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INVESTIGATION OF THE IMPACT OF INCREASED WINTER LOAD LIMITS

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Many northern states allow an increase in the gross vehicle weight (GVW) for certain vehicles in the winter to more efficiently use the increased load carrying capacity of frozen pavement structures. The increased load limits and dates are usually set according to legislation, which may not account for seasonal differences in the depth of frost.

This report documents the effects of increasing the winter load limits for a pilot study in Minnesota and suggests a possible method for placing and removing increased winter load limits. The pilot study was conducted in which the northern sugar beet haulers were allowed to increase the winter weight of the 6-axle tractor-trailer combination vehicles from 391 kN (88,000 lbs.) to 416 kN (93,500 lbs.). This load limit was chosen to match North Dakota since this was the final destination. The sugar beet haulers were allowed to increase the GVW when the frost level reached 150 mm (6 in.) into the subgrade layer and end when 150 mm of the base layer thawed. Frost and thaw depths in the pavement structures were monitored with Watermark (WM) and thermocouple (TC) sensors.

It was found that there was a significant increase in the structural carrying capacity of the frozen pavement as measured by decreased deflections during FWD testing. A similar trend was seen in the strain data from the Mn/ROAD site. The condition surveys conducted showed no visible signs of increased surface distress due to the increased loads, however the results from this study are limited because the transporter was able to participate in the study for only three weeks.

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TABLE OF CONTENTS

Page

CHAPTER ONE - INTRODUCTION

CHAPTER TWO - LITERATURE REVIEW

CHAPTER THREE - METHODOLOGY OF PILOT STUDY

CHAPTER FOUR - RESULTS OF PILOT STUDY

CHAPTER FIVE - CONCLUSIONS AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Many northern states allow an increase in the gross vehicle weight (GVW) of certain vehicles during the winter to more efficiently use the increased load carrying capacity of frozen pavement structures. An increase in winter load limits encourages the transport of goods on routes when the stiffness of the pavement structure is at a maximum and therefore may result in a decrease in the transport of goods during the spring-thaw period. Unfortunately, longer pavement life may not always be realized because the increased load limits and periods may be set according to legislation and not placed according to the actual frost depth in pavement structures.

A pilot study was conducted to monitor the effects of increasing the winter load limits and suggest a possible method for placing and removing increased winter load limits. The winter load limit would be set such that a balance was met between: the capacity of pavements and bridges, federal and state legislated axle limits, safety issues, and industry needs. In the pilot study, the northern sugar beet haulers were allowed to increase the winter weight for a fleet of 6-axle tractor-trailer combination vehicles from 391 kN (88,000 lbs.) to 416 kN (93,500 lbs.). Minnesota's northern frost zone was chosen for the study because the frozen period is longer than in other regions in Minnesota. This load limit was chosen to match North Dakota's limit because this was the final destination of the participating vehicles.

The sugar beet haulers were allowed to increase the GVW when the frost level reached at least 150 mm (6 in.) into the subgrade layer and were required to end when 150 mm (6 in.) of the base layer thawed. The depth of the frost and thaw in the pavement structures were measured using Watermark (WM) and thermocouple (TC) sensors. The measured data had a reasonable accuracy and were used to develop viable relationships that could predict the subsurface freezing

and thawing based on air temperatures. The ability to retrieve data using a modem proved valuable in ensuring reliable and timely data collection.

The results from this study are limited since the transporter was only able to cooperate with the study for 18 days on one test site and 5 days on the other two sites for a total number of 1350 trips. If the transporter had been able to begin December 21, 1998, when 150 mm (6 in.) of frost first occurred, rather than January 20, 1999, the duration of the study would have been 67 days.

There was a significant increase in the structural carrying capacity of the sites inferred by the decrease in deflections measured during FWD testing. A similar trend was seen in the strain data from the Mn/ROAD site. The condition surveys conducted showed no visible signs of increased surface distress due to the increased loads during the short study period.

This study is primarily concerned with the effects on the pavement structures, however, there are a number of other factors that exceed the scope of this study and need to be considered when increasing the winter load limits. These include bridge upgrading costs and truck safety issues such as turning, accelerating, and braking. The costs associated with upgrading the bridges in Minnesota will have a significant influence on how widespread higher load limits could be implemented.

Several recommendations resulted from this study and some of these have been pursued as resources became available. It was recommended that it should be determined how much axle weights could be increased during the winter before the pavement structure begins rapid deterioration due to increased brittle fracture or other mechanisms. It was also recommended that if Minnesota's bridges are of sufficient strength, it would be worthwhile to determine the effects of increasing the GVW throughout the year for vehicles that use tridem axles. Greater use of tridem axles could reduce pavement damage on the state highway system and increase payload. Third, it would be beneficial to install more frost and temperature sensors throughout Minnesota to allow more efficient implementation of seasonal load limit policies that maximize economic benefit and manage risk. Finally, in order to implement an improved method for placing and removing winter load limits, further study is required to develop specific methods that utilize the freezing index and thawing index.

As a result of recommendation three, additional frost and temperature sensors were installed at six environmental monitoring sites across Minnesota during 2003 to allow more efficient implementation of seasonal load limit policies. In addition to the installation of more environmental monitoring sites, a task force was established during 2002-2003 to re-define the frost zone boundaries in hopes of maximizing economic benefits and managing risk related to seasonal load limits policies. As a result of the investigation performed under this task force, spring load restrictions and winter load increases now utilize the same zonal boundaries.

