integer values when bisected repeatedly.

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# Chapter 3

Task #3: Develop Model of Freight Shipments in Minnesota and Estimate Traffic Impacts of Load Restrictions

## 3.1 Introduction

To estimate the impact of SLR quantitatively, it is necessary to build a freight demand model to measure how truck Vehicle Kilometers of Travel (VKT) (or vehicle miles of travel (VMT)) changes during the SLR period. A pavement performance model is also needed to estimate how pavement life changes under different traffic scenarios. Lyon, Olmsted and Clay County will be modeled to represent typical areas of Minnesota. Lyon County, Minnesota is modeled first to test the methodology. A flowchart of the framework for analyzing the Benefit/Cost of SLR is shown in Figure 3.1 and is detailed below.

## Flowchart of SLR Benefit/Cost Analysis

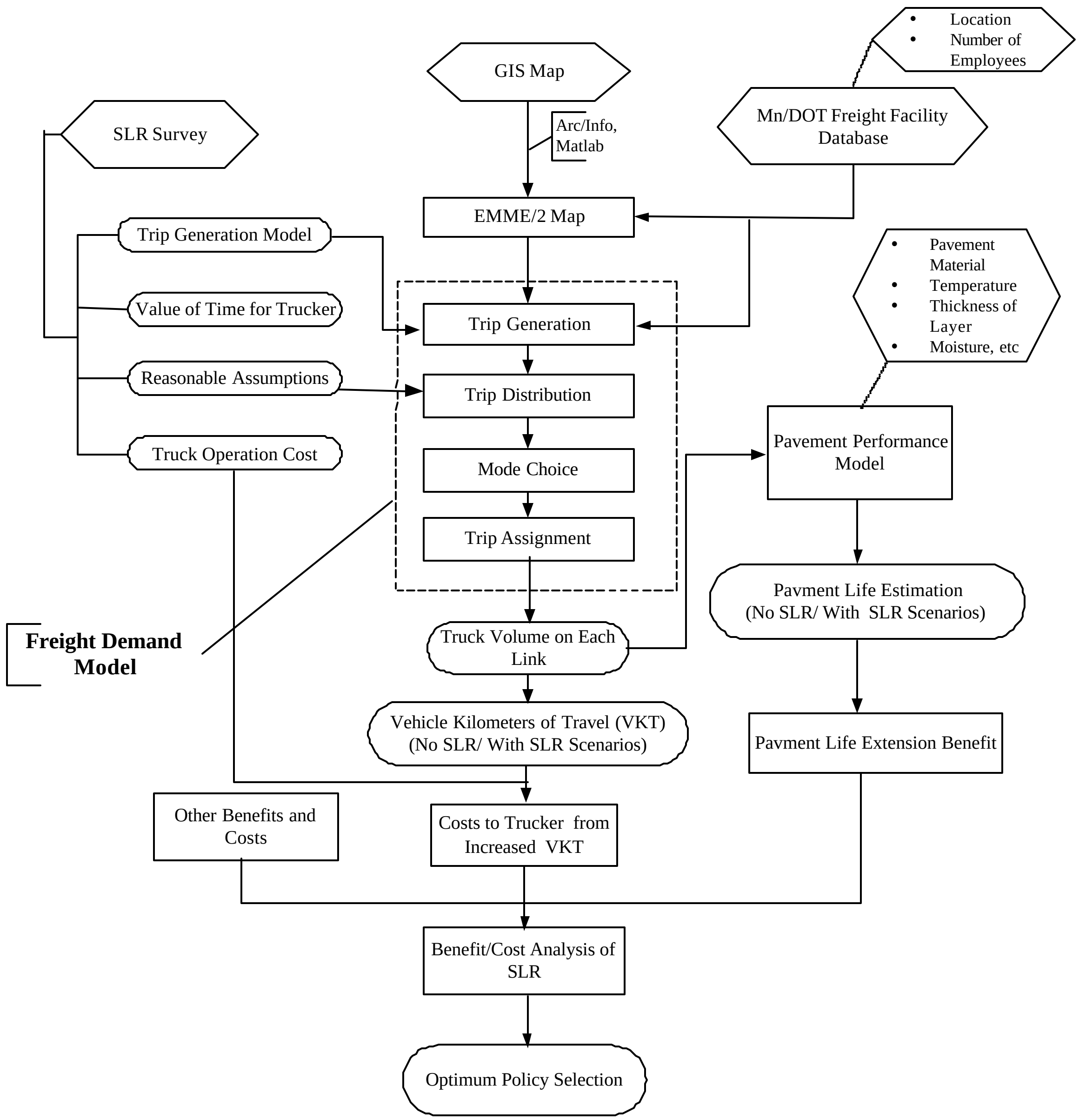


**Figure 3.1: Flowchart of the SLR Benefit/Cost Analysis**

The first step is to obtain the data needed for modeling. A GIS map with total traffic volume on most of the roads is obtained from the county GIS coordinator, together with a detailed road restriction map [1]. The GIS map is transformed to EMME/2 format using Arc/Info and Matlab programming [2]. Freight facilities in the county are located in the map using the Mn/DOT freight facilities database.

As discussed in Chapter 2, a two-round survey was conducted in 2003 using both mail-out/mail-back and on-site interview methods. The object of the survey was to provide SLR background information, parameters like truck total operating cost, value of time, and truck trip generation rate for each freight facility type, which could be used in the Benefit/Cost analysis.

A freight demand model was implemented to emulate the truck freight pattern in three Minnesota counties (Lyon, Olmsted, Clay). The model calculates truck trip demands generated in each freight facility within each county, determines their destinations and truck type used based on data derived from the survey, and assigns them to each link.

A transportation-planning software package, EMME/2, was used to run the freight demand model's traffic assignment to the network. The roads in each county are classified into four types during the SLR period: 5-, 7-, 9- and 10-ton roads. Outside the SLR period 5, 7, and 9-ton roads can accommodate 9-ton axle loadings unless otherwise posted, (and 10-ton roads can accommodate 10-ton axle loadings). These numbers represent the maximum allowable axle weight limits during the SLR period. It is important to note that some roads are restricted year round. Lyon County restricts a portion of their roads throughout the year, while engineers from Olmsted and Clay counties stated that "virtually all" of their restricted roads revert back to 9 tons outside of the spring load restriction period. In the basic analysis, the freight demand model is run using two scenarios. The first scenario does not have SLR policy (without SLR), indicating that 9-ton trucks can run on all roads without restriction. The second scenario (with SLR) imposes the SLR policy (with 100% compliance) so that the all trucks are subject to the load restriction policy. The two scenarios are compared to see how SLR changes truck traffic patterns and VKT. Subsequent chapters consider additional scenarios.

The total truck VKT can be calculated for each scenario. In the subsequent Benefit/Cost Analysis, the change in truck travel due to SLR can be converted to costs using the truck operating cost estimated from the survey as described in Chapter 2. Similarly, the change in truck travel can be converted to changes in pavement damage, using the pavement performance model developed in Chapter 1, and can be considered benefits for road owners associated with the existing SLR policy.

### 3.2 Truck fleet composition

The freight demand and pavement performance model require vehicle classification counts and the truck fleet composition. To simplify the modeling process, three types of trucks are defined: 2-, 3-, and 5-axle. Truck parameters are listed in Table 3.1. It is worth noting that the gross weight and tare weight data comes from a Canadian study [3] and weight distribution per axle data comes from Iowa Department of Transportation [4].

**Table 3.1 – Truck parameters in the model**

| Truck Type | Gross* Weight (ton) | Tare* Weight (ton) | Front Axle Type | Middle Axle Type | Rear Axle Type | Weight Distribution per axles (empty truck) | Weight Distribution per axles (full truck)# |
|---|---|---|---|---|---|---|---|
| 2 axles | 12 | 3.4 | Steer | - | Dual wheels | 1.00:1.15 | 1.00:1.65 |
| 3 axles | 21 | 8.0 | Steer | - | Dual Tandem | 1.00:1:36 | 1.00:1.98 |
| 5 axles | 39 | 14.4 | Steer | Dual Tandem | Dual Tandem | 1.00:1.50:1.00 | 1.00:3.09:3.07 |

Detailed truck classification and traffic counts were conducted by Mn/DOT both during and after the 2004 SLR period in Lyon County (some additional data was also collected in Olmsted County, which arrived too late for analysis, but is used in the calibration of the Olmsted County model). Counts collected during the SLR period in Lyon County are used to calculate the truck fleet composition, which shows the percent of each category of truck in the fleet. Counts were taken at 63 sites throughout Lyon County, Minnesota for 48 hours at each site. The counts were halved to give the 24-hour ADT for each site. The sample consisted of ten 5-ton roads, twelve 7-ton roads, seven 9-ton roads, and twenty-one 10-ton roads (as classified during the SLR period). Counts were conducted at another ten sites, but these were considered unusable by Mn/DOT because they were unreliable due to equipment malfunctions. Another three sites were also not reported. Of the sites not used, two were 10-ton roads, four were 9-ton roads, two were 7-ton roads, and five were 5-ton roads. Three sites reported no trucks over the 48-hour time and these sites were included in the average truck ADT, but were excluded from the truck category breakdown.

For each site, data was available for passenger vehicles per day, single unit 2-axle trucks, single unit 3+-axle trucks, 3-axle semis, 4-axle semis, 5+-axle semis, trucks with trailers and buses, and trucks with twin trailers.

As noted above, the trucks were categorized into 2-axle, 3-axle, and 5+-axle. All 2-axle single unit trucks, trucks with trailers, and buses were categorized as 2-axle vehicles. All 3-axle single unit trucks and 3-axle semis were categorized as 3-axle vehicles. The 4-axle semis make up a very small percentage of all truck traffic, and were categorized as 3-axle vehicles. All 5+-axle semis were combined with twin trailer traffic to obtain the category for 5-axle vehicles. The percentages of each of the three categories of trucks for each of the categories of roads as well as the truck ADT for each category are in Table 3.2. This truck fleet composition is adopted in the freight demand model.

**Table 3.2 – Truck ADT and breakdown of trucks by road category**

| Road Category | Truck ADT | % Trucks | % 2-axle | % 3-axle | % 5-axle |
|---|---|---|---|---|---|
| 5-ton | 4 | 6.5% | 85.4% | 14.6% | 0% |
| 7-ton | 29 | 8.3% | 54.2% | 29.7% | 16.1% |
| 9-ton | 27 | 9.1% | 47.5% | 27.1% | 25.3% |
| 10-ton | 410 | 17.3% | 24.8% | 9.8% | 65.4% |

According to the above truck parameter and truck fleet composition, the actual carrying capacity of each type of truck on each different road type can be calculated.

In Table 3.3, truck net vehicle weight, gross vehicle weight and payload parameters come from a Canadian study by TRIMAC Consulting Service [3]. Weight restriction is calculated using the "Restricted Gross Weight Table" from Mn/DOT [5]. Axle weight distribution data is from the 1985 Truck Weight Index from the Iowa Department of Transportation as shown in Table 3.1 [4]. The net weight that a truck can carry is the minimum of the gross weight limit and gross vehicle weight minus vehicle tare weight. Truck fleet composition used in subsequent modeling is shown in Table 3.3.

**Table 3.3 - Truck fleet parameters on each type of road**

| Truck Configuration | Net Vehicle Weight (ton) | Gross Vehicle Weight (ton) | Payload (ton) | Weight Restriction (ton) | Actual carrying capacity (ton) | Proportion of fleet |
|---|---|---|---|---|---|---|
| **5 ton road** | **Carrying capacity of a typical 5 ton truck** | | | | **4.0** | |
| 2 Axle | 3.4 | 12 | 8.6 | 7.3 | 3.9 | 85.4% |
| 3 Axle | 8 | 21 | 13 | 12.9 | 4.9 | 14.6% |
| **7 ton route** | **Carrying capacity of a typical 7 ton truck** | | | | **8.8** | |
| 2 Axle Truck | 3.4 | 12 | 8.6 | 10.2 | 6.8 | 54.2% |
| 3 Axle Truck | 8 | 21 | 13 | 18.1 | 10.1 | 29.7% |
| 5 Axle Truck | 14.4 | 39 | 24.6 | 27.8 | 13.4 | 16.1% |
| **9 ton route** | **Carrying capacity of a typical 9 ton truck** | | | | **13.0** | |
| 2 Axle Truck | 3.4 | 12 | 8.6 | 13.1 | 8.6 | 47.5% |
| 3 Axle Truck | 8 | 21 | 13 | 23.6 | 13 | 27.1% |
| 5 Axle Truck | 14.4 | 39 | 24.6 | 35.7 | 21.3 | 25.3% |
| **10 ton route** | **Carrying capacity of a typical 10 ton truck** | | | | **17.4** | |
| 2 Axle Truck | 3.4 | 12 | 8.6 | >13.1 | 8.6 | 24.8% |
| 3 Axle Truck | 8 | 21 | 13 | >23.6 | 13 | 9.8% |
| 5 Axle Truck | 14.4 | 39 | 24.6 | 35.7 | 24.6 | 65.4% |

### 3.3 Road network and zone structure

To run the model, it is necessary to define a network and traffic zone structure. The network geometry needs to be coded to a standard node-link format, such as that used by EMME/2. The easiest way to do that is to transform a network obtained from GIS maps into this node-link format, using a program developed in Matlab, and described in Appendices 1 and 2 [2]. In Lyon County, there are 225 traffic analysis zones (TAZs) evenly located within the county. Since Lyon County is largely an agricultural county, each of these TAZs represents a *virtual farm*. In Olmsted County there are 212 TAZs, and in Clay County there are 222 TAZs. In Clay County, the traffic analysis zones are evenly spaced across a 16 x 14 matrix. Each zone is approximately 3256 m (10682 ft) (east-west direction) by 3502 m (11490 ft) (north-south direction). Two of the zones that were not close enough to any roads (the north-central portion of the map) were deleted to make room for more external stations. Network summary statistics are given in Table 3.4.

**Table 3.4 – Descriptive Network Statistics**

| County | Lyon | Olmsted | Clay |
|---|---|---|---|
| Total number of zones | 250 | 250 | 250 |
| Internal zones | 225 | 212 | 222 |
| External zones | 25 | 38 | 28 |
| Number of Freight facilities | 59 | 126 | 63 |
| Number of Links<br>(including centroid connectors) | 4494 | 5032 | 5888 |
| Number of Regular Nodes | 1379 | 1866 | 1891 |
| 10 ton roads km (mile) | 266 (166) | 309 (193) | 332 (208) |
| 9 ton roads km (mile) | 191 (119) | 183 (114) | 241 (151) |
| 7 ton roads km (mile) | 260 (163) | 604 (378) | 123 (77) |
| 5 ton roads km (mile) | 1437 (898) | 818 (511) | 2286 (1429) |

The freight facilities in Lyon County were located using the Mn/DOT freight facility database and input into the transportation network. In Lyon and Olmsted counties, each freight facility is assigned to a unique Traffic Analysis Zone (TAZ). In Clay County, each of the firms generating trips is assigned to the TAZ with the nearest centroid. When connecting centroids to the network, it is assumed that any and all freight facilities and trips generated within a TAZ have access to the highest rated (least restricted) road available in that zone. Thus, if a TAZ has both 5-ton and 9-ton roads available, the centroid will be connected to 9-ton road.

In the network, four corresponding types of modes: ‘c’,’l’,’m’,’h’ were set up. Mode ‘c’ represents trucks with a small load (5-tons per axle or less), which can run on all four types of roads. Mode “l” represents trucks with light loads (7-tons per axle or less), which can run on 7-ton or higher-level roads. Mode ‘m’ represents trucks with moderate loads (9-tons per axle or less), which can run on 9-ton or higher-level roads. Mode ‘h’ represents heavy trucks, which can only run on 10-ton roads.

In accordance with the road restriction map [1], different modes are assigned to each link in the road network as link attributes, resulting in a road network with a hierarchy of 5, 7, 9 and 10-ton roads (See Figure 3.2 for a Clay County example).

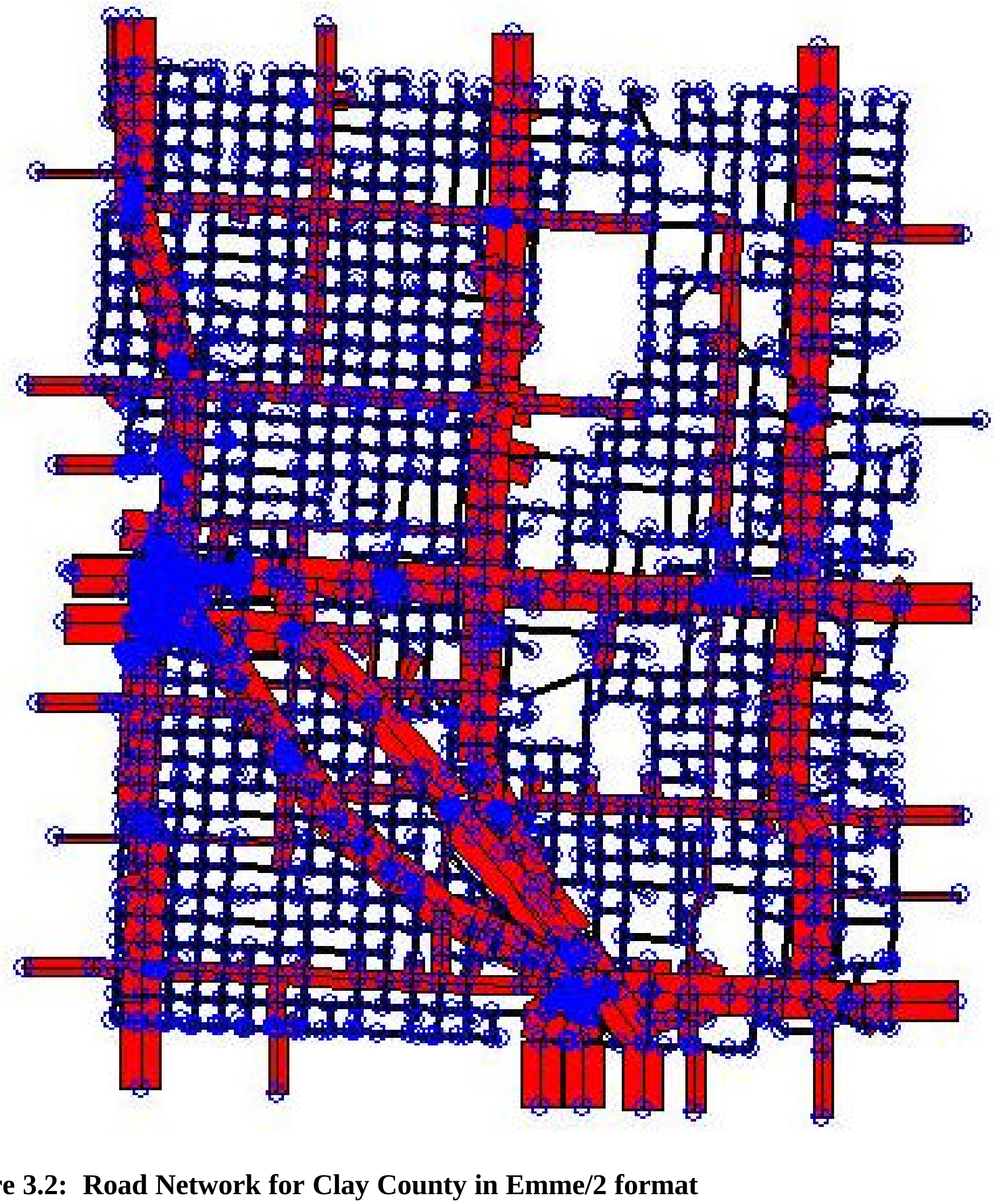

**Figure 3.2: Road Network for Clay County in Emme/2 format**

*Bar thickness indicates road type. The thickest bars represent 10-ton routes, while successively thinner bars represent 9, 7, and 5-ton roads, respectively.*

A different speed function is assigned to the different level of roads. It is worth noting here that the speed specified on each type of road is only used to determine the fastest route in the trip assignment process, and therefore, the absolute value of speed does not significantly affect the result of the freight demand model. Only the relative speed difference has impact to the results of freight demand model. Generally speaking, higher grade roads have higher average speed than lower grade roads. For instance, most 9-ton roads have shoulders (and/or wider shoulders versus 5- and 7-ton rural routes), which make drivers feel more comfortable traveling at a higher speed. Here 5, 7, 9 and 10-ton roads are assumed to have speeds of 48, 64, 80, and 96 km/h (30, 40, 50 and 60 mph), respectively. The speed specified here is used solely for modeling of truck demand (i.e. the flows were calibrated, and the speeds were adjusted to make the flows match better) and is not necessarily the actual running speed on these roads.

### 3.4 Trip Generation

Trip generation is the first step of the modeling process. It requires estimating the truck demand generated within the county. It is assumed that the truck demand is generated from various kinds of freight facilities within the county. According to the Mn/DOT freight facility database classification, there are eight land-use categories associated with freight transportation: Farm, Agriculture Chemical Center, Grain Elevator, Manufacturing Plant, Retail Outlet, Trucking Facility, Wholesale Distribution Center, and Other Freight Facilities. Figures 3.3 and 3.4 map the locations of these facilities in Lyon and Clay County, respectively.

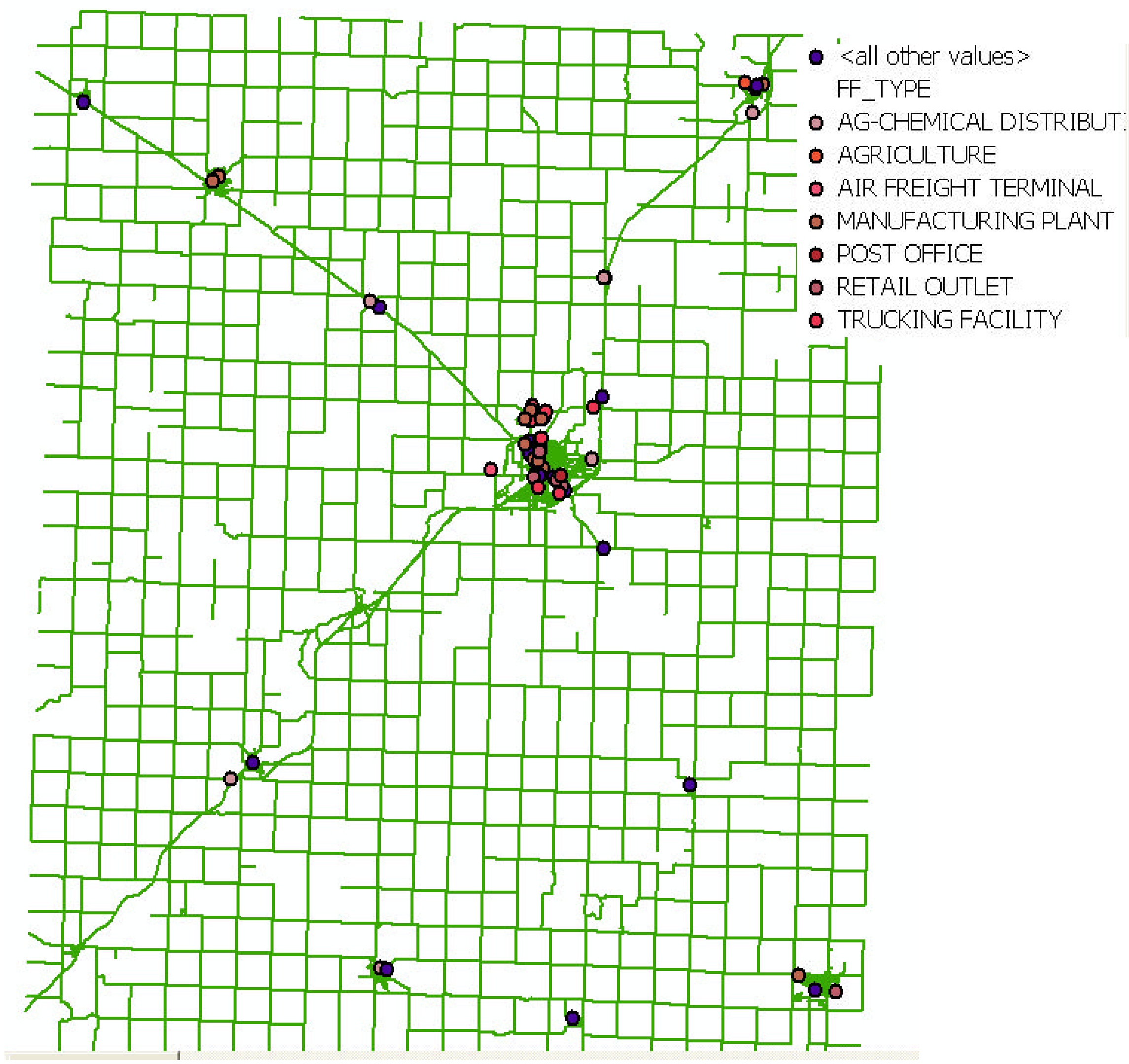


**Figure 3.3: Freight facility locations in Lyon County**

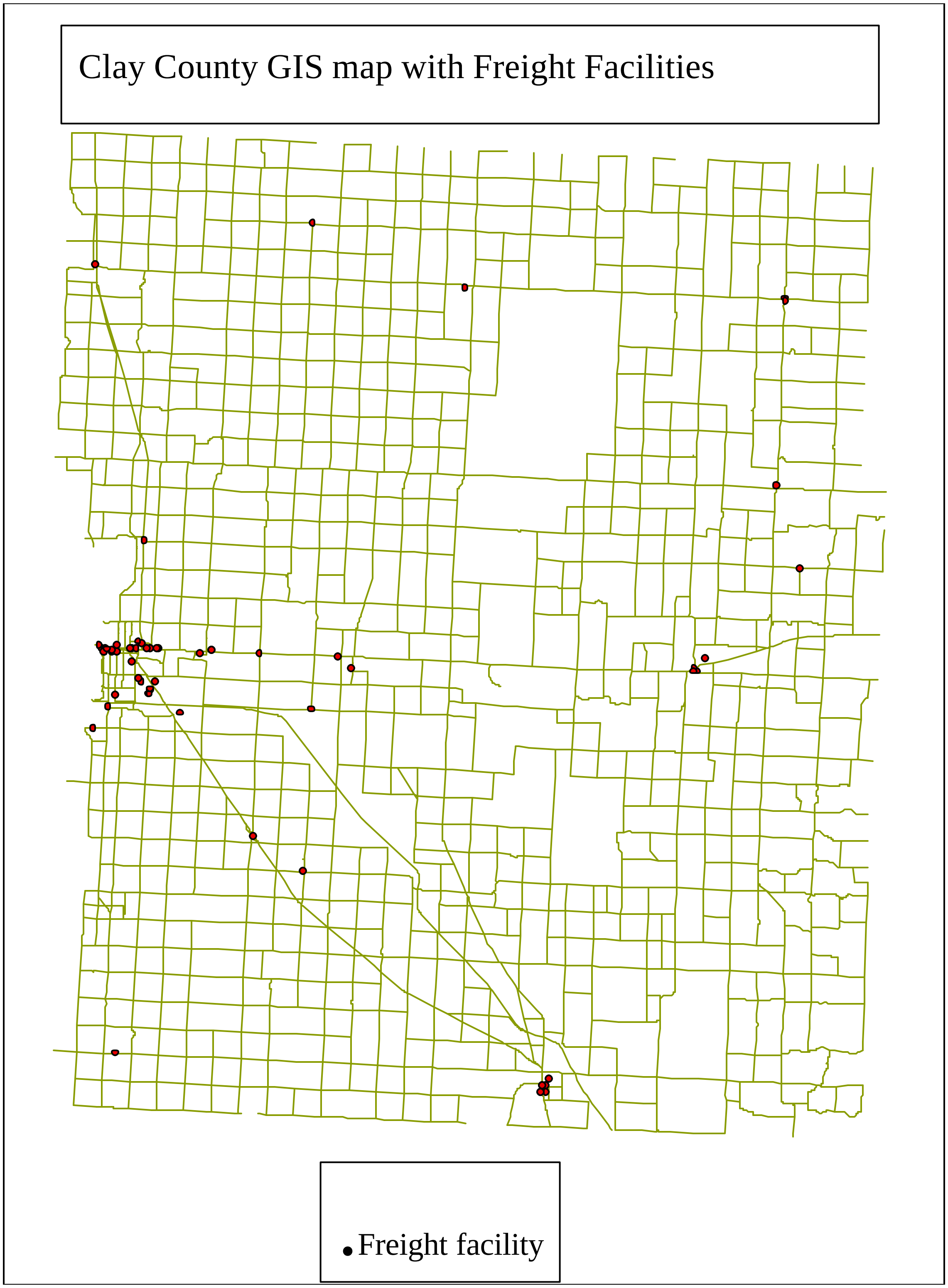


**Figure 3.4: Clay County GIS map with Freight Facilities**

**Trip generation for non-farm facilities**

In the process of developing a thorough freight demand model for Minnesota as part of the Spring Load Restriction (SLR) Cost-Benefit Study, research was undertaken to develop freight generation models by freight facility type. This section will provide an overview of previous freight generation studies, the methodology used in the surveying and analysis process, and the results.

Iding *et al.* [6] introduce a freight trip generation model from their native Netherlands. They noted that freight trip generation has been given little research over the past though it accounts for a growing percentage of the traffic congestion on today's roads. They discovered that in different industry sectors trip intensities can vary by an order of magnitude, thus a trip generation model should be fit for each sector independently. They used employee count and site area as independent variables describing trip generation depending upon the type of activity performed at the firm. The model of choice was simple linear regression. Simple linear regression is also used in ITE's Trip Generation Manual [7], where the independent variable used to describe the number of trips varies by facility.

As noted in Chapter 2, a survey was mailed to 2,523 freight industry candidates during the first half of 2003. The thirteenth question on the long form asks, "How many truckloads did your firm carry last year?" The goal of the analysis was to explain the variance in this number as a function of a scale variable. The fourth question asks, "How many direct employees does your firm have?" The number of direct employees was chosen as the scale variable because the data provided by the firms is thought to be more precise than other responses, and it has been shown to explain trip rates in previous studies.

The data was further divided into seven common freight facility types by matching the firm with its listing in the freight facilities database and analysis of the products that the firms' trucks carry. The seven types are: Agriculture Chemical Distribution Center, Agriculture, Grain Elevator, Manufacturing, Trucking Facility, Waste and Recycling Center, Wholesale Distribution Center. Table 3.5 displays descriptive statistics for the responses received from these freight facility types.

**Table 3.5 – Descriptive Freight Facility Statistics**

| | | Direct Employees | | Truck Loads | |
|---|---|---|---|---|---|
| Facility Type | N | Mean | Standard Deviation | Mean | Standard Deviation |
| Ag Chem | 18 | 23 | 32 | 1866 | 1480 |
| Agriculture | 28 | 28 | 52 | 2342 | 3282 |
| Grain | 38 | 20 | 25 | 3410 | 4700 |
| Manufacturing | 15 | 569 | 1925 | 5005 | 8602 |
| Trucking | 90 | 63 | 134 | 16471 | 33619 |
| Waste | 4 | 68 | 38 | 25280 | 27891 |
| Wholesale | 13 | 216 | 289 | 18367 | 41536 |

Four model types were used in this analysis. Simple linear regression has been used in all previous studies. Box-Cox, Cobb-Douglas and quadratic models account for some non-linearity; these were also fit to see if the fit to the data improved. The number of truckloads (TL) carried was the dependent variable and the number of direct employees (DE) on staff was the independent variable. All nil and zero responses were eliminated prior to model fitting.

Linear Regression: $TL = \beta_1 + \beta_2 * DE$

Quadratic Model: $TL = \beta_1 + \beta_2 * DE + \beta_3 * DE^2$

Cobb-Douglas Model: $TL = e^{b1} \times DE^{b2}$

Several models were fit during the analysis, from the simple linear model as used in the ITE Trip Generation Manual to Box-Cox, Cobb-Douglas and quadratic variants that account for curvature in the data. After fitting four options, shown in Table 3.6, it was determined that the Cobb-Douglas model provides the best fit. The Cobb-Douglas model accounts for non-linearity in the relationship between the number of employees and the number of truckloads. The relationship varies greatly between freight facility type, thus it is best to use a separate model for each facility type.

The model fit well with the exception of the manufacturing freight facility type. This is the best model that is available for these data, however in further research this freight facility type should be further broken down to account for the wide variation among firms.

For retail facilities, which are not in the model above, a linear trip generation model described in Iding's report was used [6], which gives detailed freight trip generation rates classified by firm types. It is assumed these retail facilities are food stores.

Table 3.7 shows summary results under the "without SLR" scenario. Under the SLR scenario, truckers have to increase truck trips if they choose the lower level roads. The truck trip increase is determined by the actual carrying capacity of each type of roads. For instance, assuming the above proportion, the average carrying capacity on a 7-ton road is 8.8 tons per truck while on a 9-ton road the capacity is 13.0 tons per truck. Theoretically, during SLR, if only a 7-ton route is available, the trucker has to undertake 1.48 times the normal number of truck trips (1.48=13/8.8). Similarly, the trucker has to use 3.25 times as many truck trips if a 5-ton route is chosen (3.25=13/4.0). This overestimates the truck trip during the SLR period for the following reasons:

- Some industries will choose to shift cargo transportation to the No SLR period. They do not transport cargo during the period. For example, some farms will store grain during SLR period.
- The SLR does not affect some industries because their products, when fully loaded onto trucks, do not exceed the load limits.

The SLR survey (Chapter 2) provided some information on how each industry is affected by SLR as shown in Table 3.8. The table lists the percentages of industries that are affected by SLR and must reduce their load size. The truckload increase factors due to SLR are calculated in the following method. It is assumed only a percentage of trucks are affected by SLR for each industry. Among those affected, only a certain proportion reduced load size, the other trucks shifted their timing to avoid SLR.

**Table 3.6 – Trip Generation Models**

| Industry Type | N | ß$_1$ | *t*-statistic | ß$_2$ | *t*-statistic | ß$_3$ | *t*-statistic | $R^2$ |
|---|---|---|---|---|---|---|---|---|
| | | | | Linear Regression Model | | | | |
| Ag Chem | 18 | 1355.90 | 3.43 | 22.18 | 2.16 | - | - | 0.225 |
| Agriculture | 28 | 2073.22 | 2.90 | 9.58 | 0.78 | - | - | 0.023 |
| Grain | 38 | 946.75 | 1.29 | 123.31 | 5.38 | - | - | 0.446 |
| Manufacturing | 15 | 4629.34 | 1.94 | 0.66 | 0.54 | - | - | 0.022 |
| Trucking | 90 | 5333.62 | 1.91 | 176.23 | 9.31 | - | - | 0.496 |
| Waste | 4 | -23850.53 | -3.54 | 727.86 | 8.11 | - | - | 0.971 |
| Wholesale | 13 | -1358.44 | -0.12 | 91.22 | 2.73 | - | - | 0.404 |
| | | | | Quadratic Model | | | | |
| Ag Chem | 18 | 711.03 | 1.51 | 82.64 | 2.74 | -0.51 | -2.11 | 0.402 |
| Agriculture | 28 | 764.06 | 0.93 | 132.69 | 2.70 | -0.64 | -2.58 | 0.228 |
| Grain | 38 | -22.11 | -0.02 | 245.60 | 2.64 | -1.43 | -1.35 | 0.474 |
| Manufacturing | 15 | 5218.77 | 1.96 | -8.22 | -0.52 | 0.00 | 0.56 | 0.047 |
| Trucking | 90 | -749.01 | -0.25 | 388.83 | 7.08 | -0.34 | -4.08 | 0.577 |
| Waste | 4 | -2120.00 | -0.23 | 38.33 | 0.14 | 4.41 | 2.55 | 0.996 |
| Wholesale | 13 | -7447.02 | -0.57 | 198.82 | 1.67 | -0.14 | -0.94 | 0.453 |
| | | | | Cobb-Douglas Model | | | | |
| Ag Chem | 18 | 5.41 | 10.82 | 0.68 | 3.70 | - | - | 0.461 |
| Agriculture | 28 | 5.05 | 9.83 | 0.77 | 4.01 | - | - | 0.382 |
| Grain | 38 | 5.47 | 12.76 | 0.78 | 4.75 | - | - | 0.385 |
| Manufacturing | 15 | 5.35 | 3.30 | 0.26 | 0.66 | - | - | 0.033 |
| Trucking | 90 | 5.67 | 23.71 | 0.92 | 12.73 | - | - | 0.648 |
| Waste | 4 | 0.48 | 0.72 | 2.23 | 13.67 | - | - | 0.989 |
| Wholesale | 13 | 1.87 | 2.28 | 1.34 | 7.50 | - | - | 0.836 |
| | | | | Box-Cox Model | | | | |
| Ag Chem | 18 | 2.42 | 2.16 | 3.81 | 4.24 | - | - | 0.529 |
| Agriculture | 28 | 4.68 | 8.74 | 1.18 | 4.52 | - | - | 0.440 |
| Grain | 38 | 5.54 | 13.40 | 0.71 | 4.80 | - | - | 0.390 |
| Manufacturing | 15 | 5.38 | 1.81 | 0.43 | 0.32 | - | - | 0.008 |
| Trucking | 90 | 5.37 | 20.79 | 1.30 | 12.82 | - | - | 0.651 |
| Waste | 4 | 0.48 | 0.71 | 2.23 | 13.67 | - | - | 0.989 |
| Wholesale | 13 | 2.84 | 3.9 | 0.84 | 7.22 | - | - | 0.825 |

**Table 3.7 – Summary Truck trip rate of other freight facilities**

| Freight Catalog | Minnesota model |
|---|---|
| Agriculture chemical distribution center | 129.84 |
| Grain elevators* | 83.4 |
| Manufacture plant | 29.0 |
| Retail outlet | 128.7 |
| Trucking facility | 388.4 |
| Whole sale outlet | 29.87 |

**Note that we do not adopt the grain elevator truck-trip rate from the trip generation model. According to our survey, many grain elevators use rail to transport grain. Through talking to staff in several grain elevators, 60% of the outgoing freight from grain elevators are assumed to use trucks and the remaining 40% rail. The trips required from a grain elevator are based on the freight entering that elevator, which is considered more accurate than using a trip rate based on number of employees. The amount of grain leaving by truck is the amount of grain entering discounted by 40%. The number of trucks required is computed based on tonnage.*

**Table 3.8 – SLR impacts on industry**

| Industry | Count | Affected by SLR | Reduce Load Size | Industry reclassification | 7-ton road increase factor | 5-ton road increase factor |
|---|---|---|---|---|---|---|
| Agricultural | 99 | 86.9% | 79.8% | Agriculture | 1.16 | 2.38 |
| Agriculture Chem | 28 | 100.0% | 96.4% | Chemical | 1.43 | 3.13 |
| Aggregate | 16 | 87.5% | 75.0% | Manufacture | | |
| Timber | 7 | 85.7% | 85.7% | Manufacture | | |
| Construction | 23 | 82.6% | 43.5% | Manufacture | 1.01 | 2.04 |
| Beverages | 5 | 100.0% | 40.0% | Retail | | |
| Petroleum | 19 | 89.5% | 73.7% | Retail | | |
| Food Products | 20 | 60.0% | 40.0% | Retail | 0.81 | 1.57 |
| Dairy | 6 | 66.6% | 33.3% | Wholesale | | |
| General Products | 52 | 46.2% | 19.2% | Wholesale | | |
| Paper | 7 | 28.6% | 14.3% | Wholesale | | |
| Industrial Supplies | 32 | 21.9% | 18.8% | Wholesale | 0.74 | 0.91 |
| Overall | 315 | 71.4% | 79.1% | | 1.12 | 2.12 |

The reported industry type from the survey was categorized to be consistent with the freight facility category in the freight demand model. From this, the average increase factor in each industry was calculated. For industries that are not included in the survey, the sample average was used to approximate the increase factor.

Although waste and recycling centers and post offices are missing from the freight facility database, their existence is still assumed. It is assumed a 2-axle postal truck will run on all roads once a day in both with and without SLR scenarios, and a 3-axle garbage truck will cover all roads once a week in the without SLR scenario and twice a week during the SLR period.

**Truck trips generated by farms**

Truck trips generated by farms are associated with the amount of agricultural product that needs to be transported. First the total production of grain in Lyon County was obtained, followed by a determination of the truck fleet carrying the grain. From this data, the truck trip rates can be calculated. Crop production for each of the counties (Lyon, Olmsted and Clay) for the year 2001 are summarized in Table 3.9 [8].

**Table 3.9 – Major Crop Production**

| Crop | Lyon County (Tons) | Olmsted County (Tons) | Clay County (Tons) |
|---|---|---|---|
| Corn | 558,911 | 391,429 | 82,973 |
| Soybean | 140,593 | 68,875 | 106,005 |
| All wheat | 4,515 | 0 | 221,869 |
| Oats | 2,465 | 5882 | 819 |
| Total | 706,484 | 466,186 | 411,666 |

In Lyon County, assuming the crops are evenly distributed among the 225 virtual farms and are evenly transported each day, 8.6 tons needs to be transported from each farm every day. (8.6=706,484/(225*365)).

In Clay County, assuming the crops are evenly distributed among the 222 virtual farms and are evenly transported each day, 5.08 tons needs to be transported from each farm every day. (5.08=411,666/ (222*365)).

In Olmsted County, assuming the crops are evenly distributed among the 212 virtual farms and are evenly transported each day, 6.02 tons needs to be transported from each farm every day. (6.02 = 466,186/ (212*365)).

During the SLR period, farms may transport less grain than usual to avoid extra shipping costs. To explore the fluctuation of grain hauling due to SLR, data was obtained from All-American Coop, which runs grain elevators in Stewartville and Viola, both in Olmsted County, Minnesota.

A comparison was made between the quantity of commodities hauled to and from the elevator in April and the commodities hauled during the other months of the year. April was specifically chosen because it is the only month that SLR is in effect for the entire month. March and May, the months before and after April did not experience a decrease due to SLR because extra loads could be hauled immediately before and after the SLR period. For commodities hauled from the elevator from 1995 to 2003, there was an 8.5% decrease in hauled-in tons during April compared to the average tons hauled in other months. The monthly fluctuation of tons hauled out is illustrated in Figure 3.5. The haul-in data also showed a decrease in the month of April. This decrease was more pronounced at 11.5%. Monthly tonnage is illustrated in Figure 3.6. Because there is a conservation of mass, over time, the tons hauled in equals the tons hauled out. Because of this equality, the average of the two percentages — 10% — approximates the percent decrease of tons hauled during the month of April. This 10% percent decrease of grain hauling during SLR is taken into account in the modeling.

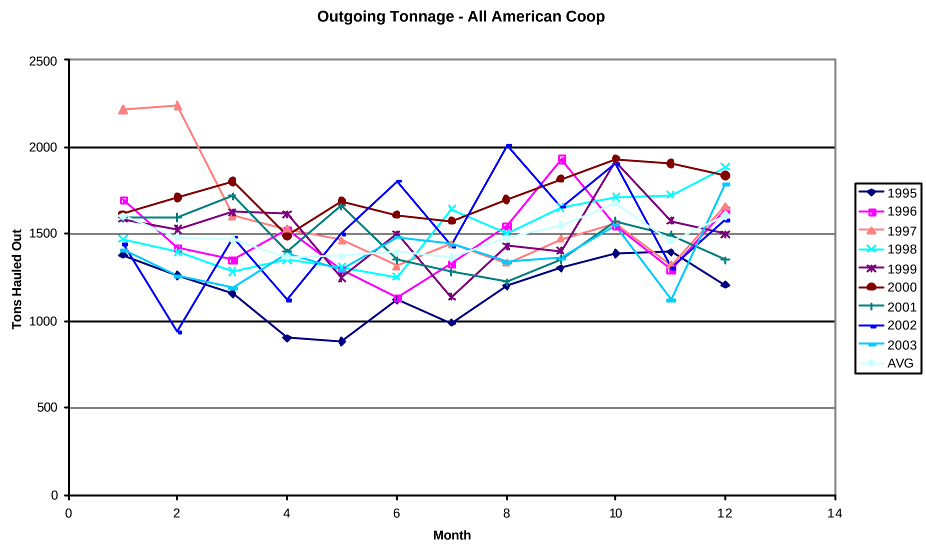


**Figure 3.5: Outgoing grain tonnage from All American Co-op in Olmsted County 1995-2003.**

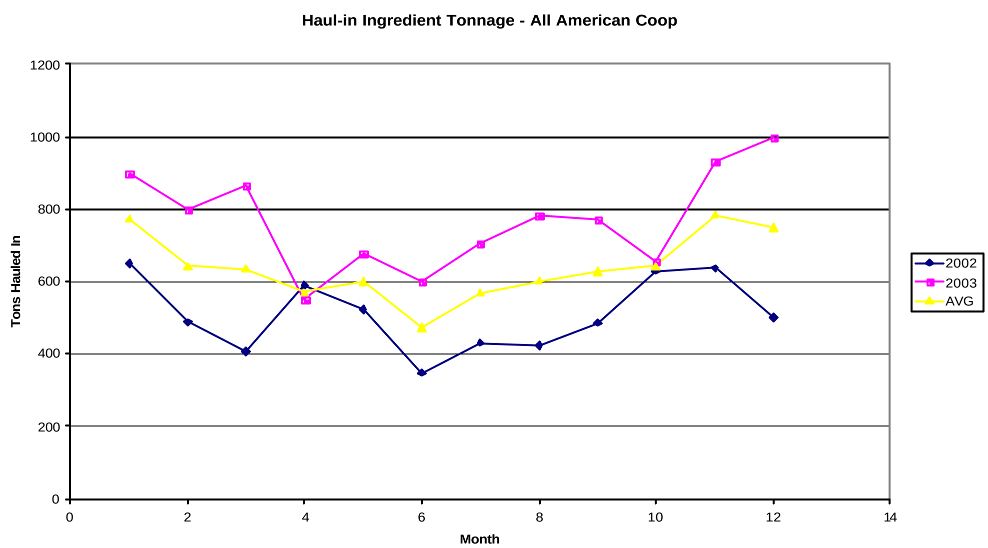


**Figure 3.6: Incoming grain tonnages from All American Co-op in Olmsted County 2002-2003.**

Considering the seasonal fluctuation of grain hauling, in Lyon County, 8.67 tons of grain per day will be hauled in the period without SLR and 7.88 tons grain per day will be hauled during the SLR period. In Clay County 4.65 tons would need to be transported each day during the month of April, while 5.12 tons needs to be delivered during the remainder of the year. In Olmsted County, 6.02 tons would need to be transported each day during the month of April, and 5.47 tons the rest of the year.

If SLR is not implemented, 9-ton routes are available for farms to carry grain to nearest grain elevator. The carrying capacity of a typical 9-ton truck is 13.0 tons as shown in Table 3.3. The daily truck trip for each farm outside the SLR period is shown in Table 3.10.

**Table 3.10 – Trip Rates for Farms**

| Highest Road Accessible in Zone | Lyon County | Olmsted County | Clay County |
|---|---|---|---|
| Outside the Spring Load Restriction Period | | | |
| 9-ton | 0.67=8.67/13.0 | 0.46=6.02/13.0 | 0.39=5.08/13.0 |
| During the Spring Load Restriction Period | | | |
| 5-ton | 1.97 = 7.88/4.0 | 1.37 = 5.47/4.0 | 1.16 = 4.65/4.0 |
| 7-ton | 0.90 = 7.88/8.8 | 0.62 = 5.47/8.8 | 0.53 = 4.65/8.8 |
| 9-ton | 0.61 = 7.88/13.0 | 0.42 = 5.47/13.0 | 0.36 = 4.65/13.0 |

If SLR is implemented, each farm has to determine what kind of roads to use to reach its destination. Table 3.3 shows average carrying capacity of a typical truck on each type of road. In Lyon County 7.88 tons of grain needs to be carried out for each farm every day during the SLR period. In Clay County, 4.65 tons of grain needs to be carried out. Using the truck fleet information, it is assumed that truck fleet composition on different types of roads follows the patterns in Table 3.3 during the SLR period. The trip rates during the SLR period are shown in Table 3.10.

### 3.5 Trip Distribution

Trip distribution is based on the origin-destination sketch map in Figure 3.7. It is assumed that each farm will deliver its grain product to the nearest grain elevator and return empty. Each farm receives deliveries from the nearest Agricultural Chemical (Ag-Chem) facility and the trucks return to the Ag-Chem facilities empty. For the other types of freight facilities, it is assumed all traffic is bound for external stations. The trips to each external station will be distributed in proportion to the real traffic count at these external points. There is also external to external traffic, which is assumed to be 20 percent of the total traffic stream at each exit. A Matlab program (Appendix 3) was written to realize the above function.

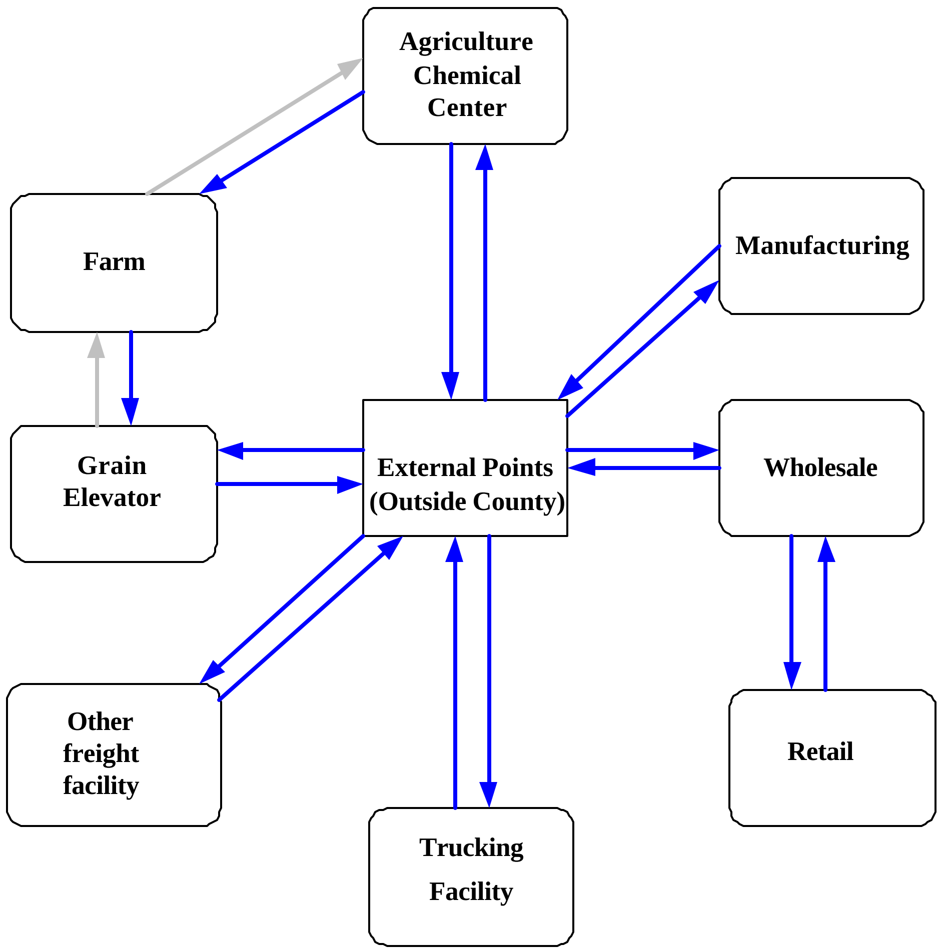


**Figure 3.7: Freight demand pattern in Lyon County**

### 3.6 Vehicle Type Assignment

It is assumed that truckers will choose the most economically beneficial vehicle. In the absence of restrictions, truckers will tend to choose the trucks with the highest payload capacity they have so they can carry more goods. However, weight restriction limits may prevent this, especially if a trucker would face a significant amount of detouring. Truckers faced with weight restrictions must compare the costs of detouring versus the costs of using trucks with a lower weight or payload capacity, which may result in using more trucks. The total cost for a trip is:

$$C = (T_T + T_L) * N * c$$

where:

$C$ – Total cost

$T_T$ – Travel time for each trip (hour)

$T_L$ – Time for loading and unloading (30 minutes is required for loading and unloading cargo for each truckload)

$N$ – Number of Truckloads

$c$ – Value of time (dollar per hour)

The trucker will find the route that has the least total cost. For example, if a 9-ton route is the highest level of route they can find between the origin and destination, they will check to see if using a 7-ton route will lower their costs. Choosing a 7-ton truck means they will have to use 1.48 = 13/8.8 truckloads instead of 1 and will spend 18.9 = 0.69*30 minutes more on loading and unloading, but they will travel over a shorter route. The trucking firm will calculate the total cost of each choice and then select the most economical one.

### 3.7 Route Assignment

In the route assignment, it is assumed that truckers will behave according to user equilibrium assignment theory in which they will choose routes with the least travel time (T). Since rural areas are being modeled, congestion effects are ignored, which makes this equivalent to an all-or-nothing shortest path assignment. (Although congestion may occur, it is for a fairly short time).

$$T = 60 * L / v$$

T: Travel time (minutes).

L: road section length (kilometer)

V: vehicle speed (km/h), assumed to be 48, 64, 80 and 96 km/h (30, 40, 50, and 60 mph) for 5, 7, 9 and 10-ton roads respectively.

The constant “60” converts the unit of hour to minutes.

It should be noted that interstate highways are assigned a speed of 104 km/hr (65 mph), which distinguishes them from other 10-ton roads.

### 3.8 Calibration and Validation

The freight demand model was run using the Emme/2 software, providing truck volumes for each road section. It is important to know if the model can sufficiently simulate actual conditions.

Two methods were used to check and calibrate the model. The first method used the observed total traffic count map. Lyon County data is shown in Figure 3.8**.** If trucks are assumed to be a certain proportion of the total traffic spread evenly on the roads, the truck pattern should be similar to the real total traffic pattern. Fortunately, the result this study's freight demand model (without SLR scenario) (Figure 3.9) has a similar pattern to the observed total traffic counts in Lyon County (after SLR).

Another method was used to compare observed truck traffic on links outside the SLR period to their counterpart link counts in the model. Appendix 6 summarizes all the sites that reported data during the no SLR period and their modeled truck average daily traffic during the 10 months without SLR.

Figure 3.10 compares the model with observations. It can be seen from the plot that the two data sets have a strong linear relationship. In order to find how close the model reflects the actual conditions, a regression of this data was performed. The R-squared value for the regression of this data is 0.836. This value shows a strong correlation between the model and observed AADT.

To proceed in calibrating the model, a scaling factor was determined to transform the modeled truck rates to more accurate rates. The sum of the daily truck traffic for all the observation sites was found and compared to the sum of the daily truck traffic on the links representing those sites in the model. The sum of the actual truck traffic is 7611.5 trucks while the sum of the modeled truck traffic is 6284.9 trucks. The actual traffic was found to be 1.21 times the modeled traffic. Therefore, the traffic volume for each scenario was scaled up by a factor of 1.21. Table 3.11 gives the adjusted VKT with and without SLR for the three counties. A 21 percent adjustment factor was also applied to Clay County, for which there was inadequate data to conduct a localized calibration.

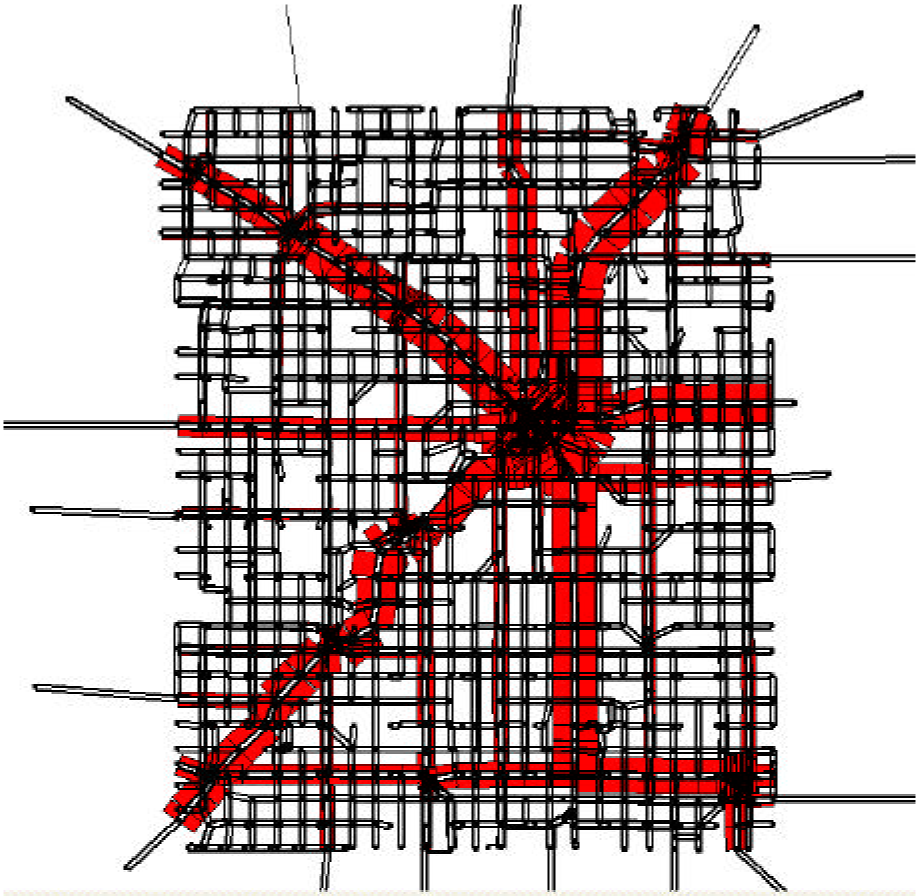

**Figure 3.8: Total observed traffic counts in Lyon County**

*Bar thickness indicates traffic levels. The thickest bars represent the heaviest levels of traffic.*

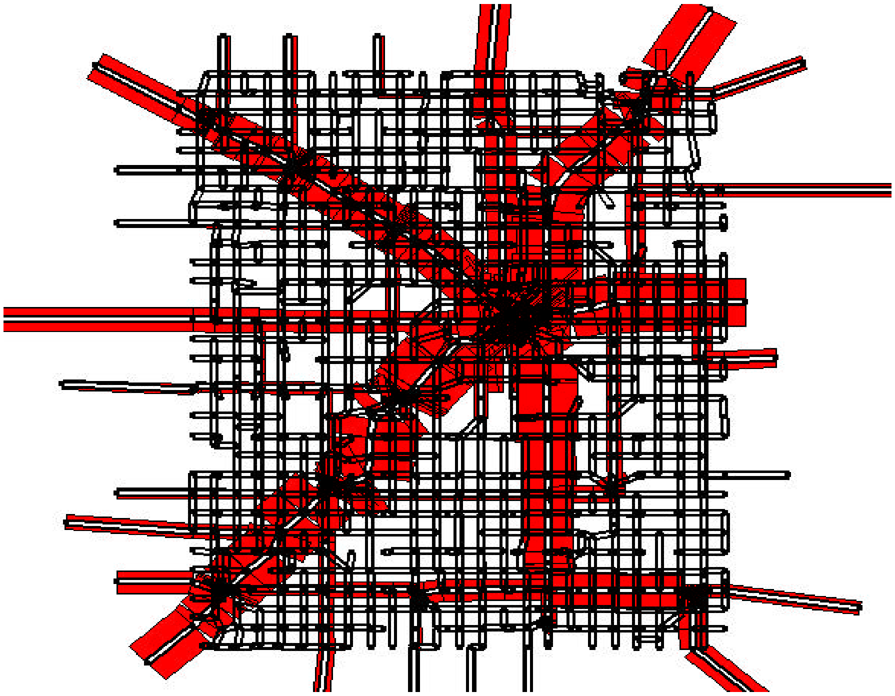

**Figure 3.9: Truck volume map from Model (Scenario 1-without SLR)***

*Bar thickness indicates traffic levels. The thickest bars represent the heaviest levels of traffic.*

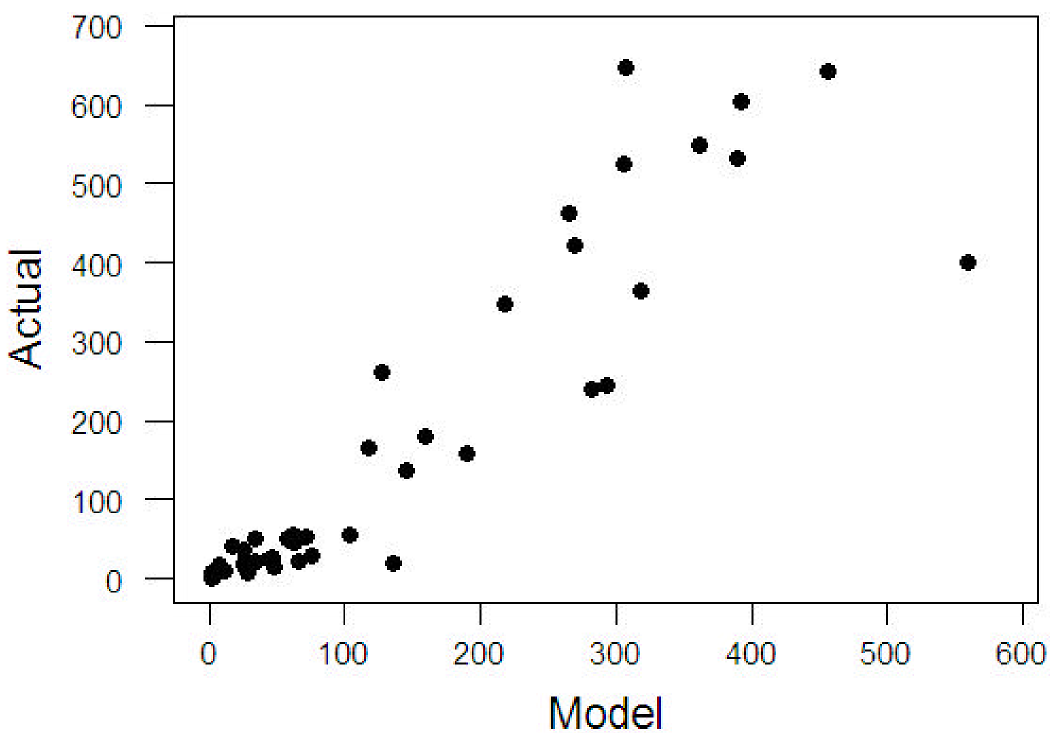


**Figure 3.10: Plot of model vs. observed truck AADT for Lyon County**

**Table 3.11 – Truck VKT from Base Runs**

| | | Lyon County | | Olmsted County | | Clay County | |
|---|---|---|---|---|---|---|---|
| Scenario Number | Scenario | Raw VKT | Calibrated VKT | Raw VKT | Calibrated VKT | Raw VKT | Calibrated VKT |
| 1 | No SLR | 83,184 | 100,653 | 264,420 | 319,948 | 182,708 | 221,077 |
| 2 | With SLR | 108,496 | 131,280 | 346,200 | 418,902 | 171,951 | 208,061 |
| 3 & 2' | Lift SLR on 7 and 9 only | 102,594 | 124,138 | 320,100 | 387,321 | 181,983 | 220,199 |

## 3.9 Conclusions

The freight demand model estimates truck volumes on each section of the roads under different policy scenarios. The model shows an increase of 30.4%, 30.9%, and 6.3% in truck distance traveled in Lyon, Olmsted, and Clay counties respectively if SLR is implemented strictly on all 5, 7, and 9-ton roads compared to the scenario without SLR. The model also concludes a 23.3%, 21.1%, and 5.8% increase of truck distance traveled in Lyon, Olmsted, and Clay counties, respectively, if restrictions are imposed only on 5-ton roads.

**References**


[1] Public Works of Lyon County. *Lyon load restriction map (2003)* and *traffic volume map (2000)*. http://www.lyonco.org/dept/pw/compplan.html.

[2] Li, Ning, Xi Zou, D. Levinson, *"Sharing Data Between Arc/Info and Emme/2: A practice in Lyon County, Minnesota"*, proceedings at Transportation Research Forum's 2004 Annual Forum, Evanston, Illinois March 21-23

[3] TRIMAC Consulting Services Canada, *Evaluation of truck traffic patterns and impacts*, http://www.tc.gc.ca/pol/en/Report/truckGrain1999/C4.htm

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[5] Minnesota Department of Transportation, *Restricted Gross Weight Table,* 2004.

[6] Iding, M.H.E, Wilhelm J, and Lori A. *Freight trip generation by firms. Paper for the 42nd European Congress of Regional Science Association*, Dortmund, 2002

[7] *ITE's Trip Generation Manual* (7th ed.). (2003). Washington, D. C: Institute of Transportation Engineers.

[8] National Agriculture Statistics Service, *grain production of Minnesota counties 2001*. http://www.nass.usda.gov/mn/agstat02/p097118.pdf

# Chapter 4

Task #4: Conduct Benefit/Cost Analysis of Alternative Load Restriction Policies (including current policy) Using Mechanistic Models.

## 4.1 Introduction

Benefit/cost analysis combines the results of the Freight Demand Model (FDM) (Described in Chapter 3) and the Pavement Performance Model (PPM) (Described in Chapter 1). The FDM estimates truck volume on each link of the road network and the PPM estimates the pavement life under these truck volumes in different policy scenarios. Knowing the overlay cost of each road type, pavement savings due to SLR can be calculated. The FDM also provides the amount of additional truck VKT due to SLR, which can be used with information about operating cost or truck value of time (described in Chapter 2) to calculate cost to truckers due to SLR. Combining these numbers over the life of the road, and discounting back to the present to obtain a Net Present Value, allows for the computation of a benefit/cost ratio of lifting or retaining the policy.

## 4.2 Benefit/Cost Analysis Methodology

Changing the current SLR policy has the potential to provide benefits to the trucking industry, in terms of operating costs and time savings, while imposing costs upon the road owners, in the form of shorter pavement life. Thus, it is important to calculate how much the SLR saves on pavement costs. The cost estimates for Lyon County roads come from cost estimates from State District Engineers and a statewide study performed by Goodhue County Engineer Greg Isakson (*See Appendix 4-1*). The average cost for each road category in Minnesota is calculated. It is worth noting that the Metro area is not included in the average for its unique higher cost than all other districts. Tables 4.1a and 4.1b lists all the average costs for each road category in Minnesota.

**Table 4.1a Average costs for each road category in Minnesota (per km)**

| Average Cost per center-line kilometer by Category | | | |
|---|---|---|---|
| **Category** | **Reconstruct** | **Structural Overlay** | **Functional Overlay** |
| CSAH 9,10-ton | $235,938 | $66,875 | $39,063 |
| CSAH 7-ton | $190,625 | $72,813 | $40,625 |
| CR 9-ton | $258,333 | $64,583 | $34,375 |
| CR 7-ton | $171,875 | $64,063 | $35,938 |
| CR 5-ton paved | $112,500 | $34,375 | $28,125 |
| CR 5-ton Agg | $87,500 | $31,250 | N/A |
| MSA 9,10-ton | $932,813 | $233,333 | $77,083 |
| MSA 7-ton | $729,167 | $191,667 | $77,083 |
| Residential Streets | $1,443,750 | $450,000 | $51,667 |

| | | | |
|---|---|---|---|
| Township Rd, Paved | $725,000 | $240,625 | $50,625 |
| Township Rd, Agg | $68,750 | $18,750 | $18,750 |

**Table 4.1b Average costs for each road category in Minnesota (per mile)**

| Average Cost per center-line kilometer by Category | | | |
|---|---|---|---|
| **Category** | **Reconstruct** | **Structural Overlay** | **Functional Overlay** |
| CSAH 9,10-ton | $379,624 | $107,602 | $62,852 |
| CSAH 7-ton | $306,716 | $117,156 | $65,366 |
| CR 9-ton | $415,658 | $103,914 | $55,309 |
| CR 7-ton | $276,547 | $103,077 | $57,824 |
| CR 5-ton paved | $181,013 | $55,309 | $45,253 |
| CR 5-ton Agg | $140,788 | $50,281 | N/A |
| MSA 9,10-ton | $1,500,896 | $375,433 | $124,027 |
| MSA 7-ton | $1,173,230 | $308,392 | $124,027 |
| Residential Streets | $2,322,994 | $724,050 | $83,132 |
| Township Rd, Paved | $1,166,525 | $387,166 | $81,456 |
| Township Rd, Agg | $110,619 | $30,169 | $30,169 |

The average structural and functional overlay cost for 7 and 9-ton roads in Lyon County was calculated based on cost and length percentage for each type of road (Tables 4.2a and 4.2b). The functional overlay cost was adopted to calculate the cost of pavement for 7 and 9-ton roads. Thus, a functional overlay of a 7-ton road in Lyon County has an average cost of $42,113 per center-line kilometer ($67,380/mile) and a functional overlay of a 9-ton road has an average cost of $42,853 per center-line kilometer ($68,565/mile). Similar calculations were performed for Clay County (Table 4.3a and 4.3b). Re-graveling of 5-ton roads has an average cost of $18,750 per center-line kilometer ($30,000/mile) according to the FHWA manual [1].

**Table 4.2a Cost estimates of different road types (Lyon County weighted average, km)**

| Road Category | Structural overlay cost per center-line km ($) | Functional overlay cost per center-line km ($) | Length* (km) | Percentage |
|---|---|---|---|---|
| **5 ton road (gravel)** | | | | |
| Average<br>Annual cost (6 years) | | 18,750 | 1,437 | |
| **7 ton road** | | | | |
| CSAH 7-ton | 72,813 | 40,625 | 179 | 89.60% |
| County road 7-ton | 64,063 | 35,938 | 11.2 | 5.60% |
| MSA 7 ton | 191,667 | 77,083 | 9.6 | 4.80% |
| Average cost | 78,028 | 42,113 | | |
| **9 ton road** | | | | |
| CSAH 9-ton | 66,875 | 39,063 | 216.8 | 90.00% |
| County road 9-ton | 64,583 | 34,375 | 0 | 0% |
| MSA 9 ton | 233,125 | 77,083 | 24 | 10.00% |
| Average cost | 83,450 | 42,853 | | |

**The length of classified roads comes from a survey by the pavement group (See Chapter 1, Appendix 2), which differs slightly from the total length in the GIS database we obtained and implemented in the Emme/2-based Freight Demand Model.*

**Table 4.2b Cost estimates of different road types (Lyon County weighted average, miles)**

| Road Category | Structural overlay cost per center-line mile ($) | Functional overlay cost per center-line mile ($) | Length* (mile) | Percentage |
|---|---|---|---|---|
| **5 ton road (gravel)** | | | | |
| Average<br>Annual cost (6 years) | | 30,000 | 893 | |
| **7 ton road** | | | | |
| CSAH 7-ton | 117,156 | 65,366 | 111 | 89.60% |
| County road 7-ton | 103,077 | 57,824 | 7 | 5.60% |
| MSA 7 ton | 308,392 | 124,027 | 6 | 4.80% |
| Average cost | 125,547 | 67,760 | | |
| **9 ton road** | | | | |
| CSAH 9-ton | 107,602 | 62,852 | 135 | 90.00% |
| County road 9-ton | 103,914 | 55,309 | 0 | 0% |
| MSA 9 ton | 375,098 | 124,027 | 15 | 10.00% |
| Average cost | 134,271 | 68,950 | | |

**Table 4.3a: Cost estimates of different road types in Clay County (weighted average, costs per km)**

| | Structural overlay cost per center-line km ($) | Functional overlay cost per center-line km ($) | Length (km) | Percentage |
|---|---|---|---|---|
| Road Category | | | | |
| 5 ton road | | | | |
| Average Cost | | 18,750 | 2618 | 100% |
| 7 ton road | | | | |
| CSAH 7-ton | 72,813 | 40,625 | 94.92 | 77.50% |
| CR 7-ton | 64,063 | 35,938 | 27.57 | 22.50% |
| MSA 7-ton | 191,667 | 77,083 | 0 | 0% |
| Average Cost | 70,844 | 39,570 | | |
| 9 ton road | | | | |
| CSAH 9-ton | 66,875 | 39,063 | 226.5 | 93.89% |
| CR 9-ton | 64,583 | 34,375 | 13.72 | 5.69% |
| MSA 9-ton | 223,125 | 77,083 | 1.02 | 0.42% |
| Average Cost | 67,401 | 38,956 | | |

**Table 4.3b: Cost estimates of different road types in Clay County (weighted average, costs per mile)**

| | Structural overlay cost per center-line km ($) | Functional overlay cost per center-line km ($) | Length (km) | Percentage |
|---|---|---|---|---|
| Road Category | | | | |
| 5 ton road | | | | |
| Average Cost | | 30,000 | 1627 | 100% |
| 7 ton road | | | | |
| CSAH 7-ton | 116,501 | 65,000 | 59 | 77.50% |
| CR 7-ton | 102,501 | 57,501 | 17 | 22.50% |
| MSA 7-ton | 306,667 | 123,333 | 0 | 0% |
| Average Cost | 113,350 | 63,312 | | |
| 9 ton road | | | | |
| CSAH 9-ton | 107,000 | 62,501 | 141 | 93.89% |
| CR 9-ton | 103,333 | 55,000 | 9 | 5.69% |
| MSA 9-ton | 357,000 | 123,333 | 1 | 0.42% |
| Average Cost | 107,842 | 62,330 | | |

In both scenarios (with and without SLR), it is assumed that a functional overlay is conducted for 7 and 9-ton roads when the road serviceability drops to a certain level. The functional overlay is assumed to last 17 years for 7 and 9-ton roads with SLR, which means the road will be overlaid whether or not rutting failure is the dominant failure mode.

Pavement life extension benefit on 7 and 9-ton roads are calculated on a link-by-link basis. The pavement performance model estimates the years before rutting failure, which may be longer or shorter than the actual pavement life. It is assumed an overlay will be undertaken every 17 years due to other types of pavement failure. Thus, when the pavement performance model estimates a pavement life to be more than 17 years, 17 years of pavement lifetime is adopted. For each link, the pavement life is estimated for two scenarios. For most links, the pavement lasts longer in the scenario with SLR than in the scenario without. The overlay costs in both scenarios are discounted to the present value in an analysis period of 42.5 years. The difference (without – with SLR) is the pavement life extension cost associated with lifting the SLR policy.

The following cash flow diagrams (Figures 4.1 and 4.2) show the cash flow of overlays in the two scenarios. For 7 and 9-ton roads, it is assumed that overlays will be performed during a pavement life cycle to maintain a certain level of serviceability. It is assumed 7 and 9-ton roads are on average in the middle of one overlay, which is half of the previous pavement's time between overlays. An example to show how the pavement life savings due to SLR is calculated follows below.

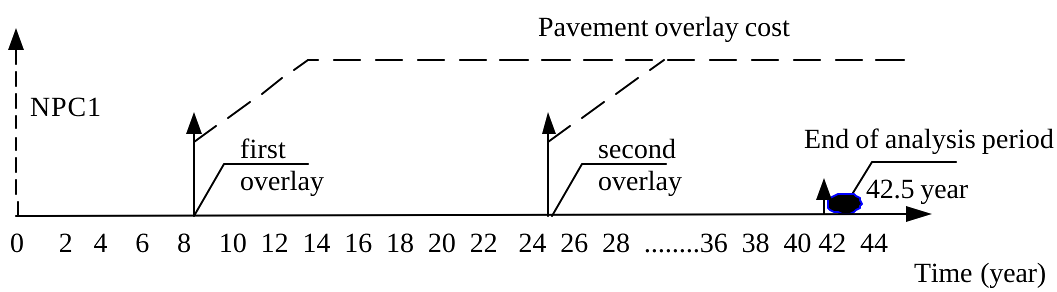


**Figure 4.1 Cash flow chart for With SLR scenario**

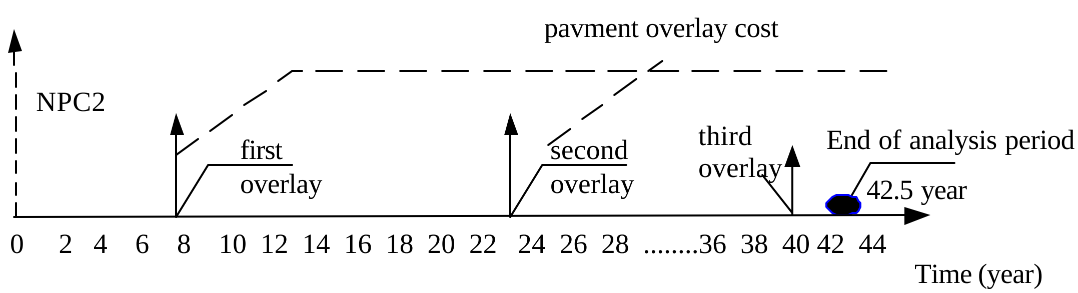


**Figure 4.2 Cash flow chart for Without SLR scenario**

One 7-ton road section in Lyon County has a length of 1.584 km (0.98 mi). The functional overlay cost of 7-ton roads is $42,112 per km ($67,758/mi). Each overlay will cost $66,706 for this road section. This road section has estimated life of 14.2 and 14.5 years for the scenarios with and without SLR respectively. In the without SLR scenario, the first, second and the third overlay happen at 7.1, 21.3 and 35.5 years respectively. The first and second overlay cost $66,706.

It is worth noting that the third overlay has a residual life outside the analysis period. The cost of third overlay is multiplied by the ratio of the usable life in the analysis period versus its actual life. Here the road will be used for 7 years (42.5-35.5) in the analysis period while it has a 14.2 years actual life. Thus the third overlay cost is estimated as $32,839 = (7/14.2*66706).

Each overlay cost is discounted to obtain the net present cost (NPC) assuming a 3.5% interest rate ($i$). Thus the NPC of the first overlay is calculated as $\$66,706 * \frac{1}{(1+i)^{7.2}} = \$ 52,248$. The NPC of these three overlay adds up to $93,981, which is the total overlay cost for this road section in the following 42.5 years.

Similarly, the total overlay cost of this road section in the scenario with SLR can be calculated, which has a NPC of $91,652. Thus the net present value of total savings due to SLR on this road section is $93,981 - $91,652 = $2,329. The calculation process is listed in Table 4.4.

**Table 4.4 Pavement life extension benefit for one link**

| Link 1 | From node id: 41 | | | To node id : 9 | | |
|---|---|---|---|---|---|---|
| | Length (km) | | 1.584 | Cost per km ($) | | $42,112 |
| | No SLR scenario<br>Estimated life (year ) | | 14.2 | With SLR Scenario<br>Estimated life (year) | | 14.5 |
| Number of Overlay | Year | Cost($) | NPC($) | Year | Cost ($) | NPC ($) |
| 1st overlay | 7.1 | 66,706 | 52,248 | 7.3 | 66,706 | 51,962 |
| 2nd overlay | 21.3 | 66,706 | 32,053 | 21.8 | 66,706 | 31,530 |
| 3rd overlay | 35.5 | 32,839 | 9,680 | 36.3 | 28,455 | 8,161 |
| Sum of Net Present Cost (NPC) | | | 93,981 | | | 91,652 |
| Savings due to SLR | | | | | | 2,329 |

For each link, the net present value of the overlay costs NPC1 and NPC2 in the two scenarios are calculated, respectively. The pavement life savings due to SLR is NPC2-NPC1.

Because the calculation involves thousands of 7 and 9-ton links, the data is exported into a spreadsheet and macros are written to perform the analysis.

## 4.3 Benefit/Cost Analysis Results

The baseline analysis compares the existing SLR policy with an alternative that lifts SLR on some roads. (Other scenarios with different policies, as well as model sensitivity, were tested and are presented in Chapter 6). It is expected this will increase pavement maintenance and reconstruction costs to the road agency and simultaneously reduce shipping cost to truckers. In this section, a benefit/cost analysis of lifting SLR on 7 and 9-ton roads while retaining SLR on 5-ton gravel roads is conducted (this scenario is called 2' – pronounced 2-prime). Thus, all 7-ton roads become 9 ton roads, while 5-ton, 9-ton and 10-ton roads keep the original axle load limits.

According to above methods, the present value of increased pavement costs due to lifting SLR on 7-ton roads for the following 42.5 years is summarized in Table 4.4. For instance, the total increased pavement overlay cost in Lyon County in the following 42.5 years adds up to $438,642 under the 17 year pavement life assumption (as shown in Table 4.5).

**Table 4.5 Increased pavement cost on 7 and 9 ton roads (Cost of Lifting Policy).**

| Default Pavement Life Assumption | Lyon County | Olmsted County | Clay County |
|---|---|---|---|
| 15 | $278,446 | $1,901,101 | $205,986 |
| *17* | *438,642* | *1,939,797* | *233,192* |
| 20 | 500,782 | 1,993,094 | 286,291 |
| 25 | 644,082 | 2,047,814 | 344,159 |
| 30 | 763,415 | 2,110,108 | 394,596 |

The reduced costs to truckers can be calculated using total truck operating cost per kilometer. The method calculates the reduced cost to the truckers due to lifting SLR as the reduced VKT (VMT) multiplied by total truck operating cost per kilometer. According to the freight demand model (Chapter 3), lifting SLR caused a 7,142 decrease of daily truck VKT (4,439 VMT) in Lyon County. The truck operating cost is $0.69/km (Chapter 2). Thus, the total reduced cost to all freight shippers and carriers is $4,927 per day. Assuming 8 weeks enforcement of SLR, the total annual cost is $275,963. The cash flow diagram is shown in Figure 4.3. The net present value of the reduced cost to truckers in the following 42.5 years are shown in Table 4.6. For Lyon County, this adds up to $6,057,602, assuming a 3.5% interest rate.

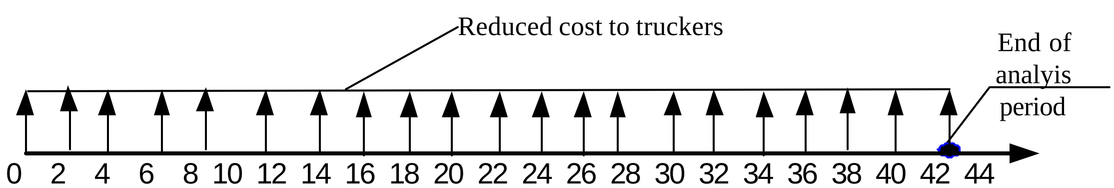


**Figure 4.3 Cash flow diagram of reduced cost to truckers**

**Table 4.6 Reduced Cost to Truckers from Lifting SLR (Benefit of Lifting Policy)**

| County | Reduced Cost to Truckers |
|---|---|
| Lyon | 6,057,602 |
| Olmsted | 30,549,655 |
| Clay | 744,030 |

In Clay County, lifting SLR on 7 and 9-ton roads (Scenario 2' versus Scenario 1) caused a daily VKT decrease of 877 kilometers. Thus, the total reduced cost to the trucking industry in Clay County is $605 per day. Assuming 8 weeks enforcement of SLR, the total annual cost is $33,897. The net present value of the reduced cost to truckers in the following 42.5 years is $744,030, assuming a 3.5% interest rate.

If all other costs and benefits due to SLR are ignored, the benefit of lifting SLR (the reduced costs to truckers) can be compared to the cost of lifting SLR (increased pavement maintenance cost). The benefit/cost ratio of lifting SLR can be calculated.

The assumptions of the cycle on an overlay that must be implemented on 7 and 9-ton road is also an important factor affecting the results. Included are the results of alternative assumptions, which assume (in the absence of rutting failure due to lack of SLR) 17 (standard), 15, 20, 25 and 30 years before failure on 7 and 9-ton roads. It can be seen from Table 4.7, lifting SLR on 7 and 9-ton road results in a benefit/cost ratio well above 1.0 under the 5 assumptions for all three counties.

**Table 4.7 Benefit/Cost ratio from removing SLR on 7 and 9-ton roads only (retaining SLR on 5-ton roads) assuming different time before failure (Scenario 1 vs. Scenario 2')**

| Default Pavement Life Assumption | Benefit/Cost Ratio Lyon County | Benefit/Cost Ratio Olmsted County | Benefit/Cost Ratio Clay County |
|---|---|---|---|
| 15 | 21.76 | 16.07 | 3.61 |
| *17* | *13.81* | *15.75* | 3.19 |
| 20 | 12.10 | 15.33 | 2.60 |
| 25 | 9.41 | 14.92 | 2.16 |
| 30 | 7.93 | 14.48 | 1.89 |

The results from all three counties argue that the costs to truck users of maintaining the SLR on 7 and 9-ton roads exceeds the benefits in terms of preserved pavement life. Further sensitivity analyses will test the robustness of this finding.

## References

[1] Federal Highway Administration, US Department of Transportation, *Gravel Roads: Maintenance and Design Manual South Dakota Local Transportation Assistance program*, November 2000, http://www.epa.gov/owow/nps/gravelroads/intro.pdf

## Special Report: Benefit Cost Analysis for Spring Load Restriction in the City of Crystal

### INTRODUCTION

During the 7-8 week Spring Load Restriction period, the City of Crystal in Minnesota restricts all of their roads, including State Aid Roads, to 4 tons. This limits trucks to a maximum load per axle of 4 tons. While these restrictions provide benefits to the city and other municipal agencies in the form of pavement life savings, there are costs borne by various trucking industries. This chapter outlines the methodology used in determining the costs and benefits associated with this policy.

### Background

The City of Crystal is a western suburb of Minneapolis with 22,500 residents. The majority of the land use is residential, with 9,400 housing [1][2]. Most residential streets are classified as 5-ton, with the exception of those located south of 36$^{th}$ street. These roads were recently rebuilt to a 7-ton standard [3]. Nearly all of the commercial and industrial uses are adjacent to County and State Aid roads (Figures 4.4, 4.5).

It should be noted that the State Aid roads classified as 9-tons north of 36$^{th}$ street are in their original 1960s 5-ton state [3].

Most of the industrial and commercial establishments that generate truck traffic are located in two sections of the city. The roads surrounding these areas are all 9 and 10-ton County or State Aid roads. In addition, many of the residential neighborhoods have signs posted prohibiting truck traffic. Given these conditions, an assumption is made that the only heavy trucks traveling on residential (5-ton) streets are garbage/recycling trucks and school buses.

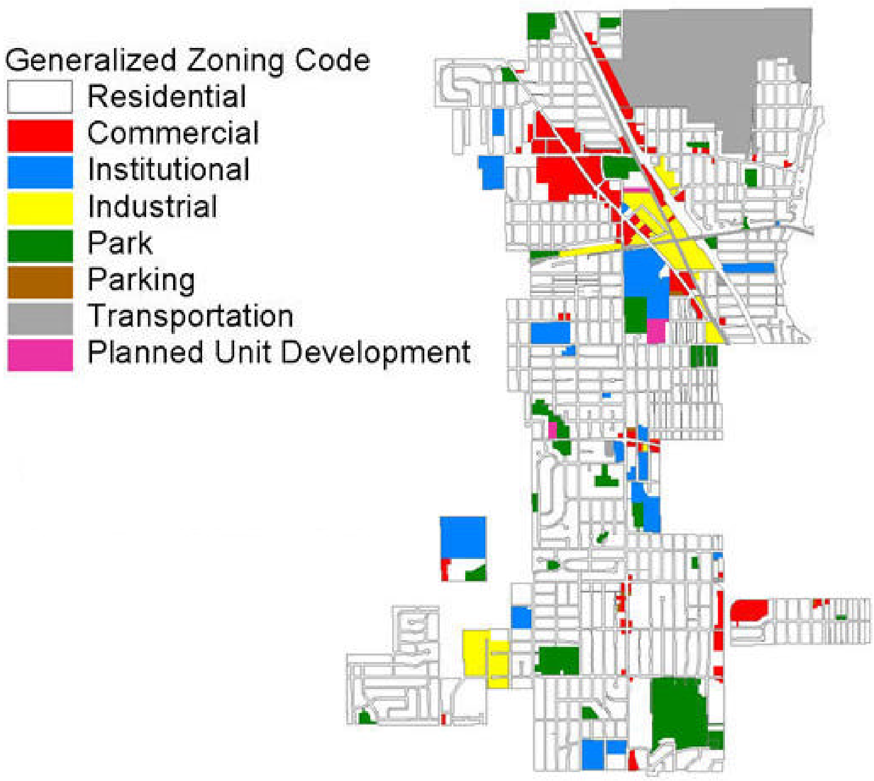


Figure 4.4. Zoning Map for Crystal, MN

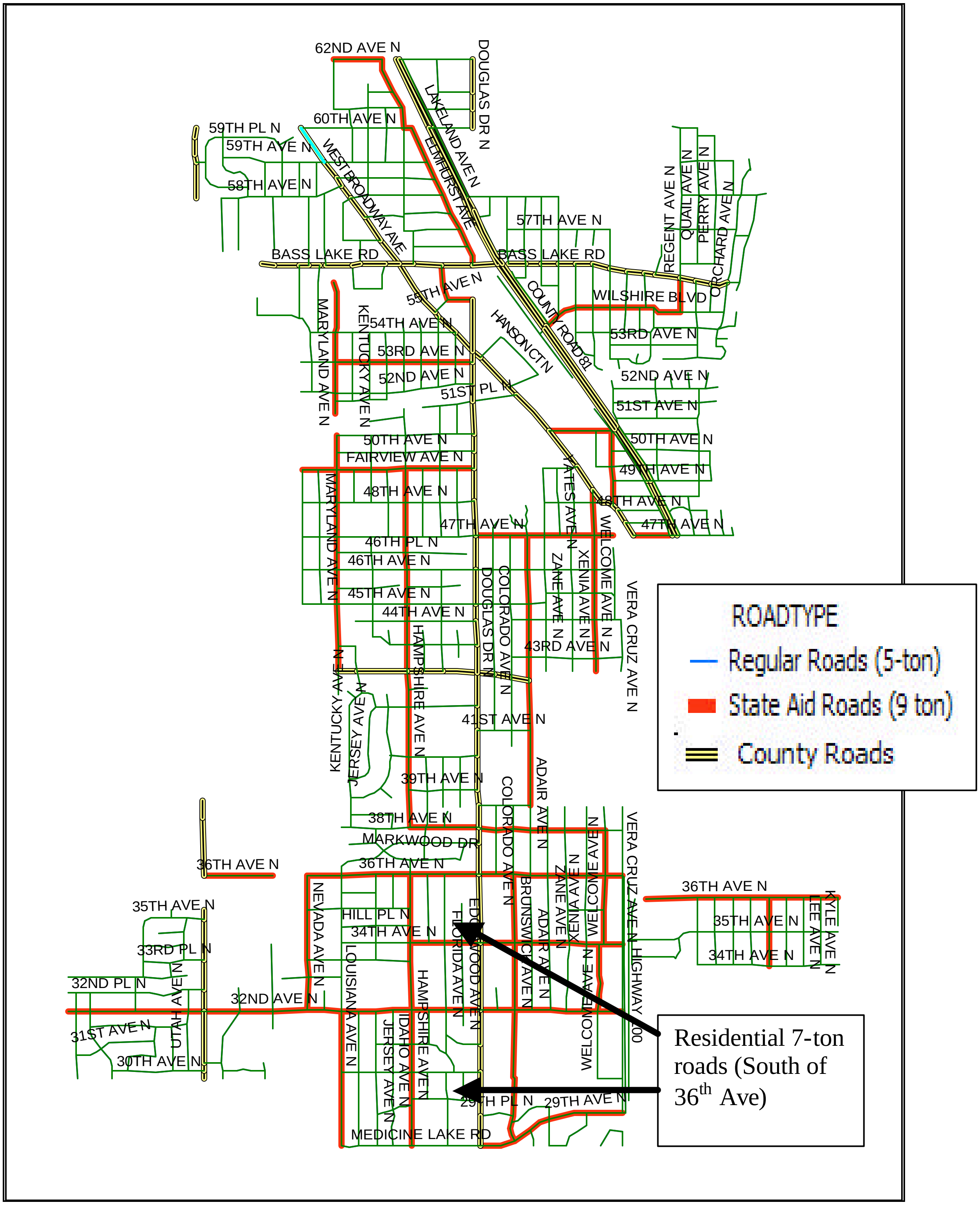


Figure 4.5 – Recycling and Trash Pickup Schedule

**Garbage and Recycling Trucks**

The City of Crystal regulates garbage and recycling pick-up by dividing the city into three zones. Each zone is assigned a day (Monday, Tuesday, or Wednesday) in which refuse and recycling haulers are permitted to service the area (Figure 4.6). Typical fleet composition data such as truck types and weights were obtained from one of the area's major service providers (Table 4.8).