As a result of recommendation four, an investigation to improve the placement and removal of winter load limits commenced in 2001. The preliminary model resulting from this investigation is currently being implemented into the seasonal load limit monitoring process. As a result, the start of winter load increases are no longer set by fixed calendar dates, but determined for each frost zone using measured and forecasted daily temperatures for several cities within each zone. In addition to starting date changes, the end of the winter load increase period is no longer tied to the starting date of spring load restrictions or March 7, whichever came first. Please see the Mn/DOT Technical Memorandum 03-02-MRR-01 for further details.

Finally, the monitoring of seasonal load limits (i.e., winter load increase and spring load restriction) starting and ending dates has been automated using an ORACLE based system. The climatic data currently collected is obtained directly from the National Weather Service via FTP sites. Work is currently underway to incorporate the Mn/DOT road weather information system (R/WIS) climatic data into the seasonal load limit-monitoring program. Including this data would increase the density and distribution of data points throughout Minnesota, thereby allowing the dissemination of cumulative freezing and thawing indices via contour maps, in lieu of the current two-dimensional graphs. It is also believed that these contour maps would increase understanding and improve the clarity of the information presented.

CHAPTER ONE

INTRODUCTION

Introduction

This report documents the project period from 1998 to 1999 and therefore does not explain the policy changes that occurred subsequently nor does this report document current (2004) policy.

Many northern-tier states (Figure 1) and Canadian provinces increase the gross vehicle weight (GVW) limits during the winter period when a pavement structure is frozen and able to withstand increased loads. This policy increases pavement life when it results in a decrease in the transport of goods during the spring when the pavement is in a thaw-weakened condition. Minnesota law (1999) set the beginning and ending dates and the magnitude of the increased loads without regard to the actual freeze/thaw conditions, which vary from year to year. The 1999 law allowed a blanket winter load limit increase as follows [1]:

> *"Vehicles operating on Ten Ton Routes in northern portion of Minnesota ... may exceed statutory weight limits by 10 percent during the period of December 1 through December 31 each year. During the period of January 1 through March 7 each winter, the 10 percent increase in weight limitations is in effect on all Ten Ton Routes statewide. ... No permit is required to operate with the increase weights on 10 Ton Routes which are not part of the Interstate System. The duration of a ten percent increase in load limits is subject to implementation of springtime load restrictions, or March 7. The increase applies to all vehicles*

without regard to the nature of commodity transported. The vehicle must be licensed for the gross weight it attains."

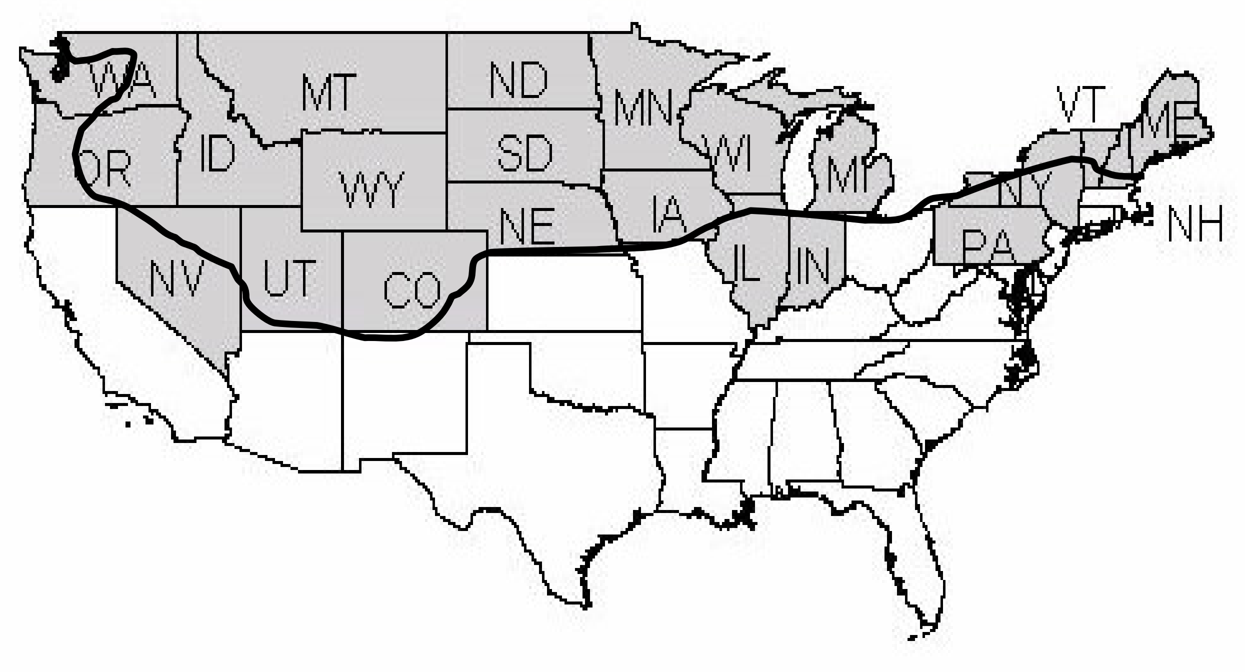

Figure 1. The approximate frost line and states subject to freeze-thaw cycles.

Background

Before discussing the winter load limit policy for Minnesota, it is important to understand annual load limits and the agencies that control these limits. In general, vehicle weight limits have been set by legislation, both on a state and a federal level. The Federal – Aid Highway Act of 1956 regulates the truck size and weight limits on the Interstate highways. A grandfather clause in this act permits the use of higher GVW and wider widths if states had other regulations in place prior to July 1, 1956.

The Federal Highway Administration (FHWA) regulates the load limits on the Interstates and requires states to enforce the load restrictions on all other regional and national highways according to the Surface Transportation Assistance Act (STAA) of 1982. The Interstate load limits are 89, 151 and 356 kN (20,000, 34,000 and 80,000 lbs.) for single, tandem and gross loads, respectively [2]. All permits for vehicles carrying divisible loads greater than 356 kN (80,000 lbs.) must conform to requirements as approved by the FHWA [3]. States, counties and municipalities may issue divisible load and vehicle permits for all regional and national highways other than the Interstate System [3]. Divisible load permits are typically more difficult to receive since it is generally expected that the transporter should divide the cargo to comply with the statutory limits.

In Minnesota, the state government first determined early road design standards [4]. These early roads were designed for wagons and light vehicles. In 1921, the first weight restrictions were imposed, setting the maximum GVW at 125 kN (28,000 lbs.). In 1957, it was required that the weight of four consecutive axles on a five-axle combination vehicle not exceed 267 kN (60,000 lbs.). Since the late 1960s, the load limits for pavements in Minnesota have been determined according to Minnesota Department of Transportation (Mn/DOT) Investigation 603 [5,6]. By 1963, the maximum single axle, tandem axle, and GVW limit were increased to 80 kN (18,000 lbs.), 142 kN (32,000 lbs.), and 326 kN (73,280 lbs.), respectively. These weights were increased again in 1977 to 89 kN (20,000 lbs.), 151 kN (34,000 lbs.), and 356 kN (80,000 lbs.), respectively. Load limits increase ten percent beginning on December 1 in the northern zone and January 1 for the remainder of Minnesota. This increase in winter load limits is removed when spring load restrictions (SLR) are placed or by March 7, whichever is sooner.

A primary concern with a fixed-date methodology is that pavements in Minnesota are not always completely frozen by the start dates. Increased vehicle weight limits may cause premature pavement deterioration if a pavement is in an unfrozen thaw-weakened condition [7]. The pilot study, documented in this report, was conducted to determine an improved method for placing and removing increased winter load limits. During this pilot study, an industry that transports divisible loads was allowed to increase the load limit for a specific vehicle type during a defined period of frozen conditions.

Objective

The objective of this study was to investigate the effects of increasing the winter load limits in Minnesota. The winter load limit was set at a level such that a balance was met between:

- load capacity of the pavement and bridge structures,
- federal and state legislated axle limits,
- truck safety issues, and
- the transporters needs.

Scope

The route, transporter, and measurement standards were defined for this study to determine the effects of increased winter load limits and to compare the use of tridem axles with tandem axles. A route location was selected in northern Minnesota to maximize the duration of the study, since the area north of US TH10 and MN TH 210 (Figure 2) was allowed to transport increased loads beginning December 1. Also, the pavement needed to have a certain depth of frost for the study to begin and the northern area typically freezes sooner and thaws later than the southern areas of Minnesota.

Figure 2. Five zones used in Minnesota to place and remove SLR.

The selected route also needed to be a part of the 10-ton trunk highway system to minimize any premature pavement deterioration on the county and municipal highway systems. Finally, any bridges located along the route needed to have the structural capacity to withstand the increased loads.

The transporter participating in the study needed to be flexible enough to adjust to problems and have the necessary equipment for the study. The requirements included:

- location in northern Minnesota,
- the ability to return to normal legal load levels if there were a sudden thawing event,
- quick response time relaying vehicle weight data and the number of trips taken,

- an acceptable record of compliance with the Department of Public Safety in weight restrictions, inspections, accidents, and safety issues,
- ability to provide data regarding any economical benefit to Minnesota's economy due to the increased load period,
- strict control over the 6-axle tractor-trailer combinations with the correct axle spacings and safe condition, and
- adequate movement of goods during the study period to ensure adequate data collection.

Frost was monitored at pilot study test sites and at the Minnesota Road Research Project (Mn/ROAD) using frost and temperature sensors. Distress surveys were conducted and compared to historical data to quantify any pavement changes due to the increased winter load limits. Also, deflection and strain data were measured to quantify the increase in strength of the frozen pavement structures.

Mn/ROAD is a valuable source of seasonal and structural data for various pavement structures. The flexible pavement test sections used in this study are shown in Table 1 and are comprised of various thicknesses of hot-mix asphalt (HMA) surface layers and aggregate base layers. Most of the Mn/ROAD sections have a subgrade soil that is about 50 percent fine-grained particles with an R-value of about 12 to 15. Some test sections were constructed using an imported sandy subgrade with an R-value of about 70. The asphalt cement is a 120/150 penetration grade, ranging from 5.4 percent to 6.4 percent based on Marshall mix design. The base aggregate materials used in the test sections are Cl. 3 Sp. (Class 3 Special), Cl. 4 Sp., Cl. 5 Sp. and Cl. 6 Sp. The term "special" indicates that the gradation limits, Table 2, were stricter that typical Mn/DOT specifications to ensure greater uniformity of the material.

Table 1. Summary of Mn/ROAD flexible pavement test sections included in study.

Test Section	Surface Thickness, mm	Asphalt Cement	Asphalt Content, %	Base Thickness, mm	Base Material	Subgrade Soil Design R–value
24	75	120/150 pen	6.4	100	Cl. 6 Sp.	70
27	75	120/150 pen	6.4	280	Cl. 6 Sp.	12
30	125	120/150 pen	5.8	305	Cl. 3 Sp.	12

Table 2. Gradation and plasticity specifications for the aggregates at Mn/ROAD.