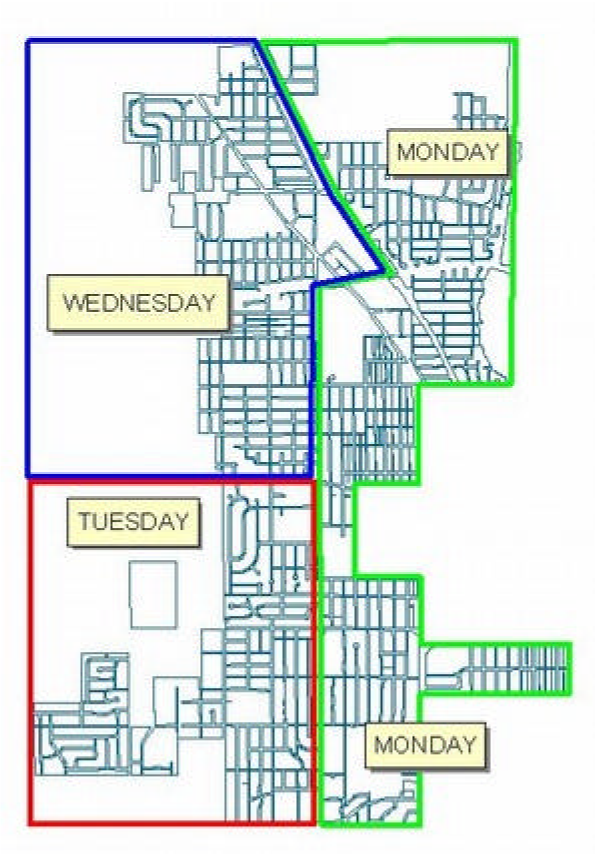


Figure 4.6 – GIS map of road types for the City of Crystal, MN

Source: City of Crystal Website – Zoning and Trash pickup maps
http://www.ci.crystal.mn.us/index.asp

Table 4.8 - Garbage Truck Fleet Compositions

Peterbuilt 320 - 31 Yard Streetforce
Maximum Weight

| | Front axle | Rear axles | Total |
|---|---|---|---|
| Empty weight – kg (lbs) | 7,155 (15,742) | 8,905 (19,591) | 16,060 (35,333) |
| Payload weight – kg (lbs) | 708 (1,558) | 5,745 (12,640) | 6,454 (14,198) |
| Total weight – kg (lbs) | 7,850 (17,269) | 14,650 (32,231) | 22,500 (49,500) |

Peterbuilt 320 - Composting Truck - 20 yd packer
Maximum Weight

| | Front axle | Rear axles | Total |
|---|---|---|---|
| Empty weight – kg (lbs) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) |
| Payload weight – kg (lbs) | 1,567 (3,448) | 7,574 (16,662) | 9,091 (20,000) |
| Total weight – kg (lbs) | 5,315 (11,692) | 17,872 (39,318) | 23,186 (51,010) |

Source: Randy's Sanitation, Telephone interviews with various waste haulers, March-June, 2004

Telephone interviews reveal the typical garbage and composting trucks employed by each company are capable of serving 500-600 customers [4]. During SLR, the weight restrictions require the companies to operate their trucks to half of their capacity. Thus, a company that serves 500-600 customers on each of the three days must run two routes per day, assuming full compliance. Each route is also followed by a composting truck.

Due to the load restrictions, the composting trucks operate to roughly half of their payload capacity. The total weight is not to exceed 18,180 – 18,640 kg (40,000 – 41,000 lbs). (Payload weight is 4,550 kg or 10,000 lbs less than its capacity). The general garbage collection vehicles (the 31 yard Streetforce trucks) are also restricted to 18,180 – 18,640 kg (40,000 – 41,000 lbs).

It is assumed that each company's customers are randomly distributed throughout the City of Crystal, with at least one customer on every block. Therefore, each company must drive on all of the roads in a zone to service the customers. Since there are six companies that operate in the City of Crystal, it is assumed that each road in a zone is driven on six times that day by regular garbage trucks, and six times by composting trucks.

Waste Management provides recycling service in the City of Crystal. It is assumed that all of the streets in a zone are driven on by the recycling truck on either Monday, Tuesday, or Wednesday. Unlike garbage pick-up, recycling service is offered every other week. An interview with a Waste Management operator revealed that they typically employ a single-axle truck (steer plus tandem) that serves 300 households before reaching its capacity (Table 4.9).

The Waste Management operator stated in a telephone interview that when the truck reaches its "capacity" of 300 households (due to volume, not weight), the total weight is typically less than 13,640 kg (30,000 lbs). Although this requires 31 routes running through the City of Crystal every other week, it is assumed most roads are driven on only once.

Table 4.9 – Typical recycling truck weight distributions

| 2-axle recycling truck | Front axle | Rear axles | Total |
|---|---|---|---|
| Empty weight – kg (lbs) | 3,636 (8,000) | 7,091 (15,600) | 10,727 (23,600) |
| Payload weight – kg (lbs) | 1,455 (3,200) | 2,818 (6,200) | 4,273 (9,400) |
| Total weight – kg (lbs) | 5,091 (11,200) | 9,909 (21,800) | 15,000 (33,000) |

Source: Randy's Sanitation, Telephone interviews with various waste haulers, March-June, 2004

### Buses

Buses represent another class of heavy vehicles that frequently travel on residential streets. Data from the Robbinsdale Area School district (which Crystal lies entirely within) was obtained to determine the routes of school buses, as well as how many children they picked up so that average weights could be estimated.

Metro Transit runs several bus routes through the City of Crystal. Route information obtained from them revealed that all of the buses travel exclusively on County and State Aid roads [5].

## METHODOLOGY

### Determining Pavement Damage

It is unlikely that Metro Transit and the Robbinsdale Area School district would alter their practices to comply with the Spring Load Restrictions. Furthermore, school buses are exempt from weight restrictions. However, the garbage and recycling service providers are affected by the policy and have altered their practices (reducing truck loads but increasing the number of routes) to comply.

Since the garbage and recycling truck types and axle weights are known, this data can be input into the MnPAVE model to determine the damage coefficients, based on the assumption that rutting is the dominant failure mode. It is assumed that the garbage and compost trucks operate at 50 percent of their payload capacity half of the time, and spend 25 percent of their time operating at 25 and 75 percent of their capacity, respectively (Table 4.10). Both the Garbage and Composting trucks are 2-axle trucks (steer plus dual tandem).

Waste Management uses a 2-axle truck for recycling operations. Although the maximum weight the vehicle can obtain is 15,000 kg (33,000 lbs), the 25, 50 and 75 percent "full" values are based off a maximum of 13,640 kg (30,000 lbs), as cited by the Waste Management operator (Table 4.11).

During SLR, the trucks are restricted to half of their payload capacity. It is assumed that the trucks operate at 25 percent of their payload capacity half of the time, and spend 25 percent of their time operating at 12.5 and 37.5 percent of their full capacity, respectively (Table 4.12).

Table 4.10 – Axle weight distributions at 25, 50 and 75 percent of capacity

Peterbuilt 320 – 31 Yard Streetforce

| Maximum Weight | | | |
|---|---|---|---|
| | Front axle | Rear axles | Total |
| Empty weight – kg (lbs) | 7,155 (15,742) | 8,905 (19,591) | 16,060 (35,333) |
| Payload weight – kg (lbs) | 708 (1,558) | 5,745 (12,640) | 6,453 (14,198) |
| Total weight – kg (lbs) | 7,850 (17,269) | 14,650 (32,231) | 22,500 (49,500) |

| | 50% | | | Lower 25% | | | Upper 25% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Steer | Tandem | Total | Steer | Tandem | Total | Steer | Tandem | Total |
| Empty wt - kg (lbs) | 7,156 (15,742) | 8,905 (19,591) | 16,060 (35,333) | 7,156 (15,742) | 8,905 (19,591) | 16,061 (35,333) | 7,156 (15,742) | 8,905 (19,591) | 16,061 (35,333) |
| Payload wt - kg (lbs) | 354 (779) | 2,873 (6,320) | 3,227 (7,100) | 177 (390) | 1,436 (3,160) | 1,614 (3,550) | 531 (1,169) | 4,309 (9,480) | 4,840 (10,649) |
| Total wt - kg (lbs) | 7,510 (16,521) | 11,778 (25,911) | 19,288 (42,433) | 7,333 (16,132) | 10,341 (22,751) | 17,674 (38,883) | 7,687 (16,911) | 13,214 (29,071) | 20,901 (45,982) |

Peterbuilt 320 – 20 yard packer (composting truck)

| Maximum Weight | | | |
|---|---|---|---|
| | Front axle | Rear axles | Total |
| Empty weight – kg (lbs) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) |
| Payload weight – kg (lbs) | 1,567 (3,448) | 7,574 (16,662) | 9,091 (20,000) |
| Total weight – kg (lbs) | 5,315 (11,692) | 17,872 (39,318) | 23,186 (51,010) |

| | 50% | | | Lower 25% | | | Upper 25% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Steer | Tandem | Total | Steer | Tandem | Total | Steer | Tandem | Total |
| Empty wt - kg (lbs) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) |
| Payload wt - kg (lbs) | 780 (1,715) | 3,766 (8,285) | 4,545 (10,000) | 392 (862) | 1,893 (4,166) | 2,273 (5,000) | 1,175 (2,586) | 5,680 (12,497) | 6,818 (15,000) |
| Total wt - kg (lbs) | 4,527 (9,959) | 14,114 (31,051) | 18,641 (41,010) | 4,139 (9,106) | 12,242 (26,932) | 16,368 (36,010) | 4,923 (10,830) | 16,028 (35,263) | 20,914 (46,010) |

Table 4.11 – Axle weight distribution for the Recycling Truck

| Maximum Weight | | | |
|---|---|---|---|
| | Front axle | Rear axle | Total |
| Empty weight – kg (lbs) | 3,636 (8,000) | 7,091 (15,600) | 10,727 (23,600) |
| Payload weight – kg (lbs) | 1,455 (3,200) | 2,818 (6,200) | 4,273 (9,400) |
| Total weight –kg (lbs) | 5,091 (11,200) | 9,909 (21,800) | 15,000 (33,000) |

| | 50% | | | Lower 25% | | | Upper 25% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Steer | Rear axle | Total | Steer | Rear axle | Total | Steer | Rear axle | Total |
| Empty wt - kg (lbs) | 3,636 (8,000) | 7,091 (15,600) | 10,727 (23,600) | 3,636 (8,000) | 7,091 (15,600) | 10,727 (23,600) | 3,636 (8,000) | 7,091 (15,600) | 10,727 (23,600) |
| Payload wt - kg (lbs) | 485 (1,067) | 970 (2,133) | 1,455 (3,200) | 242 (533) | 485 (1,067) | 727 (1,600) | 727 (1,600) | 1,455 (3,200) | 2,182 (4,800) |
| Total wt - kg (lbs) | 4,121 (9,067) | 8,060 (17,733) | 12,182 (26,800) | 3,879 (8,533) | 7,576 (16,667) | 11,455 (25,200) | 4,364 (9,600) | 8,545 (18,800) | 12,909 (28,400) |

Table 4.12 – Axle weight distributions at 12.5, 25 and 37.5 percent of capacity.

Peterbuilt 320 – 31 Yard Streetforce

| Maximum Weight - under SLR | | | |
|---|---|---|---|
| | Front axle | Rear axles | Total |
| Empty weight – kg (lbs) | 7,155 (15,742) | 8,905 (19,591) | 16,060 (35,333) |
| Payload weight – kg (lbs) | 354 (779) | 2,873 (6,320) | 3,227 (7,100) |
| Total weight – kg (lbs) | 7,510 (16,521) | 11,778 (25,911) | 19,288 (42,433) |

| | 50% | | | Lower 25% | | | Upper 25% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Steer | Tandem | Total | Steer | Tandem | Total | Steer | Tandem | Total |
| Empty wt - kg (lbs) | 7,155 (15,742) | 8,905 (19,591) | 16,060 (35,333) | 7,155 (15,742) | 8,905 (19,591) | 16,060 (35,333) | 7,155 (15,742) | 8905 (19,591) | 16,060 (35,333) |
| Payload wt - kg (lbs) | 177 (390) | 1,436 (3,160) | 1,614 (3,550) | 89 (195) | 718 (1,580) | 807 (1,775) | 266 (584) | 2,155 (4,740) | 2,420 (5,325) |
| Total wt - kg (lbs) | 7,333 (16,132) | 10,341 (22,751) | 17,674 (38,883) | 7,244 (15,937) | 9,623 (21171) | 16,867 (37,108) | 7,421 (16,326) | 11,060 (24,331) | 18,481 (40,658) |

Peterbuilt 320 – 20 yard packer (composting truck)

| Maximum Weight - under SLR | | | |
|---|---|---|---|
| | Front axle | Rear axles | Total |
| Empty wt – kg (lbs) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) |
| Payload wt – kg (lbs) | 780 (1,715) | 3,766 (8,285) | 4,545 (10,000) |
| Total wt – kg (lbs) | 4,527 (9,959) | 14,114 (31,051) | 18,641 (41,010) |

| | 50% | | | Lower 25% | | | Upper 25% | | |
|---|---|---|---|---|---|---|---|---|---|
| | Steer | Tandem | Total | Steer | Tandem | Total | Steer | Tandem | Total |
| Empty wt - kg (lbs) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) | 3,747 (8,244) | 10,348 (22,766) | 14,095 (31,010) |
| Payload wt - kg (lbs) | 390 (858) | 1,883 (4,143) | 2,273 (5,000) | 195 (429) | 941 (2,071) | 1,136 (2,500) | 585 (1,286) | 2,824 (6,214) | 3,409 (7,500) |
| Total wt - kg (lbs) | 4,137 (9,102) | 12,231 (26,909) | 16,368 (36,010) | 3,942 (8,673) | 11,290 (24,837) | 15,232 (33,510) | 4,332 (9,530) | 13,173 (28,980) | 17,505 (38,510) |

Full compliance with SLR is also assumed. Due to its lower "full" weight versus garbage trucks and exemptions, the recycling truck does not reduce its loads during SLR.

These three different payload cases (three different axle weight distributions) are input into the MnPAVE model for each type of truck (Table 4.13). The calculated damage coefficients (based on rutting failure) are then substituted into the damage equations.

The trucks are considered 25, 50 and 75 percent loaded.

Table 4.13 – Axle weight distribution

| Truck Type | Restrictions | No of trucks per day | Total Weight kg (lbs) | Front Axle kg (lb) | Rear Axle kg (lb) |
|---|---|---|---|---|---|
| **Peterbuilt 320 - 31 Yard Streetforce (P1 Type)** | 25% Full | $N_{1-1}$ | 17,674 (38,883) | 7,333 (16,132) | 10,341 (22,751) |
| | 50% Full | $N_{1-2}$ | 19,288 (42,433) | 7,510 (16,521) | 11,778 (25,911) |
| | 75% Full | $N_{1-3}$ | 20,901 (45,982) | 7,687 (16,911) | 13,214 (29,071) |
| | 25% Full - SLR | $N_{1-1s}$ | 16,867 (37,108) | 7,244 (15,937) | 9,623 (21,171) |
| | 50% Full - SLR | $N_{1-2s}$ | 17,674 (38,883) | 7,333 (16,132) | 10,341 (22,751) |
| | 75% Full - SLR | $N_{1-3s}$ | 18,481 (40,658) | 7,421 (16,326) | 11,060 (24,331) |
| **Peterbuilt 320 - Composting Truck - 20 yd packer (P2 Type)** | 25% Full | $N_{2-1}$ | 16,368 (36,010) | 4,139 (9,106) | 12,242 (26,932) |
| | 50% Full | $N_{2-2}$ | 18,641 (41,010) | 4,527 (9,959) | 14,114 (31,051) |
| | 75% Full | $N_{2-3}$ | 20,914 (46,010) | 4,923 (10,830) | 16,029 (35,263) |
| | 25% Full - SLR | $N_{2-1s}$ | 15,232 (33,510) | 3,942 (8,673) | 11,290 (24,837) |
| | 50% Full - SLR | $N_{2-2s}$ | 16,368 (36,010) | 4,137 (9,102) | 12,231 (26,909) |
| | 75% Full - SLR | $N_{2-3s}$ | 17,505 (38,510) | 4,332 (9,530) | 13,173 (28,980) |
| **Recycling (R)** | 25% Full | $N_{3-1}$ | 11,455 (25,200) | 3,879 (8,533) | 7,576 (16,667) |
| | 50% Full | $N_{3-2}$ | 12,182 (26,800) | 4,121 (9,067) | 8,060 (17,733) |
| | 75% Full | $N_{3-3}$ | 12,909 (28,400) | 4,364 (9,600) | 8,545 (18,800) |

Considering the notation from Table 4.13:

– the daily average heavy traffic flow, no SLR is:

$$N_{1-1} + N_{1-2} + N_{1-3} + N_{2-1} + N_{2-2} + N_{2-3} + N_{3-1} + N_{3-2} + N_{3-3}$$

– the daily average heavy traffic flow during SLR is:

$$N_{1-1s} + N_{1-2s} + N_{1-3s} + N_{2-1s} + N_{2-2s} + N_{2-3s} + N_{3-1} + N_{3-2} + N_{3-3}$$

where $N$ is the daily traffic flow and the subscripts refer to the different truck types and weight distributions, respectively.

Each of the daily traffic flow terms are multiplied by a damage coefficient, $a_i^{\,j}$ to determine a pavement's lifetime before rutting failure. Thus, the pavement lifetime before rutting failure for a road with no SLR is given by the equation:

Lifetime (pavement structure, $N_{1\_1}, N_{1\_2}, N_{1\_3}, N_{2\_1}, N_{2\_2}, N_{2\_3}, N_{3\_1}, N_{3\_2}, N_{3\_3}$) =

$$(a_{1\_1}N_{1\_1} + a_{1\_2}N_{1\_2} + a_{1\_3}N_{1\_3} + a_{2\_1}N_{2\_1} + a_{2\_2}N_{2\_2} + a_{2\_3}N_{2\_3} + a_{3\_1}N_{3\_1} + a_{3\_2}N_{3\_2} + a_{3\_2}N_{3\_2})^{-1}$$

The lifetime (before rutting failure) for a pavement structure with SLR in place is:

Lifetime (pavement structure, $N_{1\_1}, N_{1\_2}, N_{1\_3}, N_{1\_1s}, N_{1\_2s}, N_{2\_1}, N_{2\_2}, N_{2\_3}, N_{2\_1s}, N_{2\_2s}, N_{2\_3s}, N_{3\_1}, N_{3\_2}, N_{3\_3}$) =

$$(a_{1\_1}N_{1\_1} + a_{1\_2}N_{1\_2} + a_{1\_3}N_{1\_3} + a_{1\_1s}N_{1\_1s} + a_{1\_2s}N_{1\_2s} + a_{1\_3s}N_{1\_3s} + a_{2\_1}N_{2\_1} + a_{2\_2}N_{2\_2} + a_{2\_3}N_{2\_3} + a_{2\_1s}N_{2\_1s} + a_{2\_2s}N_{2\_2s} + a_{2\_3s}N_{2\_3s} + a_{3\_1}N_{3\_1} + a_{3\_2}N_{3\_2} + a_{3\_2}N_{3\_2})^{-1}$$

Using the assumptions of pavement structures for the various types of roads (Table 4.14), the damage coefficients, $a_i^j$ were calculated (Table 4.15).

Table 4.14 – Pavement Structure on Crystal's city streets

| 5 ton streets | 7 ton streets (south of 36th Ave) | 9 ton (MSA) - streets |
|---|---|---|
| • 2" bituminous layer (5.1 cm)<br>• 6" aggregate base (15.2 cm)<br>• soil - sandy clay loam | • 3.5" (8.9 cm) bituminous layers<br>▪ 1 1/2" (3.8 cm) bituminous wear layer<br>▪ 2" (5.1 cm) bituminous base layer<br>• 8" (20.3 cm) reclaim base - aggregate Class 5<br>• soil – clay | • 3.5" (8.9 cm) bituminous layers<br>▪ 1 1/2" (3.8 cm) bituminous wear layer<br>▪ 2" (5.1 cm) bituminous base layer<br>• 8" (20.3 cm) aggregate base Class 5<br>• 12" (30.5 cm) select granular borrow<br>• soil – clay |

Source: (Mathisen and Frietzke 2004)

The daily traffic flows ($N_{i-j}$) were determined based on several assumptions. Each road has 6 garbage and 6 composting trucks driving on it once per week. Since the weights on the trucks vary, it is assumed for each type (garbage and composting), 2 of the trucks that drive over each particular road are 25 percent full, 2 of them are 50 percent full and 2 trucks are 75 percent full. Recycling trucks drive over a road once every two weeks. Because there is only one truck, it is assumed that 0.33 trucks that drive over each particular road section are 25 percent full, 0.34 trucks are 50 percent full, and 0.33 trucks are 75 percent full. These flows are converted into an average daily flow (Table 4.16).

Table 4.15 – Damage coefficients

| | | $a_{1\_1}$ | $a_{1\_2}$ | $a_{1\_3}$ | $a_{2\_1}$ | $a_{2\_2}$ | $a_{2\_3}$ | $a_{3\_1}$ | $a_{3\_2}$ | $a_{3\_3}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 ton street | No SLR | 1.22E-02 | 1.25E-02 | 1.36E-02 | 6.58E-03 | 7.79E-03 | 8.73E-03 | 6.27E-03 | 8.81E-03 | 8.81E-03 |
| | with SLR | 9.19E-03 | 9.43E-03 | 1.03E-02 | 5.00E-03 | 5.89E-03 | 6.59E-03 | 4.75E-03 | 6.65E-03 | 6.65E-03 |
| 7 ton street | No SLR | 3.19E-03 | 3.31E-03 | 3.73E-03 | 1.75E-03 | 2.21E-03 | 2.59E-03 | 1.88E-03 | 2.66E-03 | 2.66E-03 |
| | with SLR | 2.52E-03 | 2.61E-03 | 2.94E-03 | 1.37E-03 | 1.73E-03 | 2.02E-03 | 1.46E-03 | 2.06E-03 | 2.06E-03 |
| MSA 9 ton | No SLR | 1.11E-03 | 1.17E-03 | 1.42E-03 | 7.12E-04 | 9.80E-04 | 1.20E-03 | 8.06E-04 | 1.12E-03 | 1.12E-03 |
| | with SLR | 8.02E-04 | 8.49E-04 | 1.02E-03 | 5.11E-04 | 7.02E-04 | 8.59E-04 | 5.80E-04 | 8.05E-04 | 8.05E-04 |

| | | $a_{1\_1s}$ | $a_{1\_2s}$ | $a_{1\_3s}$ | $a_{2\_1s}$ | $a_{2\_2s}$ | $a_{2\_3s}$ |
|---|---|---|---|---|---|---|---|
| 5 ton street | No SLR | 0 | 0 | 0 | 0 | 0 | 0 |
| | with SLR | 2.99E-03 | 2.99E-03 | 3.07E-03 | 1.11E-03 | 1.58E-03 | 1.68E-03 |
| 7 ton street | No SLR | 0 | 0 | 0 | 0 | 0 | 0 |
| | with SLR | 6.68E-04 | 6.68E-04 | 6.95E-04 | 2.69E-04 | 3.76E-04 | 4.09E-04 |
| MSA 9 ton | No SLR | 0 | 0 | 0 | 0 | 0 | 0 |
| | with SLR | 3.07E-04 | 3.07E-04 | 3.26E-04 | 1.48E-04 | 2.00E-04 | 2.24E-04 |

Table 4.16 – Traffic flows, no SLR

Traffic every pickup day (Monday, Tuesday, or Wednesday)

| | $N_{1-1}$ | $N_{1-2}$ | $N_{1-3}$ | $N_{2-1}$ | $N_{2-2}$ | $N_{2-3}$ | $N_{3-1}$ | $N_{3-2}$ | $N_{3-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 – 6 trucks | 2 | 2 | 2 | 2 | 2 | 2 | 0.333 | 0.334 | 0.333 |
| Scenario 2 – 9 trucks | 6 | 2 | 1 | 6 | 2 | 1 | 0.333 | 0.334 | 0.333 |

Daily Traffic flow

| | $N_{1-1}$ | $N_{1-2}$ | $N_{1-3}$ | $N_{2-1}$ | $N_{2-2}$ | $N_{2-3}$ | $N_{3-1}$ | $N_{3-2}$ | $N_{3-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.024 | 0.024 | 0.024 |
| Scenario 2 | 0.857 | 0.286 | 0.143 | 0.857 | 0.286 | 0.143 | 0.024 | 0.024 | 0.024 |

In the first scenario (Scenario 1), it is assumed that each company serves the same number of garbage and compost customers each day of collection (Monday, Tuesday and Wednesday). This means that each truck handles approximately 550 customers and that the even distribution of the 3 different truck weights previously mentioned hold true.

In the second scenario (Scenario 2), it is assumed that each company serves a different number of customers each day. Some companies may serve only 200 customers, requiring 1 truck for garbage and 1 for composting, while others may serve 1000 customers, therefore needing 2 trucks. In this scenario, it is assumed that no more than 9 trucks are need for each day of collection. Also, the weight distributions will be different, with fewer trucks that are 75 percent full, but more that are 25 percent full.

During SLR, the number of trucks used and their weight distributions change. All of the trucks are overweight to begin with. In the first scenario, the payload capacity is reduced by 50%, so the number of trucks used by each firm to serve their customers must double (assuming full compliance). The total number of trucks required for each collection day is 12, with 4 trucks at 12.5 percent of their full capacity, 4 trucks at 25 percent of their capacity, and 4 trucks at 37.5 percent of capacity.

In the second scenario during SLR, the number of trucks needed by each firm does not double, since some of the trucks were not operating to full capacity. The number of trucks needed, as in the first scenario, increases by 6 trucks, bringing the total to 15 trucks per collection day. The weight distributions change as well, and are accounted for (Table 4.17).

Table 4.17 – Traffic flows, with SLR

Traffic every pickup day (Monday, Tuesday, or Wednesday)

| | $N_{1-1}$ | $N_{1-2}$ | $N_{1-3}$ | $N_{2-1}$ | $N_{2-2}$ | $N_{2-3}$ | $N_{3-1}$ | $N_{3-2}$ | $N_{3-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 – 12 trucks | 4 | 4 | 4 | 4 | 4 | 4 | 0.333 | 0.334 | 0.333 |
| Scenario 2 – 15 trucks | 8 | 3 | 1 | 8 | 3 | 1 | 0.333 | 0.334 | 0.333 |

Daily Traffic flow

| | $N_{1-1}$ | $N_{1-2}$ | $N_{1-3}$ | $N_{2-1}$ | $N_{2-2}$ | $N_{2-3}$ | $N_{3-1}$ | $N_{3-2}$ | $N_{3-3}$ |
|---|---|---|---|---|---|---|---|---|---|
| Scenario 1 | 0.571 | 0.571 | 0.571 | 0.571 | 0.571 | 0.571 | 0.024 | 0.024 | 0.024 |
| Scenario 2 | 1.143 | 0.429 | 0.143 | 1.143 | 0.429 | 0.143 | 0.024 | 0.024 | 0.024 |

It is important to note that the number of trucks traveling on 5 and 7-ton roads will not change during SLR. When nearing their capacity or restricted weight, waste haulers will complete a block or street before returning to a waste handling facility so that they do not have to return to the same block. Thus, each waste hauler will drive on the 5 and 7-ton roads only once. Because the trucks must drive on 9-ton roads to get to the waste transfer facility, it is assumed that the increase in truck traffic due to SLR primarily impacts 9-ton roads (the effect on 10-ton roads is neglected).

The corresponding numbers and coefficients (the $N$'s and $a$'s) are substituted into the relevant equations (with and without SLR) to compute the time before rutting failure. The benefit provided to the road owners from the SLR policy is determined by calculating the difference in rutting failure times for each scenario (with and without SLR) and translating them into monetary benefits in terms of cost savings. These benefits are compared to the costs the policy imposes on waste haulers in the City of Crystal.

## CALCULATIONS AND RESULTS

### Costs to Truckers

The total cost to truckers is measured in two ways, via operating costs per kilometer and value of time. To compute the cost to truckers using operating costs per kilometer, the increase in vehicle kilometers traveled (VKT) due to SLR must be determined. Chapter 2 revealed that the average operating costs for rubbish firms is $1.54 per kilometer. Extra truck trips due to SLR means additional trips that must be made to a waste transfer facility. The trucks travel to the waste transfer facility in Brooklyn Park to unload. It is assumed they take the fastest path along the 9 and 10 ton roads, including US-169. Assuming the trucks are in the geographic center of Crystal on average when they need to go to the dump, the distance is 11.41 km (22.82 km roundtrip) [6]. Since both scenarios require 6 additional trucks to serve their customers during SLR, the annual cost to the truckers is:

| | |
|---|---|
| A extra trucks | 6 |
| B times a week | 3 |
| C weeks of SLR | 8 |
| D kilometers per truck | 22.82 |
| E Cost per kilometer | $1.54 |
| A*B*C*D*E = | $5,060 |

Using a 3.5% interest rate, the present value over 42.5 years is:

| | |
|---|---|
| NPV = | $111,066 |

Calculating the cost to truckers using the value of time requires knowing how much extra time is imposed on the trucking companies due to SLR as well as what the hourly value is. A recent study by Smalkoski revealed the average industry-wide value of time is $49.42 per hour (Chapter 2). Interviews with waste haulers that operate in the city of Crystal stated that a trip to the waste transfer facility took anywhere from 40 to 80 minutes, depending on how many trucks where using it at the time. For the purposes of this analysis, an average of 60 minutes (1 hour) will be used. Since both scenarios required 6 extra trucks per day to serve customers during SLR, the annual cost to the truckers is:

| | |
|---|---|
| A extra hours per day | 6 |
| B days a week | 3 |
| C weeks of SLR | 8 |
| F Cost per hour | $49.42 |
| A*B*C*F = | $7,116 |

Using a 3.5% interest rate, the present value over 42.5 years is:

| | |
|---|---|
| NPV = | $156,205 |

**Benefits to the Road Owners**

The benefits to the road owners were determined by calculating the differences between the time before rutting failure for each scenario (Table 4.18) and transforming them into monetary benefits using the equation (1) below. Note that the time before rutting failure exceeds the expected life of the road. In other words, the MnPAVE rutting model indicates that roads will fail for some other reason rather than rutting failure associated with spring loadings. If the road fails for some other reason before it would fail due to rutting, then the economic costs associated with rutting are nil. This is discussed more below.

Table 4.18 – Time before rutting failure

| Scenario 1 | | Time before rutting failure (years) | | |
|---|---|---|---|---|
| | | 5 ton roads | 7 ton roads | 9 ton roads |
| 6 trucks | no SLR | 55.22 | 201.33 | 511.14 |
| 12 trucks | with SLR | 58.01 | 209.09 | 440.06 |
| | ratio | 1.05 | 1.04 | 0.86 |

| Scenario 2 | | Time before rutting failure (years) | | |
|---|---|---|---|---|
| | | 5 ton roads | 7 ton roads | 9 ton roads |
| 9 trucks | no SLR | 39.01 | 145.24 | 381.33 |
| 15 trucks | with SLR | 40.20 | 149.75 | 369.52 |
| | ratio | 1.03 | 1.03 | 0.97 |

The pavement life extension benefit due to SLR is calculated using the formula described in Chapter 4.

$$PLB = AC*PLE*L \qquad (1)$$

Where: PLB = pavement life extension benefit (in U.S. Dollars, USD)
AC = Annual overlay cost
PLE = Pavement life extension (difference in years before rutting failure)
L = Section length (in kilometers)

Similar to the assumptions outlined for Lyon County, it is assumed that two functional overlays are performed during a pavement life cycle. It is assumed the pavements are 8.5 years old on average, or half of a pavement's 17 year life cycle. Since pavement life extension occurs at each overlay, then overlays occur 8.5 years, 25.5 years and 42.5 years from the present. Thus, the analysis period covers 42.5 years (consistent with values used in Chapter 4). Using the number of kilometers of each type of road (5, 7 and 9 ton), overlay costs (See Chapter 4, Appendix 1) and the equation above, the future benefits are transformed to a single net present value (NPV) using a discount rate of 3.5% [7]. (Table 4.19)

Table 4.19 – Benefits for 5, 7, 9 ton roads due to SLR

Scenario 1

| Benefits | (Net Present Value) |
|---|---|
| 5 ton | |
| 8.5 year overlay | $95,658 |
| 25.5 year overlay | $106,602 |
| 42.5 year overlay | $59,398 |
| Subtotal | $261,658 |

| Benefits | (Net Present Value) |
|---|---|
| 7 ton | |
| 8.5 year overlay | $31,602 |
| 25.5 year overlay | $35,217 |
| 42.5 year overlay | $19,623 |
| Subtotal | $86,442 |
| Total Benefit = | $348,100 |

Scenario 2

| Benefits | (Net Present Value) |
|---|---|
| 5 ton | |
| 8.5 year overlay | $155,278 |
| 25.5 year overlay | $173,043 |
| 42.5 year overlay | $96,420 |
| Subtotal | $424,741 |

| Benefits | (Net Present Value) |
|---|---|
| 7 ton | |
| 8.5 year overlay | $38,933 |
| 25.5 year overlay | $43,388 |
| 42.5 year overlay | $24,176 |
| Subtotal | $106,497 |
| Total Benefit = | $531,238 |

Including the disbenefits to the 9-ton roads (lighter trucks but more traffic) gives the results shown in Table 4.20.

Table 4.20 Including the disbenefits to the 9 ton roads (lighter trucks but more traffic)

| Disbenefits | (Net Present Value) |
|---|---|
| 9 ton | |
| 8.5 year overlay | ($14,551) |
| 25.5 year overlay | ($16,215) |
| 42.5 year overlay | ($9,035) |
| Subtotal | ($39,801) |
| Total Benefit = | $308,299 |

| Disbenefits | (Net Present Value) |
|---|---|
| 9 ton | |
| 8.5 year overlay | ($73,570) |
| 25.5 year overlay | ($81,987) |
| 42.5 year overlay | ($45,683) |
| Subtotal | ($201,240) |
| Total Benefit = | $329,998 |

Assuming roads are only subject to rutting failure, a comparison of the benefits of SLR for the road owners versus the costs to the trucking industry might suggest that the benefits outweigh the costs for every scenario. However, an examination of Table 4.18 reveals that without SLR, the pavement on 5-ton roads will last at least 39 years before failing, based on rutting criterion (Scenario 2). The other scenarios show pavement lasting much longer before failing due to rutting.

Since roads are ideally given a functional overlay every 17 years (as other failure modes often are reached by this time), road failure in the City of Crystal is due to some other mode largely independent of spring loading.

## Conclusions

According to the MnPAVE model, the SLR policy produces no benefit to the road owners in the City of Crystal, as it does not extend the life of the pavement within its normal lifetime. The roads would fail for other reasons (which MnPAVE is unable to model) before they would fail due to excessive loadings in the springtime. However, distresses due to the spring thaw can manifest themselves in other forms besides rutting. Based on rutting failure criteria, the SLR policy imposes costs upon the waste hauling industry. It is recommended that more sophisticated models be developed and better data on actual pavement structure and conditions be collected to gain further insight into various road failure phenomena.

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# Chapter 5

Task #6: Conduct a sensitivity analysis to estimate distribution of costs and benefits under different conditions (mild, normal, severe) with current regulations, new regulations, and pricing scenarios. Improving roads will be considered as an alternate.

### 5.1 Introduction

Sensitivity analysis is an important part of Benefit/Cost analysis. In section 2, various road upgrading scenarios are discussed. In section 3, the cost to truckers is calculated using the value of time method. In section 4, a sensitivity analysis is conducted for pavement life savings. In section 5, a different pavement performance model is used to compare the result with the MnPAVE model.

## 5.2 Road Upgrading

Since removing SLR on 7 and 9-ton roads (without upgrading the roads) appears to have a Benefit/Cost ratio above 1.0, alternative policies of upgrading both the paved 7 and 9-ton roads and lifting restrictions are tested. Table 5.1 describes the scenarios:

**Table 5.1 Summary of upgrading scenarios**

| Scenario Number | Scenario information | 7 ton road overlay type (first/ second) | 9 ton road overlay type (first/ second) | Road type (Axle tonnage limit) | Road type (Axle tonnage limit) | Road type (Axle tonnage limit) | Road type (Axle tonnage limit) |
|---|---|---|---|---|---|---|---|
| 1 | With SLR | functional/ functional | functional/ functional | 5 | 7 | 9 | 10 |
| 2' | Modified No SLR scenario | functional/ functional | functional/ functional | 5 | 9 | 9 | 10 |
| 3 | Scenario 3 | structural / functional | functional/ functional | 5 | 9 | 9 | 10 |
| 4 | Scenario 4 | structural/ functional | structural/ functional | 5 | 9 | 10 | 10 |
| 5 | Scenario 5 | structural / structural | structural/ functional | 5 | 10 | 10 | 10 |

Scenario 1 is the "with SLR" scenario, which is the current SLR policy. The roads in the network are classified into 5, 7, 9 and 10-ton roads. A functional overlay will be implemented every 17 years on 7 and 9-ton roads, which keeps the road type unchanged.

Scenario 2' (scenario two-prime) is a modified "without SLR" scenario, wherein SLR is retained on 5-ton paved and unpaved roads, but removed from 7 and 9-ton roads. In other words, 7-ton roads are reclassified as 9-ton roads during the SLR period. Again, a functional overlay will be implemented on 7 and 9-ton roads every 17 years, which keeps the road types unchanged. This was analyzed in the Task 4 report.

In addition to these scenarios, policy options of upgrading 7 and 9-ton roads using structural overlays are tested. A structural overlay increases the strength of the road significantly, and allows it to be classified as able to accommodate a higher tonnage. A functional overlay also adds strength, but less strength than a structural overlay (the overlay is thinner), and so is not credited for increasing the allowable tonnage.

Scenario 3 only upgrades 7-ton roads to 9-ton roads, which means a structural overlay is performed on 7-ton roads at the first overlay and a functional overlay at the second overlay. Two functional overlays are conducted on 9-ton roads.

Scenario 4 is the result of upgrading the 7-ton and 9-ton roads at the first overlay, which means a structural overlay is performed on 7 and 9-ton roads on the first overlay and a functional overlay on 7 and 9-ton roads at the second overlay. Thus, the 7-ton roads are reclassified as 9-ton and 9-ton roads become 10-ton roads after first overlay. The road classification stays the same after the second overlay.

Scenario 5 is the result of upgrading 7 and 9-ton roads to 10-tons roads during their two overlays. The 7-ton roads experience two structural overlays and 9-ton road experience one structural overlay, thus they all become 10 ton roads ultimately.
Scenarios 3, 4 and 5 are alternative policies to the current SLR policy (Scenario 1). It is worth noting that 5-ton gravel roads remain unchanged during all these processes.

The upgraded road network will result in a change in the truck volumes on the network. The truck volume should decrease due to the improvement of road conditions (trucks can now obey the law and be loaded heavier, thus there should be fewer trucks). There will be a cost reduction due to reduced truck VKT. However, there is an increased agency cost due to the structural overlay. The net benefit of each scenario is compared to determine which policy is more favorable.

Due to the complexity of calculations, some aggregating assumptions are made to avoid conducting the analysis on a link-by-link basis. An analysis of Scenario 2' vs. Scenario 1 showed a less than 10% difference in the two methods, giving confidence that the aggregate approximation is sufficient for these purposes.

There are three timing sub strategies of upgrading roads for scenario 3, 4 and 5. These control when the upgrades are undertaken, and when the restrictions are removed.

- A: upgrade 7 and 9-ton roads and remove restrictions on 7 and 9-ton roads at the first scheduled overlay.
- B: remove 7-ton road restrictions immediately and upgrade the 7 and 9-ton roads at the first overlay.
- C: upgrade 7 and 9-ton roads and remove restrictions on 7 and 9-ton roads immediately.

The calculations and cash-flow diagrams underlying these analyses are detailed in Appendix 5-1.

Tables 5.2, 5.3, and 5.4 summarize the benefit/cost ratio of each road upgrading strategy, compared with the current Scenario 1 (retaining SLR) in Lyon, Olmsted, and Clay Counties, respectively.

These results show in Lyon and Clay Counties that a general upgrading strategy is not economically sound, as all of these strategies have a benefit/cost ratio less than 1.0. In

Olmsted County, several upgrading strategies have a benefit/cost ratio above 1.0. In both Lyon and Olmsted (but not Clay) strategy 3B (lifting SLR on 7 and 9 ton roads now and upgrading 7 ton roads at the first overlay) has the highest Benefit/Cost ratio.

None of this is to say that upgrading specific facilities is not warranted (or that upgrading all facilities is the best option in Olmsted County), as this is an aggregate analysis that does not permit drawing those conclusions on a specific basis. In fact, upgrading selected links should achieve a higher benefit/cost ratio than can be obtained either by upgrading all links (Scenarios 3, 4 and 5) or upgrading no links (Scenario 2'). However, a detailed engineering analysis, beyond the scope of this project, is required to determine which links should be upgraded. Future research, beyond the scope of this project, is needed to gain greater understanding of the effects of Spring Loads, and the merits of Spring Load Restrictions on gravel roads.

**Table 5.2 Benefit/Cost ratios for alternative road upgrading scenarios in Lyon County (Scenario below vs. scenario 1: retain SLR)**

| Scenario Number | Calibrated Truck VKT (km) | Calibrated Truck VMT (Miles) | Present value of benefit (to trucking industry) ($) | Present value of costs (to road owner)($) | Benefit/ Cost ratio |
|---|---|---|---|---|---|
| 3A | 124,912 | 77,585 | 4,059,356 | 7,050,469 | 0.58 |
| 3B | 123,002 | 76,399 | 6,058,968 | 7,186,269 | 0.84 |
| 3C | 117,569 | 73,024 | 6,058,968 | 19,999,857 | 0.30 |
| 4A | 124,912 | 77,585 | 5,137,450 | 12,838,528 | 0.40 |
| 4B | 123,002 | 76,399 | 7,137,063 | 12,974,328 | 0.55 |
| 4C | 117,569 | 73,024 | 7,668,125 | 32,074,420 | 0.24 |
| 5A | 124,912 | 77,585 | 6,235,707 | 17,228,756 | 0.36 |
| 5B | 123,002 | 76,399 | 8,235,319 | 17,364,556 | 0.47 |
| 5C | 117,569 | 73,024 | 9,608,819 | 37,955,811 | 0.25 |

**Table 5.3 Benefit/Cost ratios for alternative road upgrading scenarios in Olmsted County (Scenario below vs. scenario 1: retain SLR)**

| Scenario Number | Truck VKT (km) | Truck VMT (Miles) | Present value of benefit (to trucking industry) ($) | Present value of costs (to road owner)($) | Benefit/ Cost ratio |
|---|---|---|---|---|---|
| 3A | 322,101 | 200,063 | 14,830,847 | 14,231,015 | 1.04 |
| 3B | 321,195 | 199,500 | 22,136,426 | 14,482,572 | 1.53 |
| 3C | 321,095 | 199,438 | 22,136,426 | 36,342,379 | 0.61 |
| 4A | 322,101 | 200,063 | 15,342,255 | 18,722,774 | 0.82 |
| 4B | 321,195 | 199,500 | 22,647,834 | 18,974,331 | 1.19 |
| 4C | 321,095 | 199,438 | 7,668,125 | 45,712,708 | 0.17 |
| 5A | 322,101 | 200,063 | 15,362,588 | 26,964,992 | 0.57 |
| 5B | 321,195 | 199,500 | 22,668,167 | 27,216,550 | 0.83 |
| 5C | 321,095 | 199,438 | 22,935,680 | 56,754,437 | 0.40 |

**Table 5.4 Benefit/Cost ratios for alternative road upgrading scenarios in Clay County. (Scenario below vs. scenario 1: retain SLR)**

| Scenario Number | Calibrated Truck VKT (km) | Calibrated Truck VMT (miles) | Present value of benefit (to trucking industry) ($) | Present value of costs (to road owner)($) | Benefit/ Cost Ratio |
|---|---|---|---|---|---|
| 3A | 220,199 | 137,625 | 411,968 | 2,816,901 | 0.15 |
| 3B | 213,359 | 133,350 | 614,901 | 2,952,701 | 0.21 |
| 3C | 212,608 | 132,880 | 614,901 | 11,581,563 | 0.05 |
| 4A | 220,199 | 137,625 | 3,624,182 | 7,934,073 | 0.46 |
| 4B | 213,359 | 133,350 | 3,827,115 | 8,069,873 | 0.47 |
| 4C | 212,608 | 132,880 | 5,409,430 | 22,256,576 | 0.24 |
| 5A | 220,199 | 137,625 | 3,750,448 | 9,377,473 | 0.40 |
| 5B | 213,359 | 133,350 | 3,953,380 | 9,513,273 | 0.42 |
| 5C | 212,608 | 132,880 | 5,632,550 | 24,190,235 | 0.23 |

## 5.3 Value of Time Method

In the baseline analysis described in Chapter 4, the operating cost method was used to determine the cost to truckers. In Chapter 2, operating cost per unit length and a value of time were estimated. In this section the value of time is considered to compare the sensitivity of the benefit/cost ratio to this alternative estimate of truck costs.

According to the freight demand model, in Lyon County, lifting SLR reduces 49.4 hours of travel time per day for truckers. The SLR survey shows the value of time for truckers is $49.42 per hour. Thus, the total cost to all freight shippers and carriers is $3,700 per day. Assuming 8 weeks of SLR, the total annual cost is $207,210. The net present value of the cost to truckers in the following 42.5 years adds up to $ 4,548,419, assuming a 3.5% discount rate.

Table 5.5 gives the benefit/cost ratio of lifting SLR on 7 and 9-ton roads in Lyon County using both methods. (Cost per km and Value of Time)

**Table 5.5 Benefit/Cost ratio from removing SLR on 7 and 9-ton roads only (retaining SLR on 5-ton roads) assuming different times before failure (Scenario 1 vs. Scenario 2') in Lyon County, Comparison of operating cost and value of time methods**

| Years before pavement failure | Benefit/Cost Ratio (using cost per km) | Benefit/Cost Ratio (using value of time) |
|---|---|---|
| 15 | 21.76 | 16.34 |
| *17* | *13.81* | *10.37* |
| 20 | 12.10 | 9.08 |
| 25 | 9.41 | 7.06 |
| 30 | 7.93 | 5.96 |

It can be seen from Table 5.5 that the difference in the calculated benefit/cost ratio using these two methods is less than 20%. Comparatively speaking, the value of time method depends on our assumption of vehicle speed on each type of road, which requires an additional assumption beyond the operating cost method. Thus, the cost per km (mile) to truckers to calculate total costs to truckers is adopted as the baseline for the analysis.

### 5.4 Cost per Kilometer (mile)

The total operating cost per km (mile) for truckers affects the result directly, so a sensitivity test on total operating cost per km (mile) is conducted. If the operating cost per km (mile) for truckers is assumed to be 25% higher or lower than its base price ($0.69/km or $1.11/mile), the benefit/cost ratios will vary, as shown in Table 5.6. It can be seen from the table that a 25% variation on cost per km (mile) does not change the basic conclusion since all benefit/cost ratios remain well above 1.0.

**Table 5.6 Benefit/Cost ratio from removing SLR on 7 and 9-ton roads only (retaining SLR on 5-ton roads) assuming different cost per km (Scenario 1 vs. Scenario 2') in Lyon County**

| Years before pavement failure | Benefit/Cost Ratio (cost per km = $0.69 ) | Benefit/Cost Ratio (cost per km =0.69*75% ) | Benefit/Cost Ratio (cost per km = $0.69*125% ) |
|---|---|---|---|
| 15 | 21.76 | 16.32 | 27.20 |
| *17* | *13.81* | *10.36* | *17.26* |
| 20 | 12.10 | 9.08 | 15.13 |
| 25 | 9.41 | 7.06 | 11.76 |
| 30 | 7.93 | 5.95 | 9.91 |

### 5.5 Pavement Life Savings

The accuracy of pavement life derived from the Mn/PAVE model is an important factor affecting the final benefit/cost ratio. If the pavement life difference with and without SLR were underestimated, this might create risk to road operators for lifting SLR. Thus, a sensitivity study on the savings in pavement life due to SLR is conducted to test the robustness of the results.

The pavement life on 7 and 9-ton roads with and without SLR was estimated. On most links, pavement life in the scenario with SLR has a longer life than pavement life without SLR. The average pavement life on all links is calculated under the two scenarios and the overall ratio of the life without SLR/with SLR of all these links is calculated. In this sensitivity analysis, all links are assumed to have the county-wide "with SLR" average life for the "with SLR" scenario, and the county-wide "without SLR" average life for the "without SLR" scenario. The average difference in life for alternative cases is computed as below.

The percentage difference between the county-wide average pavement life savings is multiplied by 1, 2, 3, 5 and 10 respectively to get the new estimated life without SLR (on 7 and 9-ton roads). This will significantly increase the advantages associated with the SLR policy.

$$L_n^{'} = L_s \times \left(1 - \left(\frac{L_n}{L_s} \times c\right)\right)$$

$L_n^{'}$: Adjusted pavement life in scenario without SLR

$L_n$: Pavement life in scenario without SLR from Mn/PAVE model

$L_s$: Pavement life in scenario with SLR from Mn/PAVE model

$c$: constant (c=1,2,3,5,10 )

The sensitivity analysis is done for the base assumption of 7 and 9-ton road pavement life (lasting 17 years) and the result is shown in Table 5.7 for Lyon and Olmsted counties.

**Table 5.7 Sensitivity analysis of Lyon and Olmsted counties (scenario 1 vs scenario 2') (base case-17 years)**

| Pavement life savings | Lyon County | | Olmsted County | |
|---|---|---|---|---|
| | Index factor( $B_c$ ) | Benefit/Cost Ratio | Index factor( $B_c$ ) | Benefit/Cost Ratio |
| Original (1 time) | 1 | 13.81 | 1 | 15.75 |
| 2 times | 0.49 | 6.77 | 0.48 | 7.56 |
| 3 times | 0.32 | 4.42 | 0.30 | 4.73 |
| 5 times | 0.19 | 2.62 | 0.17 | 2.68 |
| 10 times | 0.08 | 1.10 | 0.06 | 0.95 |

Increasing the pavement life difference between scenarios with and without SLR, provides 5 benefit/cost ratios associated with lifting SLR when n=1, 2, 3, 5 and 10. The benefit/cost ratio is indicated as $B_c$ (c=1, 2, 3, 5, 10). To see how the assumption affects the results, the Index factor is calculated. The benefit/cost ratio of lifting SLR ($B_1$) when n=1 is used as the base. The index factor is calculated as the benefit/cost ratio $B_c$ (c=2, 3, 5, 10) divided by $B_1$.

### 5.6. Mn/DOT Investigation 183 "Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota"

The Pavement Performance Model is a crucial part in the Benefit/Cost analysis. To this point, a pavement performance model based on Mn/PAVE has been used to calculate pavement life in terms of rutting failure, which is one of the major causes of pavement failure due to loading during springtime (Mn/PAVE also estimates fatigue failure, but the results from this were dominated by rutting in the model, i.e. rutting occurs before fatigue and is thus the critical failure according to the model). But due to the complexity of pavement failure mode, there may be other types of pavement failures associated with Spring thaw conditions.

Erland Lukanen developed another model from Investigation 183 data [1], which were collected in the 1960s and 1970s. These results may or may not be more accurate than Mn/PAVE. Though they are empirical and based on actual failures, rather than what is theoretically predicted, the empirical data are on average 30 years old, and there have been significant changes in the way that pavements are constructed, hopefully making them better. Damage coefficients from the Inv 183 data were applied to the results from the Freight Demand Model and used to estimate the pavement life. Then the benefit/cost ratio was recalculated and compared for Lyon County. Two things are important to note. First, the Inv 183 data predict that more life is saved with SLR than Mn/PAVE. However, the Inv 183 data also estimate a longer overall life for most pavements than Mn/PAVE, so that life is saved farther into the future, somewhat offsetting the first effect. That savings must be discounted back to the present, diminishing its significance.

Overall, the results, shown in Table 5.8, seem to be fairly consistent, if a bit lower with the Inv 183 model. Both models show benefit/cost ratios above 1.0 for lifting SLR on 7 and 9-ton roads [1].

**Table 5.8 Benefit/Cost ratio from removing SLR on 7 and 9-ton roads only (retaining SLR on 5-ton roads) assuming different time before failure (Scenario 1 vs. Scenario 2') in Lyon County Using Inv 183 and Mn/Pave Pavement Performance Models**

| Assumption | Increased pavement cost (Cost) (MnPave) | Increased pavement cost (Cost) (Inv 183 | Benefit/Cost Ratio (Inv 183 model) | Benefit/Cost Ratio (Mn/Pave Model) |
|---|---|---|---|---|
| 15 | $278,446 | $521,733 | 11.61 | 21.76 |
| *17* | *438,642* | *604,292* | *10.02* | *13.81* |
| 20 | 500,782 | 752,289 | 8.05 | 12.10 |
| 25 | 644,082 | 959,492 | 6.31 | 9.41 |
| 30 | 763,415 | 1,061,317 | 5.71 | 7.93 |

## References

[1] Lukanen, Erland (1980) Mn/DOT Investigation 183 “Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota” Minnesota Department of Transportation, St. Paul, Minnesota

# Chapter 6: Policy Development

**TASK 5 Policy Development:** Develop a pricing/tax/fine/regulatory structure to internalize damage cost of pavement into trucking costs.

## 6.1 Introduction

The transportation experience shapes the nature of policy making. Planning, deployment, and management follow. This reshapes experience, and the process continues. We visualize this process in Figure 6.1. Understanding the transportation experience is the key to understanding policy, planning, deployment, and management. An operative word is learning: transportation professionals have learned from experience in managing roadways both paved and unpaved, and in operating a truck-based freight transportation system. That learning has yielded rules (guidelines, regulations, etc.) that tell how to create, deploy, and operate systems. Those rules become policies. Think of Figure 6.1 as the *experiential policy model.* The transportation experience is embedded not only in geographic, economic, social, and political environments; it is also corralled by the limits of technological structure and nature of specific modes. The nature of transportation and the greater environment, collated with the transportation experience, gives rise to perceptions, principles and attitudes. Those beliefs generate a layer of policies (both government and private) that translate into actions. Action and reaction indicates the modes adjust performance to cope with problems. Those actions shape and re-shape the transportation experience.

The experiential policy model says that perceptions, principles and attitudes are forged from experience interacting with the nature of transportation systems. For example, principles bearing on the organization of systems, as well as public and private sector roles, stem from experiences when systems were deployed.

Relating this argument to the debate about spring load restrictions, it must be remembered that the policy imposing spring load restrictions was created in a different era, under different conditions. Trucking was less important; roads (much less paved roads) were less well constructed. As conditions change, policy and associated financing needs to be reconsidered.

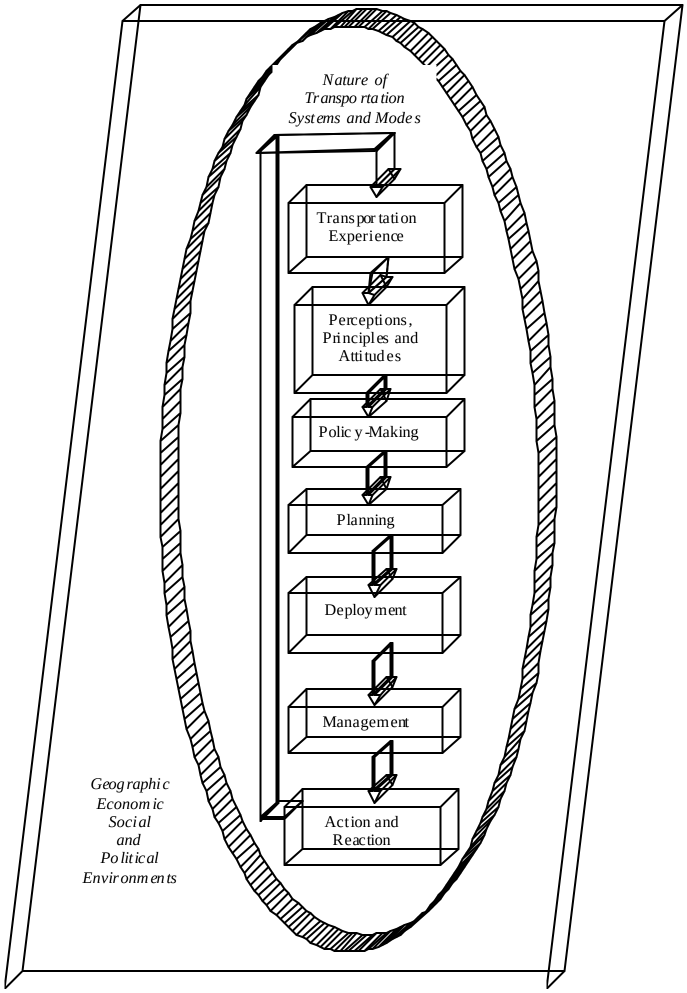



***Figure 6.1 Experiential Policy Model***

## 6.2 Application to Lifting of the Spring Load Restriction

Several alternatives to recover costs associated with the possible lifting of the Spring Load Restriction on 7 and 9-ton roads in Minnesota present themselves. First the analysis in Chapters 4 and 5 of this report suggests that the benefits to truckers from lifting the SLR outweighs the costs incurred by agencies who own the roads in terms of earlier repair of the road. This argues that there are multiple solutions that could be considered "win-win". However the actual compliance with the SLR may be below 100%. In that case, charging trucks for the full damage associated with lifting the SLR assuming 100% compliance would generate more revenue than the costs that actually would occur when lifting the SLR.

For instance (using fictional numbers for illustration), the benefits of lifting the SLR assuming 100% compliance are $2 (to shippers are carriers), while the costs are $1 (to the road agency). It would appear reasonable to charge an extra $1 (spread over all shipments somehow). However, assume the compliance with the law is presently only 10%. Then it is likely that the real benefits associated with the change are about $0.20 and the real costs are about $0.10. The ratio of benefits to costs is the same. However, charging $1 would raise 5 times the $0.20 real benefits truckers accrue from the change in policy.

That $1 would compensate road owners for the real damage that is done during the spring thaw period, but would outweigh the benefits ($0.20) truckers would receive from lifting the policy. In other words, truckers would be better off violating a law with lax enforcement than being legal and paying a large charge. Road owners who politically need consensus from trucking operators to enable financial recovery of damages would be better off with a $0.10 charge than with nothing.

### 6.3 How much revenue?

The amount of revenue required statewide can be estimated based on the analysis conducted in Chapter 4.

The Freight Demand Models provides calibrated estimates of the truck travel in Lyon, Olmsted, and Clay counties in Minnesota. The total truck travel in Minnesota can be obtained from the Federal Highway Statistics. The expansion factor (*F*) is simply

$$F = \frac{V_{Minnesota}}{V_{Lyon} + V_{Olmsted} + V_{Clay}}$$

where *V* is the variable on which the expansion is conducted. This might be size of the network or a measure of truck travel. Clearly different variables will give somewhat different expansion factors.

The estimated statewide cost $C_{Minnesota}$ of the policy is the expansion factor multiplied by the sum of the countywide factors:

$$C_{Minnesota} = F\left(C_{Lyon+} + C_{Olmsted} + C_{Clay}\right)$$

County engineers have reported the size of the networks in each county. The state and county Geographic Information Systems, and other maps give lane-kilometers for Lyon, Olmsted, Clay counties by type of road (5, 7, 9, 10) (Table 6.1).

Table 6.1 Network Size by Road Type

| County | 5 ton | 7 ton | 9 ton | 10 ton | Total |
|---|---|---|---|---|---|
| Lyon | 2,874 | 520 | 382 | 532 | 4,308 |
| Olmsted | 1,636 | 1210 | 368 | 618 | 3,832 |
| Clay | 4,572 | 246 | 482 | 1,328 | 6,628 |
| Three county total | 9,082 | 1,976 | 1,232 | 2,478 | 14,768 |

Minnesota Total: 436,211 lane-km (271,107 lane-mile) (Source: FHWA Highway Statistics 2002, Table HM-60)

This gives us a three-county expansion factor of $F_{3lane\text{-}km}$=29.54.

The damages in the counties associated with removing SLR from 7 and 9-ton roads, and either maintaining the roads at their current classification (comparing scenario 1 and scenario 2') or upgrading them (comparing scenario 1 and 3B) for two different estimates of pavement damage (using the MnPAVE and Investigation 183 Pavement Performance Models) are as shown in Table 6.2. In addition, a scenario looking at Maintaining the roads if the estimates from the MnPAVE Pavement Performance Model underestimated pavement life savings by a factor of 10 are shown for comparison.

$$A = P\frac{i(1+i)^n}{(1+i)^n - 1}$$

Where A = annual equivalent, i=interest rate, n=number of periods

Table 6.2: Net Present Value (*P*) of Increased Pavement Cost – Alternative Scenarios

| Area | Maintain 2' – 1 (MnPAVE) | Maintain 2' – 1 (Estimated Inv 183) | Upgrading at first overlay 3B –1 (MnPAVE) | Upgrading at first overlay 3B –1 (Estimated Inv 183) | Maintain 2' – 1 (MnPave underestimates Pavement Life Savings by Factor of 10) |
|---|---|---|---|---|---|
| Lyon County | $438,642 | $604,292 | $6,058,968 | $8,347,094 | $7,310,700 |
| Olmsted County | $1,939,797 | $2,672,347 | $22,136,426 | $30,496,088 | $24,247,463 |
| Clay County | $233,192 | $321,255 | $2,952,701 | $4,067,767 | $3,331,314 |
| Three county total | $2,611,631 | $3,597,895 | $31,148,095 | $42,910,949 | $34,889,477 |
| *P* = Statewide Estimate = $F_{3lane\text{-}km}$*Three-county total | $77,147,580 | $106,281,809 | $920,114,726 | $1,267,589,442 | $1,030,635,144 |
| *A* = Annual Cost (*i*= 3.5% interest, *n*=42.5 years) | $3,514,734 | $4,842,048 | $41,919,114 | $57,749,567 | $46,954,267 |
| Diesel Fuel Surcharge | $0.005 | $0.007 | $0.064 | $0.088 | $0.072 |
| Annual Fee | $42 | $58 | $501 | $690 | $561 |

## 6.4 Strategies

Given that some amount of revenue is to be raised, there are several strategies for doing so. These charges probably should be statewide. County-level charges may be difficult to enforce without all of the counties agreeing to do so. (Trucks could purchase fuel elsewhere, or register elsewhere, to avoid a local tax. It is harder, and less worthwhile, to do that at a state level).

**Diesel Fuel surcharge –** most trucks use some form of diesel fuel. There already exist diesel fuel taxes in Minnesota, making collection straightforward. The use of diesel fuel is roughly proportional to the amount of travel trucks undertake. Presently the tax on diesel fuel is $0.20/gallon [1]. In total, 652,549,000 gallons of "Special fuels" were consumed in Minnesota in 2002 [1]. This implies to cover the costs of removing the SLR on 7 and 9-ton roads, a year-round $0.005 - $0.007/gallon diesel fuel surcharge would be sufficient. To perform a structural upgrade on all 7-ton paved roads to a 9-ton standard would require a surcharge of $0.064 - $0.088/gallon of diesel fuel. The reason for taxing diesel only, and not all fuels is that trucks are the reason the roads would need to be upgraded or maintained more frequently, the additional pavement damage due to cars is, relatively speaking, negligible.

**Annual fee –** there are a number of annual fees that trucks already pay, so there is already a collection system in place. Each truck would pay the same, proportional to their axle loadings, but independent of the mileage traveled. State annual vehicle receipts in Minnesota for Trucks and Truck-Tractors were $178,797,000 in 2002 [1]. There were 34,729 truck/tractors and 48,938 farm trucks in Minnesota in 2002 [1]. Allocating the cost uniformly to all truck/tractors and farm trucks would give a charge of $42 - $58 per farm truck and truck/tractor vehicle per year to recover the additional damage to roads associated with lifting the SLR on 5 and 7-ton roads. The annual fee on trucks and tractors to upgrade 7-ton paved roads to a 9-ton standard would be $501 - $690.

**Weight-Distance tax –** Oregon uses weight-distance taxes [2]. In 1999, Oregon voters passed Measure 76, and placed in the state constitution the idea of "cost responsibility", ensuring that cars and trucks each pay their fair share.

"Revenues . . . that are generated by taxes or excises imposed by the state shall be generated in a manner that ensures that the share of revenues paid for the use of light vehicles, including cars, and the share of revenues paid for the use of heavy vehicles, including trucks, is fair and proportionate to the costs incurred for the highway system because of each class of vehicle. The Legislative Assembly shall provide for a biennial review and, if necessary, adjustment, of revenue sources to ensure fairness and proportionality."

Weight-Distance taxes are not without controversy. At the behest of certain truckers, the Oregon Legislation repealed the tax in 1999 – hoping to replace it with a more general gas tax that would favor heavier loads at the expense of lighter loads, but the bill was referred to voters who defeated it in 2000, restoring the weight-distance tax.

The Oregon Highway Cost Allocation Study is conducted biennially to support highway-financing decisions. The 2003 report states that light vehicles (weighing 3,636 kg (8,000 pounds) or less) should pay 66.6% of state highway user revenue, and heavy vehicles should pay the remaining 33.4%, which is within 0.5% of actual payments [2].

Employing a weight-distance tax in Minnesota would require a change in revenue policy well beyond what is required to recover costs from the Spring Load Restrictions, but remains a good idea to maximize both fairness and efficiency in the highway financing system.

**Permitting system –** this would require a new regulatory apparatus. Though it would be possible in principle to charge directly based on use, the enforcement required to do so would entail a significant transactions cost that may obviate the gains from policy change.

### 6.5 How should the revenue be spent?

Because most of the economic burden associated with lifting the Spring Load Restriction would be borne by local governments (counties and municipalities), the revenue that is collected to recover the costs of the additional pavement damage associated with lifting the SLR should be dedicated to local governments (counties, municipalities, townships) to spend on maintaining and rebuilding roads. Local governments would then need to prioritize projects based on local engineering and other information.

### 6.6 Discussion

Unlike the railroads, which integrated rolling stock and track in the same organization, the highway system has a disjoint control of trucks (owned by trucking firms) and pavements (owned by governmental road agencies), which has created a number of extra costs that proper management of the system might avoid. Pavements are rated for different loads of trucks; roads are restricted to 5-ton, 7-ton, 9-ton, and 10-ton axle weight trucks. Shipments across this network are constrained by the lowest weight limit permitted on the roads to be used (or risk violation – though weight enforcement off the interstate highways varies widely by county). Some roads should be upgraded, some trucks should have more axles, but the disjoint nature of the control makes this coordination difficult.

A major solution to these problems lies in rethinking highway financing. The ability to charge truckers different amounts for different roads would put the proper incentives for socially beneficial behavior back in the system [3]. Economists have been arguing this for several decades, and the policy community, which has some working examples and the promise of modern revenue collection technologies, is finally absorbing it. A second solution, to improve materials to the point that they are "too cheap to meter", that is so that they are sufficiently strong that it doesn't matter the load using them (within reason), is the analog to building your way out of congestion. Laying pavements with near zero variable (per use) costs may be technically possibly, but their upfront fixed (one time) costs are likely to be very high.

**References**

[1] US Federal Highway Administration Highway Statistics 2002

[2] Oregon Department of Transportation. *Volume I: Final Report 2003 Oregon Highway Cost Allocation Study Prepared for Oregon Department of Administrative Services.* ODOT Transportation Development Division Policy Section and ECONorthwest. May 2003 <http://www.oea.das.state.or.us/highwaycost/hwaycost.htm>.

[3] Small, Kenneth. Clifford Winston and Carol Evans *Road Work : a new highway pricing and investment policy*. Washington, D.C.: Brookings Institution, 1989.

# Appendix A

## Definitions for the Main Types of Roads

## - From Minnesota State Aid Manual -

# GENERAL INFORMATION

**5-892.000**

## 5-892.001 MAPS OF MINNESOTA

A. See Fig. A 5-892.001, Fig. B 5-892.001 and Fig. C 5-892.001.

## 5-892.002 SYSTEMS DEFINITIONS

### STATE AID SYSTEMS

County State Aid Highway - C.S.A.H. - A road or street established and designated under county jurisdiction in accordance with Minnesota Statutes Chapter 162.

- Municipal State Aid Street - M.S.A.S.- A street within a city or village having a population of 5,000 or more, established and designated under municipal jurisdiction in accordance with Minnesota Statutes Chapter 162.

### OTHER SYSTEMS

County Road - Co. Rd. - A road established and designated under the sole authority of the county board.

Township Road - Twp. Rd. - A road established by and under the authority of the town board, or reverted to township jurisdiction by the county board.

City Street - City St. - Any street under the jurisdiction of a municipality not otherwise designated as a Trunk Highway, State Aid Street/Highway or County Highway.

### FUNCTIONAL CLASSIFICATION PLAN

A plan by which highways and streets are grouped in classes according to the character of service they are intended to provide.

### RURAL SYSTEM DEFINITIONS

Principal Arterials Serve corridor movements having trip lengths and travel density characteristics indicative of statewide or interstate travel. Also serve all urbanized areas and a large majority of the small-urban areas with over 25,000 population.

Minor Arterials Link cities, larger towns, and other traffic generators, such as major resort areas. Consistent with population density, space minor arterials so that all developed areas of the state are within a reasonable distance of an arterial highway.

Major Collectors These routes: (1) provide service to the larger towns not served by higher systems and other traffic generation of equivalent intra-county importance such as consolidated schools and county parks; (2) link these places with nearby large towns or cities or with arterials; and (3) serve important intra county travel corridors.

Minor Collectors At intervals consistent with population density these routes collect traffic from local roads and bring all developed areas within a reasonable distance to a collector road and provide service to the remaining small communities.

Local Serve primarily to provide access to adjacent land. Includes all roads not classified as arterial or collectors.

### URBAN SYSTEM DEFINITIONS

Principal Arterials Serves major centers of activity within metropolitan areas, corridors of highest traffic volume and longest trip desires, and provides continuity to the rural arterial system. In larger urban areas, they provide service for major movements within the urbanized area itself, in addition to serving rurally oriented traffic.

Minor Arterial Provide for traffic of a more land access orientation. Service should be more of an intra-community nature. The system includes urban connections to rural major collector roads.

Collector The collector system serves to distribute traffic from the arterial to their destination, which may be on a local or collector street. Conversely, the collector street "collects" traffic from the local streets and channels it into the arterial system. The collector system serves both land access and local traffic movement within the various neighborhoods and areas.

Local Comprised of all facilities not on one of the higher systems. It serves primarily to provide direct access to abutting land and access to the higher order systems.

**FEDERAL AID SYSTEM**

National Highway System - N.H.S. - This is a system of highways of national importance, identified by the State of Minnesota and approved by Congress. The National Highway System consists predominately of Interstate highways and specifically designated Minnesota Trunk Highways classified as principal arterials.

Federal-aid Highways All rural highways functionally classified as a major collector or higher, and all urban streets classified as collectors or higher are eligible to receive Federal-aid funds. Functional classification shall be as shown on the approved County or City map.

Federal Aid Secondary - F.A.S. - A system of rural roads that are functionally classified as major collectors and were jointly selected by the appropriate local officials and the Minnesota Department of Transportation and approved by the Federal Highway Administration. This system is no longer used to determine where Federal-aid funds can be spent, but is retained for reporting purposes for FHWA.

Federal Aid Urban - F.A.U. - A system within each urban area consisting of Trunk Highways, County State Aid Highways, Municipal State Aid Streets or city streets that are functionally classified as arterial or collectors and were selected by the appropriate local officials with concurrence by the Minnesota Department of Transportation and approved by the Federal Highway Administration. This system is no longer used to determine where Federal-aid funds can be spent, but is retained for reporting purposes for FHWA.

Forest Highway - F.H. - A route located within the boundaries of national forests and jointly selected by local officials, the Minnesota Department of Transportation and the U.S. Forest Service, subject to the approval of the Federal Highway Administration.

**9.1 METRIC TON ROUTE SYSTEM**

In order for a highway or street to legally carry 9.1 metric ton traffic, it must be designated as a 9.1 metric ton route described in statute as the 9.1 metric ton Route System. Minnesota Statute 169.832 gives the Commissioner of Transportation the authority to designate routes, with the approval of the local road authority.

By statute (Section 169.825, Subd. 10), all routes not designated shall have a gross vehicle weight limit of 33 239 kg (8.2 tons), unless otherwise posted.

Springtime restrictions may be posted by the local road authority. If a roadway is not posted and is not a designated 9.1 metric ton route, then Section 169.87 restricts all non-concrete surfaced roadways to a springtime limit of 4.5 tons

To designate a 9.1 metric ton route, the procedures listed below must be followed:

A. Designation must not cause any undue hazard to traffic safety, and the roadway must have the structural capacity and be able to carry the expected volumes of traffic.

# Appendix B

## Survey Responses from County Engineers and State Aid Data

| No | County | Mile | Mile - State Aid | Mile - Asphalt | Mile - Concrete | Percent of system with: | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10 tons | 9 tons | 7 tons | 5 tons | Other | Note |
| 1 | Aitkin | 509.00 | 374.00 | 215.00 | 0.00 | 0.00% | 34.00% | 8.00% | 58.00% | 0.00% | - |
| 2 | Anoka | 422.00 | 287.00 | 422.00 | 0.00 | 11.00% | 51.00% | 33.00% | 5.00% | 0.00% | - |
| 3 | Benton | 450.00 | 225.00 | 350.00 | 0.00 | 1.00% | 25.00% | 25.00% | 49.00% | 0.00% | - |
| 4 | Blue Earth | 720.00 | 420.00 | 416.00 | 4.00 | 2.00% | 15.00% | 82.00% | 1.00% | 0.00% | - |
| 5 | Brown | 335.00 | 318.00 | 282.00 | 0.00 | 1.00% | 13.00% | 70.00% | 16.00% | 0.00% | - |
| 6 | Cass | 866.00 | 352.00 | 425.00 | 0.00 | 3.40% | 27.90% | 13.10% | 55.60% | | - |
| 7 | Chippewa | 298.60 | 243.60 | 179.30 | 0.80 | 1.30% | 22.50% | 36.50% | 0.00% | 39.70% | - |
| 8 | Chisago | 377.00 | 234.00 | 285.00 | 0.00 | 2.00% | 22.00% | 66.00% | 10.00% | 0.00% | - |
| 9 | Clay | 780.00 | 404.00 | 260.00 | 21.00 | 8.00% | 50.00% | 31.00% | 11.00% | 0.00% | - |

| No | County | Mile | Mile - State Aid | Mile - Asphalt | Mile - Concrete | Percent of system with: | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10 tons | 9 tons | 7 tons | 5 tons | Other | Note |
| 10 | Dakota | 437.00 | 326.00 | 354.00 | 2.00 | 1.00% | 65.00% | 8.00% | 26.00% | 0.00% | - |
| 11 | Douglas | 546.45 | 389.31 | 382.70 | 0.00 | 6.00% | 10.00% | 51.00% | 33.00% | 0.00% | - |
| 12 | Freeborn | 634.00 | 448.00 | 404.00 | 2.00 | 1.00% | 18.00% | 15.00% | 66.00% | 0.00% | - |
| 13 | Grant | 475.00 | 242.00 | 152.00 | 0.00 | no inf. | 28.00% | 4.00% | no inf . | no inf . | - |
| 14 | Kittson | 467.00 | 373.00 | 205.37 | 0.78 | 0.00% | 30.00% | 30.00% | 40.00% | 0.00% | - |
| 15 | Lac qui Parle | 498.00 | 362.00 | 210.00 | 0.00 | 2.00% | 6.00% | 33.00% | 59.00% | 0.00% | - |
| 16 | Lake of the Woods | 575.00 | 195.00 | 138.00 | 0.00 | 0.00% | 23.00% | 1.00% | 71.00% | 5.00% | - |
| 17 | Lyon | 488.24 | 319.03 | 320.00 | 0.00 | 2.00% | 25.00% | 32.00% | 41.00% | 0.00% | - |
| 18 | Marshall | 850.00 | 670.00 | 380.00 | 0.00 | 0.00% | 30.00% | 30.00% | 40.00% | 0.00% | - |
| 19 | Mcleod | 405.00 | 256.00 | 295.00 | 1.00 | 7.00% | 32.00% | 30.00% | 31.00% | 0.00% | - |
| 20 | Meeker | 1054.00 | 273.00 | 247.00 | 0.00 | 0.00% | 10.00% | 60.00% | 27.00% | 3.00% | - |

| No | County | Mile | Mile - State Aid | Mile - Asphalt | Mile - Concrete | Percent of system with: | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10 tons | 9 tons | 7 tons | 5 tons | Other | Note |
| 21 | Mille Lacs | 406.00 | 255.00 | 256.00 | 4.00 | 2.00% | 10.00% | 80.00% | 8.00% | 0.00% | - |
| 22 | Morrison | 722.39 | 442.69 | 667.94 | 1.80 | 1.00% | 67.10% | 31.10% | 0.80% | 0.00% | - |
| 23 | Murray | 424.00 | 354.00 | 264.00 | 0.00 | 0.00% | 26.00% | 46.00% | 28.00% | 0.00% | - |
| 24 | Nicollet | 305.00 | 245.00 | 219.00 | 0.40 | 17.00% | 17.00% | 20.00% | 46.00% | 0.00% | - |
| 25 | Nobles | 440.00 | 345.00 | 362.00 | 0.33 | 0.64% | 80.00% | 1.10% | 18.26% | 0.00% | - |
| 26 | Pipestone | 925.00 | 235.00 | 260.00 | 0.74 | 11.00% | 12.00% | 7.00% | 70.00% | 0.00% | - |
| 27 | Polk | 962.71 | 806.00 | 559.20 | 23.61 | 5.50% | 20.80% | 34.20% | 39.50% | 0.30% | - |
| 28 | Ramsey | 302.00 | 272.00 | 271.00 | 31.00 | 6.80% | 90.30% | 2.50% | 0.40% | 0.00% | - |
| 29 | Sherburne | 411.00 | 216.00 | 402.00 | 0.00 | 1.00% | 34.00% | 61.00% | 3.00% | 1.00% | - |
| 30 | Steele | 326.00 | 271.00 | 291.00 | 0.00 | 5.00% | 25.00% | 45.00% | 5.00% | 0.00% | - |

| No | County | Mile | Mile - State Aid | Mile - Asphalt | Mile - Concrete | Percent of system with: | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 10 tons | 9 tons | 7 tons | 5 tons | Other | Note |
| 31 | Stevens | 371.58 | 243.29 | 158.67 | 0.00 | 1.00% | 21.00% | 21.00% | 57.00% | 0.00% | Some of the roads posted at 7 ton are designed to 9 ton |
| 32 | Waseca | 378.70 | 249.90 | 192.62 | 56.74 | 12.00% | 4.00% | 49.00% | 0.00% | 35% - 6 tones | - |
| 33 | Wilkin | 507.00 | 312.00 | 169.00 | 2.00 | 1.00% | 26.00% | 11.00% | 62.00% | 0.00% | - |
| 34 | Winona | 387.00 | 315.36 | 314.78 | 0.64 | 5.00% | 60.00% | 33.00% | 2.00% | 0.00% | - |

| No | County | Typical Cross Sections | |
|---|---|---|---|
| | | 10 tons | 9 tons |
| 1 | Aitkin | non | 4.5” Bit. 8” Class 5 aggregate base - 12’ lane, 6’ shoulder |
| 2 | Anoka | no information | no information |
| 3 | Benton | 3 ½” Bit., 12” aggregate base 6” Select Granular Borrow, Based on R=15 | 3.5” Bit, 10” aggregate base, based on R =15 |
| 4 | Blue Earth | 5” Bit. on 15” aggregate basee | 5” Bit., 12” aggregate base |
| 5 | Brown | 8" Bit. 12" gravel base - 12' lanes, 8'shoulders | 3" 2350 overlay, 5" 2331 surfacing, 6" Class 5, 6" Class 4 aggregate base -12' lanes, 6' shoulders |
| 6 | Cass | 3.5-6" Bit, 5'-12" Class 5 aggregate base - 12' lanes 4'-6' paved shoulders | 3.5-6" Bit, 5'-12" Class 5 aggregate base - 12' lanes 2'-6' paved shoulders |
| 7 | Chippewa | no information | 8” Bit., 6” Class 5 aggregate base - 12' lane width |
| 8 | Chisago | 1.5” non-wear 2” wear Bit.- 8’ paved shoulders with 4% to crown 12’ driving lane with 2% | 1.5” non-wear 2” wear Bit.- 8’ paved shoulders with 4% to crown 12’ driving lane with 2% |
| 9 | Clay | Layer thickness = 9-7-9, Material = concrete - lane width - 20 | Layer thickness = 11”, Material = bituminous - lane width - 24’ |

| No | County | Typical Cross Sections | |
|---|---|---|---|
| | | 10 tons | 9 tons |
| 10 | Dakota | Concrete – unknown depth, 86’ curb to curb, 4 lane divided roadway | variable bituminous depths - many roadway types, 4-6 lane divided to 2 lane rural |
| 11 | Douglas | 4.5" Bit. 14" aggregate base (12' Lanes, 8' paved shoulders) | 12' Lanes, 8' paved shoulders 4.5" Bit Pav. 14" aggregate base |
| 12 | Freeborn | Too many cross section | |
| 13 | Grant | no information | Old roads 7-9” bit and 6-10” gravel<br>New roads: 5” bit and 12” gravel |
| 14 | Kittson | non | 3” Bit, 12” Class 5 aggregate base |
| 15 | Lac qui Parle | non information | 7½” LV Bit. Mixture, 5” Salvage Aggr. & Recycle Bit. Base, 3” Class 5 Aggregate Base, |
| 16 | Lake of the Woods | non | 8” Bit, 8” Class 6 aggregate base |
| 17 | Lyon | 5” Bit., 15” aggregate base - 24' pavement, 6’ shoulder, | 3.5” Bit, 15” aggregate base - 24' pavement |
| 18 | Marshall | non | 2.5" Bit. rd.mix, 6" bit. plant mix; 6" aggregate base Class 3, 3" aggregate base Class 5 (24' Bit pavement.) |
| 19 | Mcleod | 7-10” Bit., 12-15” aggregate base -12’ 12’ lane width, 8’ shoulder | 8-9” Bit., 6-8”aggregate base - 12’ lane width, 8’ shoulder |
| 20 | Meeker | non | 6” Bit (Plant Mix), 5 ½” Class 5 aggregate base |

| No | County | Typical Cross Sections | |
|---|---|---|---|
| | | 10 tons | 9 tons |
| 21 | Mille Lacs | no information | 1980's design, 24' paved top 4" bit. On 10-12" class 5 shoulder width 4-6 feet gravel 1:4 slopes |
| 22 | Morrison | 3.5" Bit (PM ), 6" Class 5 aggregate base - 44' curb to curb, 2-12' lanes, 2-10' parking lanes, urban design with storn | 3-1/2-5" PM Bit surface 6-8"Class 5 aggregate base - 2 12' lanes, 4' paved shoulders, 2' class 1 agg shoulder: |
| 23 | Murray | non | 4-5" Bit. 10-11" Gravel Base |
| 24 | Nicollet | 9" Bit mix, 6" gravel base - Various lane widths; some new construction, but mostly old resurfaced pavements | mostly 8" Bit mix, 8" gravel base - Newer pavements; witl new geometric standards |
| 25 | Nobles | 10" -12" Bit. 4" gravel base -12' 12' lane width | 7"-10" Bit, 4" gravel base -12' lane width |
| 26 | Pipestone | 5" Bit. 14" aggregate base | 4" Bit. 9" aggregate base |
| 27 | Polk | no information | 6" Bit. Pvmt. 10" aggrregate base |
| 28 | Ramsey | 7" of bituminous or 8" of concrete pavement 12' lane width | 7" of bituminous or 8" of concrete pavement 12' lane width |
| 29 | Sherburne | 2" Plant Mix Bit.; 1.5" Bit. Base; 5" Class 5 Base Subgrade-24' Width 12" Depth Select Granular Borrow | 2" Mix Bit. 2331; 1.5" Mix Bit. 2331; 5" Class 5 aggregate base, Subgrade-24' Width 12" Depth Select Granular Borrow |
| 30 | Steele | 6" Bit., 4" concret, unknow aggregate base | 5-6" Bit. 12" aggregate base 2 feet granular subbase |

| No | County | Typical Cross Sections | |
|---|---|---|---|
| | | 10 tons | 9 tons |
| 31 | Stevens | 8” 2350 MV Bit., 15-18” Cl 5 aggregate base | 6” 2350 LV-MV Bit., 12-15” Cl 5 aggregate base |
| 32 | Waseca | 8” Non- Reinforced, Undoweled Conc. Pvmt 4” aggregate base | 9” Bit. 4” aggregate base |
| 33 | Wilkin | 8" Bit, 10" gravel base | 8" Bit., 10" gravel base |
| 34 | Winona | 7” Concrete pavement, 9´concrete pavement overlayed with 3” Bit, 7” bituminous with 8”+ base - 12’ lane widths | 4”-7” Bit. with varying depths of aggregate base - 12’-11' lane widths |

| No | County | Typical Cross Sections | | |
|---|---|---|---|---|
| | | 7 tons | 5 tons | Other |
| 1 | Aitkin | 3” Bit. of 6”Class 5 aggregate base - 12’ lane, 2’ shoulder | 4” class 5 aggregate surfacing -24’ total width | non |
| 2 | Anoka | no information | no information | non |
| 3 | Benton | 2" Bit., 8” aggregate base | 2” Bit, 6” aggregate base | gravel surface |
| 4 | Blue Earth | 3" Bit, 12” aggregate base | 3” Bit, 10” aggregate base | non |
| 5 | Brown | 4"-6" Bit., 8"-12" gravel base -12'-11' lanes, 2'-4' shoulders | 4"-6" gravel | non |
| 6 | Cass | 2-4" bit, 3-6" aggregate base - 11'-12' lanes 0-4' paved or aggregate | aggrgate surfacing or 2" paved surface - 12' lanes 0-3' paved or aggrgate shoulders | non |
| 7 | Chippewa | no information | non | no information |
| 8 | Chisago | 1.5” non-wear 2” wear Bit - 1.5’ Gravel Shoulders 12’ driving lane with 2% to crown | Gravel roads - 2’ driving lanes 4%-6% to crown | non |
| 9 | Clay | Layer thickness = 9”, Material = bituminous -lane width - 24’ | Layer thickness = 4” (bituminous)and 12" (gravel) | non |