Sieve Size, mm (in.)	Pavement Base/Subbase Material			
	Cl. 3 Sp.	Cl. 4 Sp.	Cl. 5 Sp.	Cl. 6 Sp.
	Percent Passing			
37.5 (1.5)	-	100	-	-
25.4 (1)	-	95/100	100	100
19 (0.75)	-	90/100	90/100	85/100
12.5 (0.5)	100	-	-	-
9.5 (0.375)	95/100	80/95	70/85	50/70
4.75 (No. 4)	85/100	70/85	55/70	30/50
2.00 (No. 10)	65/90	55/70	35/55	15/30
0.425 (No. 40)	30/50	15/30	15/30	5/15
0.075 (No. 200)	8/15	5/10	3/8	0/5
Plasticity Requirements				
LL	35 max.	35 max.	25 max.	25 max.
PI	PI<12	PI<12	PI<6	PI<6

There are a number of other factors that exceed the scope of this study, but which need to be considered before increasing winter load limits. These include bridge upgrading costs as well as truck size and safety issues such as turning, accelerating, and braking. The costs associated with upgrading the bridges in Minnesota will have a significant influence on how widespread higher winter loads could be implemented and the overall cost of any policy change.

CHAPTER TWO

LITERATURE REVIEW

The literature review includes winter load limit policies in the northern-tier states and Canadian provinces that surround Minnesota. Techniques used to predict pavement design life are discussed briefly and the status of Minnesota's bridge structures is included to better understand the effect of increased loads. Related issues are safety and enforcement of load limits. Finally, the need to balance the short- and long-term benefits and costs of increased load limits is discussed.

Winter Load Limit Policies in the Surrounding States and Provinces

The GVW and axle load limits are different in Minnesota, Iowa, North Dakota, South Dakota, Wisconsin, Michigan, Manitoba, and Ontario. Iowa does not allow an increase in load limits during the winter. Michigan [8] and South Dakota [9] do not allow an increase in axle weights or GVW limits in the winter since their weight limits are higher throughout the year. For example, Michigan grandfathered a maximum GVW of 730 kN (164,000 lbs.) for certain vehicles on the interstate system [2].

Wisconsin uses a policy called the “Frozen Road Declaration,” which allows for an increase in the GVW of certain vehicles to 436 kN (98,000 lbs.) in the winter [10]. This applies to the state trunk highway system but does not apply to the national systems of interstates and defense highways, where the maximum GVW is 356 kN (80,000 lbs.). The dates for beginning and ending increased winter load limits are reviewed annually based on forecasted weather conditions. Typically, the beginning date is December 18, and has ranged between December 8 and December 26. This period typically ends March 3, and has ranged between February 16 and March 16 [10].

North Dakota's policy allows a 10 percent weight increase for the movement of all products on state trunk highways beginning December 1 and ending March 7 of each year [11]. This policy does not include the interstate system and the maximum GVW allowed on the state trunk highway system is 105,500 lbs., for specific vehicles. The 10 percent weight increases are granted each year upon authorization by the commissioner of the North Dakota Department of Transportation.

Manitoba [12] and Ontario [13] increase the GVW limit during the winter. Ontario allows vehicles that transport raw forest products to increase load limits by 10 percent. The policy is called “freeze–up” and is defined in the Highway Traffic Act, Section 119.2. In this policy, the Official of the Ministry, who is designated by the Minister, decides the beginning and ending dates of the freeze–up period, as well as the geographic area. Manitoba allows for a 10 percent increase in load limits beginning December 1 and ending on the last day in February. Aside from seasonal increases, Manitoba allows GVW ranging between 125 kN (28,000 lbs.) and 613 kN (137,800 lbs.) and Ontario allows for 623 kN (140,000 lbs.) GVW. Both provinces set load limits based on the route and the vehicle.

Pavement Design Life

The American Association of State Highway and Transportation Officials (AASHTO) Design Guide [14] for pavement structures is based on results from the American Association of State Highway Officials (AASHO) road test site in Illinois. In general, pavements are designed to withstand expected traffic loads over a specific time period. In the AASHTO Guide, design traffic loads are converted to 80-kN (18-kip) equivalent single axle loads (ESAL) and then summed over the design period to estimate the expected cumulative traffic load.

ESALs are, in part, a function of the load equivalency factor (LEF) determined from the AASHO Road Testing facility. LEFs vary according to the number of axles and the weight of the axles, however they do not vary seasonally. Instead, the monthly changes in the roadbed soil modulus are estimated for a typical year and an empirical relationship estimates the relative damage [14]. Using this relationship, it is estimated that the relative damage in the winter is significantly low (less than 1%), Figure 3, when compared to other seasons.

Strain data can be related to the pavement life with the use of transfer equations. One equation was developed by the Asphalt Institute to predict the number of 80kN (18-kip) ESALs for 20% fatigue cracking. This equation estimates pavement life based on the HMA layer maximum tensile strain, modulus, volume of asphalt cement, and volume of voids. A description of various transfer functions is given elsewhere [15]. Both ESALs and transfer functions are used to estimate the damage to pavement structures from tandem and tridem axles.

$$N_f = C * 18.4 * \left(4.32 \times 10^{-3}\right) * \left(\frac{1}{\varepsilon}\right)^{3.29} * \left(\frac{1}{E}\right)^{0.854} \quad (1)$$

where N_f = number of 80kN (18 kip) ESALs to failure,

ε_t = maximum tensile strain in HMA layer,

E = HMA dynamic modulus, psi.,

$C = 10^M$,

where $M = 4.84 * \left(\frac{V_b}{(V_v + V_b)} - 0.69\right)$,

V_b = volume of asphalt cement, %, (5.9% for test section 30) and

V_v = volume of air voids, %, (8.2% for test section 30).