| No | County | Typical Cross Sections | | |
|---|---|---|---|---|
| | | 7 tons | 5 tons | Other |
| 10 | Dakota | variable depth bituminous - 2 lane rural, 24’ top with shoulders | Gravel | non |
| 11 | Douglas | 12' Lanes, 4' paved shoulders 3.5" Bituminos Pav. 8" Agg. Base | Gravel | non |
| 12 | Freeborn | Too many cross section | | non |
| 13 | Grant | no information | Gravel | non |
| 14 | Kittson | 3” bit, 8” Cl. 5aggregate base | Aggregate surfacing | non |
| 15 | Lac qui Parle | 7” Bit. Mixture, 4” Class 5 aggregate base | 3” Class 1 Aggregate | non |
| 16 | Lake of the Woods | 4” bit, 8” Cl. 5 aggregate base | 3” Class 5 aggregate surfacing | 3” Cl. 5, poor subgrade |
| 17 | Lyon | 1.5” road mix, 2” bit, 6” aggregate base - 22'-24' pavement | 28’ gravel surface | non |
| 18 | Marshall | 3" bit. plant mix, 6" aggregate base Class 3, 4" aggregate base Class 5 (24' Bit pavement` | Aggregate surfacing | non |
| 19 | Mcleod | 6-7” bit., 6-8” aggregate base - 12’ lane, 8’ shoulder | Gravel surface | non |
| 20 | Meeker | 4” Bit., (Plant Mix), 4” aggrehate base Class 5 | 4” Bit. (Plant Mix). 2” aggregare base Class 5 | non |

| No | County | Typical Cross Sections | | |
|---|---|---|---|---|
| | | 7 tons | 5 tons | Other |
| 21 | Mille Lacs | 1950's road design 24' paved top depth varies often over laid when mat is in poor condition, 8 to 10" class 5 - 4' or less shoulder-gravel, in slop | Non engineered section Gravel class 5- 5" - 28 foot wide slopes soften 1:2 | non |
| 22 | Morrison | 2-4" bit (Plant Mix),, 6-8"Class 5 aggregate base surface - 2 12' lanes, 4' class 1 agg shoulders | 6" aggregate surface - 2 14' lanes | non |
| 23 | Murray | 2" Bit, 10" Gravel Base | 4" Gravel Surface | non |
| 24 | Nicollet | mostly 6" mix over 8" gravel base - Aging pavements of all widths | 4" mix over the existing gravel-surfacing (meant to be for dust control in the River bottom areas) - | non |
| 25 | Nobles | 4"-7" Bit. 4" gravel base | 4" gravel surface - 12' Lanes | non |
| 26 | Pipestone | 4" bit., less then 9" Aggregate Base | Aggregate surfacing | non |
| 27 | Polk | 9" Aggr. Base 4" 2340 mix or 8.5"mix | 2" agregate surfaceing | non |
| 28 | Ramsey | no information | no information | non |
| 29 | Sherburne | 2" Wearing Course; 4" Class 5 aggregate base | 1.5"-2" Bit Mix; 0"-4" gravel base | non |
| 30 | Steele | 3-4" Bit., 10-12" aggregate base | 4" agregate surfaceing | non |

| No | County | Typical Cross Sections | | |
|---|---|---|---|---|
| | | 7 tons | 5 tons | Other |
| 31 | Stevens | 4-6" Bit., 8-12" Cl 5 aggregate base | 24-28' top of Cl 5 Agg. surfacing | non |
| 32 | Waseca | 7" Bit. Pvmt. 4" aggregate base | non | 6 ton gravel roads |
| 33 | Wilkin | 6"Bit., 6 inches gravel base | gravel surfacing | non |
| 34 | Winona | 4" Bit. with aggregate base or aggregate surfaced - 10'-12' lane widths | Bituminous or aggregate surface with poor drainage and a small amount of aggregate base | non |

| No | County | Types of soil | | | Percent of roads design with: | | | Current Design Procedure |
|---|---|---|---|---|---|---|---|---|
| | | Soil SF=130 | Soil SF=100 | Soil SF=75 or less | Soil Factor | R-value | Other | |
| 1 | Aitkin | 50.00% (R=10) | 50.00% (R=20 ) | 0.00% | 100.00% | 0.00% | 0.00% | R-value - 2003 |
| 2 | Anoka | no information | | | no information | | | R-value |
| 3 | Benton | 80.00% (R=15) | 20.00% (R=30+) | 0.00% | 20.00% | 25.00% | 65.00% | R-value - 1978 |
| 4 | Blue Earth | 100.00% | 0.00% | 0.00% | 90.00% | 10.00% | 0.00% | R-value - 10%<br>Soil Factor -90% |
| 5 | Brown | 100% (R=12) | 0.00% | 0.00% | 75.00% | 9.00% | 16% - gravel road | R-value - 2002 |
| 6 | Cass | - | mostly | - | 90.00% | 10.00% | 0.00% | SF - 50%<br>R-value - 50% |
| 7 | Chippewa | 100.00% | 0.00% | 0.00% | 58.50% | 1.80% | 39.70% | Soil Factor and R-Value |
| 8 | Chisago | 50.00% | 23.00% | 27.00% | 40.00% | 60.00% | 0.00% | R-value - 1997<br>Lane one way N-18<br>Minimum Bituminous G.E |
| 9 | Clay | 50.00% | 50.00% | 0.00% | 90.00% | 10.00% | 0.00% | R-value, Soil Factor, GE |

| No | County | Types of soil | | | Percent of roads design with: | | | Current Design Procedure |
|---|---|---|---|---|---|---|---|---|
| | | Soil SF=130 | Soil SF=100 | Soil SF=75 or less | Soil Factor | R-value | Other | |
| 10 | Dakota | 10.00% | 50.00% | SF=75 30.00%<br>S.F.=50 10.00% | 50.00% | 50.00% | 0.00% | SF - 20% widening of turnlanes,etc<br>R-value - 80% for complete |
| 11 | Douglas | 0.00% | 90.00% | SF=75 7.00%<br>S.F=50 3.00% | 94.00% | 6.00% | 0.00% | R-value<br>Soil Factor |
| 12 | Freeborn | - | mostly | - | 100.00% | 0.00% | 0.00% | Soil Factor |
| 13 | Grant | 60.00% | 40.00% | 0.00% | 100.00% | 0.00% | 0.00% | Soil Factor |
| 14 | Kittson | 50.00% | 50.00% | 0.00% | 100.00% | 0.00% | 0.00% | Soil Factor |
| 15 | Lac qui Parle | 54.00% | 7.00% | 39.00% | 100.00% | 0.00% | 0.00% | Soil Factor |
| 16 | Lake of the Woods | 100.00% | 0.00% | 0.00% | 95.00% | 5.00% | 0.00% | Soil Factor |
| 17 | Lyon | 50.00% | 50.00% | 0.00% | 98.00% | 2.00% | 0.00% | Soil Factor - 1983 |
| 18 | Marshall | 65.00% | 30.00% | 5.00% (SF=50) | 90.00% | 10.00% | 0.00% | Soil Factor |
| 19 | Mcleod | 80%<br>(R 14-18 under 20 - miles of road | 20.00% | 0.00% | 90-95% | 5-10% | 0.00% | R-value - for 10 tons<br>Soil Factor - the others |
| 20 | Meeker | 10.00% | 75.00% | 15.00% | 100.00% | 0.00% | 0.00% | Soil Factor - 1956 |

| No | County | Types of soil | | | Percent of roads design with: | | | Current Design Procedure |
|---|---|---|---|---|---|---|---|---|
| | | Soil SF=130 | Soil SF=100 | Soil SF=75 or less | Soil Factor | R-value | Other | |
| 21 | Mille Lacs | 50.00% | 50.00% | 0.00% | 50.00% | 40.00% | 10.00% | R-value - 1981 |
| 22 | Morrison | 0.00% | 75.00% | 10% - SF=75<br>15% - SF=50 | 90.00% | 10.00% | 0.00% | R-value - 10%<br>SF -90% |
| 23 | Murray | no info | | | 100.00% | 0.00% | 0.00% | Soil Factor |
| 24 | Nicollet | 100.00% | 0.00% | 0.00% | 30.00% | 70.00% | 0.00% | R-value - 1998 |
| 25 | Nobles | 85.00% | 15.00% | 0.00% | 90.00% | 7.00% | 3.00% | R-value - 2000 |
| 26 | Pipestone | 90.00% | 10.00% | 0.00% | 90.00% | 10.00% | 0.00% | Soil Factor |
| 27 | Polk | 60.00% | 40.00% | 0.00% | 90.00% | 10.00% | 0.00% | Soil Factor |
| 28 | Ramsey | 20.00%<br>*R < 20* | 70%<br>*R:20 to 50* | 10%<br>*R >50* | 50.00% | 25.00% | 25% - Roads are too old to say the design metho | R-value - about 1980 |
| 29 | Sherburne | 0.00% | 83.00% | 17.00% | 99.00% | 1.00% | 0.00% | Soil Factor-State Aid and County Funded;<br>R-value - Federally Funded |
| 30 | Steele | 70.00% | 30.00% | 0.00% | 95.00% | 5.00% | 0.00% | Soil Factor - 50% - 2002<br>R-value - 50%  - 2002 |

| No | County | Types of soil | | | Percent of roads design with: | | | Current Design Procedure |
|---|---|---|---|---|---|---|---|---|
| | | Soil SF=130 | Soil SF=100 | Soil SF=75 or less | Soil Factor | R-value | Other | |
| 31 | Stevens | 100.00% | 0.00% | 0.00% | 98.00% | 2.00% | 0.00% | R-value - for 10 tons<br>Soil Factor - mostly |
| 32 | Waseca | 100.00% | 0.00% | 0.00% | 100.00% | 0.00% | 0.00% | Soil Factor |
| 33 | Wilkin | 90.00% | 10.00% | 0.00% | 98.00% | 2.00% | 0.00% | R-value, Soil Factor |
| 34 | Winona | 90%<br>R=15-25 | 0.00% | 10%<br>*R >50* | 85.00% | 15.00% | 0.00% | R-value - 1998 |

| No | County | Traffic | Traffic provider | Performance evaluation |
|---|---|---|---|---|
| 1 | Aitkin | ESAL | MnDOT | - |
| 2 | Anoka | ESAL, ADT | ADT count by agency | Ride, Condition Survey |
| 3 | Benton | ESAL | MnDOT | Condition Survey |
| 4 | Blue Earth | ADT | MnDOT | Ride, Condition Survey and Deflection Test |
| 5 | Brown | ESAL | MnDOT | Ride, Condition Survey and Deflection Test |
| 6 | Cass | ESAL, ADT | MnDOT | Ride, Condition Survey |
| 7 | Chippewa | HCADT, ESAL, ADT | Mn/DOT, other | Condition Survey and Deflection Test |
| 8 | Chisago | ESAL, ADT, max. load | MnDOT, ADT count by agency | Ride, Condition Survey |
| 9 | Clay | HCADT, ESAL, ADT | MnDOT | Ride, Condition Survey and Deflection Test |

| No | County | Traffic | Traffic provider | Performance evaluation |
|---|---|---|---|---|
| 10 | Dakota | HCADT, ESAL, ADT | ADT count by agency<br>Classification count by agency | Ride, Condition Survey and Deflection Test |
| 11 | Douglas | HCADT, ESAL | MnDOT, Roadway Classification | Condition Survey and Deflection Test |
| 12 | Freeborn | HCADT, ADT | MnDOT | Ride, Condition Survey |
| 13 | Grant | HCADT, ADT | MnDOT, Roadway Classification | Ride, Condition Survey |
| 14 | Kittson | HCADT | MnDOT | Condition Survey and Deflection Test |
| 15 | Lac qui Parle | ADT | MnDOT | Condition Survey |
| 16 | Lake of the Woods | ADT | MnDOT | - |
| 17 | Lyon | HCADT, ADT | MnDOT | Condition Survey and Deflection Test |
| 18 | Marshall | ADT | MnDOT | Ride, Condition Survey and Deflection Test |
| 19 | Mcleod | ESAL - for 10 tons<br>ADT - for other types of roads | MnDOT | Condition Survey |
| 20 | Meeker | HCADT, ADT | MnDOT | Condition Survey |

| No | County | Traffic | Traffic provider | Performance evaluation |
|---|---|---|---|---|
| 21 | Mille Lacs | ESAL | MnDOT | Ride, Condition Survey |
| 22 | Morrison | HCADT (90%), ESAL (10%) | MnDOT | Condition Survey |
| 23 | Murray | ADT | MnDOT | Condition Survey |
| 24 | Nicollet | ESAL | MnDOT | Ride, Condition Survey |
| 25 | Nobles | ESAL | ADT count by agency | Ride, Condition Survey and Deflection Test |
| 26 | Pipestone | HCADT, ADT | MnDOT (95%)<br>count by agency, road classification | Ride, Condition Survey and Deflection Test |
| 27 | Polk | ADT | MnDOT | Ride, Condition Survey and Deflection Test |
| 28 | Ramsey | HCADT, ESAL | ADT count by agency<br>Classification count by agency | Ride, Condition Survey and Deflection Test |
| 29 | Sherburne | HCADT, ESAL | MnDOT, ADT count by agency | Condition Survey |
| 30 | Steele | HCADT, ESAL, ADT | MnDOT | Condition Survey |

| No | County | Traffic | Traffic provider | Performance evaluation |
|---|---|---|---|---|
| 31 | Stevens | ESAL - for 10 tons<br>ESAL, HCADT, ADT, max load - for the other roads | MnDOT | Ride, Condition Survey and Deflection for upgrading restriction |
| 32 | Waseca | ADT | MnDOT | Condition Survey |
| 33 | Wilkin | HCADT, ESAL, ADT | MnDOT, ADT count by agency | Condition Survey |
| 34 | Winona | ESAL | MnDOT | Ride, Condition Survey |

| No | County | Main Pavement Distress | Rehabilitation Maintenance |
|---|---|---|---|
| 1 | Aitkin | Thermal cracking | Crack sealing, mill and overlay, reclaim, or overlay, depending on the situation |
| 2 | Anoka | Cracking: linear, alligator | Reclaim / overlay for rural routes - reduces reflective crackin<br>Mill / overlay for urban routes - reduces reflective cracking and does not requir |
| 3 | Benton | Cracking & rutting. | Paver laid bituminous patches. |
| 4 | Blue Earth | Cracking | Crack seal – water<br>Seal coat – ravel and fine cracks<br>Bit patches – rutting and isolated structural problems<br>Overlay – all of above and restore rid |
| 5 | Brown | Cracking | If not too bad—overlay, crackseal within couple of years, sealcoat within 6 years. If bad condition—CIR w/overlay, crackseal within a few years, sealcoat within 6 years |
| 6 | Cass | Transverse cracking | Crack filling & Sealing. Try to prevent the cracks from becoming larger. |
| 7 | Chippewa | Transverse and longitudinal cracking | Route and seal, blast and seal, and seal coating |
| 8 | Chisago | Transverse cracking, potholes | Crack sealing for the transverse cracking because it extends the life of the road and it's relatively inexpensive.Potholes are filled with cold mix to extend the life of the road and it's cheaper then rebuilding the road. |
| 9 | Clay | Cracking, rutting, and rough joints | Cracking – route and seal, low modules rubberized asphalt.<br>Rutting – fill with fine bituminous mix, works ok but appearance not good.<br>Rough Joints – fill with fine bituminous mix, works well. |

| No | County | Main Pavement Distress | Rehabilitation Maintenance |
|---|---|---|---|
| 10 | Dakota | Rutting, (thermal) transverse cracking | Cracks repair with bituminous overlay; Mill and overlay |
| 11 | Douglas | Transverse cracking | Route and Seal, Overlay |
| 12 | Freeborn | Insufficient cross section to meet structural capacity | no information |
| 13 | Grant | no information | Patch, Sealcoat and Overlay |
| 14 | Kittson | Heavy loads, weather, frost action | Bituminous overlay |
| 15 | Lac qui Parle | Overloaded trucks and trailers | Bituminous overlay - most practical and convenient |
| 16 | Lake of the Woods | Rutting | Overlay - Roads had already required overlays to upgrade to 9ton. |
| 17 | Lyon | Old age, beyond service life, alligator cracking, subbase failure | Sealcoat, Overlays, Crack sealing |
| 18 | Marshall | Thermal cracking, Oxidation | Bituminous overlay - cost effectiveness |
| 19 | Mcleod | Age deterioration, random cracking | Crack filler, seal coat, overlay |
| 20 | Meeker | Overweight vehicles | Overlays and patching |

| No | County | Main Pavement Distress | Rehabilitation Maintenance |
| --- | --- | --- | --- |
| 21 | Mille Lacs | Rutting do to heavy loads (no enforcement) | May over lay road<br>May fill cups at joints |
| 22 | Morrison | Reflective cracks | Overlay, cost to cure is economical |
| 23 | Murray | Age, distress cracking, surface raveling | Overlays when possible.- Regrading when required by condition and in-ability t continue overlays becaus |
| 24 | Nicollet | Overloading and pavement age. | -- |
| 25 | Nobles | Cracking in outside wheel path due to heavy loading | Bituminous overlay if less than 50 years old.<br>Reconstruction of roadway if over 50 years old and funding permits. |
| 26 | Pipestone | Structural | Overlay. Adds strength while improving ride. |
| 27 | Polk | Cracking, overweight vehicles | Chip Seal / Crack Seal |
| 28 | Ramsey | Thermal cracking | We start with crack sealing to try to prevent the cracks from widening and deepening. As the pavement ages we consider a mill and overlay or a cold in place recycle project. In rare case, we seal coat to glue the road together for a few years until a re |
| 29 | Sherburne | Severe alligator cracking stemming from poor subgrade material | Cold inplace patching and Paving - the least expensive |
| 30 | Steele | Cracking | Praventive maintenace progran<br>Route/Seal Cracks, Older pavemnets - overla |

| No | County | Main Pavement Distress | Rehabilitation Maintenance |
|---|---|---|---|
| 31 | Stevens | Truck loads in spring planting and fall harvest | It depends on the condition. Mostly 3" overlay. Possibly mill and overlay or remove and replace. We may do some tiling in wet or frost boil areas. |
| 32 | Waseca | Old age | Cold inplace recycling with HMA overla<br>More economical than Rebuild & New Surface. |
| 33 | Wilkin | Cracking | Route/Seal Cracks- most effective and cheapest |
| 34 | Winona | Thermal cracking | Route and seal, most cost effective |

## Mileage from MNDot Transportation Information Sysystem - data provided by State Aid

### County Roads (design tonnage)

| No | County | Length of the county paved network (miles) | | | | | | Length of the county gravel network (miles) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10-ton | 9-ton | 7-ton | 5-ton | Others | County total | 10-ton | 9-ton | 7-ton | 5-ton | Others | County total |
| 1 | AITKIN | 0.00 | 6.50 | 8.50 | 1.00 | 0.00 | 16.00 | 0.00 | 0.00 | 0.00 | 117.00 | 0.00 | 117.00 |
| 2 | ANOKA | 0.00 | 5.03 | 26.43 | 87.68 | 16.16 | 135.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | BECKER | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 161.18 | 0.00 | 161.18 |
| 4 | BELTRAMI | 1.20 | 2.30 | 2.00 | 5.00 | 0.00 | 10.50 | 0.00 | 0.00 | 0.00 | 236.50 | 0.00 | 236.50 |
| 5 | BENTON | 0.00 | 8.00 | 75.00 | 42.00 | 0.00 | 125.00 | 0.00 | 0.00 | 0.00 | 125.00 | 0.00 | 125.00 |
| 6 | BIG STONE | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 | 190.00 | 0.00 | 190.00 |
| 7 | BLUE EARTH | 0.00 | 0.00 | 34.00 | 13.00 | 0.00 | 47.00 | 0.00 | 0.00 | 0.00 | 260.00 | 0.00 | 260.00 |
| 8 | BROWN | 0.00 | 0.00 | 3.00 | 0.00 | 0.00 | 3.00 | 0.00 | 0.00 | 0.00 | 14.00 | 0.00 | 14.00 |
| 9 | CARLTON | 0.00 | 2.00 | 23.00 | 32.00 | 0.00 | 57.00 | 0.00 | 0.00 | 0.00 | 160.00 | 0.00 | 160.00 |
| 10 | CARVER | 0.00 | 51.50 | 2.00 | 0.00 | 0.00 | 53.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 11 | CASS | 0.00 | 15.45 | 10.83 | 11.37 | 13.38 | 51.03 | 0.00 | 0.00 | 0.00 | 265.46 | 5.25 | 270.71 |
| 12 | CHIPPEWA | 0.00 | 0.00 | 1.40 | 6.00 | 0.00 | 7.40 | 0.00 | 0.00 | 0.00 | 47.60 | 0.00 | 47.60 |
| 13 | CHISAGO | 0.00 | 6.40 | 33.46 | 11.23 | 0.00 | 51.09 | 0.00 | 0.00 | 0.00 | 63.60 | 0.00 | 63.60 |
| 14 | CLAY | 0.00 | 4.30 | 18.72 | 1.36 | 0.00 | 24.38 | 0.00 | 1.00 | 0.00 | 320.00 | 0.00 | 321.00 |
| 15 | CLEARWATER | 0.00 | 0.00 | 7.00 | 6.00 | 0.00 | 13.00 | 0.00 | 0.00 | 0.00 | 96.50 | 0.00 | 96.50 |
| 16 | COOK | 0.00 | 0.00 | 2.00 | 10.00 | 0.00 | 12.00 | 0.00 | 0.00 | 0.00 | 111.00 | 0.00 | 111.00 |
| 17 | D | 0.00 | 1.00 | 1.00 | 14.00 | 0.00 | 16.00 | 0.00 | 0.00 | 0.00 | 74.00 | 0.00 | 74.00 |
| 18 | CROW WING | 6.15 | 0.15 | 45.99 | 115.35 | 0.00 | 167.64 | 0.00 | 0.00 | 0.00 | 59.55 | 0.00 | 59.55 |
| 19 | DAKOTA | 0.00 | 30.00 | 3.00 | 10.00 | 0.00 | 43.00 | 0.00 | 0.00 | 0.00 | 69.00 | 0.00 | 69.00 |
| 20 | DODGE | 0.00 | 0.00 | 0.00 | 0.00 | 17.53 | 17.53 | 0.00 | 0.00 | 0.00 | 0.00 | 51.67 | 51.67 |
| 21 | DOUGLAS | 0.00 | 0.00 | 29.50 | 22.94 | 0.00 | 52.44 | 0.00 | 0.00 | 0.00 | 107.70 | 0.00 | 107.70 |
| 22 | FARIBAULT | 0.00 | 0.00 | 3.40 | 0.00 | 0.00 | 3.40 | 0.00 | 0.00 | 0.00 | 99.86 | 0.00 | 99.86 |
| 23 | FILLMORE | 0.00 | 0.00 | 6.29 | 0.00 | 0.00 | 6.29 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 24 | FREEBORN | 0.00 | 0.00 | 15.30 | 0.00 | 0.00 | 15.30 | 0.00 | 0.00 | 0.00 | 168.00 | 0.00 | 168.00 |
| 25 | GOODHUE | 0.00 | 6.90 | 13.30 | 0.00 | 0.00 | 20.20 | 0.00 | 0.00 | 0.00 | 0.00 | 54.00 | 54.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | GRANT | 0.00 | 0.00 | 0.60 | 0.00 | 0.00 | 0.60 | 0.00 | 0.00 | 0.00 | 228.80 | 0.00 | 228.80 |
| 27 | HENNEPIN | 0.00 | 37.32 | 0.00 | 0.00 | 0.00 | 37.32 | 0.00 | 6.46 | 0.00 | 0.00 | 0.00 | 6.46 |
| 28 | HOUSTON | 0.00 | 0.50 | 7.80 | 0.00 | 0.00 | 8.30 | 0.00 | 0.00 | 0.00 | 0.00 | 5.10 | 5.10 |
| 29 | HUBBARD | 0.00 | 0.00 | 13.31 | 19.82 | 0.00 | 33.13 | 0.00 | 0.00 | 0.00 | 0.00 | 165.16 | 165.16 |
| 30 | ISANTI | 0.00 | 0.00 | 109.00 | 18.20 | 0.00 | 127.20 | 0.00 | 0.00 | 0.00 | 4.40 | 0.00 | 4.40 |
| 31 | ITASCA | 0.00 | 0.00 | 2.00 | 109.00 | 0.00 | 111.00 | 0.00 | 0.00 | 0.00 | 564.00 | 0.00 | 564.00 |
| 32 | JACKSON | 0.00 | 1.00 | 14.03 | 3.50 | 0.00 | 18.53 | 0.00 | 0.00 | 0.00 | 130.35 | 0.00 | 130.35 |
| 33 | KANABEC | 0.00 | 0.00 | 30.00 | 0.00 | 0.00 | 30.00 | 0.00 | 0.00 | 0.00 | 180.00 | 0.00 | 180.00 |
| 34 | KANDIYOHI | 3.15 | 2.50 | 12.50 | 10.00 | 3.10 | 31.25 | 0.00 | 0.00 | 57.30 | 134.50 | 0.00 | 191.80 |
| 35 | KITTSON | 0.00 | 0.00 | 0.14 | 0.00 | 0.00 | 0.14 | 0.00 | 0.00 | 0.00 | 93.52 | 0.00 | 93.52 |
| 36 | G | 0.00 | 1.70 | 6.45 | 36.20 | 0.00 | 44.35 | 0.00 | 0.00 | 0.00 | 0.00 | 133.70 | 133.70 |
| 37 | PARLE | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 137.80 | 0.00 | 137.80 |
| 38 | LAKE | 1.68 | 7.90 | 0.00 | 32.17 | 0.00 | 41.75 | 0.00 | 1.67 | 0.00 | 55.14 | 0.00 | 56.81 |
| 39 | LAKE/WOODS | 0.00 | 0.00 | 0.14 | 0.00 | 0.00 | 0.14 | 0.00 | 0.00 | 0.00 | 44.90 | 0.00 | 44.90 |
| 40 | LE SUEUR | 0.00 | 0.00 | 49.00 | 4.50 | 0.00 | 53.50 | 0.00 | 0.00 | 0.00 | 188.00 | 0.00 | 188.00 |
| 41 | LINCOLN | 0.00 | 0.00 | 0.00 | 4.00 | 6.75 | 10.75 | 0.00 | 0.00 | 0.00 | 119.00 | 0.00 | 119.00 |
| 42 | LYON | 1.00 | 0.00 | 7.00 | 34.95 | 0.00 | 42.95 | 0.00 | 0.00 | 0.00 | 126.30 | 0.00 | 126.30 |
| 43 | MC LEOD | 0.00 | 4.80 | 22.30 | 18.60 | 0.00 | 45.70 | 0.00 | 0.00 | 0.00 | 96.70 | 0.00 | 96.70 |
| 44 | MAHNOMEN | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 84.50 | 0.00 | 84.50 |
| 45 | MARSHALL | 0.00 | 0.00 | 3.00 | 1.50 | 0.00 | 4.50 | 0.00 | 0.00 | 0.00 | 190.00 | 0.00 | 190.00 |
| 46 | MARTIN | 0.00 | 6.00 | 0.00 | 0.00 | 0.00 | 6.00 | 0.00 | 0.00 | 0.00 | 126.00 | 0.00 | 126.00 |
| 47 | MEEKER | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 48 | MILLE LACS | 0.00 | 3.00 | 3.00 | 20.00 | 0.00 | 26.00 | 0.00 | 0.00 | 0.00 | 125.00 | 0.00 | 125.00 |
| 49 | MORRISON | 0.00 | 208.00 | 11.00 | 6.00 | 0.00 | 225.00 | 0.00 | 54.00 | 0.00 | 0.00 | 0.00 | 54.00 |
| 50 | MOWER | 0.00 | 5.50 | 6.00 | 0.00 | 8.00 | 19.50 | 0.00 | 0.00 | 0.00 | 7.50 | 0.00 | 7.50 |
| 51 | MURRAY | 0.00 | 0.00 | 1.90 | 0.00 | 0.00 | 1.90 | 0.00 | 0.00 | 0.00 | 0.00 | 66.70 | 66.70 |
| 52 | NICOLLET | 0.00 | 0.00 | 0.00 | 6.00 | 0.00 | 6.00 | 0.00 | 0.00 | 0.00 | 53.00 | 0.00 | 53.00 |
| 53 | NOBLES | 0.00 | 13.70 | 5.43 | 0.00 | 0.00 | 19.13 | 0.00 | 3.00 | 0.00 | 72.20 | 0.00 | 75.20 |
| 54 | NORMAN | 0.00 | 0.00 | 2.30 | 17.00 | 0.00 | 19.30 | 0.00 | 0.00 | 0.00 | 279.40 | 0.00 | 279.40 |
| 55 | OLMSTED | 2.40 | 18.90 | 26.70 | 0.00 | 19.00 | 67.00 | 0.00 | 0.00 | 0.00 | 0.00 | 148.00 | 148.00 |
| 56 | OTTER TAIL | 0.00 | 8.14 | 102.64 | 21.13 | 3.53 | 135.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 57 | PENNINGTON | 0.00 | 0.00 | 3.50 | 0.00 | 0.00 | 3.50 | 0.00 | 0.00 | 0.00 | 390.00 | 0.00 | 390.00 |
| 58 | PINE | 0.00 | 0.00 | 29.41 | 0.80 | 0.00 | 30.21 | 0.00 | 0.00 | 0.00 | 0.00 | 189.33 | 189.33 |
| 59 | PIPESTONE | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 4.00 | 0.00 | 4.00 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60 | POLK | 0.00 | 5.72 | 10.20 | 0.00 | 0.00 | 15.92 | 0.00 | 0.00 | 0.00 | 137.21 | 0.00 | 137.21 |
| 61 | POPE | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 71.00 | 0.00 | 71.00 |
| 62 | RAMSEY | 0.00 | 25.31 | 3.14 | 1.28 | 0.00 | 29.73 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 63 | RED LAKE | 0.00 | 0.00 | 0.00 | 3.50 | 0.00 | 3.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 64 | REDWOOD | 2.75 | 0.00 | 0.00 | 2.25 | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 | 117.00 | 0.00 | 117.00 |
| 65 | RENVILLE | 0.00 | 0.00 | 0.00 | 6.00 | 0.00 | 6.00 | 0.00 | 0.00 | 0.00 | 260.00 | 0.00 | 260.00 |
| 66 | RICE | 0.00 | 9.16 | 63.54 | 0.00 | 0.00 | 72.70 | 0.00 | 0.00 | 0.00 | 76.19 | 0.00 | 76.19 |
| 67 | ROCK | 0.00 | 0.00 | 1.80 | 0.00 | 0.00 | 1.80 | 0.00 | 0.00 | 0.00 | 55.30 | 0.00 | 55.30 |
| 68 | ROSEAU | 0.00 | 0.50 | 2.00 | 0.00 | 0.00 | 2.50 | 0.00 | 0.00 | 0.00 | 252.00 | 0.00 | 252.00 |
| 69 | ST. LOUIS | 0.00 | 18.00 | 5.00 | 275.00 | 18.00 | 316.00 | 0.00 | 2.00 | 0.00 | 1,246.00 | 0.00 | 1,248.00 |
| 70 | SCOTT | 0.00 | 79.90 | 7.20 | 0.00 | 0.00 | 87.10 | 0.00 | 4.00 | 24.00 | 2.00 | 0.00 | 30.00 |
| 71 | SHERBURNE | 0.50 | 12.10 | 179.90 | 0.00 | 0.00 | 192.50 | 0.00 | 0.00 | 0.00 | 5.60 | 0.00 | 5.60 |
| 72 | SIBLEY | 0.00 | 0.00 | 0.00 | 16.94 | 0.00 | 16.94 | 0.00 | 0.00 | 0.00 | 80.52 | 0.00 | 80.52 |
| 73 | STEARNS | 3.65 | 112.69 | 126.77 | 26.91 | 0.00 | 270.02 | 0.00 | 0.00 | 0.00 | 57.70 | 0.00 | 57.70 |
| 74 | STEELE | 1.00 | 10.00 | 14.75 | 0.00 | 0.00 | 25.75 | 0.00 | 0.00 | 0.00 | 11.50 | 0.00 | 11.50 |
| 75 | STEVENS | 0.00 | 0.00 | 0.00 | 5.00 | 0.00 | 5.00 | 0.00 | 0.00 | 0.00 | 124.00 | 0.00 | 124.00 |
| 76 | SWIFT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 77 | TODD | 0.65 | 4.20 | 82.94 | 11.35 | 0.00 | 99.14 | 0.00 | 0.10 | 0.96 | 101.94 | 0.00 | 103.00 |
| 78 | TRAVERSE | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 237.00 | 0.00 | 237.00 |
| 79 | WABASHA | 0.00 | 0.00 | 10.36 | 0.00 | 14.09 | 24.45 | 0.00 | 0.00 | 3.79 | 0.00 | 66.63 | 70.42 |
| 80 | WADENA | 0.00 | 2.60 | 0.00 | 42.90 | 0.00 | 45.50 | 0.00 | 0.00 | 0.00 | 221.70 | 0.00 | 221.70 |
| 81 | WASECA | 0.00 | 3.00 | 39.00 | 0.00 | 0.00 | 42.00 | 0.00 | 0.00 | 0.00 | 87.00 | 0.00 | 87.00 |
| 82 | WASHINGTON | 0.00 | 15.00 | 26.00 | 15.00 | 0.00 | 56.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 83 | WATONWAN | 0.00 | 0.00 | 0.00 | 16.00 | 0.00 | 16.00 | 0.00 | 0.00 | 0.00 | 102.25 | 0.00 | 102.25 |
| 84 | WILKIN | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 213.10 | 0.00 | 213.10 |
| 85 | WINONA | 0.00 | 26.00 | 28.20 | 0.70 | 0.00 | 54.90 | 0.00 | 0.00 | 12.10 | 3.40 | 0.00 | 15.50 |
| 86 | WRIGHT | 0.00 | 4.00 | 35.60 | 73.00 | 1.20 | 113.80 | 0.00 | 0.00 | | 0.00 | 0.00 | 0.00 |
| 87 | YELLOW MEDICINE | 0.00 | 0.00 | 0.00 | 0.30 | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 164.90 | 0.00 | 164.90 |

## County State Aid Highway

| No | County | Length of the CSAH paved network (miles) | | | | | | Length of the CSAH gravel network (miles) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10-ton | 9-ton | 7-ton | 5-ton | Others | County total | 10-ton | 9-ton | 7-ton | 5-ton | Others | County total |
| 1 | AITKIN | 0.00 | 170.00 | 22.00 | 0.00 | 0.00 | 192.00 | 0.00 | 0.00 | 0.00 | 173.00 | 0.00 | 173.00 |
| 2 | ANOKA | 41.44 | 188.64 | 50.88 | 6.07 | 0.00 | 287.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | BECKER | 2.50 | 261.15 | 87.10 | 38.89 | 0.00 | 389.64 | 0.00 | 0.00 | 0.00 | 65.90 | 0.00 | 65.90 |
| 4 | BELTRAMI | 1.50 | 184.00 | 175.00 | 1.70 | 0.00 | 362.20 | 0.00 | 0.00 | 0.00 | 98.00 | 0.00 | 98.00 |
| 5 | BENTON | 5.00 | 90.00 | 75.00 | 80.00 | 0.00 | 250.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | BIG STONE | 0.00 | 116.00 | 24.00 | 0.00 | 0.00 | 140.00 | 0.00 | 0.00 | 0.00 | 57.00 | 0.00 | 57.00 |
| 7 | BLUE EARTH | 24.00 | 115.00 | 261.00 | 11.00 | 0.00 | 411.00 | 0.00 | 0.00 | 0.00 | 12.00 | 0.00 | 12.00 |
| 8 | BROWN | 33.00 | 36.00 | 194.00 | 5.00 | 0.00 | 268.00 | 0.00 | 0.00 | 0.00 | 39.00 | 0.00 | 39.00 |
| 9 | CARLTON | 38.00 | 80.00 | 76.00 | 19.00 | 0.00 | 213.00 | 0.00 | 0.00 | 0.00 | 58.00 | 0.00 | 58.00 |
| 10 | CARVER | 0.00 | 214.50 | 0.00 | 0.00 | 0.00 | 214.50 | 1.00 | 0.00 | 0.00 | 0.00 | 1.00 | 2.00 |
| 11 | CASS | 0.00 | 241.79 | 119.66 | 0.00 | 18.60 | 380.05 | 0.00 | 0.00 | 1.30 | 145.60 | 0.00 | 146.90 |
| 12 | CHIPPEWA | 2.50 | 20.40 | 137.60 | 5.40 | 0.00 | 165.90 | 0.00 | 0.00 | 0.00 | 71.00 | 0.00 | 71.00 |
| 13 | CHISAGO | 10.95 | 45.40 | 109.20 | 31.65 | 0.00 | 197.20 | 0.00 | 0.00 | 0.00 | 16.30 | 0.00 | 16.30 |
| 14 | CLAY | 21.20 | 139.00 | 49.00 | 31.00 | 14.00 | 254.20 | 0.00 | 0.00 | 0.00 | 145.00 | 0.00 | 145.00 |
| 15 | CLEARWATER | 0.00 | 77.00 | 162.00 | 3.00 | 0.00 | 242.00 | 0.00 | 0.00 | 0.00 | 74.00 | 0.00 | 74.00 |
| 16 | COOK | 10.00 | 8.00 | 78.00 | 0.00 | 0.00 | 96.00 | 0.00 | 0.00 | 0.00 | 65.00 | 5.00 | 70.00 |
| 17 | D | 92.00 | 5.00 | 50.00 | 32.00 | 46.00 | 225.00 | 0.00 | 0.00 | 0.00 | 82.00 | 0.00 | 82.00 |
| 18 | CROW WING | 17.78 | 192.01 | 100.05 | 52.94 | 0.00 | 362.78 | 0.00 | 0.00 | 0.00 | 15.38 | 0.00 | 15.38 |
| 19 | DAKOTA | 0.15 | 254.00 | 51.00 | 4.00 | 0.00 | 309.15 | 0.00 | 0.00 | 0.00 | 11.00 | 0.00 | 11.00 |
| 20 | DODGE | 4.50 | 98.50 | 80.50 | 0.00 | 25.21 | 208.71 | 0.00 | 0.00 | 0.00 | 49.30 | 0.00 | 49.30 |
| 21 | DOUGLAS | 29.70 | 64.30 | 216.99 | 3.40 | 0.00 | 314.39 | 0.00 | 0.00 | 0.00 | 50.50 | 0.00 | 50.50 |
| 22 | FARIBAULT | 0.00 | 125.80 | 121.50 | 8.00 | 0.00 | 255.30 | 0.00 | 0.00 | 0.00 | 68.40 | 0.00 | 68.40 |
| 23 | FILLMORE | 19.30 | 131.13 | 84.58 | 0.00 | 0.00 | 235.01 | 0.00 | 0.00 | 80.23 | 0.00 | 0.00 | 80.23 |
| 24 | FREEBORN | 3.60 | 84.80 | 259.50 | 8.40 | 11.00 | 367.30 | 0.00 | 0.00 | 0.00 | 54.90 | 0.00 | 54.90 |
| 25 | GOODHUE | 8.20 | 118.20 | 168.80 | 0.00 | 0.00 | 295.20 | 0.00 | 0.00 | 0.00 | 0.00 | 11.70 | 11.70 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | GRANT | 0.00 | 20.00 | 120.80 | 0.00 | 0.00 | 140.80 | 0.00 | 0.00 | 0.00 | 74.50 | 0.00 | 74.50 |
| 27 | HENNEPIN | 30.26 | 486.95 | 0.00 | 0.00 | 22.74 | 539.95 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 28 | HOUSTON | 0.00 | 47.90 | 44.30 | 0.00 | 87.30 | 179.50 | 0.00 | 0.00 | 2.80 | 0.00 | 57.90 | 60.70 |
| 29 | HUBBARD | 32.50 | 58.26 | 113.84 | 44.18 | 0.00 | 248.78 | 0.00 | 0.00 | 0.00 | 0.00 | 75.34 | 75.34 |
| 30 | ISANTI | 0.00 | 46.00 | 161.75 | 8.25 | 0.00 | 216.00 | 0.00 | 0.00 | 0.00 | 7.25 | 0.00 | 7.25 |
| 31 | ITASCA | 0.00 | 64.00 | 226.00 | 163.00 | 0.00 | 453.00 | 0.00 | 0.00 | 0.00 | 198.00 | 0.00 | 198.00 |
| 32 | JACKSON | 0.00 | 84.60 | 275.09 | 0.00 | 0.00 | 359.69 | 0.00 | 0.00 | 0.00 | 11.70 | 0.00 | 11.70 |
| 33 | KANABEC | 0.00 | 50.00 | 130.00 | 0.00 | 0.00 | 180.00 | 0.00 | 0.00 | 0.00 | 25.00 | 0.00 | 25.00 |
| 34 | KANDIYOHI | 9.00 | 217.00 | 113.90 | 4.00 | 36.00 | 379.90 | 0.00 | 0.00 | 11.50 | 13.00 | 0.00 | 24.50 |
| 35 | KITTSON | 0.00 | 116.00 | 103.28 | 0.00 | 0.00 | 219.28 | 0.00 | 0.00 | 0.00 | 140.80 | 0.00 | 140.80 |
| 36 | G | 0.00 | 119.55 | 94.11 | 33.01 | 0.00 | 246.67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 37 | PARLE | 7.70 | 26.80 | 172.10 | 0.00 | 0.00 | 206.60 | 0.00 | 0.00 | 0.00 | 146.70 | 0.00 | 146.70 |
| 38 | LAKE | 37.99 | 78.14 | 28.10 | 0.75 | 0.00 | 144.98 | 0.00 | 0.00 | 1.00 | 62.55 | 0.00 | 63.55 |
| 39 | LAKE/WOODS | 0.00 | 128.60 | 2.00 | 0.00 | 0.00 | 130.60 | 0.00 | 0.00 | 0.00 | 58.50 | 0.00 | 58.50 |
| 40 | LE SUEUR | 6.10 | 15.25 | 188.95 | 0.00 | 0.00 | 210.30 | 0.00 | 0.00 | 0.00 | 20.20 | 0.00 | 20.20 |
| 41 | LINCOLN | 9.75 | 46.50 | 148.75 | 0.00 | 0.00 | 205.00 | 0.00 | 0.00 | 0.00 | 32.50 | 0.00 | 32.50 |
| 42 | LYON | 6.50 | 135.50 | 112.00 | 1.00 | 0.00 | 255.00 | 0.00 | 0.00 | 0.00 | 42.40 | 0.00 | 42.40 |
| 43 | MC LEOD | 16.40 | 158.70 | 64.80 | 9.90 | 0.00 | 249.80 | 0.00 | 0.00 | 0.00 | 6.40 | 0.00 | 6.40 |
| 44 | MAHNOMEN | 0.00 | 19.00 | 100.00 | 0.00 | 0.00 | 119.00 | 0.00 | 0.00 | 0.00 | 69.00 | 0.00 | 69.00 |
| 45 | MARSHALL | 10.00 | 210.00 | 110.00 | 0.00 | 0.00 | 330.00 | 0.00 | 0.00 | 0.00 | 300.00 | 0.00 | 300.00 |
| 46 | MARTIN | 2.00 | 206.00 | 17.00 | 28.00 | 0.00 | 253.00 | 0.00 | 0.00 | 0.00 | 114.00 | 0.00 | 114.00 |
| 47 | MEEKER | 0.00 | 67.60 | 155.60 | 22.40 | 0.00 | 245.60 | 0.00 | 0.00 | 0.00 | 26.20 | 0.00 | 26.20 |
| 48 | MILLE LACS | 5.00 | 150.00 | 49.00 | 0.00 | 0.00 | 204.00 | 0.00 | 0.00 | 0.00 | 37.00 | 0.00 | 37.00 |
| 49 | MORRISON | 0.00 | 413.00 | 10.00 | 0.00 | 0.00 | 423.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 50 | MOWER | 13.50 | 130.50 | 64.00 | 0.00 | 51.50 | 259.50 | 0.00 | 0.00 | 0.00 | 26.00 | 0.00 | 26.00 |
| 51 | MURRAY | 0.00 | 96.50 | 190.50 | 0.00 | 0.00 | 287.00 | 0.00 | 0.00 | 0.00 | 68.60 | 0.00 | 68.60 |
| 52 | NICOLLET | 206.00 | 75.00 | 32.00 | 78.00 | 21.00 | 412.00 | 0.00 | 0.00 | 33.00 | 33.00 | 0.00 | 66.00 |
| 53 | NOBLES | 17.63 | 310.72 | 0.00 | 0.00 | 0.00 | 328.35 | 0.00 | 0.00 | 0.00 | 2.26 | 0.00 | 2.26 |
| 54 | NORMAN | 36.50 | 96.50 | 99.25 | 26.50 | 3.25 | 262.00 | 0.00 | 0.00 | 0.00 | 125.00 | 0.00 | 125.00 |
| 55 | OLMSTED | 35.50 | 89.80 | 160.00 | 0.00 | 14.00 | 299.30 | 0.00 | 0.00 | 0.00 | 0.00 | 3.30 | 3.30 |
| 56 | OTTER TAIL | 16.94 | 146.25 | 671.64 | 0.00 | 42.40 | 877.23 | 0.00 | 0.00 | 0.00 | 4.20 | 0.00 | 4.20 |
| 57 | PENNINGTON | 31.00 | 50.00 | 94.00 | 0.00 | 0.00 | 175.00 | 0.00 | 0.00 | 0.00 | 84.00 | 0.00 | 84.00 |
| 58 | PINE | 0.00 | 107.75 | 153.65 | 1.00 | 0.00 | 262.40 | 0.00 | 0.00 | 0.00 | 166.00 | 0.00 | 166.00 |
| 59 | PIPESTONE | 16.00 | 78.00 | 53.00 | 0.00 | 0.00 | 147.00 | 0.25 | 0.00 | 0.00 | 63.00 | 0.00 | 63.25 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 60 | POLK | 72.15 | 280.00 | 186.93 | 0.00 | 0.00 | 539.08 | 1.00 | 0.00 | 0.00 | 245.18 | 1.00 | 247.18 |
| 61 | POPE | 0.00 | 42.00 | 190.00 | 7.00 | 0.00 | 239.00 | 0.00 | 0.00 | 0.00 | 59.00 | 0.00 | 59.00 |
| 62 | RAMSEY | 26.39 | 247.09 | 0.00 | 0.00 | 0.00 | 273.48 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 63 | RED LAKE | 0.00 | 73.40 | 44.30 | 0.00 | 0.00 | 117.70 | none posted | | | | | 0.00 |
| 64 | REDWOOD | 174.00 | 13.00 | 106.00 | 19.00 | 0.00 | 312.00 | 0.00 | 0.00 | 0.00 | 62.00 | 0.00 | 62.00 |
| 65 | RENVILLE | 0.00 | 67.00 | 327.00 | 0.00 | 0.00 | 394.00 | 0.00 | 0.00 | 0.00 | 50.00 | 0.00 | 50.00 |
| 66 | RICE | 0.00 | 93.00 | 159.30 | 0.00 | 0.00 | 252.30 | 0.00 | 0.00 | 0.00 | 8.00 | 0.00 | 8.00 |
| 67 | ROCK | 29.00 | 102.00 | 69.50 | 0.00 | 0.00 | 200.50 | 0.00 | 0.00 | 0.00 | 53.90 | 0.00 | 53.90 |
| 68 | ROSEAU | 0.00 | 79.00 | 223.50 | 0.00 | 0.00 | 302.50 | 0.00 | 0.00 | 0.00 | 164.00 | 0.00 | 164.00 |
| 69 | ST. LOUIS | 24.00 | 459.00 | 45.00 | 476.00 | 72.00 | 1,076.00 | 0.00 | 0.00 | 0.00 | 282.00 | 0.00 | 282.00 |
| 70 | SCOTT | 9.50 | 189.20 | 11.20 | 0.00 | 0.00 | 209.90 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 71 | SHERBURNE | 4.20 | 134.80 | 73.20 | 0.00 | 0.00 | 212.20 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 2.00 |
| 72 | SIBLEY | 0.00 | 58.00 | 69.00 | 133.90 | 0.00 | 260.90 | 0.00 | 0.00 | 0.00 | 28.40 | 0.00 | 28.40 |
| 73 | STEARNS | 4.64 | 386.30 | 137.30 | 13.72 | 0.00 | 541.96 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 74 | STEELE | 7.00 | 55.00 | 183.00 | 0.00 | 0.00 | 245.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 75 | STEVENS | 0.00 | 54.00 | 91.00 | 3.00 | 0.00 | 148.00 | 0.00 | 0.00 | 0.00 | 88.00 | 0.00 | 88.00 |
| 76 | SWIFT | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 77 | TODD | 0.00 | 161.55 | 241.04 | 5.44 | 0.00 | 408.03 | 0.00 | 0.00 | 2.04 | 13.12 | 0.00 | 15.16 |
| 78 | TRAVERSE | 0.00 | 10.00 | 100.00 | 4.00 | 0.00 | 114.00 | 0.00 | 0.00 | 0.00 | 123.00 | 0.00 | 123.00 |
| 79 | WABASHA | 10.51 | 28.90 | 158.48 | 0.00 | 7.16 | 205.05 | 0.00 | 0.00 | 3.60 | 0.00 | 40.78 | 44.38 |
| 80 | WADENA | 15.50 | 103.50 | 72.50 | 4.50 | 0.00 | 196.00 | 0.00 | 0.00 | 0.00 | 16.50 | 0.00 | 16.50 |
| 81 | WASECA | 0.00 | 58.00 | 157.00 | 0.00 | 0.00 | 215.00 | 0.00 | 0.00 | 0.00 | 35.00 | 0.00 | 35.00 |
| 82 | WASHINGTON | 6.00 | 180.00 | 56.00 | 3.00 | 0.00 | 245.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 83 | WATONWAN | 122.25 | 38.50 | 30.00 | 0.00 | 0.00 | 190.75 | 0.00 | 0.00 | 0.00 | 28.00 | 0.00 | 28.00 |
| 84 | WILKIN | 10.10 | 139.42 | 42.90 | 0.00 | 0.00 | 192.42 | 0.00 | 0.00 | 0.00 | 113.86 | 0.00 | 113.86 |
| 85 | WINONA | 8.50 | 174.60 | 56.40 | 10.00 | 0.00 | 249.50 | 0.00 | 0.00 | 42.80 | 0.00 | 0.00 | 42.80 |
| 86 | WRIGHT | 31.00 | 171.00 | 149.00 | 57.60 | 0.00 | 408.60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 87 | YELLOW MEDICINE | 4.80 | 26.80 | 186.70 | 4.90 | 0.00 | 223.20 | 0.00 | 0.00 | 0.00 | 104.80 | 0.00 | 104.80 |