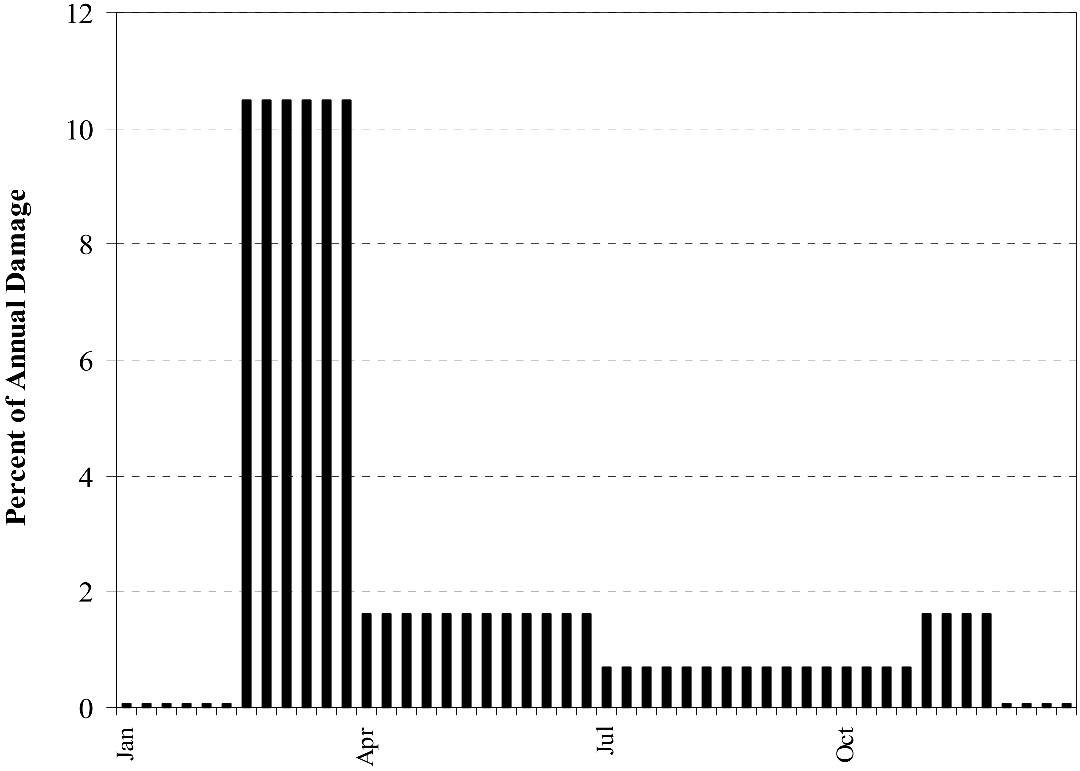

Figure 3. Relative damage calculated from the 1993 AASHTO Design Guide [14].

Bridge Design Life

The gross truck load, which a given bridge is designed to withstand, is determined by a formula that includes the number of axles, loading, and axle spacing. Once built, bridges are rated in the following two ways: the absolute maximum permissible load that the structure can be safely subjected to (operating rating), and the load that can safely utilize the structure for an indefinite period of time (inventory rating) [16, 17]. These ratings are used when considering overweight vehicle permits for bridges.

The load carrying capacity of bridges is a major factor that necessitates GVW limits. Unlike pavement structures, bridges do not gain strength when frozen. For this reason, the GVW allowed on a given corridor is governed by the load carrying capacity of the bridges along the route. In order to lessen the dynamic load effect of vehicles on the pavement structure, the speed of vehicles can also be limited. Most states use the Federal Bridge Formula [17] to determine the permissible gross load on a bridge. This formula, commonly referred to as Formula B, is as follows:

$$W = 500 * \left[\frac{LN}{N-1} + 12N + 36 \right] \tag{2}$$

where W = maximum weight carried on any group of two or more axles (lbs.),

L = distance between the extremes of any group of two or more consecutive axles (ft.), and

N = number of axles under consideration.

Current Status of Minnesota's Bridge Structures

Mn/DOT's Office of Bridges and Structures has compiled a report [16] that summarizes the number of deficient bridges and the cost to improve the bridges. In general, the sufficiency rating ranges from 0 to 100, where 100 is the highest rating. The state average sufficiency rating for all bridges was 84.8. The average age of the bridges in Minnesota was 31.4 years.

According to the report, out of 19,801 bridges in Minnesota, 3,380 were in need of improvement and the estimated cost was $788,962,826. Of these 3,380 bridges, 395 were located on Minnesota's trunk highway system and the estimated improvement cost was $245,109,332. Figure 4 shows the breakdown of the deficient bridges by road system with the estimated improvement costs [16].