# Appendix C

# Mail-Out/Mail-Back Survey

Please complete:

Contact Name ________________________________
Name of Firm ________________________________
Street Address ________________________________
City, State, Zip ________________________________
Phone Number (____) ________________________
E-mail Address ________________________________
Date Completed _____________

1. How many trucks does your firm operate?

| <u>Truck Type</u> | <u>Total Number of Axles</u> | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Pickups/Light Duty Trucks | ____ | ____ | | | | | |
| Unibody Dock Truck | ____ | ____ | | | | | |
| Platform & Flatbed | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Dry Bulk (Hopper, dump, etc.) | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Liquid/Gas Tank | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Refrigerated Van | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Livestock Van | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Dry Van | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Grain Body | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Dump Truck | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Concrete Mixer | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Pole & Logging | ____ | ____ | ____ | ____ | ____ | ____ | ____ |
| Other, please specify__________ | ____ | ____ | ____ | ____ | ____ | ____ | ____ |

2. How many miles did your firm's trucks travel over the course of 2002?

   Total? __________, in Minnesota? __________

3. Please list general types of major commodities/products that your firm hauls.

   __________, __________, ___________, __________, __________

4. How many direct employees does your firm have? __________
5. How many of the direct employees are drivers? __________

6. How many drivers are contracted / leased by your firm? __________

7. Who chooses the routes traveled by the trucks? Please indicate choice by circling.

Management     Dispatcher     Driver     Other, please specify

8. Is your company assessed financial penalties by clients for missed/late delivery or pickup time?     Please check one.     ? Yes     ? No

9. How is driver's compensation determined? Please indicate choice by circling.

Load     Time     Miles     Other, please specify

10. Is driver compensation linked to on-time deliveries?     ? Yes     ? No

11. Do you change the rate you charge clients to account for the fluctuations in gas/diesel price?     ? Yes     ? No

12. What is your approximate cost of operating each truck per mile? __________

13. How many truck loads did your firm carry in the past year? ___________

14. Do spring load restrictions affect your firm, and if yes please answer in which ways you change your operations to conform to the seasonal restrictions?

- ? Shift the seasonal timing of shipments
- ? Reduce load size / weight per vehicle
- ? Increase the number of vehicles used
- ? Change the kind of vehicles used
- ? Change routes

Other, please specify _______________

15. Roughly, what is the percentage of miles that your firm's trucks spend on roads subject to spring load restrictions? __________

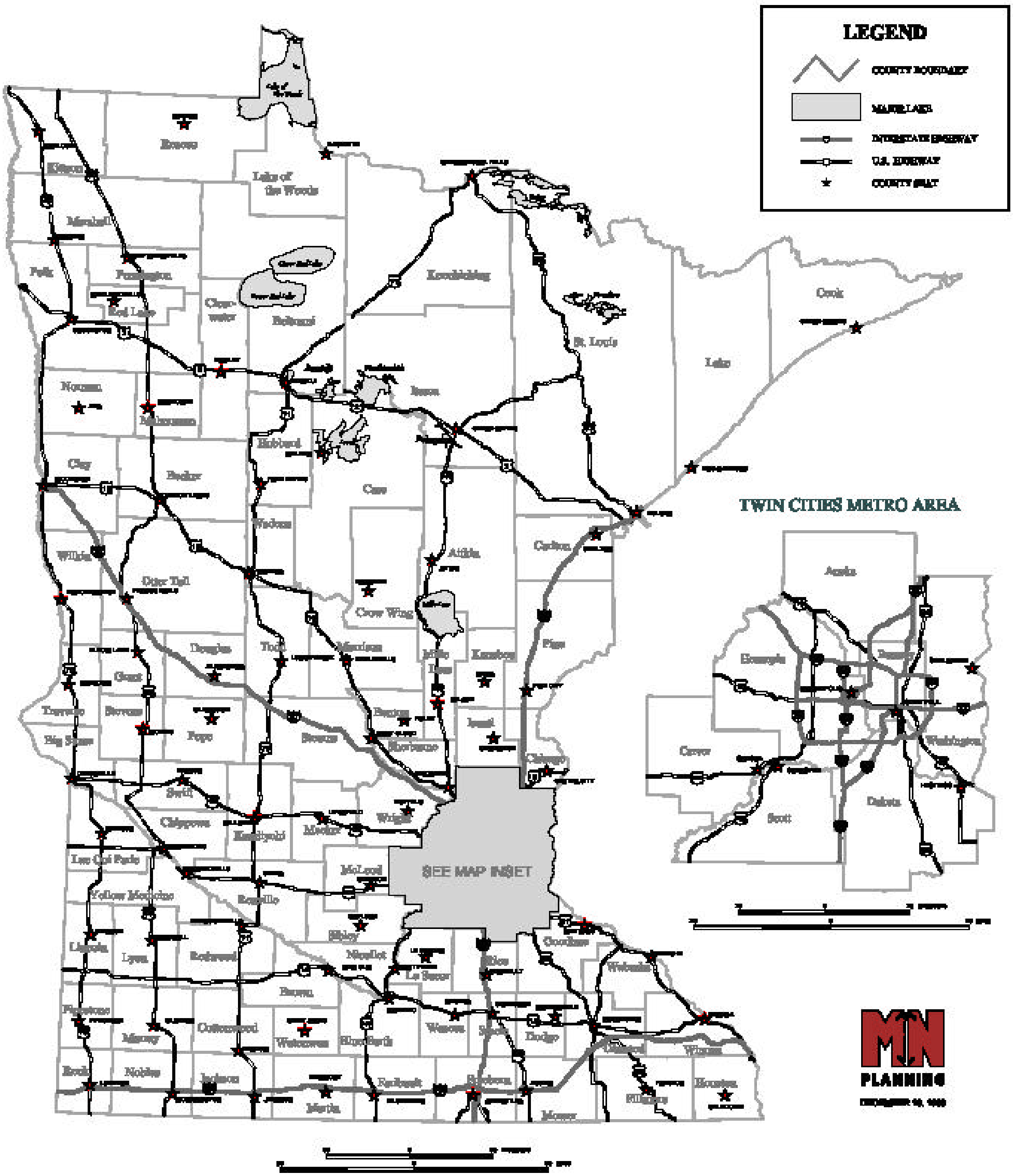
16. How many times were your firm's trucks cited last year for weight violations during the period of spring load restrictions? __________

17. Which road(s) are problematic for your firm during spring load restrictions (specific roads, and/or classifications, 5-ton, 7-ton, 9-ton)? Please list.

___________, __________, ___________, ___________, __________

18. Can we contact you at a later date to set-up an interview for additional questions? The interview should take no more than 30 minutes. ? Yes ? No

19. Please indicate by highlighting on the map provided on the back of this page, which counties your firm's trucks typically drive in?


LEGEND
TWIN CITIES METRO AREA
SEE MAP INSET
PLANNING
Roseau
Kittson
Marshall
Lake of the Woods
Koochiching
Polk
Pennington
Red Lake
Clearwater
Beltrami
Cook
Lake
St. Louis
Itasca
Norman
Mahnomen
Hubbard
Cass
Clay
Becker
Wadena
Carlton
Aitkin
Wilkin
Otter Tail
Crow Wing
Pine
Douglas
Todd
Morrison
Mille Lacs
Kanabec
Grant
Traverse
Stevens
Pope
Benton
Isanti
Big Stone
Stearns
Sherburne
Chisago
Swift
Chippewa
Kandiyohi
Meeker
Wright
Lac Qui Parle
Yellow Medicine
Renville
McLeod
Sibley
Nicollet
Le Sueur
Rice
Goodhue
Wabasha
Lincoln
Lyon
Redwood
Brown
Pipestone
Murray
Cottonwood
Watonwan
Blue Earth
Waseca
Steele
Dodge
Olmsted
Winona
Rock
Nobles
Jackson
Martin
Faribault
Freeborn
Mower
Fillmore
Houston
Anoka
Hennepin
Ramsey
Washington
Carver
Scott
Dakota

**Interview Questions**

1) How many miles did company trucks travel during 2002? (if they didn't answer in first cut survey)
2) What is you operating cost per mile? Per ton mile?

| | |
|---|---|
| Labor | ____________________ |
| Fuel and oil | ____________________ |
| Maintenance | ____________________ |
| Parking and tolls | ____________________ |
| Registration and taxes | ____________________ |
| Insurance | ____________________ |
| Vehicle purchase / lease | ____________________ |

3) How many axles are on an average company truck?
4) What percentage of trucks are sent out loaded to capacity?
5) What role, if any, does road quality play in route selection?
6) Are there any specific roads drivers try to avoid due to poor road quality?
7) If SLR causes your firm to operate different kinds of trucks than it would under normal conditions, what factors are considered before reaching a decision on truck type?
8) What was your total operating cost for the fiscal / calendar year 2002?

Now, we would like you to take a survey that will give us a better idea of how SLR affects trucking decisions as compared to ordinary operation. The survey consists of approximately 30 questions, and each question will present you with two options. There are 5 sets of questions, each with different instructions indicated by a color change. Select the option that would be most preferred by your firm and then click the "next" button. The survey should take about 10 minutes to complete. Please notify me if you have questions at any point during and upon your completion of the survey.

9) If this firm were to purchase a seasonal permit, what would be done differently during SLR? Follow Up.
10) If this firm were to purchase a single use permit, what would be done differently during an otherwise average SLR trip? Follow Up.

**Adaptive Stated Preference Presentations**

**Instruction Page**

**Thank you for agreeing to participate in this study. Clicking "Continue" will take you to the survey instrument, which consists of approximately 30 questions. The survey is adaptive based on your previous responses. You will be given two options. Please answer each question as your company would make its decisions. There are six sets of questions;**

**each new set is indicated by a color change in the instructions. The survey should take about 10 minutes.**

1. Think about your operation. Based on the following choices describing number of truck loads and time per truck load for a particular shipment, which option would you choose?
2. Think about your operation. If you could pay for a single use permit per truck load for each truck load to take an otherwise restricted, shorter route during the spring load restriction period that would save each truck load one hour, which option would you choose?
3. Think about your operation. If you could pay for a single use permit so that each truck load could be loaded to the truck's capacity, resulting in fewer truck loads for a particular shipment, which option would you choose?
4. Think about your operation. If you could pay for a seasonal permit so that each truck load could be loaded to the truck's capacity, resulting in fewer truck loads over the spring load restriction period, which option would you choose?
5. Think about your operation. If you could run overweight and take a restricted, shorter route during the spring load restriction period so that each truck load would save one hour, which option would you choose? The expected fine shown is the full fine amount multiplied by your chance of being caught for each truck load.
6. Think about your operation. If each truck load could be loaded to the truck's capacity, resulting in fewer truck loads for a particular shipment, which option would you choose? The expected fine shown is the full fine amount multiplied by your chance of being caught.

**Question 1** on the long form, how many trucks does your firm operate, was not used in this analysis due to apparent misinterpretation of included axle information. Several respondents counted only trailer axles, while others counted tractor and trailer axles. It is not possible to discern actual intent from the given information. Truck type information can still be used for classification of industry and business size.

**Question 2**, how many miles did your firm's trucks travel over the course of 2002, can be used as a possible model parameter. It can also be used to further analyze additional information from the other questions on the first-cut survey instrument as will be shown in Table 8. An additional question into total operating expenses in 2002 during the interview session will be used as a check for cost-per-mile for each interview participant.

**Question 3**, please list general types of major commodities/products that your firm hauls, is used to classify the business into an industrial classification. The industrial classifications were determined post-analysis, and are as follows: Ag Chem, Aggregate, Agricultural, Beverages, Construction, Dairy, Food Products, General Products, Industrial Supplies, Paper, Petroleum, Rubbish, and Timber. The classification can be used to determine impact and change by industry.

**Questions 4, 5, and 6** inquire about the number of employees. This information provides a sense of business size, and can be used as a model parameter in future analysis.

**Question 7**, who chooses the routes traveled by trucks, provides an indication of the decision maker that should be the subject of second-cut survey. It also provides information as to the proper recipient of enforcement action. Table 2 summarizes the results. It shows in most cases the driver is the one who decides about the routes. Some respondents chose multiple decision makers. One can see that the current enforcement method of ticketing the driver of the overweight vehicle coincides with the decision maker of the route.

| Who Makes Route Decisions | |
|---|---|
| Management | 26.0% |
| Dispatcher | 10.0% |
| Driver | 43.0% |
| Management & Dispatcher | 1.0% |
| Management & Driver | 7.5% |
| Driver & Dispatcher | 9.0% |
| Management & Driver & Dispatcher | 3.5% |

**Question 8** asked about whether the company was assessed financial penalties for late/missed deliveries. It seems average cost-per-km for companies that assessed penalties are higher than others. The cost from question 12, is cross-tabulated with penalties to show the expected difference if companies are assessed financial penalties. It is expected that firms who are assessed penalties may have to operate in a more expensive way to ensure on-time delivery.

| Assessed Financial Penalties For Late/Missed Deliveries | 24.8% | |
|---|---|---|
| | Cost/km | Cost/mile |
| Assessed Penalties | $0.81 | $1.32 |
| not Assessed Penalties | $0.63 | $1.03 |

**Question 9** inquires about how driver compensation was determined. Some respondents chose multiple compensation methods, but most drivers were paid on an hourly basis. It is our expectation that the elasticity in interview responses will change with compensation method, such that drivers that are compensated by distance will be less apt to violate SLR than those that are compensated by load or time. Results show only 14.8% of trucking companies linked their driver compensation to on-time deliveries. Almost half of the sample imposed a fuel surcharge.

| Driver Compensation | |
|---|---|
| Load | 15.0% |
| Time | 55.0% |
| Distance | 14.0% |
| Distance & Load | 4.0% |
| Distance & Time | 6.0% |
| Load & Time | 2.0% |
| Load & Time & Distance | 1.1% |
| % of Profits | 2.9% |

**Question 10**, is driver compensation linked to on-time deliveries, will be used as a model parameter to determine the value of time. Cost-per-mile, question 12, is included to show the expected difference in stated cost if driver compensation is linked to on-time deliveries.

| Driver Compensation Linked To On-Time Deliveries | | 16.3% |
|---|---|---|
| | Cost/km | Cost/mile |
| Linked | $0.59 | $0.96 |
| not Linked | $0.51 | $0.85 |

**Question 11**, do you change the rate you charge clients to account for the fluctuations in gas/diesel price, can be used as a model parameter. It is our expectation that the elasticity in interview responses will change with fuel surcharges, such that companies that impose fuel

surcharges are less susceptible to market fluctuations. The answers do not add up to 100% because some respondents failed to answer the question.

| Fuel Surcharge | |
|---|---|
| Yes | 50.6% |
| No | 41.3% |

**Question 14**, do spring load restrictions affect your firm, is used to determine which industries are most affected by SLR, and in what ways do they respond to the imposition of the restrictions. One can see that the Ag Chem, Beverage, and Rubbish industries all reported a total impact due to SLR. Most respondents chose multiple effects, thus the results do not add to 100%. This information will used as a check in the modeling of pavement effects, to account for miles traveled changes during the period of SLR.

**Spring Load Restriction Effect By Industry**

| | Count | Affected by SLR | Shift Seasonal Timing | Reduce Load Size | Increase Number of Vehicles | Change Vehicle Type | Change Routes |
|---|---|---|---|---|---|---|---|
| Overall | 315 | 71.4% | 28.0% | 79.1% | 17.8% | 14.2% | 65.3% |
| Beverages | 5 | 100.0% | 20.0% | 40.0% | 40.0% | 80.0% | 80.0% |
| Ag Chem | 28 | 100.0% | 17.9% | 96.4% | 35.7% | 17.9% | 53.6% |
| Rubbish | 1 | 100.0% | 0.0% | 100.0% | 0.0% | 0.0% | 100.0% |
| Petroleum | 19 | 89.5% | 15.8% | 73.7% | 0.0% | 26.3% | 47.4% |
| Aggregate | 16 | 87.5% | 50.0% | 75.0% | 18.8% | 6.3% | 37.5% |
| Agricultural | 99 | 86.9% | 32.3% | 79.8% | 9.0% | 11.1% | 62.6% |
| Timber | 7 | 85.7% | 14.3% | 85.7% | 14.3% | 0.0% | 28.6% |
| Construction | 23 | 82.6% | 30.4% | 43.5% | 17.4% | 8.7% | 56.5% |
| Dairy | 6 | 66.6% | 16.7% | 33.3% | 0.0% | 0.0% | 66.7% |
| Food Products | 20 | 60.0% | 5.0% | 40.0% | 25.0% | 0.0% | 50.0% |
| General Products | 52 | 46.2% | 5.8% | 19.2% | 9.6% | 5.8% | 26.9% |
| Paper | 7 | 28.6% | 0.0% | 14.3% | 0.0% | 0.0% | 28.6% |
| Industrial Supplies | 32 | 21.9% | 3.1% | 18.8% | 3.1% | 3.1% | 15.6% |

**Question 16,** how many times were your firm's trucks cited last year for weight violations during the period of spring load restrictions, will be used to verify interviewees' willingness to violate SLR. Out of 172 respondents, there were 60 citations listed. This can be checked with State Patrol lists to see if respondents were honest in their answer. This information can be used as a check for the first portion of the stated preference survey. It can also be used to establish the number of citations issued per level of demand on the transportation system; we found the 0.0060% of the truckloads resulted in a citation.

**Question 17**, which road(s) are problematic for your firm during spring load restrictions, can be used to compile a list for Mn/DOT of the most commonly cited problematic roads. It can also be used to determine the most troublesome road classification for the trucking industry. 39.5% reported that 5-ton roads were problematic, 34.3% reported that 7-ton roads were problematic, and 11.0% reported that 9-ton roads were problematic.

**Question 18**, can we contact you at a later date to set-up an interview for additional questions, will be used to develop our pool of second cut survey candidates. 49.5% of the respondents are willing to be interviewed, with 35 of those within the four counties that will be modeled in EMME/2.

**Question 19**, please indicate by highlighting on the map provided on the back of this page which counties your firm's trucks typically drive in, can be used in further analysis to determine the scope of the company.

**Comments**

Here we will list and summarize a few of the comments that were included on returned surveys.

1. Company A noted that their business is seasonal and busiest during SLR.

2. Company B noted their trucks and crews must respond to electrical outages and emergencies in all types of weather and all seasons of the year on many roads that have load restrictions.

3. Company C noted that during SLR, drivers have to put in more hours.

4. Company D noted that it is their feeling that rubbish trucks should be exempt from SLR like school buses and sewer trucks.

5. Company E noted they have to shuttle furniture with a smaller truck during SLR.

6. Company F noted a 9 ton road should not be 73,280 lbs.

# Appendix D
# Matlab Programs

The main purpose of this program is to convert a generate data file derived from GIS map to Emme/2 format. The input of this program is the generate data file “smp4lyon.m”, which records the x,y coordinates of from node , to node and some vertex of each arc. The “lengthvol” file records the length and traffic counts on each link. The output of this program is the Lyon County map in Emme/2 format.

**Program code:**

```
clear;
format long;
% lengthvol consists of length and traffic count of each link
load lengthvol;
% the data file generated by ARC/Info
 filename='smp4lyon.m';

% Open Shape file
fd1=fopen(filename,'rb');
fd2=fopen('lyonnode','w');
fprintf(fd2,'t nodes init\n');
fd3=fopen('lyonlink','w');
fprintf(fd3,'t links init\n');
fd4=fopen('Linkwithmode','w');

% Variable define
fileEnd=0;
NodeNumber =0;
Node=[];
LinkNumber =0;
LinkSize=0;
LinkLength=0;
writelink=[];
link(1,1).x=0;
link(1,2).x=0;
numberEnd=0;

% assign 1.5 lane for link with traffic count 1000-2000, 2 lane for links with traffic count more
than 2000
[p,q]=size(lengthvol);
for i=1:p
   if lengthvol(i,2)>=1000
      if lengthvol(i,2)<2000
         lengthvol(i,3)=1.5;
      else
         lengthvol(i,3)=2;
      end
   else
       lengthvol(i,3)=1;
```

```
    end
end

% Main Loop
while fileEnd==0
    a=fgetl(fd1);
    A = sscanf(a,'%f');
    if ~isempty(A)
        %if it is not 'END'
        numberEnd= 0;
        if max(size(A))~=1
            % if it's coordinate, read x and y
            LinkSize = LinkSize +1;
            link(LinkNumber,LinkSize).x = A(1);
            link(LinkNumber,LinkSize).y = A(2);
        else
            % if it is not a coordinate
            % it is a beginning of a new link
            newLink=1;
            LinkLength =0;
            LinkSize =0;
            LinkNumber = LinkNumber + 1;
            %LinkNumber
        end
    else
        % it is the end of a link, record the from-node and to-node of this link
        xtmp=link(LinkNumber,1).x;
        ytmp=link(LinkNumber,1).y;
        if ~isempty(Node)
            fromNode = find(Node(:,1)==xtmp & Node(:,2) == ytmp);
            if isempty(fromNode)
                NodeNumber =NodeNumber +1;
                fromNode = NodeNumber;
                %NodeNumber
                Node(NodeNumber,1)=xtmp;
                Node(NodeNumber,2)=ytmp;
                fprintf(fd2,'a %d %6.0f %6.0f 0 0 0 %4d\n',NodeNumber, Node(NodeNumber,1),
Node(NodeNumber,2), NodeNumber);
            end
        else
            fromNode=1;
            NodeNumber =NodeNumber +1;
            %NodeNumber
            Node(NodeNumber,1)=xtmp;
            Node(NodeNumber,2)=ytmp;
            fprintf(fd2,'a %d %6.0f %6.0f 0 0 0 %4d\n',NodeNumber, Node(NodeNumber,1),
```

```
Node(NodeNumber,2), NodeNumber);
        end
        xtmp=link(LinkNumber,LinkSize).x;
        ytmp=link(LinkNumber,LinkSize).y;
        toNode = find(Node(:,1)==xtmp & Node(:,2) == ytmp);
        if isempty(toNode)
            NodeNumber =NodeNumber +1;
            toNode= NodeNumber;
            %NodeNumber
            Node(NodeNumber,1)=xtmp;
            Node(NodeNumber,2)=ytmp;
            fprintf(fd2,'a %d %6.0f %6.0f 0 0 0 %4d\n',NodeNumber, Node(NodeNumber,1),
Node(NodeNumber,2), NodeNumber);
        end

        LinkLength= lengthvol(LinkNumber, 1)/5280;
        LinkVolume= lengthvol(LinkNumber, 2);
        LinklaneNumber=lengthvol(LinkNumber,3);
        LinkNumber;

        if ~isempty(writelink)
            addlink = find(writelink(:,1)==fromNode & writelink(:,2) == toNode);% |
writelink(:,1)==toNode & writelink(:,2) ==fromNode);
            if isempty(addlink)
                writelink(LinkNumber,1:2)=[fromNode toNode];

Linkdata(LinkNumber,1:6)=[LinkNumber,fromNode,toNode,LinkLength,LinklaneNumber,Link
Volume];
                 if Linkdata(LinkNumber,6)>=1000
                  Linkdata(LinkNumber,7)=3;
                  mode='clmh';
                 else
                      if Linkdata(LinkNumber,6)>100
                        Linkdata(LinkNumber,7)=1;
                        mode='cl';
                      else
                        Linkdata(LinkNumber,7)=0;
                        mode='c';
                     end
                   end
                fprintf(fd3,'a %d %d %4.3f  %s     1  %2.1f    5   %d   0   0\n', fromNode, toNode,
LinkLength,mode,LinklaneNumber, LinkVolume);
                fprintf(fd4,'%d %d  %4.3f %d %2.1f %d
\n',fromNode,toNode,LinkLength,Linkdata(LinkNumber,7),LinklaneNumber,LinkVolume);

            else
```

```
Linkdata(LinkNumber,1:6)=[LinkNumber,fromNode,toNode,LinkLength,LinklaneNumber,Link
Volume];
            if Linkdata(LinkNumber,6)>=1000
             Linkdata(LinkNumber,7)=3;
             mode='clmh';
            else
                if Linkdata(LinkNumber,6)>100
                  Linkdata(LinkNumber,7)=1;
                  mode='cl';
                else
                  Linkdata(LinkNumber,7)=0;
                  mode='c';

                 end

            end

          fprintf(fd3,'a %d %d %4.3f  %s     1  %2.1f    5   %d   0   0\n',
toNode,fromNode,LinkLength,mode,LinklaneNumber, LinkVolume);
          fprintf(fd4,'%d %d  %4.3f %d %2.1f %d
\n',toNode,fromNode,LinkLength,Linkdata(LinkNumber,7),LinklaneNumber,LinkVolume);


        end
     else
        writelink(LinkNumber,1:2)=[fromNode toNode];

Linkdata(LinkNumber,1:6)=[LinkNumber,fromNode,toNode,LinkLength,LinklaneNumber,Link
Volume];
         if Linkdata(LinkNumber,6)>=1000
             Linkdata(LinkNumber,7)=3;
               mode='clmh';
         else
               if Linkdata(LinkNumber,6)>100
                  Linkdata(LinkNumber,7)=1;
                  mode='cl';
               else
                  mode='c';
                  Linkdata(LinkNumber,7)=0
               end
         end

        fprintf(fd3,'a %d %d %4.3f  %s     1  %2.1f    5   %d   0   0\n', fromNode,
toNode,LinkLength,mode,LinklaneNumber,LinkVolume);
        fprintf(fd4,'%d %d %4.3f %d %2.1f %d
```

```
\n',fromNode,toNode,LinkLength,Linkdata(LinkNumber,7),LinklaneNumber,LinkVolume);


        numberEnd = numberEnd + 1;
        if numberEnd ==2

           fileEnd=1;
           break;
        end
    end
end
fclose(fd1);
fclose(fd2);
fclose(fd3);
fclose(fd4);
```

**Matlab Program of adding centroids to the Emme/2 map.**

**Program description:**

The main purpose of this program is to add centroids to the Emme/2 map. Each freight facility is located to the nearest centroid. Some external points which connect the border of Lyon County are added. Connecter links which connect centroid and the nearest regular node are added. The input files are coordinates of each freight facility, network link data, link mode data. The output files are the centroid numbers associated with each freight facility.

**Program code:**

```
clear;

load testdata;
load -ASCII chemdist.txt;
load -ASCII mafcoord.txt;
load -ASCII truckingfacility.txt;
load -ASCII retail.txt;
load -ASCII wholesale.txt;
load -ASCII outsideelevator.m
load Linkdata.mat
load Node.mat
load Linkwithmodenew

fd1=fopen('centroidlink','w');
fd2=fopen('lyonnode','a+');
fd3=fopen('lyonlink','a+');
fd4=fopen('outsideelevator','w')
fd5=fopen('insideelevator','w')
fd6=fopen('newchemnode','w')
fd7=fopen('newmalnode','w')
fd8=fopen('newtrucknode','w')
fd9=fopen('newretailnode','w')
fd10=fopen('newwholesale','w')
fd11=fopen('centroiddata','w')

% wholesale facility in lyon
bx=3.39149838;
ax=-427181.7413;
by=3.162369805;
ay=-15383939.54;
[m,n]=size(wholesale);
for i=1:m
   wholesalenew(i,1)=ax+bx*wholesale(i,1);
   wholesalenew(i,2)=ay+by*wholesale(i,2);
end


%retail facility in lyon
```

```
 %transform to new coordinates

bx=3.39149838;
ax=-427181.7413;
by=3.162369805;
ay=-15383939.54;
[m,n]=size(retail);
for i=1:m
    retailnew(i,1)=ax+bx*retail(i,1);
    retailnew(i,2)=ay+by*retail(i,2);
end


%trucking facility in lyon

%transform to new coordinates
bx=3.39149838;
ax=-427181.7413;
by=3.162369805;
ay=-15383939.54;
[m,n]=size(truckingfacility);
for i=1:m
    trucknew(i,1)=ax+bx*truckingfacility(i,1);
    trucknew(i,2)=ay+by*truckingfacility(i,2);
 end



%chemdistribution center in lyon

%transform to new coordinates
bx=3.39149838;
ax=-427181.7413;
by=3.162369805;
ay=-15383939.54;
[m,n]=size(chemdist);
for i=1:m
    chemnew(i,1)=ax+bx*chemdist(i,1);
    chemnew(i,2)=ay+by*chemdist(i,2);
 end


%manufacturing facility in lyon
%transform to new coordinates
bx=3.39149838;
ax=-427181.7413;
```

```
by=3.162369805;
ay=-15383939.54;
[m,n]=size(mafcoord);
for i=1:m
    malnew(i,1)=ax+bx*mafcoord(i,1);
    malnew(i,2)=ay+by*mafcoord(i,2);

 end


% Elevators in Lyon county
lyon=[280939.13     4934079.01
264603.57     4911572.89
280907.08     4921551.55
290699.40     4901006.54
288012.03     4942967.51
270832.70     4901953.31
279446.40     4899738.63
270462.08     4932728.75
277901.66     4924932.16
284924.75     4910578.72
256715.60     4942246.33
287941.74     4942842.19];

%Elevators in counties nearby: Lincoln, Murray, Redwood, Yellow Medicine
othercounty=[249684.32     4907359.53
227782.15     4933734.24
246515.29     4919354.37
237611.12     4906029.75
241663.91     4928665.88
263308.63     4868198.19
286614.99     4882613.84
287811.90     4869636.56
276473.77     4866452.93
295753.80     4881117.44
263191.98     4875783.46
262635.25     4868044.51
271243.56     4876212.17
291075.02     4860683.39
279431.73     4874834.63
282783.97     4861780.25
320242.52     4918999.87
331721.54     4933269.30
318817.78     4900142.64
330534.56     4897222.09
323751.60     4909379.34
```

```
311177.78       4899458.09
336465.52       4915955.17
324341.39       4940584.67
320234.66       4919007.08
296729.81       4921727.21
311139.48       4899456.27
320192.27       4919067.46
302604.88       4899837.78
346309.93       4919952.53
307913.06       4930912.15
336317.45       4916139.10
329885.94       4897575.08
346278.37       4919981.62
277839.96       4963544.41
308283.53       4943172.29
240385.96       4955912.77
248790.63       4947237.76
298694.09       4947522.38
298054.14       4965166.87
292147.63       4952076.35
240447.01       4956414.95
278052.45       4963544.14];

[m n]=size(lyon);
bx=3.39149838;
ax=-427181.7413;

by=3.162369805;
ay=-15383939.54;

for i=1:m
   lyonnew(i,1)= ax+ bx*lyon(i,1);
   lyonnew(i,2)= ay+ by*lyon(i,2);
end

[m n]=size(othercounty);
for i=1:m
   othercountynew(i,1)= ax+ bx*othercounty(i,1);
   othercountynew(i,2)= ay+ by*othercounty(i,2);
end

lyon=lyonnew;
othercounty=othercountynew;
% add 225 centroid in the network

d0x=500
```

```
xmin=443309-d0x; %254804
xmax=558734+d0x; %294068
ymin=100389-d0x; %4896921;
ymax=258575+d0x; %4946518;



dx=(xmax-xmin)/30;
dy=(ymax-ymin)/30;

centr=2000;
numberCentroid=0;
for i=1:15
   for j=1:15
      centroid=centr+(i-1)*15+j;
      numberCentroid=numberCentroid+1;
      cen((i-1)*15+j,1:3)=[centroid xmin+i*(2*dx)-dx ymin+j*(2*dy)-dy];
      fprintf(fd2,'a* %d %6.0f %6.0f 0 0 0 %4d\n',centroid, cen((i-1)*15+j,2), cen((i-1)*15+j,3),
centroid);
   end
end

% Elevators in Lyon county: find the nearest centroid and record its node number and
coordinates to file insideelevator
[numbElevat tmp]=size(lyon);
dist=[];
for i=1:numbElevat
   xtmp=lyon(i,1);
   ytmp=lyon(i,2);
   for j=1:numberCentroid
      dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
   end
   closeCentroid = find(dist(:)==min(dist));
      fprintf(fd5,'%d %6.0f %6.0f
\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3));


end
localcentroid=numberCentroid;

totalelevator=numbElevat;
% Elevators outside Lyon county: load the external elevator and write it to lyonnode

[m,n]=size(outsideelevator);
for i=1:m
     fprintf(fd2,'a* %d %6.0f %6.0f 0 0 0 %4d\n',outsideelevator(i,1),
```

```
outsideelevator(i,2),outsideelevator(i,3), outsideelevator(i,1));
 end



% add chemidistribution centroid
[m,n]=size(chemnew)
InternalCentroid=225;
dist=[];

for i=1:m
    xtmp=chemnew(i,1);
    ytmp=chemnew(i,2);
    for j=1:InternalCentroid
        dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
    end
  closeCentroid = find(dist(:)==min(dist));
        fprintf(fd6,'%d %6.0f %6.0f
%6.2f\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3),chemdist(i,3));
end


% find the nearest centroid as manufacture facility centroid

[m,n]=size(malnew)
InternalCentroid=225
dist=[];
for i=1:m
    xtmp=malnew(i,1);
    ytmp=malnew(i,2);
    for j=1:InternalCentroid
        dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
    end
    closeCentroid = find(dist(:)==min(dist));
        fprintf(fd7,'%d %6.0f %6.0f %6.2f
\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3),mafcoord(i,4));

end

% Add trucking faciliy centroid

[m,n]=size(trucknew)
InternalCentroid=225
dist=[];
for i=1:m
    xtmp=trucknew(i,1);
```

```
    ytmp=trucknew(i,2);
    for j=1:InternalCentroid
        dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
    end
   closeCentroid = find(dist(:)==min(dist));
        fprintf(fd8,'%d %6.0f %6.0f
%6.2f\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3),truckingfacility(i,4));

end




%Add retail facility centroid

[m,n]=size(retailnew)
InternalCentroid=225;
dist=[];
for i=1:m
    xtmp=retailnew(i,1);
    ytmp=retailnew(i,2);
    for j=1:InternalCentroid
        dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
    end
  closeCentroid = find(dist(:)==min(dist));
        fprintf(fd9,'%d %6.0f %6.0f
%6.2f\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3),retail(i,4));

end




% Add wholesale facility centroid
[m,n]=size(wholesalenew)
InternalCentroid=225;
dist=[];
for i=1:m
    xtmp=wholesalenew(i,1);
    ytmp=wholesalenew(i,2);
    for j=1:InternalCentroid
        dist(j)=sqrt((cen(j,2)-xtmp)^2 +(cen(j,3)- ytmp)^2)/5280;
    end
    closeCentroid = find(dist(:)==min(dist));
        fprintf(fd10,'%d %6.0f %6.0f %6.2f
```

```
\n',cen(closeCentroid,1),cen(closeCentroid,2),cen(closeCentroid,3),wholesale(i,4));

end
% Generate Links from internal centroids to nodes
type=0;

[m1,n1]=size(Linkwithmodenew);
for i=1:InternalCentroid
    Linknum=0;
    type=0;
    dist=[];
    Nodenum=[];
    x=cen(i,2);
    y=cen(i,3);
   Insidelink=[];
   dist1=[];
        %select links that has node in the area of each centroid
        for k=1:m1
            if x-0.5*dx<=Node(Linkwithmodenew(k,2),1)&
Node(Linkwithmodenew(k,2),1)<=x+0.5*dx & y-0.5*dy<=Node(Linkwithmodenew(k,2),2)&
Node(Linkwithmodenew(k,2),2)<=y+0.5*dy
                Linknum=Linknum+1;
                Insidelink(Linknum)=Linkwithmodenew(k,1);
            end
        end

        [n2,m2]=size(Insidelink);
   if m2>0
        count=0;
         for j=1:m2
            if Linkwithmodenew(Insidelink(j),5)>type
                type=Linkwithmodenew(Insidelink(j),5);

            end
         end



        type;
        Numoftype=0;

         for l=1:m2
            if Linkwithmodenew(Insidelink(l),5)==type
        % calculate distance from centroid to these nodes and add link from centroid to the nearest
one.
              Numoftype=Numoftype+1;
              Nodenum(Numoftype)=Linkwithmodenew(Insidelink(l),2);
```

```
            dist(Numoftype)=sqrt((cen(i,2)-Node(Linkwithmodenew(Insidelink(l),2),1))^2
+(cen(i,3)- Node(Linkwithmodenew(Insidelink(l),2),2))^2)/5280;
            end
        end
            closeNode=find(dist(:)==min(dist));
            Nodenum(closeNode(1));
            if type==3
                mode='clmh';
            else
                if type==2;
                mode='clm';
                else
                    if type==1
                      mode='cl';
                    else
                      mode='c';
                     end
                 end

             end

          fprintf(fd1,'a %d %d %4.3f %s    1  1  5   0   0   0\n',cen(i,1),
Nodenum(closeNode(1)),min(dist),mode);

          fprintf(fd1,'a %d %d %4.3f %s    1  1  5   0   0   0\n',
Nodenum(closeNode(1)),cen(i,1),min(dist),mode);
         % fprintf(fd11,'%d %d %4.3f %d    1    5   0   0   0\n',cen(i,1),
Nodenum(closeNode(1)),min(dist),type);
       else
        for r=1:NodeNumber
           dist1(r)=sqrt((Node(r,1)-cen(i,2))^2 +(Node(r,2)- cen(i,3))^2)/5280;
       end
        closeNodes= find(dist1(:)==min(dist1(:)));
        NearLink=find(Linkwithmodenew(:,2)==closeNodes(1));
        [m3,n3]=size(NearLink);
        type2=0;
        for z=1:m3
          if Linkwithmodenew(NearLink(z),5)>type2
              type2=Linkwithmodenew(NearLink(z),5);
          end
        end
       if type2==3
                mode='clmh';
          else
                if type2==2;
                mode='clm';
```

```
                else
                    if type2==1
                      mode='cl';
                    else
                      mode='c';
                     end
                 end

           end


          fprintf(fd1,'a %d %d %4.3f %s    1  1  5   0   0   0\n',cen(i,1),
closeNodes(1),min(dist1),mode);

          fprintf(fd1,'a %d %d %4.3f %s    1  1  5   0   0
0\n',closeNodes(1),cen(i,1),min(dist1),mode);
          %fprintf(fd11,'%d %d %4.3f %d    1    5   0   0   0\n',cen(i,1),
closeNodes(1),min(dist1),type2);


      end

 end

% Generate Links from external centroids to real expors on the boundary

[m,n]=size(outsideelevator);
 for i=1:m
  dist(i)=sqrt((Node(outsideelevator(i,4),1)-outsideelevator(i,2))^2
+(Node(outsideelevator(i,4),2)- outsideelevator(i,3))^2)/5280;
  %fprintf(fd3,'a %d %d %4.3f  clmh     1  1    5   0   0   0\n', outsideelevator(i,1),
outsideelevator(i,4), dist(i));
  %fprintf(fd3,'a %d %d %4.3f  clmh     1  1    5   0   0   0\n', outsideelevator(i,4),
outsideelevator(i,1), dist(i));
  %fprintf(fd11,'%d %d %4.3f  3    1  1    5   0   0   0\n', outsideelevator(i,1), outsideelevator(i,4),
dist(i));

  end




fclose(fd1);
fclose(fd2);
fclose(fd3);
fclose(fd4);
```

```
fclose(fd5);
fclose(fd6);
fclose(fd7);
fclose(fd8);
fclose(fd9);
fclose(fd10);
fclose(fd11);
```

**Matlab program of generating demand matrix in NoSLR scenario**

**Program description:**

The main objective of this program is to generate Origin-Destination (OD) matrix between centroids in NoSLR scenario.