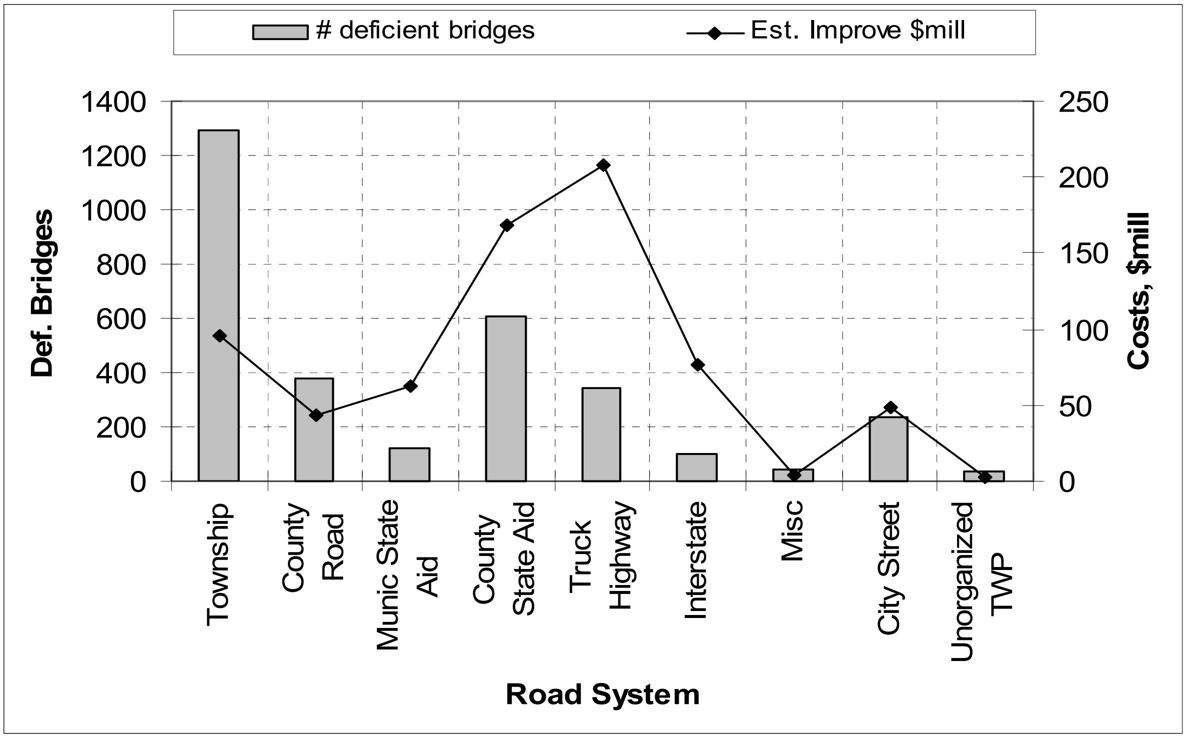

Figure 4. Number of deficient bridges in Minnesota by road system, 3.1m and over [16].

Effects of Increasing Winter Load Limits

Various studies have assessed the potential benefits and costs associated with increasing load limits [18, 19, 20]. There is a potential savings for the transporter since many vehicles used to transport goods reach the maximum GVW prior to filling the available volume of the vehicle

[19]. The benefits to the trucking industry would potentially reduce transportation costs and therefore benefit the broader economy [19, 20]. Also, an increase in GVW during the winter would more efficiently use the increased strength of the frozen pavement structures and potentially reduce spring pavement damage. However these benefits come with significant costs, which include increasing the bearing capacity of bridges along the corridors, enhancing vehicles to withstand increased loads, and enforcing the weight limits.

Comprehensive Truck Size and Weight Study

The FHWA completed a draft report [20] concerning truck size and weights that analyzes the impacts of six scenarios related to truck size and weights (TS&W). Scenario one left the current TS&W policy unmodified and was used as the baseline for comparing the remaining five scenarios. Tridem axles were studied in scenario four, also called the North American Trade Scenario, which utilized six-axle tractor-trailer combinations with a tridem axle weight of 196 kN (44,000 lbs.) or 227 kN (51,000 lbs.). Most of the United States' truck fleet is composed of two-axle single units (35.5 percent) and 5-axle semitrailer combinations (42.2 percent), with few 6-axle semitrailer combinations (3.0 percent). Canada and Mexico allow higher load limits for tridem axles spaced between 2.4 m (8 ft) and 3.7 m (12 ft) and subsequently have a higher use of 6-axle semitrailer combinations (18.5 percent and 37.3 percent, respectively). Several impacts are investigated in the FHWA study [20] including:

- Freight diversion, which included changes in the productivity of the transporter and changes in payload for each scenario.
- Highway agency costs, which were evaluated in terms of increased/decreased costs to maintain or improve pavements, bridges, and roadway geometry.
- Safety issues, which included truck crash factors, vehicle stability, and control impacts.
- Traffic operation issues, which included passenger car equivalents of the vehicles, congestion, and user delay.

- Environmental quality and consumption issues, which included air and noise pollution that are a function primarily of vehicle miles traveled.
- Rail impacts and shipper costs, which included analyses of diversion from rail to trucks and the changes in competitive costs.

Agency Cost Estimation in TS&W Study

Agency costs associated with the North American Trade Scenario were evaluated in relation to the pavements, bridges, and roadway geometry. The FHWA report [20] shows an increase in payload with the use of tridem axles and a decrease of 10.6 percent in vehicle miles traveled (VMT) in comparison to the base case. This equates to an estimated decrease of $2.4 billion for a 227 kN (51,000 lbs.) or $3.0 billion for a 196 kN (44,000 lbs.) tridem axle in pavement restoration costs over 20 years. The estimated costs associated with improving bridge structures along these corridors range between $51 and $65 billion for capital costs and $203 and $264 billion for user costs with the use of 196 kN (44,000 lbs.) or 227 kN (51,000 lbs.) tridem axles. This was the only instance in the FHWA study that user costs associated with scenarios were quantified. These user costs were from traffic congestion that occurred while the bridges were improved or replaced. The FHWA study estimated a cost of $100 million beyond that of the base case to improve the roadway geometry.