**Program code:**

```
clear;
change5=1;
change7=1;
tic
format long;
load -ASCII insideelevator.m;
load -ASCII outsideelevator.m;
load -ASCII newchemnode;
load -ASCII newtrucknode;
load -ASCII exteeleformal.m;
load -ASCII newmalnode;
load -ASCII newretailnode;
load -ASCII newwholesale;
load -ASCII newotherfreight;
load -ASCII centroiddata.m;
load cen.mat
load cdata.mat

% The size of matrix is derived from the d211. we have 250 centroids in the road network
```

```
M0=zeros(250,250);
M1=zeros(250,250);
M2=zeros(250,250);
M3=zeros(250,250);
% Centroids are labeled with id number starting with 2000.
Centr=2000;

% all centroids
% Total Trip from farms
%  trip from each farm to internal elevator
% Tirp distribution between farm and internal elevator
% Each farm will find the nearest grain elevators.

[m1 n1]=size(insideelevator);
origin=cen(1:225,1:3);
dest1=insideelevator(1:m1, 1:3);
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
count1=zeros(Dsize,2);
dij=[];
for i=1:Osize
   for j=1:Dsize
       dij(j) =sqrt((origin(i,2)-dest1(j,2))^2 +(origin(i,3)-dest1(j,3))^2 )/5280;
   end
   mindist=min(dij);
   closeelevator=find(dij(:)==mindist);
   close=closeelevator(1,1);
        min(centroiddata(i,4),centroiddata(dest1(close,1)-Centr,4));
      if  min(centroiddata(i,4),centroiddata(dest1(close,1)-Centr,4))==0
           Pi=0.67;
      M0(i,dest1(close,1)-2000)=M0(i,dest1(close,1)-2000)+Pi;
   else
```

```
      if  min(centroiddata(i,4),centroiddata(dest1(close,1)-Centr,4))==1
            Pi=0.67;
       M1(i,dest1(close,1)-2000)=M1(i,dest1(close,1)-2000)+Pi;
      else
         if min(centroiddata(i,4),centroiddata(dest1(close,1)-Centr,4))==2
           Pi=0.67;
         M2(i,dest1(close,1)-2000)=M2(i,dest1(close,1)-2000)+Pi;
         else
           Pi=0.67;
            M3(i,dest1(close,1)-2000)=M3(i,dest1(close,1)-2000)+Pi;
         end
      end
   end
  % return trip are all empty truck which can go on any road
  M0(dest1(close,1)-2000,i)=M0(dest1(close,1)-2000,i)+Pi;
  % calculating how many trip each grain elevator attracts
  count1(close,1)=count1(close,1)+1;
  count1(close,2)=count1(close,2)+Pi;

end
sum1=0;
for i=1:250
   for j=1:250
    sum1=sum1+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end
sum1

% find the nearest chem distribution center for each farm, truck goes from nearest chem distribution center to the farm
[m1 n1]=size(newchemnode);
origin=cen(1:225,1:3);
```

```
dest1=newchemnode(1:m1, 1:3);
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
count=zeros(Dsize,1);
dij=[];
for i=1:Osize
  for j=1:Dsize
     dij(j) =sqrt((origin(i,2)-dest1(j,2))^2 +(origin(i,3)-dest1(j,3))^2 )/5280;
  end
  mindist=min(dij);
  closechem=find(dij(:)==mindist);
  close=closechem(1,1);
  count(close)=count(close)+1;
  od(i)=close;
  end
%trip distribution
for i=1:Osize
   demand(i)=newchemnode(od(i),4)/count(od(i));

     if min(centroiddata(i,4),centroiddata(dest1(od(i),1)-2000,4))==0
      M0(dest1(od(i),1)-2000,i)=M0(dest1(od(i),1)-2000,i)+demand(i);
  else
      if min(centroiddata(i,4),centroiddata(dest1(od(i),1)-2000,4))==1
        M1(dest1(od(i),1)-2000,i)=M1(dest1(od(i),1)-2000,i)+demand(i);

      else
         if min(centroiddata(i,4),centroiddata(dest1(od(i),1)-2000,4))==2
         M2(dest1(od(i),1)-2000,i)=M2(dest1(od(i),1)-2000,i)+demand(i);
         else
         M3(dest1(od(i),1)-2000,i)=M3(dest1(od(i),1)-2000,i)+demand(i);
         end
      end
```

```
   end
 % for return trip, they are all empty
   M0(i,dest1(od(i),1)-2000)=M0(i,dest1(od(i),1)-2000)+demand(i);
      end


sum2=0;
for i=1:250
    for j=1:250
     sum2=sum2+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end
sum2

%trip from Manufacturing to few external points,doulbe direction,the demand is assigned to each external points in proportion to real traffic counts.
origin=newmalnode;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize

   if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-Centr)+origin(i,4)*dest1(j,6);
    M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-Centr)+origin(i,4)*dest1(j,6);
   else
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
         M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-Centr)+origin(i,4)*dest1(j,6);
```

```
        M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
      else
          if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
        M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
        M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
          else
         M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
        M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
          end
      end
   end


end
end
  sum3=0;


for i=1:250
    for j=1:250
     sum3=sum3+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end


sum3
 % trip from wholesale to external few points double direction
origin=newwholesale;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
```

```
 for i=1:Osize
   for j=1:Dsize

  if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
   M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
   M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
  else
      if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
        M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
        M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
      else
          if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
        M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
        M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
          else
         M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
        M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
          end
      end
  end
   end
end
  sum4=0;

for i=1:250
   for j=1:250
                                                                    sum4=sum4+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
```

```
 end
end
sum4


% trip from retail to external points. (adopting previous method)
origin=newretailnode;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
total=0;
for i=1:Dsize
 total=total+dest1(i,4);
end
  for i=1:Osize
    for j=1:Dsize


    if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
    else
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
    M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
       else
           if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
    M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
```

```
Centr)+origin(i,4)*dest1(j,6);
           else
    M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
           end
       end
   end
  end

end



sum5=0;


for i=1:250
    for j=1:250
     sum5=sum5+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end


sum5


   % trip from inside other freight facility  to external double direction (bidirectional)


origin=newotherfreight;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize
```

```
      if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
   else
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
    M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
       else
           if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
    M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
           else
    M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);


           end
       end
   end


     end


end


sum55=0;


for i=1:250
    for j=1:250
```

```
      sum55=sum55+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end

sum55
%trip from trucking facility to external points
 origin=newtrucknode;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
   else
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
    M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
       else
           if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
    M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
           else
    M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
    M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
```

```
          end
        end
    end

      end
     end

sum6=0;
for i=1:250
    for j=1:250
     sum6=sum6+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end

sum6
%trip from Grain elevator to few external points
%  assuming 60% going out and 60% going into
origin=insideelevator;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize

   if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+count1(i,2)*0.60*dest1(j,6)*1;
    M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+count1(i,2)*0.60*dest1(j,6)*1;
   else
       if min(centroiddata(origin(i,1)- Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
```

```
        M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
        M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
      else
          if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
        M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
        M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
          else
         M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
         M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-Centr)+count1(i,2)*0.60*dest1(j,6);
       end
      end
  end


end
end
  sum7=0;


for i=1:250
    for j=1:250
     sum7=sum7+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end


sum7


% external to external traffic
% The fifith column is the ADT on the road lead to the external points, thus each direction should be half of the ADT.
```

```
origin=outsideelevator;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize
   if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
    M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,5)*0.13*0.50*0.20*origin(j,6);


   else
     if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
         M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,5)*0.13*0.50*0.20*origin(j,6);
      else
          if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
         M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,5)*0.13*0.50*0.20*origin(j,6);


         else
         M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,5)*0.13*0.50*0.20*origin(j,6);
         end
         end
     end


    end
   end
sum8=0;

for i=1:250
    for j=1:250
```

```
     sum8=sum8+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end

sum8
    % % trip from Chemical distribution Center to external points
origin=newchemnode;
dest1=outsideelevator;
[Osize tmp]=size(origin);
[Dsize tmp]= size(dest1);
dij=[];
 for i=1:Osize
    for j=1:Dsize
        min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))
   if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==0
       M0(origin(i,1)-Centr,dest1(j,1)-Centr)=M0(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
       M0(dest1(j,1)-Centr,origin(i,1)-Centr)=M0(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
   else
       if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==1
         M1(origin(i,1)-Centr,dest1(j,1)-Centr)=M1(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
         M1(dest1(j,1)-Centr,origin(i,1)-Centr)=M1(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
       else
           if min(centroiddata(origin(i,1)-Centr,4),centroiddata(dest1(j,1)-Centr,4))==2
         M2(origin(i,1)-Centr,dest1(j,1)-Centr)=M2(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
         M2(dest1(j,1)-Centr,origin(i,1)-Centr)=M2(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
           else
         M3(origin(i,1)-Centr,dest1(j,1)-Centr)=M3(origin(i,1)-Centr,dest1(j,1)-
Centr)+origin(i,4)*dest1(j,6);
```

```
        M3(dest1(j,1)-Centr,origin(i,1)-Centr)=M3(dest1(j,1)-Centr,origin(i,1)-
Centr)+origin(i,4)*dest1(j,6);
          end
       end
   end


end
end
  sum9=0;
for i=1:250
    for j=1:250
     sum9=sum9+M0(i,j)+M1(i,j)+M2(i,j)+M3(i,j);
 end
end
sum9
     t=toc;
```

**Matlab Program building demand matrix in format of Emme/2**

**Program description:**

This program convert OD matrix into the format of Emme/2, which will be used as d311 file of Emme/2 databank.

**Program code:**

```
clear;
tic
load M0.mat;
load M1.mat;
load M2.mat;
load M3.mat;

fd1=fopen('MatrixJune23S5','a');
fprintf(fd1,'t matrices init   /@(#) d311.in 1.3@(#)\n');
fprintf(fd1,'a matrix=mf01 wod76d 0 olmsted 5 ton road demand\n');
centr=2000;
[Osize,Dsize]=size(M0);
for i=1:Osize
   fprintf(fd1,'%d ',i+centr);

   for j=1:Dsize
      fprintf(fd1,'%d:%1.5f ',j+centr, M0(i,j));
      if ~mod(j,5)
         fprintf(fd1,'\n');
         fprintf(fd1,'%d ',i+centr);
      end
   end
   fprintf(fd1,'\n');
end
fprintf(fd1,'a matrix=mf02 wod76d 0 olmsted 6 ton road demand\n');
```

```
centr=2000;
[Osize,Dsize]=size(M1);
for i=1:Osize
   fprintf(fd1,'%d ',i+centr);

   for j=1:Dsize
      fprintf(fd1,'%d:%1.5f ',j+centr, M1(i,j));
      if ~mod(j,5)
         fprintf(fd1,'\n');
         fprintf(fd1,'%d ',i+centr);
      end
   end
   fprintf(fd1,'\n');
end
fprintf(fd1,'a matrix=mf03 wod76d 0 olmsted 7 ton road demand\n');
centr=2000;
[Osize,Dsize]=size(M2);
for i=1:Osize
   fprintf(fd1,'%d ',i+centr);

   for j=1:Dsize
      fprintf(fd1,'%d:%1.5f ',j+centr, M2(i,j));
      if ~mod(j,5)
         fprintf(fd1,'\n');
         fprintf(fd1,'%d ',i+centr);
      end
   end
   fprintf(fd1,'\n');
end
fprintf(fd1,'a matrix=mf04 wod76d 0 olmsted 9,10 ton road demand\n');
centr=2000;
[Osize,Dsize]=size(M3);
```

```
for i=1:Osize
    fprintf(fd1,'%d ',i+centr);


    for j=1:Dsize
        fprintf(fd1,'%d:%1.5f ',j+centr, M3(i,j));
        if ~mod(j,5)
            fprintf(fd1,'\n');
            fprintf(fd1,'%d ',i+centr);
        end
    end
    fprintf(fd1,'\n');
end
fclose(fd1);
%fclose(fd2);
%fclose(fd3);
%fclose(fd4);
t=toc
```

**Matlab program of calculating truck VKT in the road network**

**Program description:**

The function of this program is to calculate the total truck VKT knowing truck volume on each section of the roads.

**Program code:**

```
a=[      ];
    fromnode=a(:,1);
    tonode=a(:,2);
    volume=a(:,3);
    time=a(:,4);
    length=a(:,5);
    evloume=a(:,3);

  [p,q]=size(a);
   for i=1:p
      if fromnode(i)<2000 & tonode(i)<2000
       evolume(i)=volume(i)+1.71;
    else
        evolume(i)=0;
     end

       if  evolume(i)==0;
           time(i)=0;
                end
       end
   evolume1=evolume';
    VMTemme = sum(length.*evolume1)*1.6
```

**Comparison of truck AADT to model under "no SLR" scenario.**

| Site | Road Category | AADT (trucks only) | Model |
|---|---|---|---|
| 2536 | 5 | 0 | 1.71 |
| 2537 | 5 | 0 | 1.71 |
| 2540 | 5 | 8 | 1.71 |
| 2541 | 5 | 5 | 1.71 |
| 2569 | 5 | 3 | 1.71 |
| 2576 | 5 | 1 | 1.71 |
| 2578 | 5 | 6 | 1.71 |
| 2582 | 5 | 1 | 3.71 |
| 2584 | 5 | 4 | 3.71 |
| 2586 | 5 | 6 | 1.71 |
| 2589 | 5 | 3 | 3.71 |
| 2592 | 5 | 9 | 11.71 |
| 2530 | 7 | 24 | 43.71 |
| 2531 | 7 | 14 | 47.71 |
| 2532 | 7 | 17 | 25.71 |
| 2542 | 7 | 22 | 33.71 |
| 2543 | 7 | 49 | 57.71 |
| 2546 | 7 | 19 | 135.71 |
| 2562 | 7 | 35 | 25.71 |
| 2563 | 7 | 27 | 45.71 |
| 2566 | 7 | 20 | 25.71 |
| 2575 | 7 | 45 | 63.71 |
| 2577 | 7 | 20 | 25.71 |
| 2593 | 7 | 46 | 61.71 |
| 2539 | 9 | 41 | 17.71 |
| 2547 | 9 | 7 | 27.71 |
| 2549 | 9 | 21 | 65.71 |
| 2556 | 9 | 29 | 75.71 |
| 2565 | 9 | 54 | 103.71 |
| 2568 | 9 | 49 | 33.71 |
| 2580 | 9 | 17 | 7.71 |
| 2533 | 10 | 179 | 159.71 |
| 2535 | 10 | 533 | 389.71 |
| 2538 | 10 | 550 | 361.71 |
| 2544 | 10 | 244 | 293.71 |
| 2545 | 10 | 158 | 189.71 |
| 2548 | 10 | 605 | 391.71 |
| 2552 | 10 | 239 | 281.71 |
| 2557 | 10 | 365 | 317.71 |
| 2559 | 10 | 137 | 145.71 |
| 2560 | 10 | 165 | 117.71 |
| 2564 | 10 | 399.5 | 559.71 |
| 2570 | 10 | 19 | 31.71 |

| | | | |
|---|---|---|---|
| 2571 | 10 | 524 | 305.71 |
| 2581 | 10 | 643 | 455.71 |
| 2583 | 10 | 463 | 265.71 |
| 2587 | 10 | 52 | 71.71 |
| 2588 | 10 | 262 | 127.71 |
| 2591 | 10 | 347 | 217.71 |
| 2594 | 10 | 647 | 307.71 |
| 2595 | 10 | 55 | 61.71 |
| 2597 | 10 | 423 | 269.71 |

# Appendix E

# Typical Construction Costs for Local Minnesota Roads

## Typical Construction Costs for Local Minnesota Roads

Two sources were received in our attempt to determine statewide costs for rehabilitation of roads. The first came through phone conversations with five of the eight State District Engineers. The second is a life-cycle cost analysis via Goodhue County Engineer, Greg Isakson. Both methods gave viable cost estimates, but the values varied to a great extent. The 50-yr life cycle cost gave statewide average values of $434,694 for reconstruction of a road ($275,264 for regrading, $159,430 for paving) and $74,542 for an overlay. The district engineers provided numbers that ranged from $200,000 to $2 million for reconstruction of a road and $50,000 to $80,000 for a functional overlay.

### District Estimations

The first cost estimates came from the District Engineers through phone conversations. These values were received from five of the eight State Districts. The estimates are given for county state aid highways, county roads, Minnesota state aid roads, and residential streets and include the costs for reconstruction, structural overlays, and functional overlays. These estimates presented a very wide range of values. The information varied because of different assumptions made by each district. The estimates and factors influencing those costs estimates for each reporting district are listed below in Table 1.

Table 1 District Cost Estimates

**District 1**

| Category | Reconstruct | Structural Overlay | Functional Overlay |
|---|---|---|---|
| CSAH 9,10-ton | $500,000 | $175,000 | $80,000 |
| CSAH 7-ton | $400,000 | $175,000 | $80,000 |
| CR 9-ton | $450,000 | $175,000 | $80,000 |
| CR 7-ton | $350,000 | $150,000 | $70,000 |
| CR 5-ton paved | NA | NA | NA |
| CR 5-ton Agg | $250,000 | $50,000 | 50,000-regravel |
| MSA 9,10-ton | $800,000 | $200,000 | $120,000 |
| MSA 7-ton | $700,000 | $200,000 | $120,000 |
| Residential Streets | NA | NA | NA |
| Township Rd, Paved | $300,000 | $140,000 | $70,000 |
| Township Rd, Agg | $200,000 | 30,000-regravel | 30,000-regravel |

Factors influencing costs

1) Duluth and surrounding area

**District 4**

| Category | Reconstruct | Structural Overlay | Functional Overlay |
|---|---|---|---|
| CSAH 9,10-ton | $200,000 | $115,000 | $80,000 |
| CSAH 7-ton | NA | NA | NA |
| CR 9-ton | NA | NA | NA |
| CR 7-ton | NA | NA | NA |
| CR 5-ton paved | NA | NA | NA |
| CR 5-ton Agg | NA | NA | NA |
| MSA 9,10-ton | $2,000,000 | NA | NA |
| MSA 7-ton | NA | NA | NA |
| Residential Streets | $2,300,000 | NA | $100,000 |
| Township Rd, Paved | NA | NA | NA |
| Township Rd, Agg | NA | NA | NA |

Factors influencing costs:

1) Mainly Rural roads (Detroit Lakes area)
2) Costs are all inclusive (Bituminous surface, shoulders, lining, etc.)
3) Structural Overlays are considered 3-in.
4) Functional Overlays are considered 1.5 to 2-in.

**District 7**

| Category | Reconstruct | Structural Overlay | Functional Overlay |
|---|---|---|---|
| CSAH 9,10-ton | $540,000 | $80,000 | $40,000 |
| CSAH 7-ton | NA | NA | NA |
| CR 9-ton | $540,000 | $80,000 | $40,000 |
| CR 7-ton | NA | NA | NA |
| CR 5-ton paved | NA | NA | NA |
| CR 5-ton Agg | $100,000 | NA | NA |
| MSA 9,10-ton | $2,370,000 | $800,000 | $170,000 |
| MSA 7-ton | $2,200,000 | $600,000 | $170,000 |
| Lt. Industrial | $2,320,000 | $720,000 | $108,000 |
| Residential Streets | $2,020,000 | $630,000 | $92,000 |
| Township Rd, Paved | NA | NA | NA |
| Township Rd, Agg | $20,000 | NA | NA |

Factors influencing costs:

1) All costs come from Nobles County in Southwestern MN
2) Costs are all inclusive (Bituminous surface, shoulders, lining, etc.)
3) Mainly rural roads

4) Estimates tend to be higher than for District 4 and District 8's estimates due to county's tendency to use 8-ft shoulders instead of 4-ft shoulders. The shoulders are widened because of the high volume of farm equipment using the roads.
5) $93,500/mi cost of grading road (reconstruction).

**District 8**

| Category | Reconstruct | Structural Overlay | Functional Overlay |
|---|---|---|---|
| CSAH 9,10-ton | $270,000 | $58,000 | $50,000 |
| CSAH 7-ton | $210,000 | $58,000 | $50,000 |
| CR 9-ton | $250,000 | $55,000 | $45,000 |
| CR 7-ton | $200,000 | $55,000 | $45,000 |
| CR 5-ton paved | $180,000 | $55,000 | $45,000 |
| CR 5-ton Agg | $70,000 | NA | NA |
| MSA 9,10-ton | $800,000 | $120,000 | $80,000 |
| MSA 7-ton | $600,000 | $120,000 | $80,000 |
| Residential Streets | NO DATA | NO DATA | $40,000 |
| Township Rd, Paved | NO DATA | NO DATA | NO DATA |
| Township Rd, Agg | $20,000 | NA | NA |

Factors influencing costs:

1) Estimates are for Bituminous surface only
   a) another $23,000 - $30,000 estimated for all inclusive cost.
2) Mainly rural roads
3) $82,500/mi cost of grading road (reconstruction).

**Metro**

| Category | Reconstruct | Structural Overlay | Functional Overlay |
|---|---|---|---|
| CSAH 9,10-ton | $2,000,000 | $500,000 | $135,000 |
| CSAH 7-ton | $1,600,000 | $400,000 | $100,000 |
| CR 9-ton | $1,800,000 | $500,000 | $135,000 |
| CR 7-ton | $1,600,000 | $400,000 | $100,000 |
| CR 5-ton paved | $1,300,000 | $300,000 | $100,000 |
| CR 5-ton Agg | $250,000 | NA | NA |
| MSA 9,10-ton | $1,400,000 | $275,000 | $100,000 |
| MSA 7-ton | $1,200,000 | $275,000 | $100,000 |
| Residential Streets | $1,200,000 | $275,000 | $100,000 |
| Township Rd, Paved | $1,200,000 | $275,000 | $100,000 |
| Township Rd, Agg | $250,000 | NA | NA |

Factors influencing costs:

1) Urban roads
2) Estimates are upper bounds, all inclusive (subgrade, curb and gutter, lining, etc).
3) Estimates were taken from both Dakota and Ramsey counties. Costs ranged from $500,000 for reconstruction in rural areas in Dakota County to $2-million in Ramsey County.

**50-yr Life Cycle Cost Analysis**

The second source of information came from Goodhue County Engineer Greg Isakson. Mr. Isakson recently conducted a statewide study to determine the amount of time counties allow their roads to deteriorate before a reconstruction or an overlay is applied. Mr. Isakson sent out instructions to the other Minnesota counties that later responded to this study. The study found that on average, counties allowed the roads to deteriorate beyond their terminal serviceability as defined by the county engineer, assuming that in the 50-yr life of a road, the road should be rehabilitated at the 17-yr and 34-yr points to maintain a usable condition. The study found that on average, the roads were not being serviced at these times. The report provides statewide averages for regrading, paving, overlaying, and grading rock. These values are $275,264, $159,430, $74,542, and $160,265 respectfully.

These costs are all-inclusive, including engineering costs associated with the county. The factors influencing the costs do not vary from district to district as in our first cost estimates, so the values can be compared directly and a statewide average found. The figures from the study can be seen below in Table 2.

Table 2 Cost Estimates from 50-yr Life Cycle Cost Analysis

| | AVE.COST MILE REGRADE | PAVE | OVERLAY | GRADE ROCK |
|---|---|---|---|---|
| **Statewide Ave Values** | **$275,264** | **$159,430** | **$74,542** | **$160,265** |
| **DIST. 1** | $294,250 | $96,374 | $47,270 | $198,464 |
| AITKIN | $454,784 | $144,788 | $63,275 | |
| CARLTON - CSAH | $454,784 | $144,788 | $63,275 | |
| CARLTON - CR | Used alternate method | | | |
| COOK | $475,898 | $175,000 | $75,000 | $300,000 |
| ITASCA | $412,915 | $97,155 | $41,904 | $179,509 |
| KOOCHICHING | $544,565 | $197,510 | $39,332 | $350,327 |
| LAKE | Used alternate method | | | |
| PINE | $700,000 | $200,000 | $90,000 | $400,000 |
| ST. LOUIS | | | | |
| | ---------------DISTRICT 1 AVERAGE-------------- | | | |
| | $507,158 | $159,874 | $62,131 | $307,459 |

**DIST. 2**

| | | | | |
|---|---|---|---|---|
| BELTRAMI | Used alternate method | | | |
| CLEARWATER | Used alternate method | | | |
| HUBBARD - CSAH | $380,000 | $200,000 | $65,000 | $300,155 |
| HUBBARD - CR | $50,000 | $10,500 | $44,000 | $193,125 |
| KITTSON | $110,000 | $130,000 | $65,000 | $95,000 |
| LAKE OF THE WOODS | $238,757 | $98,406 | $77,930 | $209,140 |
| MARSHALL | $103,000 | $121,000 | $60,000 | $103,000 |
| NORMAN | Used alternate method | | | |
| PENNINGTON | Used alternate method | | | |
| POLK | $151,530 | $132,630 | $54,452 | $117,779 |
| RED LAKE | $188,476 | $224,017 | $55,800 | $104,745 |
| ROSEAU | $135,380 | $171,821 | $68,802 | $74,909 |

| --------------DISTRICT 2 AVERAGE-------------- | | | |
|---|---|---|---|
| $169,643 | $136,047 | $61,373 | $149,732 |

**DIST. 3**

| | | | | |
|---|---|---|---|---|
| AITKIN | $294,250 | $96,374 | $47,270 | $198,464 |
| BENTON | $302,000 | $96,500 | $63,000 | |
| CASS | $197,133 | $99,095 | $74,077 | $41,890 |
| CROW WING | $189,214 | $95,196 | $59,283 | |
| ISANTI | $340,655 | $133,818 | $42,000 | $198,000 |
| KANABEC | Used alternate method | | | |
| MILLE LACS | $426,367 | $136,914 | $63,606 | $350,000 |
| MORRISON | $124,250 | $94,965 | $39,476 | $84,170 |
| SHERBURNE CSAH | $149,103 | $89,034 | $46,909 | $132,063 |
| SHERBURNE CR | $149,103 | $89,034 | $46,909 | $132,063 |
| STEARNS | Used alternate method | | | |
| TODD | $142,300 | $251,865 | $125,000 | $142,300 |
| WADENA | $239,933 | incl. In grad. | $63,104 | $68,517 |
| WRIGHT | $654,828 | $167,414 | $90,517 | $0 |

| ----------------DISTRICT 3 AVERAGE-------------- | | | |
|---|---|---|---|
| $267,428 | $122,746 | $63,429 | $134,747 |

| | | | | |
|---|---|---|---|---|
| **DIST 4** | $204,425 | $141,327 | $77,699 | $100,000 |
| BECKER | $304,224 | $136,194 | $86,788 | $199,592 |
| BIGSTONE | $213,074 | $318,551 | $83,137 | $88,000 |
| CLAY | Used alternate method | | | |
| DOUGLAS | $157,914 | $112,748 | $60,000 | $135,000 |
| GRANT | Used alternate method | | | |
| MAHNOMEN | $424,535 | | $65,680 | |

| | | | | |
|---|---|---|---|---|
| OTTER TAIL | $342,000 | $150,000 | $65,000 | $116,000 |
| POPE | Used alternate method | | | |
| STEVENS | $184,941 | $167,400 | $64,803 | $75,000 |
| SWIFT | Used District average method ->>> | | | |
| TRAVERSE | $137,561 | $206,000 | $70,000 | $105,000 |
| WILKIN CSAH | $0 | $0 | $0 | $60,000 |
| WILKIN CR | | | | |
| | -----------------DISTRICT 4 AVERAGE-------------- | | | |
| | $218,742 | $154,028 | $63,679 | $109,824 |

| | | | | |
|---|---|---|---|---|
| **METRO** | Used alternate method | | | |
| ANOKA | Used alternate method | | | |
| CARVER | $950,224 | | $26,273 | |
| HENNEPIN | Used alternate method | | | |
| CHISAGO | | | | |
| DAKOTA | Used alternate method | | | |
| RAMSEY | Used alternate method | | | |
| SCOTT | Used alternate method | | | |
| WASHINGTON | | | | |
| | -----------------METRO AVERAGE ---------------- | | | |
| | $950,224 | #DIV/0! | $26,273 | #DIV/0! |

| | | | | |
|---|---|---|---|---|
| **DIST. 6** | $303,661 | $128,146 | $60,000 | $225,000 |
| DODGE | $369,363 | $190,120 | $45,845 | $305,323 |
| FILLMORE | $397,166 | $131,992 | $50,900 | $190,965 |
| FREEBORN | $518,035 | $179,703 | $64,007 | $377,491 |
| GOODHUE | $883,680 | $239,153 | $112,842 | $424,634 |
| HOUSTON | Used alternate method | | | |
| MOWER | $417,021 | $350,266 | $103,351 | $250,000 |
| OLMSTED | $400,000 | $110,000 | $85,000 | $400,000 |
| RICE | $300,000 | $150,000 | $90,000 | |
| STEELE | $363,271 | $175,162 | $87,000 | $320,000 |
| WABASHA | Used alternate method | | | |
| WINONA | | | | |
| | -----------------DISTRICT 6 AVERAGE ------------ | | | |
| | $439,133 | $183,838 | $77,661 | $311,677 |

| | | | | |
|---|---|---|---|---|
| **DIST. 7** | Used alternate method | | | |
| BLUE EARTH | $169,946 | $142,121 | $53,263 | $84,000 |
| BROWN | $176,000 | $180,000 | $60,000 | $110,000 |
| COTTONWOOD | $278,253 | $317,964 | $61,000 | $100,000 |
| FARIBAULT | $124,038 | $219,286 | $47,804 | $105,148 |
| JACKSON | Used alternate method | | | |
| LE SUEUR - CSAH | Used alternate method | | | |
| LE SUEUR - CR | $120,719 | $256,683 | $67,666 | $100,570 |
| MARTIN | $153,554 | $143,392 | $133,673 | $75,362 |
| NICOLLET | $551,367 | $141,332 | $59,329 | $133,152 |
| NOBLES | $232,106 | $124,658 | $74,187 | $184,179 |
| ROCK | $96,000 | $103,200 | $103,200 | $114,000 |
| SIBLEY | Used alternate method | | | |
| WASECA | $148,029 | $220,346 | $36,724 | $58,817 |
| WATONWAN | | | | |
| | -----------------DISTRICT 7 AVERAGE -------------- | | | |
| | $205,001 | $184,898 | $69,685 | $106,523 |

| | | | | |
|---|---|---|---|---|
| **DIST. 8** | $200,689 | $223,289 | $65,000 | $140,000 |
| CHIPPEWA | Used District average method ->>> | | | |
| KANDIYOHI | $114,139 | $113,818 | $64,599 | $109,000 |
| LAC QUI PARLE | $215,325 | $175,000 | $56,000 | $83,500 |
| LINCOLN | Used District average method ->>> | | | |
| LYON | $159,474 | $191,221 | $60,000 | $150,000 |
| MC LEOD - CSAH | $161,136 | $194,944 | $60,000 | $150,000 |
| MC LEOD - CR | Used District average method ->>> | | | |
| MEEKER | $179,845 | $154,465 | $50,000 | $140,000 |
| MURRAY - CSAH | $150,000 | $153,000 | $50,000 | $140,000 |
| MURRAY - CR | $178,623 | $112,617 | $50,000 | $125,000 |
| PIPESTONE | $118,761 | $179,557 | $712,271 | $83,554 |
| REDWOOD | $167,553 | $171,609 | $70,000 | $100,000 |
| RENVILLE - CSAH | $100,000 | $170,000 | $70,000 | $100,000 |
| RENVILLE - CR | $166,779 | $230,431 | $66,368 | $82,470 |
| YELLOW MEDICINE | | | | |
| | -----------------DISTRICT 8 AVERAGE-------------- | | | |
| | $159,360 | $172,496 | $114,520 | $116,960 |

# Appendix F

# Calculations and Cash-flow diagrams for alternative policy scenarios

*Scenario 3A:*

Figure A-1 shows the cash flow in scenario 3A. In this case, the 7-ton roads are upgraded at the first overlay and restrictions are lifted at that time. The first overlay occurs 8.5 years from now. There is an increased overlay cost at the end of that year because instead of a functional overlay, a structural overlay is performed. The improved network reduces truck VMT compared to the with SLR scenario. Thus there is a reduced cost to truckers every year after the 8.5th year.

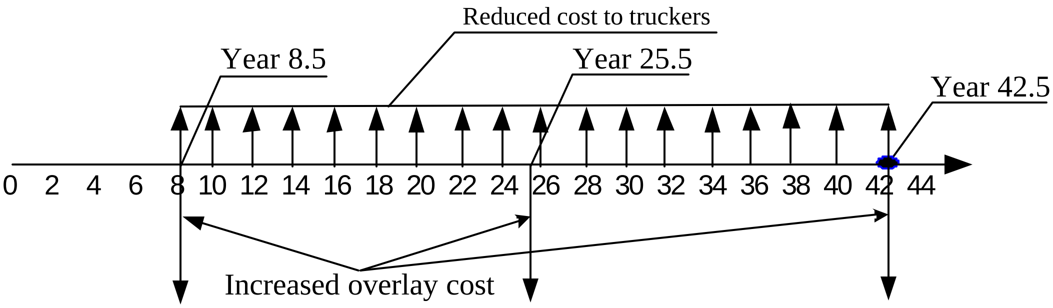



**Figure A-1. Cash flow diagram of scenario 3A**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County at year 8.5 is:

(($ 124,844) – ($ 67,380)) * (260 km) / (1.6 km/mile) = $ 9,337,900

At the second overlay, because the formerly 7-ton roads are now 9-ton roads, there is an increased cost of overlaying these roads:

(($ 68,565/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 192,563.

It is necessary to find net present value of these costs:

$$\$\ 9{,}337{,}900 * \frac{1}{(1+i)^{8.5}} + \$\ 192{,}562 * \frac{1}{(1+i)^{22.5}} = \underline{\$\ 7{,}050{,}469}$$

**Benefit:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 77,585 miles per day. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost is:

($ 0.69 / km) * ((82,050 miles/day) – (77,585 miles/day)) * (1.6 km/mile) = $ 4,929.25/day

Assuming 8 weeks of SLR enforcement (and 100% compliance), the annual saving is:

($ 6,238.37 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 276,038

The present value of reduced cost to trucker is for the time from year 8.5 to year 42.5 is:

$$\$\ 276{,}037.98 * \frac{((1+i)^{34}-1)}{i*(1+i)^{34}(1+i)^{8.5}} = \underline{\$\ 4{,}059{,}356}$$

The benefit/cost ratio is 0.58.

*Scenario 4A:*

Figure A-2 shows the cash flow in scenario 4A. In this sub scenario, the 7-ton roads and 9-ton roads are upgraded at the first overlay and restrictions are lifted at that time. The first overlay occurs 8.5 years from now. There is an increased overlay cost at the end of that year because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the with SLR scenario. Thus there is a reduced cost to truckers every year after the 8.5th year.

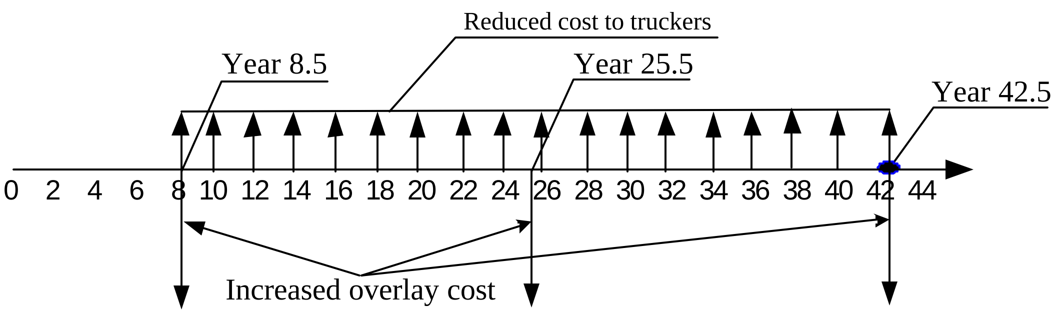



**Figure A-2 Cash flow diagram of scenario 4A**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County in year 8.5 is:

(($ 124,844/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 9,337,900

The increased overlay cost for 9-ton roads in Lyon County in year 8.5 is:

(($ 133,520/mile) – ($ 68,565/mile)) * (191 km) / (1.6 km/mile) = $ 7,754,003

At the second overlay, because the roads have been upgraded, there is additional cost. Roads that were formerly 7-ton roads are now 9-ton roads and 9-ton roads are now 10-ton roads. There is no additional overlay cost for 10-ton roads, but there is an increased cost for the functional overlays of the formerly 7-ton roads:

(($ 68,565/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 192,563.

It is necessary to find net present value of these costs:

$$(\$\ 9{,}337{,}900 + \$\ 7{,}754{,}003) * \frac{1}{(1+i)^{8.5}} + \$\ 192{,}562 * \frac{1}{(1+i)^{25.5}} = \underline{\$\ 12{,}838{,}529}$$

**Benefit:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 76,400 miles per day for the period from year 8.5 to year 42.5. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost from year 8.5 to year 42.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,400 miles/day)) * (1.6 km/mile) = $ 6,238/day
Assuming 8 weeks of SLR enforcement, the annual savings from year 8.5 to year 42.5 are:

($ 6,238 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

The present value of reduced cost to truckers is for the time from year 8.5 to year 42.5 is:

$$\$\ 349{,}349 * \frac{((1+i)^{34}-1)}{i*(1+i)^{34}(1+i)^{8.5}} = \underline{\$\ 5{,}137{,}451}$$

The benefit/cost ratio is 0.40.

*Scenario 5A:*

Figure A-3 shows the cash flow in scenario 5A. In this sub scenario, the 7-ton roads and 9-ton roads are upgraded at the first overlay and restrictions are lifted in year 8.5. The formerly 7-ton roads are also upgraded a second time in year 25.5. There is an increased overlay cost at the end each of these years because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. Thus there is a reduced cost to truckers every year after the 8.5th year.

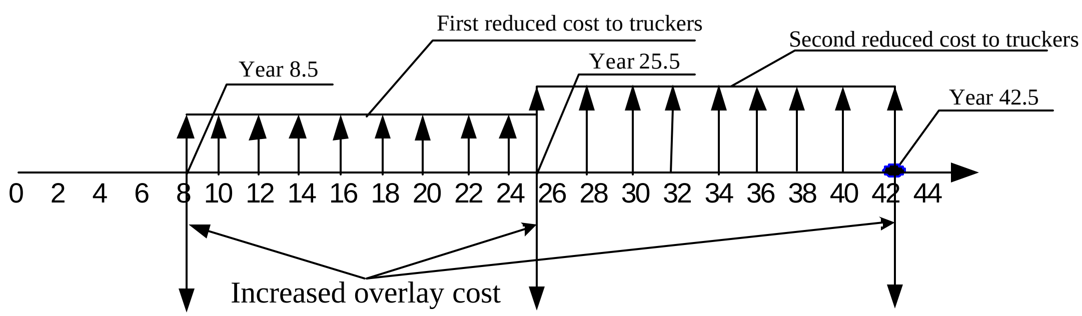



**Figure A-3 Cash flow diagram of scenario 5A**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County in year 8.5 is:

(($ 124,844/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 9,337,900

The increased overlay cost for 9-ton roads in Lyon County in year 8.5 is:

(($ 133,520/mile) – ($ 68,565/mile)) * (191 km) / (1.6 km/mile) = $ 7,754,003

The increased overlay cost for formerly 7-ton roads in Lyon County in year 25.5 is:

(($ 133,520/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 10,747,750

There is no additional overlay cost for 10-ton roads.

It is necessary to find net present value of these costs:

$$(\$\ 9{,}337{,}900 + \$\ 7{,}754{,}003) * \frac{1}{(1+i)^{8.5}} + \$\ 10{,}747{,}750 * \frac{1}{(1+i)^{25.5}} = \underline{\$\ 17{,}228{,}757}$$

**Benefit:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 76,400 miles per day for the period from year 8.5 to year 25.5. For the period from 25.5 to 42.5, truck VMT decreases from 82,050 miles per day to 73,024 miles per day. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost from year 8.5 to year 25.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,400 miles/day)) * (1.6 km/mile) = $ 6,238/day

The daily saving on truck operation cost from year 25.5 to year 42.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (73,024 miles/day)) * (1.6 km/mile) = $ 9,965/day

Assuming 8 weeks of SLR enforcement, the annual savings from year 8.5 to year 25.5 are:

($ 6,238 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

Assuming 8 weeks of SLR enforcement, the annual savings from year 8.5 to year 25.5 are:

($ 9,965 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 558,061

The present value of reduced cost to truckers is for the time from year 8.5 to year 42.5 is:

$$\$\ 349{,}349 * \frac{((1+i)^{17}-1)}{i*(1+i)^{17}(1+i)^{8.5}} + \$\ 558{,}061 * \frac{((1+i)^{17}-1)}{i*(1+i)^{17}(1+i)^{25.5}} = \underline{\$\ 5{,}137{,}451}$$

The benefit/cost ratio is 0.36.

*Scenario 3B:*

Figure A-4 shows the cash flow in scenario 3B. In this sub scenario, the restrictions are removed immediately on the 7-ton roads. 7-ton roads are also upgraded at the time of the first overlay which occurs 8.5 years from now. There is an increased overlay cost at the end of that year because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. Thus there is a reduced cost to truckers every year.

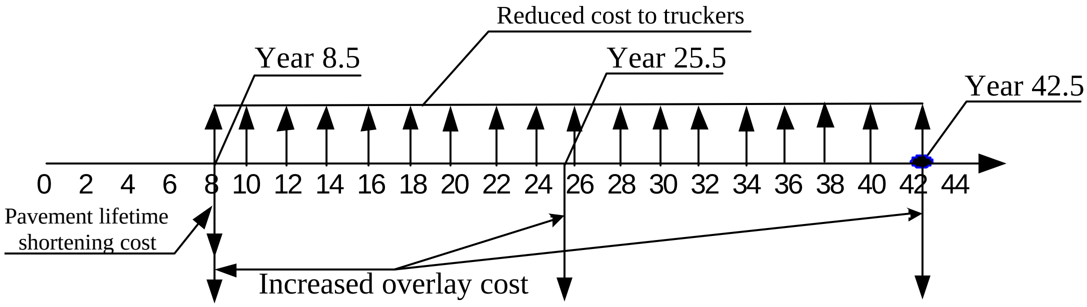



**Figure A-4 Cash flow diagram of scenario 3B**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County at year 8.5 is:
(($ 124,844) – ($ 67,380)) * (260 km) / (1.6 km/mile) = $ 9,337,900

At the second overlay, because the formerly 7-ton roads are now 9-ton roads, there is an increased cost of overlaying these roads:

(($ 68,565/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 192,563.

There is also a cost due to pavement life shortening because of the lifted restrictions which is incurred around the end of the current pavement's life which is assumed to be at the time of the first overlay. This shortening cost was calculated based on the reduced life of the road compared to a scenario that retained the SLR scenario. The value of this pavement life shortening is estimated approximately $ 181,925.

It is necessary to find net present value of these costs:

$$(\$\ 9{,}337{,}900 + \$\ 181{,}925) * \frac{1}{(1+i)^{8.5}} + \$\ 192{,}562 * \frac{1}{(1+i)^{22.5}} = \underline{\$\ 7{,}186{,}269}$$

**Benefit:**

By lifting the restrictions, the VMT decreases from 82,050 miles per day to 77,585 miles per day from now year 42.5. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost for this period is:

($ 0.69 / km) * ((82,050 miles/day) – (77,585 miles/day)) * (1.6 km/mile) = $ 4,929 /day
Assuming 8 weeks of SLR enforcement, the annual saving from now until year 42.5 is:

($ 4929 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 276,038

The present value of reduced cost to trucker is for the time from year 8.5 to year 42.5 is:

$$\$\ 276,038 * \frac{((1+i)^{42.5} - 1)}{i * (1+i)^{42.5}} = \$\ 6,058,969$$

The benefit/cost ratio is 0.84.

*Scenario 4B:*

Figure A-5 shows the cash flow in scenario 4A. In this sub scenario, 7-ton roads and 9-ton roads are upgraded at the first overlay in 8.5 years and restrictions are lifted now. There is an increased overlay cost at the end of that year because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. Thus there is a reduced cost to truckers every year.

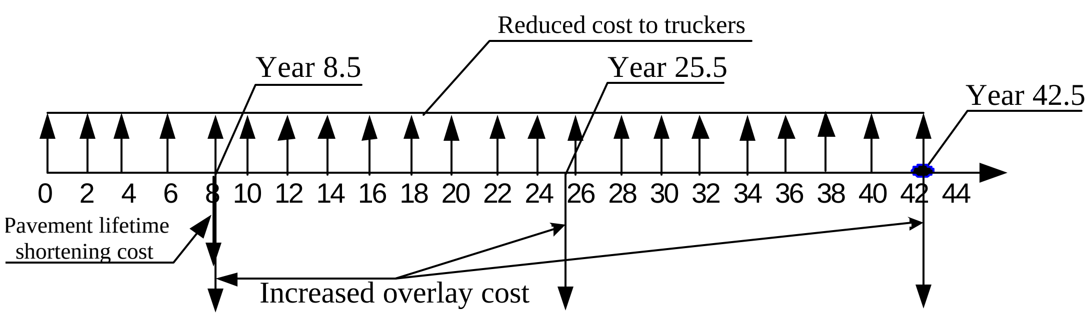



**Figure A-5 Cash flow diagram of scenario 4B**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County in year 8.5 is:

(($ 124,844/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 9,337,900

The increased overlay cost for 9-ton roads in Lyon County in year 8.5 is:

(($ 133,520/mile) – ($ 68,565/mile)) * (191 km) / (1.6 km/mile) = $ 7,754,003

At the second overlay, because the roads have been upgraded, there is additional cost. Roads that were formerly 7-ton roads are now 9-ton roads and 9-ton roads are now 10-ton roads. There is no additional overlay cost for 10-ton roads, but there is an increased cost for the functional overlays of the formerly 7-ton roads:

(($ 68,565/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 192,563.