The FHWA report [20] used the assumption that less vehicle exposure will lead to fewer crashes. Thus it was estimated that the number of crashes per ton of product transported would decrease with an increase in the use of tridem axles. This conclusion results because more product is transported per truck resulting in fewer trucks on the road and less exposure.

An additional complicating factor is whether these heavier vehicles can operate as safely as lesser weight vehicles. The report states that generally the addition of an axle to a semitrailer will improve the performance and stability of the vehicle. A minor improvement in traffic operations was noted. Overall, it was estimated that in comparison to the base case, the North American Trade Scenario would lead to a 12 percent decrease in VMT, a 6 percent decrease in fuel use, and air pollution costs would decrease with a decrease in VMT. Noise pollution costs were estimated to increase by 6 percent in comparison to the base case because there is an increase in tires for each vehicle and thus an increase in the noise level from the highway.

Enforcement and Truck Safety Issues

There are many enforcement and safety issues to consider when discussing the increased vehicle load limits. Often, the enforcement of load limits on America's highways is a difficult task since there are an insufficient number of personnel to identify overloaded vehicles, fines are seldom quantified according to actual pavement damage, and offenders often escape fines [21]. It has been recommended that: more weight enforcement personnel be assigned to monitor our roadways, more portable scales and weigh-in-motion scales be available to screen potentially overweight trucks, and increased fines and penalties be imposed on repeat offences [19].

Several advantages were noted to the highway system and its users by increasing enforcement efforts [19]. It was estimated that increased enforcement would decrease the cost to repair damaged pavements and bridges by decreasing the number of overloaded vehicles. The benefits would also extend to transporters who operate legally by eliminating the competitive advantage of illegally overloaded vehicles. Increased enforcement efforts would also reduce the number of crashes caused by dangerously overweight trucks.

A special report was assigned to the Committee for the Truck Weight Study by the National Research Council to explore truck weight limits [19]. Several issues were documented concerning seasonal load limits. First, a seasonal increase in the amount of truck traffic could cause an increase in the number of crashes and highway congestion. Second, increasing the legal load limit could potentially reduce the number of vehicles required to transport the same amount of goods. Third, changing operating weights can have an effect on the related performance of the truck such as rollover potential and accelerating and braking distance ability. It is critical to only allow for an increase in the GVW that will not compromise the safety of the vehicle. An option would be to encourage the use of different vehicles with lower crash rates. Finally, it was noted that a change in the design of a vehicle might affect the crash rates and severity.

Summary

Many states and provinces allow an increase in the GVW during the winter when frozen pavement structures are stiffer. This policy gives the transportation industry the opportunity to more efficiently utilize the carrying potential of the vehicle and the frozen pavement structure. There is a great deal of literature concerning vehicle load limits, however, there is a general lack of documentation concerning the effects of increased winter load limits on the pavement structures. Typically, an increase in vehicle load limits will increase the wear on a roadway and reduce pavement life. However, this effect is minimized when the pavement structure is frozen. Unfortunately, bridges do not gain strength when frozen and therefore may prohibit increased GVW on specific routes.

Other factors need to be addressed to determine if increased winter load limits should be allowed. Truck safety is important to ensure the safe transport of goods on our nation's highways. Enforcement is a key issue in the success of an increased winter load limit policy. If the transportation industry does not adhere to the rules regarding where increased load limits are allowed and when these periods exist seasonally, then premature pavement damage will occur.

CHAPTER THREE

METHODOLOGY OF PILOT STUDY

Introduction

To better understand the effects of increased winter load limits on Minnesota's infrastructure, several issues were investigated in a small-scale pilot study. The pilot study was conducted in northern Minnesota, where a sugar beet hauling company was permitted to increase the winter load limit for 6-axle tractor-trailer combinations for a defined period of time. The route used in the pilot study was monitored to document pavement structural data, traffic loads, and environmental conditions.

The destination of the sugar beets transported on the route was a factory in North Dakota. Therefore the North Dakota Department of Transportation (NDDOT) worked with Mn/DOT because North Dakota TH 200 would be subjected to heavier loads originating in Minnesota. To monitor the frost and thaw depth and define the increased winter load limit period, frost and temperature sensors were installed in the roadway. The pavement surface condition of the roads used in the pilot study was determined before and after the increased load period. The structural capacity of the route was tested using the falling weight deflectometer (FWD) and strain data were collected from Mn/ROAD for analysis. Finally, a simple analysis was performed to determine the feasibility of allowing higher winter load limits using information from the pilot study.

Selected Route

The pilot study route began on MN TH 9 just north of Ada and proceeded west on MN TH 200 to the North Dakota border, and was approximately 20 miles in length. Three 500 ft test sections were monitored along the route. They consisted of a HMA surface, portland cement concrete (PCC) surface and a PCC section with a HMA overlay, Table 3. The historical ride data is shown in Table 4. The three sugar beat piling stations located along the route were Ada North (TH 9), Ada West (TH 200), and Midway (TH 200).

Table 3. Pavement site information for three test sections near Ada, MN.