There is also a cost due to pavement life shortening because of the lifted restrictions which is incurred around the end of the current pavement's life which is assumed to be at the time of the first overlay. This shortening cost was calculated based on the reduced life of the road compared to a scenario that retained the SLR scenario. The value of this pavement life shortening is estimated as $ 181,925.

It is necessary to find net present value of these costs:

$$(\$\ 9{,}337{,}900 + \$\ 7{,}754{,}003) * \frac{1}{(1+i)^{8.5}} + \$\ 192{,}562 * \frac{1}{(1+i)^{25.5}} = \underline{\$\ 12{,}974{,}328}$$

**Benefit:**

By lifting the restrictions now, truck VMT to decrease from 82,050 miles per day to 77,585 miles per day for the period from now until to year 8.5. For the period from year 25.5 to year 42.5, truck VMT decreases from 82,050 miles per day to 76,400 miles per day. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost from now to year 8.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (77,585 miles/day)) * (1.6 km/mile) = $ 4,929/day

The daily saving on truck operation cost from year 8.5 to year 42.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,400 miles/day)) * (1.6 km/mile) = $ 6,238/day

Assuming 8 weeks of SLR enforcement, the annual savings from now to year 8.5 are:

($ 6,238 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 276,038

The annual savings from year 25.5 to year 42.5 are:

($ 9,965 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

The present value of reduced cost to truckers is for the time from year is:

$$\$\ 276{,}038 * \frac{((1+i)^{8.5} - 1)}{i * (1+i)^{8.5}} + \$\ 349{,}349\ \frac{((1+i)^{42.5} - 1)}{i * (1+i)^{42.5} (1+i)^{8.5}} = \underline{\$\ 7{,}137{,}063}$$

The benefit/cost ratio is 0.55.

*Scenario 5B:*

Figure A-6 shows the cash flow in scenario 5A. In this sub scenario, the 7-ton roads and 9-ton roads are upgraded at the first overlay and restrictions are lifted in year 8.5. The formerly 7-ton roads are also upgraded a second time in year 25.5. There is an increased overlay cost at the end each of these years because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. Thus there is a reduced cost to truckers every year after the 8.5th year.

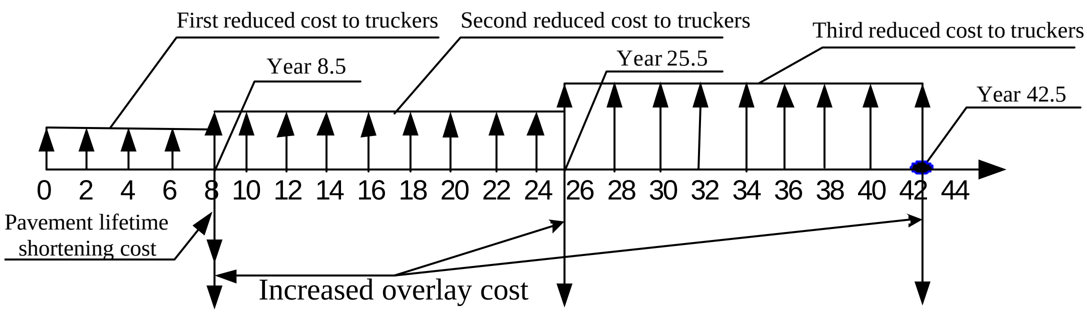



**Figure A-6 Cash flow diagram of scenario 5B**

**Cost:**

The increased overlay cost for 7-ton roads in Lyon County in year 8.5 is:

(($ 124,844/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 9,337,900

The increased overlay cost for 9-ton roads in Lyon County in year 8.5 is:

(($ 133,520/mile) – ($ 68,565/mile)) * (191 km) / (1.6 km/mile) = $ 7,754,003

The increased overlay cost for formerly 7-ton roads in Lyon County in year 25.5 is:

(($ 133,520/mile) – ($ 67,380/mile)) * (260 km) / (1.6 km/mile) = $ 10,747,750

There is no additional overlay cost for 10-ton roads.

There is also a cost due to pavement life shortening because of the lifted restrictions which is incurred around the end of the current pavement's life which is assumed to be at the time of the first overlay. This shortening cost was calculated based on the reduced life of the road compared to a scenario that retained the SLR scenario. The value of this pavement life shortening is $ 181,925.

It is necessary to find net present value of these costs:

$$(\$\ 9{,}337{,}900 + \$\ 7{,}754{,}003 + \$\ 181{,}925) * \frac{1}{(1+i)^{8.5}} + \$\ 10{,}747{,}750 * \frac{1}{(1+i)^{25.5}} = \underline{\$\ 17{,}364{,}556}$$

**Benefit:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 77,585 miles per day for the period from now until year 8.5. For the period from year 8.5 to year 25.5, the VMT decreases from 82,050 miles per day to 76,400 miles per day. For the period from year 25.5 to 42.5, truck VMT decreases from 82,050 miles per day to 73,024 miles per day. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost from now to year 8.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,400 miles/day)) * (1.6 km/mile) = $ 4,929/day

The daily saving on truck operation cost from year 8.5 to year 25.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,400 miles/day)) * (1.6 km/mile) = $ 6,238/day

The daily saving on truck operation cost from year 25.5 to year 42.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (73,024 miles/day)) * (1.6 km/mile) = $ 9,965/day

Assuming 8 weeks of SLR enforcement, the annual savings from now to year 8.5 are:

($ 4,929 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 276,038

Assuming 8 weeks of SLR enforcement, the annual savings from year 8.5 to year 25.5 are:

($ 6,238 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

Assuming 8 weeks of SLR enforcement, the annual savings from year 8.5 to year 25.5 are:

($ 9,965 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 558,061

The present value of reduced cost to truckers is for the time from year 8.5 to year 42.5 is:

$$\$\ 276{,}038 * \frac{((1+i)^{8.5}-1)}{i*(1+i)^{8.5}} + \$\ 349{,}349 * \frac{((1+i)^{17}-1)}{i*(1+i)^{17}(1+i)^{8.5}} + \$\ 558{,}061 * \frac{((1+i)^{17}-1)}{i*(1+i)^{17}(1+i)^{25.5}} =$$

<u>$ 8,235,320</u>

The benefit/cost ratio is 0.47.

*Scenario 3C:*

Figure A-7 shows the cash flow in scenario 3C. In this sub scenario, the 7-ton roads are upgraded immediately. There is an increased overlay cost at the end of years 17 and 34 because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. For scenario 3C, it is better to compare the costs of each scenario instead of the Cost due to choosing an alternative because the overlays happen at different times. After the total of each cost has been found, then the difference will give the Cost.

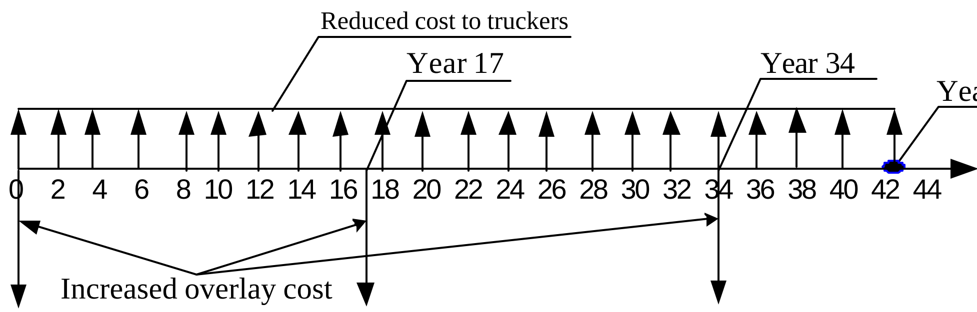



**Figure A-7 Cash flow diagram of scenario 3C**

**Costs:**

Costs of SLR policy:

The first cost that is incurred for this scenario is a structural overlay on 7-ton roads at year 8.5 and a functional overlay on 9-ton roads. The next cost will be functional overlays on 9-ton and formerly 7-ton roads. The total net present value of these costs is the sum of the following:

$$(\$\ 67{,}380/\text{mile}) * (260\text{ km}) / (1.6\text{ km/mile}) * \frac{1}{(1+i)^{8.5}}$$

$$+ \quad (\$\ 68{,}565/\text{mile}) * (260\text{ km}) / (1.6\text{ km/mile}) * \frac{1}{(1+i)^{22.5}}$$

$$+ \quad (\$\ 68{,}565/\text{mile}) * (191\text{ km}) / (1.6\text{ km/mile}) * \frac{1}{(1+i)^{8.5}}$$

$$+ \quad (\$\ 68{,}565/\text{mile}) * (191\text{ km}) / (1.6\text{ km/mile}) * \frac{1}{(1+i)^{22.5}}$$

$$= \quad \$\ 22{,}241{,}430$$

Costs of Scenario 3C:

The first cost that is incurred for this scenario is an immediate structural overlay on 7-ton roads and a functional overlay on 9-ton roads. The next cost will be functional overlays on 9-ton and formerly 7-ton roads at years 17 and 34. The total net present value of these costs is the sum of the following:

$$
\begin{aligned}
& (\$\ 124{,}844/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) \\
+ \quad & (\$\ 68{,}565/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{17}} \\
+ \quad & (\$\ 68{,}565/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{34}} \\
+ \quad & (\$\ 68{,}565/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) \\
+ \quad & (\$\ 68{,}565/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{17}} \\
+ \quad & (\$\ 68{,}565/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{34}} \\
= \quad & \$\ 42{,}241{,}288
\end{aligned}
$$

The Cost is the difference of these costs:

($ 42,241,288) – ($ 22,241,430) = $ 19,999,858

**Benefits:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 77,585 miles per day for the period from now until year 42.5. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost is:

($ 0.69 / km) * ((82,050 miles/day) – (77,585 miles/day)) * (1.6 km/mile) = $ 4,929/day

Assuming 8 weeks of SLR enforcement, the annual savings from now to year 42.5 are:

($ 4,929 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 276,038

The present value of reduced cost to truckers is:

$$\$\ 276{,}038 * \frac{((1+i)^{42.5} - 1)}{i * (1+i)^{42.5}} = \underline{\$\ 6{,}058{,}969}$$

The benefit/cost ratio is 0.30.

*Scenario 4C:*

Figure A-8 shows the cash flow in scenario 4C. In this sub scenario, the 7-ton roads and 9-ton roads are upgraded immediately. There is an increased overlay cost at the end each of years 17 and 34 because instead of functional overlays, structural overlays are performed on the 7 and 9-ton roads. The improved network reduces truck VMT compared to the "with SLR" scenario. For scenario 4C, it is better to compare the costs of each scenario instead of the cost due to choosing an alternative because the overlays happen at different times. After the total of each cost has been found, then the difference will give the cost.

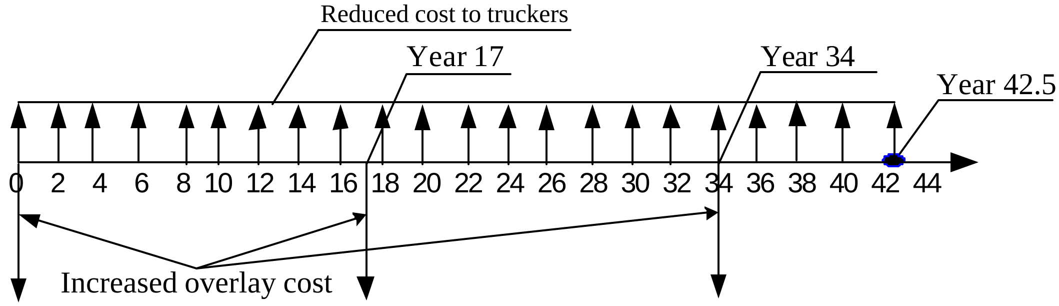



**Figure A-8 Cash flow diagram of scenario 4C**

**Costs:**

Costs of SLR policy are the same as calculated in 3C.
Costs of Scenario 4C:

The first costs that are incurred for this scenario are immediate structural overlays on 7 and 9-ton roads. The next cost will be functional overlays on 9-ton and formerly 7-ton roads at years 17 and 34. The total net present value of these costs is the sum of the following:

$$
\begin{aligned}
& (\$\ 124{,}844/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) \\
+\ & (\$\ 68{,}565/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{17}} \\
+\ & (\$\ 68{,}565/\text{mile}) * (260\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{34}} \\
+\ & (\$\ 133{,}520/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) \\
+\ & (\$\ 68{,}565/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{17}} \\
+\ & (\$\ 68{,}565/\text{mile}) * (191\ \text{km}) / (1.6\ \text{km/mile}) * \frac{1}{(1+i)^{34}} \\
=\ & \$\ 54{,}315{,}851
\end{aligned}
$$

The Cost is the difference of these costs:

($ 54,315,851) – ($ 22,241,430) = $ 32,074,421

**Benefits:**

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 76,399 miles per day for the period from now until year 42.5. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost is:

($ 0.69 / km) * ((82,050 miles/day) – (76,399 miles/day)) * (1.6 km/mile) = $ 6,238/day

Assuming 8 weeks of SLR enforcement, the annual savings from now to year 42.5 are:

($ 4,929 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

The present value of reduced cost to truckers is:

$$\$ 349{,}349 * \frac{((1+i)^{42.5}-1)}{i*(1+i)^{42.5}} = \underline{\$ 7{,}668{,}126}$$

The benefit/cost ratio is 0.24.

*Scenario 5C:*

Figure A-9 shows the cash flow in scenario 5C. In this sub scenario, the 7-ton roads and 9-ton roads are upgraded immediately. The formerly 7-ton roads are also upgraded a second time in year 17. The improved network reduces truck VMT compared to the “with SLR” scenario. For scenario 5C, it is better to compare the costs of each scenario instead of the Cost due to choosing an alternative, because the overlays happen at different times. After the total of each cost has been found, then the difference will give the Cost.

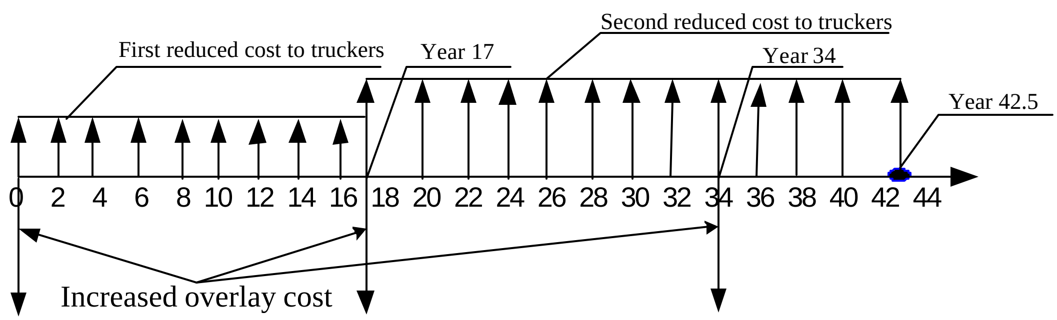



**Figure A-9 Cash flow diagram of scenario 5C**

**Costs:**

Costs of SLR policy are the same as calculated in 3C.

Costs of Scenario 3C:

The first cost that is incurred for this scenario is an immediate structural overlay on 7-ton roads and a functional overlay on 9-ton roads. The next cost will be functional overlays on 9-ton and formerly 7-ton roads at years 17 and 34. The total net present value of these costs is the sum of the following:

($ 124,844/mile) * (260 km) / (1.6 km/mile)

\+ ($ 133,520/mile) * (260 km) / (1.6 km/mile) * $\frac{1}{(1+i)^{17}}$

\+ ($ 68,565/mile) * (260 km) / (1.6 km/mile) * $\frac{1}{(1+i)^{34}}$

\+ ($ 133,520/mile) * (191 km) / (1.6 km/mile)

\+ ($ 68,565/mile) * (191 km) / (1.6 km/mile) * $\frac{1}{(1+i)^{17}}$

\+ ($ 68,565/mile) * (191 km) / (1.6 km/mile) * $\frac{1}{(1+i)^{34}}$

= $ 60,197,242

The Cost is the difference of these costs:
($ 42,241,288) – ($60,197,242) = <u>$ 37,955,811</u>

**Benefits**:

The upgrade of road network caused truck VMT to decrease from 82,050 miles per day to 76,399 miles per day for the period from now until year 17 and from 82,050 miles per day to 73,024 miles/day for the period from year 17 to year 42.5. Assuming the total operation cost per kilometer is $0.69, the daily saving on truck operation cost from now until year 17 is:

($ 0.69 / km) * ((82,050 miles/day) – (76,399 miles/day)) * (1.6 km/mile) = $ 6,238/day

The daily saving on truck operation cost from year 17 until year 42.5 is:

($ 0.69 / km) * ((82,050 miles/day) – (73,024 miles/day)) * (1.6 km/mile) = $ 9,965/day

Assuming 8 weeks of SLR enforcement, the annual savings from now to year 17 are:

($6,238 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 349,349

Assuming 8 weeks of SLR enforcement, the annual savings from year 17 to year 42.5 are:

($9,965 / day) * (7 days/week) * 8 (weeks/SLR period) = $ 558,061

The present value of reduced cost to truckers is:

$$\$\ 349{,}349 * \frac{((1+i)^{17}-1)}{i*(1+i)^{17}} + \$\ 558{,}061 * \frac{((1+i)^{25.5}-1)}{i*(1+i)^{25.5}(1+i)^{17}} = \underline{\$\ 9{,}608{,}820}$$

The benefit/cost ratio is 0.25.

# Appendix G
# Seasonal Load Restriction Law

**169.87 Seasonal load restriction; route designation.**

*Note: 2002 the Office of Revisor of Statutes, State of Minnesota.*

Subdivision 1. **Optional power.** (a) Local authorities, with respect to highways under their jurisdiction, may prohibit the operation of vehicles upon any such highway or impose restrictions as to the weight of vehicles to be operated upon any such highway, whenever any such highway, by reason of deterioration, rain, snow, or other climatic conditions, will be seriously damaged or destroyed unless the use of vehicles thereon is prohibited or the permissible weights thereof reduced.

(b) The local authority enacting any such prohibition or restriction shall erect or cause to be erected and maintained signs plainly indicating the prohibition or restriction at each end of that portion of any highway affected thereby, and the prohibition or restriction shall not be effective unless and until such signs are erected and maintained.

(c) Municipalities, with respect to highways under their jurisdiction, may also, by ordinance, prohibit the operation of trucks or other commercial vehicles, or may impose limitations as to the weight thereof, on designated highways, which prohibitions and limitations shall be designated by appropriate signs placed on such highways.

(d) The commissioner shall likewise have authority, as hereinabove granted to local authorities, to determine and to impose prohibitions or restrictions as to the weight of vehicles operated upon any highway under the jurisdiction of the commissioner, and such restrictions shall be effective when signs giving notice thereof are erected upon the highway or portion of any highway affected by such action.

(e) When a local authority petitions the commissioner to establish a truck route for travel into, through, or out of the territory under its jurisdiction, the commissioner shall investigate the matter. If the commissioner determines from investigation that the operation of trucks into, through, or out of the territory involves unusual hazards because of any or all of the following factors; load carried, type of truck used, or topographic or weather conditions, the commissioner may, by order, designate certain highways under the commissioner's jurisdiction as truck routes into, through, or out of such territory. When these highways have been marked as truck routes pursuant to the order, trucks traveling into, through, or out of the territory shall comply with the order.

Subd. 2. **Seasonal load restriction.** Except for portland cement concrete roads, between the dates set by the commissioner of transportation each year, the weight on any single axle shall not exceed five tons on a county highway, town road, or city street that has not been restricted as provided in subdivision 1. The gross weight on consecutive axles shall not exceed the gross weight allowed in sections 169.822 to 169.829 multiplied by a factor of five divided by nine. This reduction shall not apply to the gross vehicle weight.

-2Subd. 3. **School bus and Head Start bus.** Weight restrictions imposed pursuant to subdivisions 1 and 2 do not apply to a school bus or Head Start bus transporting students, Head Start children, or Head Start parents when the gross weight on a single axle of the school bus or Head Start bus does not exceed 14,000 pounds; provided that, road authorities may restrict any highway under their jurisdiction to a lesser axle weight by written order to school boards and Head Start grantees 24 hours in advance of required compliance with such reduced axle weight.

Subd. 4. **Vehicle transporting milk.** Until June 1,2003, a weight restriction imposed under subdivision 1 by the commissioner of transportation or a local road authority, or imposed by subdivision 2, does not apply to a vehicle transporting milk from the point of production to the point of first processing if, at the time the weight restriction is exceeded, the vehicle is carrying milk loaded at only one point of production. This subdivision does not authorize a vehicle described in this subdivision to exceed a weight restriction of five tons per axle by more than two tons per axle.

Subd. 5. **Utility vehicles.** (a) Weight restrictions imposed by the commissioner under subdivision 1 do not apply to a two-axle or three-axle utility vehicle that does not exceed a weight of 20,000 pounds per single axle and 36,000 pounds gross vehicle weight for a two-axle vehicle or 48,000 pounds gross vehicle weight for a three-axle vehicle, if the vehicle is owned by:

(1) a public utility as defined in section 216B.02;

(2) a municipality or municipal utility that operates the vehicle for its municipal electric, gas, or water system; or

(3) a cooperative electric association organized under chapter 308A.

(b) The exemption in this subdivision applies only when the vehicle is performing service restoration or other work necessary to prevent an imminent loss of service.

Subd. 6. **Recycling vehicles.** Weight restrictions imposed under subdivisions 1 and 2 do not apply to a two-axle vehicle that does not exceed 20,000 pounds per single axle and is used exclusively for recycling, while engaged in recycling in a political subdivision that mandates curbside recycling pickup.

HIST: (2720-279) 1937 c 464 s 129; 1947 c 505 s 1; 1949 c 695 s 1; 1951 c 445 s 1; 1967 c 12 s 1; 1967 c 467 s 1; 1973 c 85 s 1; 1981 c 321 s 9; 1982 c 617 s 15; 1986 c 444; 1994 c 603 s 15; 1999 c 154 s 2; 1999 c 230 s 16; 2000 c 433 s 2,3

* NOTE: Subdivisions 5 and 6, as added by Laws 2000, chapter *433, sections 2 and 3, are repealed June 1, 2003. Laws 2000, *chapter 433, section 4.

# Appendix H Spring Load Capacity - Calculated from relationship developed using Inv. 183 Data

Mn/DOT Investigation 183, *Application of AASHO Road Test Results to Design of Flexible Pavements in Minesota,* was an AASHO Road Test Satellite study for flexible pavements in Minnesota. Inv 183 included 58 test sections that were established on in-service Minnesota Trunk Highways. The composition of the pavement section by layer thickness and type plus the stiffness of the subgrade soil was identified for each section. The surface condition of each section was monitored for 14 years for most of the sections. Traffic was monitored on the sections to determine traffic volume and weight by vehicle type on a seasonal basis in 1964 and in 1970. Traffic data collected on those same sections included counts for AADT, HCADT, and seasonal weightings using portable scales. Because seasonal weightings were part of the study, calculations could be made that characterized the number of equivalent 18,000-pound single axle loads (ESALs) applied to the sections by season. Using the seasonal ESALs, a factor representing the percent of the unfrozen ESAL applications that occurred in the spring, SPPT, was calculated and assigned to each test section. The total ESAL accumulation to a terminal serviceability of 2.5, based on the AASHO Present Serviceability Index concept, was established for each section as part of the overall study.

The Inv 183 study is a performance-based study, as opposed to a mechanistic-empirical study, that is most useful for relating layer thicknesses and underlying subgrade support to ESAL capacity. The Inv 183 study is useful for the spring load restriction study because it provides the only known performance-based data set from pavements that are similar to today's typical local road pavements. Some of the sections in Inv 183 had spring load restrictions and the layer thickness distribution is similar to today's local roads. The drawback to using Inv 183 for the spring load study is that the data represents different construction methods and HMA mix than is used today, and a different traffic stream, particularly as it relates to tire design, vehicle suspension, and type of vehicles in the traffic stream.

The application of Inv 183 to the current spring load restriction study is based on a simple regression model (Figure A-100) that has the base 10 logarithm of the number of ESALs to the terminal serviceability as the dependent variable and the thickness of the asphalt, thickness of the aggregate, base 10 logarithm of the subgrade R-value, and the percent of the total unfrozen'ESALs that occurred during the spring as the independent variables. This simple regression shows that the variable for the percent of the ESALs that were applied in the spring is significant at only the 90 percent level, which is marginal for regression purposes, but the sign of the coefficient for the SPPT variable is negative, which is considered to be the expected response, and the magnitude of the coefficient seems reasonable. Other variable transformations and/or interactions provide better overall fits (R-squared), but the resulting models tend to be less useful for this study. The primary reason to look at the Inv 183 data for this study is to compare performance predictions from Inv 183 to the performance predictions that are based on MnPAVE.

| Regression Statistics | |
|---|---|
| Multiple R | 0.72807 |
| R Square | 0.53009 |
| Adjusted R Square | 0.49323 |
| Standard Error | 0.41765 |
| Observations | 56 |

ANOVA

| | df | SS | MS | F | Significance F |
|---|---|---|---|---|---|
| Regression | 4 | 10.03536 | 2.50884 | 14.38268 | 0.00000 |
| Residual | 51 | 8.89617 | 0.17443 | | |
| Total | 55 | 18.93153 | | | |

| | Coefficients | Standard Error | t Stat | P-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| Intercept | 0.20099 | 0.34115 | 0.58917 | 0.55835 | -0.48389 | 0.88588 |
| AC | 0.13738 | 0.02963 | 4.63642 | 0.00002 | 0.07789 | 0.19686 |
| Agg | 0.03569 | 0.01218 | 2.93024 | 0.00506 | 0.01124 | 0.06014 |
| Log(R-value) | 1.07065 | 0.19692 | 5.43708 | 0.00000 | 0.67532 | 1.46598 |
| SPPT | -0.00571 | 0.00340 | -1.68205 | 0.09867 | -0.01253 | 0.00111 |

**Figure A-10. Regression Coefficient from the Inv 183 data.**

The regression equation is:

$$Log(ESAL) = 0.201 + 0.137\, AC + 0.0357\, AGG + 1.071\, Log(R) - 0.0057\, SPPT$$

where:

| | | |
|---|---|---|
| ESAL | = | Accumulated ESALs (in thousands) at PSI of 2.5 |
| AC | = | Thickness of asphalt, inches |
| AGG | = | Thickness of aggregate, inches |
| R | = | Subgrade R-value (Hveem Stabilometer at 240 psi exudation pressure) |
| SPPT | = | Percent of non-frozen ESALs that are applied during spring |

The effect SPPT has on the ESAL capacity, according to the equation, is that if all of the loadings occurred during the spring (100 percent SPPT), the overall capacity would be approximately one fourth of what it would be if none of the traffic occurred during the spring (0 percent SPPT). Neither 0 nor 100 SPPT is a realistic number, and both are outside of the range of SPPT values from Inv 183 (SPPT range of 3 to 66 percent), so comparison of the predicted ESALs at SPPT values of 0 and 100 are more useful to describe the regression equation rather than to infer the performance behavior expected.

The above equation was used to calculate damage factors that can be compared to the damage factors calculated from MnPAVE as described in Task 1 of the spring load study. In order to do this, the truck loadings for the three truck categories, 2-axle and 3-axle trucks and 5-axle tractor semi-trailer trucks were used to calculate a truck ESAL factor for the empty and loaded values used in Chapter 1. The loading conditions included typical loadings that would be legally able to travel on three categories of roads, 9-ton, 7-ton, and 5-ton roads during the spring restriction period, and during the remainder of the year. The truck loads, by axle, are shown in Table A-1.

**Table A-1. Vehicle and axle weights used in Task 1 analysis.**

| Truck Type | Restrictions | Weight (t) | Front Axle (t) | Middle Axle (t) | Rear Axle (t) |
|---|---|---|---|---|---|
| 2 Axles | Empty | 3.4 | 1.581 | - | 1.819 |
| | 5 ton road | 7.276 | 2.746 | - | 4.53 |
| | 7 ton road | 10.186 | 3.844 | - | 6.342 |
| | 9 ton road | 12 | 4.528 | - | 7.472 |
| 3 Axles | Empty | 8 | 3.387 | - | 4.613 |
| | 5 ton road | 12.922 | 4.366 | - | 8.557 |
| | 7 ton road | 18.091 | 6.112 | - | 11.979 |
| | 9 ton road | 21 | 7.095 | - | 13.905 |
| 5 Axles | Empty | 14.4 | 4.114 | 6.171 | 4.114 |
| | 5 ton road | 19.968 | 2.797 | 8.613 | 8.558 |
| | 7 ton road | 27.87 | 3.885 | 12.006 | 11.979 |
| | 9 ton road | 35.833 | 4.995 | 15.402 | 15.436 |

The axle loadings were used to calculate vehicle ESAL factors for the pavement sections used in the Chapter 1 evaluation. Table A-2 shows the calculated ESAL values by axle group for one of the pavement sections analyzed. The axle or axle group in the case of tandems, weights, and respective axle ESAL factors are shown for the three vehicles and the four loading. The resulting truck ESAL factor is shown in the far right column (commonly called the 'truck factor').

**Table A-2. Truck ESAL factors for 2 inches HMA over 6 inches aggregate (SN = 1.72).**

| Truck Type | Road Posting | Weight (kips) | | | | ESAL Factors | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Axle | | | Axle | | | |
| | | Vehicle | Front | Middle | Rear | Front | Middle | Rear | Vehicle |
| 2 Axles | Empty | 6.800 | 3.162 | --- | 3.638 | 0.0018 | --- | 0.0029 | 0.0048 |
| | 5 ton | 14.552 | 5.492 | --- | 9.060 | 0.0119 | --- | 0.0656 | 0.0775 |
| | 7 ton | 20.372 | 7.688 | --- | 12.684 | 0.0370 | --- | 0.2325 | 0.2695 |
| | 9 ton | 24.000 | 9.056 | --- | 14.944 | 0.0655 | --- | 0.4533 | 0.5188 |
| 3 Axles | Empty | 16.000 | 6.774 | --- | 9.226 | 0.0241 | --- | 0.0091 | 0.0332 |
| | 5 ton | 25.844 | 8.732 | --- | 17.114 | 0.0575 | --- | 0.0737 | 0.1312 |
| | 7 ton | 36.182 | 12.224 | --- | 23.958 | 0.2009 | --- | 0.2553 | 0.4562 |
| | 9 ton | 42.000 | 14.190 | --- | 27.810 | 0.3659 | --- | 0.4632 | 0.8292 |
| 5 Axles | Empty | 28.800 | 8.228 | 12.342 | 8.228 | 0.0467 | 0.0242 | 0.0062 | 0.0771 |
| | 5 ton | 39.936 | 5.594 | 17.226 | 17.116 | 0.0127 | 0.0754 | 0.0737 | 0.1618 |
| | 7 ton | 55.740 | 7.770 | 24.012 | 23.958 | 0.0384 | 0.2576 | 0.2553 | 0.5512 |
| | 9 ton | 71.666 | 9.990 | 30.804 | 30.872 | 0.0933 | 0.7074 | 0.7140 | 1.5147 |

Table A-3 lists the vehicle truck factors in terms of ESALs for the pavement sections included in the Task 1 analysis. The calculation of ESAL factors is based on the collective behavior of the AASHO Road Test and therefore is not likely to exactly fit the conditions under evaluation here. For example, there is no capability to calculate different ESAL factors for different subgrade stiffness values or for the different seasons of the year whereas the mechanistic-empirical analysis used by MnPAVE will show differences for both of these factors.

**Table A-3. Truck Factors for an empty and loaded pass for pavement sections analyzed.**

| Axle Limit | Thickness, inches | | | Paired Truck Factor (ESAL) | | |
|---|---|---|---|---|---|---|
| | AC | Agg | SN | 2-axle | 3-axle | 5-axle |
| 5-ton | 2.0 | 6 | 1.72 | 0.0411 | 0.0822 | 0.1195 |
| 7-ton | 2.0 | 6 | 1.72 | 0.1371 | 0.2447 | 0.3142 |
| 9-ton | 2.0 | 6 | 1.72 | 0.2618 | 0.4312 | 0.7959 |
| 5-ton | 2.0 | 8 | 2.00 | 0.0450 | 0.0906 | 0.1317 |
| 7-ton | 2.0 | 8 | 2.00 | 0.1452 | 0.2599 | 0.3358 |
| 9-ton | 2.0 | 8 | 2.00 | 0.2707 | 0.4469 | 0.8179 |
| 5-ton | 2.0 | 10 | 2.28 | 0.0479 | 0.0970 | 0.1406 |
| 7-ton | 2.0 | 10 | 2.28 | 0.1530 | 0.2750 | 0.3563 |
| 9-ton | 2.0 | 10 | 2.28 | 0.2798 | 0.4637 | 0.8406 |
| 5-ton | 3.0 | 4 | 1.88 | 0.0434 | 0.0872 | 0.1267 |
| 7-ton | 3.0 | 4 | 1.88 | 0.1417 | 0.2532 | 0.3265 |
| 9-ton | 3.0 | 4 | 1.88 | 0.2668 | 0.4399 | 0.8082 |
| 5-ton | 3.0 | 5 | 2.02 | 0.0452 | 0.0912 | 0.1324 |
| 7-ton | 3.0 | 5 | 2.02 | 0.1458 | 0.2610 | 0.3373 |
| 9-ton | 3.0 | 5 | 2.02 | 0.2713 | 0.4481 | 0.8196 |
| 5-ton | 3.0 | 6 | 2.16 | 0.0468 | 0.0946 | 0.1373 |
| 7-ton | 3.0 | 6 | 2.16 | 0.1498 | 0.2687 | 0.3479 |
| 9-ton | 3.0 | 6 | 2.16 | 0.2760 | 0.4565 | 0.8310 |
| 5-ton | 3.0 | 8 | 2.44 | 0.0489 | 0.0991 | 0.1436 |
| 7-ton | 3.0 | 8 | 2.44 | 0.1569 | 0.2827 | 0.3660 |
| 9-ton | 3.0 | 8 | 2.44 | 0.2846 | 0.4728 | 0.8526 |
| 5-ton | 3.0 | 10 | 2.72 | 0.0495 | 0.1001 | 0.1448 |
| 7-ton | 3.0 | 10 | 2.72 | 0.1617 | 0.2924 | 0.3774 |
| 9-ton | 3.0 | 10 | 2.72 | 0.2912 | 0.4861 | 0.8695 |
| 5-ton | 3.0 | 12 | 3.00 | 0.0486 | 0.0980 | 0.1414 |
| 7-ton | 3.0 | 12 | 3.00 | 0.1635 | 0.2962 | 0.3804 |
| 9-ton | 3.0 | 12 | 3.00 | 0.2947 | 0.4941 | 0.8793 |
| 5-ton | 3.5 | 15 | 3.64 | 0.0434 | 0.0870 | 0.1252 |
| 7-ton | 3.5 | 15 | 3.64 | 0.1576 | 0.2853 | 0.3622 |
| 9-ton | 3.5 | 15 | 3.64 | 0.2913 | 0.4898 | 0.8732 |
| 5-ton | 4.0 | 6 | 2.60 | 0.0494 | 0.1001 | 0.1449 |
| 7-ton | 4.0 | 6 | 2.60 | 0.1600 | 0.2889 | 0.3735 |
| 9-ton | 4.0 | 6 | 2.60 | 0.2887 | 0.4810 | 0.8630 |
| 5-ton | 4.0 | 8 | 2.88 | 0.0491 | 0.0992 | 0.1433 |
| 7-ton | 4.0 | 8 | 2.88 | 0.1631 | 0.2953 | 0.3801 |
| 9-ton | 4.0 | 8 | 2.88 | 0.2936 | 0.4915 | 0.8761 |
| 5-ton | 4.0 | 10 | 3.16 | 0.0475 | 0.0958 | 0.1381 |
| 7-ton | 4.0 | 10 | 3.16 | 0.1631 | 0.2957 | 0.3786 |
| 9-ton | 4.0 | 10 | 3.16 | 0.2953 | 0.4959 | 0.8813 |
| 5-ton | 4.0 | 12 | 3.44 | 0.0452 | 0.0909 | 0.1308 |
| 7-ton | 4.0 | 12 | 3.44 | 0.1606 | 0.2909 | 0.3706 |
| 9-ton | 4.0 | 12 | 3.44 | 0.2938 | 0.4941 | 0.8788 |

The performance equation from Inv 183 described earlier and the truck factors shown in Table A-3 allow damage factors to be calculated for the same three loading conditions used in the MnPAVE analysis. The loading conditions include 9-ton, 7-ton, and 5-ton spring restrictions (9-ton is actually a year-around load limit while 7-ton and 5-ton are axle load restrictions during the spring thaw period and 9-ton the remainder of the year) for 2-axle, 3-axle, and 5-axle trucks.

Calculation of damage factors from the Inv 183 equation required some assumptions be made. Two subgrade types were included in the analysis, an A-6 soil and an A-7 soil. The R-values assigned were 11 and 8 respectively, representing the lower value for each category shown in Table 1.1 in “BEST PRACTICES FOR THE DESIGN AND CONSTRUCTION OF LOW VOLUME ROADS,” Mn/DOT Report MN/RC –2002-17. The SPPT variable was assigned a value of 33 (equal traffic flow for spring, summer, and fall) for the No Restriction condition. (The SPPT values in the Inv 183 database are based on relative amount of traffic during the weighings and therefore are not weighted by length of season. If a one-week sample taken during spring thaw, summer, and fall are all equal, the SPPT for that condition is 33, or one third of the total ESALs for the three weighings.) The SPPT value used for the ‘unrestricted’ condition is 0 and the SPPT value used for the spring thaw period is 100. , The Inv 183 equation was used to calculate the ESAL capacity of each of the pavement sections analyzed based on these assumptions.

The resulting damage factors were compared to those derived from the MnPAVE analysis by simply calculating the ratio of the Inv 183 damage factors to the MnPAVE derived damage factors. Figure A-11 and Figure A-12 show these ratios for the unrestricted 9-ton loading conditions, and for the spring thaw 7-ton load limit condition respectively.

The equal damage line shown in Figure A-11 and Figure A-12 highlights the damage ratio of 1, where Inv 183 and MnPAVE predict the same damage. Ratios higher than 1 are where Inv 183 is showing more damage than MnPAVE and ratios less than 1 is where MnPAVE damage factors are higher than those generated by Inv 183. Interestingly enough, the average damage factor ratio for all pavements and loading conditions considered in this study is 1.00, indicating a general agreement between MnPAVE and Inv 183 for damage for these thinner pavements; the variations in the ratios show there are differences in how these two analysis approaches distribute the damage.

The most notable difference from the two figures is that the Inv 183-based damage factors showsless relative damage for thin pavement sections than for thick pavement sections, as defined by axle load capacity, than MnPAVE does. The Inv 183 damage factors also show the spring postings provide more protection than the MnPAVE analysis does. Otherwise, for 9-ton unrestricted loadings, the Inv 183 damage factors are less than MnPAVE damage factors for thin pavement sections and more than MnPAVE damage factors for thicker pavement sections. The Inv 183 spring damage factors tend to be higher than the MnPAVE for the sections with higher axle load capacity, but the higher axle load capacity sections are not as much of an issue in this study.

To characterize the typical sections used in the study, the axle load capacity for all of these sections were calculated on the basis of 75 mils allowable deflection for 9-ton axle loads, and the equation relating the peak Benkelman beam plus two standard deviations deflection to the pavement GE and subgrade R-value. The resulting axle load capacity, in tons, for the sections included in the analysis ranged from 5.6 tons to 10.8 tons per single axle.

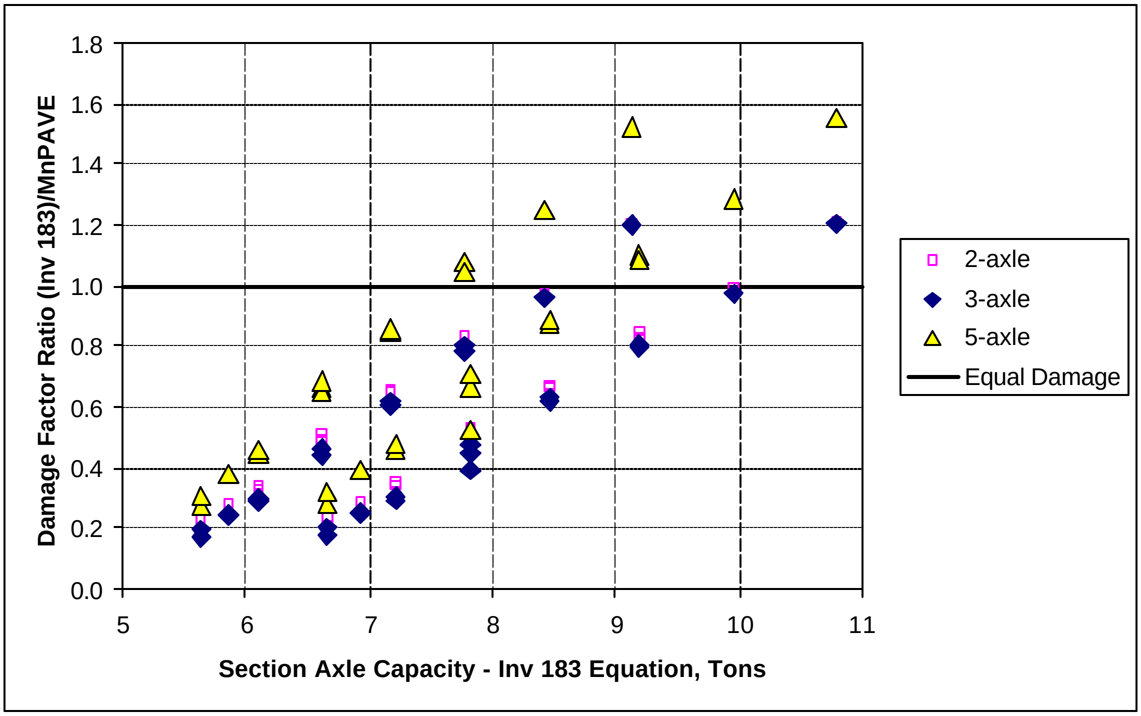



Figure A-11. Comparison of Inv 183 to MnPAVE damage factors for unrestricted conditions.

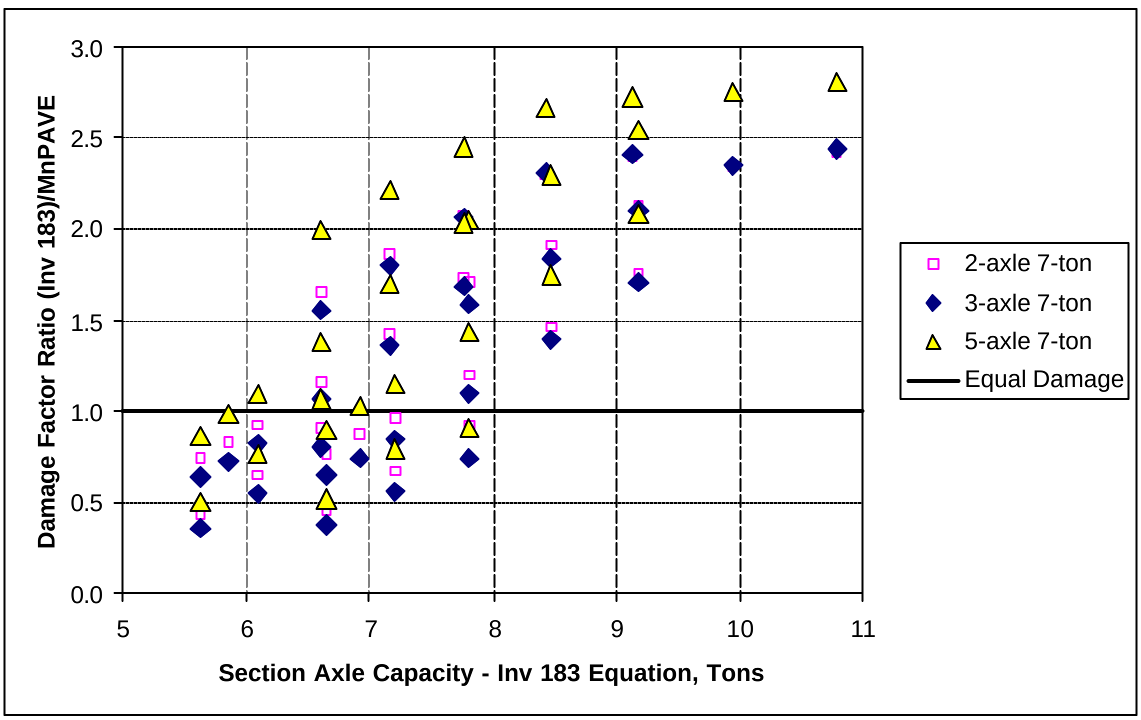



Figure A-12. Comparison of Inv 183 to MnPAVE damage factors for spring thaw conditions.