Site	Milepost	ADT	HCADT	Year	Layer	Thickness, mm (in.)
Near Halstad on MNTH 200	0.354 to 0.603	1049	85	1978	HMA	75 (3)
					PCC	230-180-230 (9-7-9)
West of Ada on MNTH 200	6.9 to 7.0	829	154	1955	PCC	230-180-230 (9-7-9)
					Base	380 (15)
North of Ada on MNTH 9	194 to 194.1	1750	110	1965	HMA	165 (6.5)
					Base	130 (5)

Table 4. Historical ride data for the three test sections near Ada, MN.

Site	PSR	SR	PQI
Halstad MNTH 200	2.3	2.5	2.4
Ada West MNTH 200	3.5	3.9	3.7
Ada North MNTH 9	4.1	3.8	3.9

The only bridge on this route was on TH 200 between Minnesota and North Dakota. Mn/DOT's Office of Bridges and Structures was notified of the proposed increased loads on the bridge and it was determined that this bridge could accept the increased loads. A new bridge was under construction at the time of the pilot study and completed September 1999.

The Transporter

The northern sugar beet industry (American Crystal Sugar Company) participated in this study. Transystems was contracted by American Crystal Sugar Company to transport sugar beets from the Minnesota piling stations to the North Dakota factory. Any economic benefit that resulted from the pilot study was in the form of reduced transport costs. The loads and configurations of Transystems' vehicles are shown in Figure 5 and Table 5.

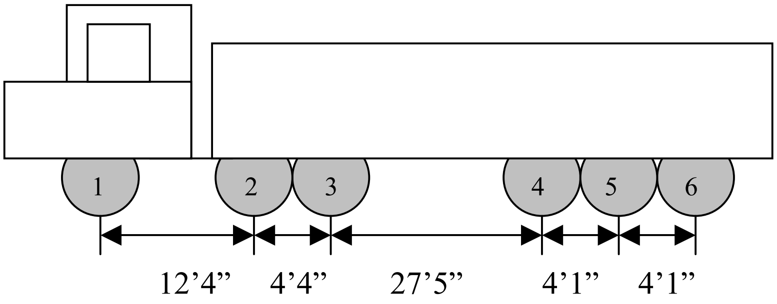

Figure 5. The 6 – axle, tractor-trailer vehicle configuration.

Table 5. Vehicle axle loads and gross vehicle weight, GVW, kN (lbs.).

Axles	GVW: 356 kN (80,000 lbs.)	GVW: 391 kN (88,000 lbs.)	GVW: 416 kN (93,500 lbs.)
Steer Axle	53 (12,000)	53 (12,000)	53 (12,000)
#2 – #3	151 (34,000)	166 (37,400)	177 (39,740)
#1 – #3	218 (49,000)	240 (53,900)	255 (57,270)
#4 – #6	187 (42,000)	206 (46,200)	218 (49,090)
#3 – #6	294 (66,000)	323 (72,600)	343 (77,140)
#2 – #6	325 (73,000)	360 (80,900)	380 (85,320)
#1 – #6	356 (80,000)	391 (88,000)	416 (93,500)

Frost Depth

Several methods were used to measure or estimate the frost depth to determine the dates at which a pavement was frozen or thawed. These methods included the installation of frost and temperature sensors in MN TH 200 and the use of freezing and thawing indices to estimate the depth of frost in the pavement structure based on air temperature. Deflection and environmental data were collected at pilot study locations and at the Mn/ROAD facility during fall of 1998 and the winter and early spring of 1999 to determine trends in the load carrying capacity of various pavement structures.

Frost and Temperature Sensors

The frost depth was monitored using sensors installed along the pilot study route and at Mn/ROAD. For this study, in situ temperature and moisture state are of primary importance for predicting the increased stiffness of pavement layers during the winter. Frost and thaw depths were measured from thermocouple sensors (TC) paired with Watermark sensors (WM). The TC and WM sensors were only placed in the HMA shoulder of MN TH 200. Even though MN TH 9 would have been a more ideal setting, this flexible pavement section was included in the pilot study after the sensors had been installed. The depth of the sensors is shown in Table 6. Care must be taken when using WM sensors and it is recommended that they only be used in conjunction with thermocouple sensors.

Table 6. Sensor depths at MNTH 200, milepost 7, near Ada, MN.

WM #	Depth, mm	TC #	Depth, mm	Pavement Layer
-	-	1	25.4	HMA Shoulder
-	-	2	75	HMA Shoulder
1	390	3	390	Aggregate Base
2	150	4	150	Aggregate Base
3	230	5	230	Aggregate Base
4	305	6	305	Aggregate Base
5	380	7	380	Aggregate Base
6	460	8	460	Soil Subgrade
7	535	9	535	Soil Subgrade
8	600	10	600	Soil Subgrade
9	685	11	685	Soil Subgrade
10	790	12	790	Soil Subgrade
11	915	13	915	Soil Subgrade
12	990	14	990	Soil Subgrade
13	1090	15	1090	Soil Subgrade
14	1220	16	1220	Soil Subgrade
15	1320	17	1320	Soil Subgrade
16	1395	18	1395	Soil Subgrade
17	1525	19	1525	Soil Subgrade
18	1665	20	1665	Soil Subgrade
-	-	21	Outside Air	-

Freezing and Thawing Index

The depth of freezing and thawing depends in part on the magnitude and duration of the temperature differential below or above freezing at the ground surface [7]. The freezing or thawing index (FI and TI, respectively) can be used to quantify the intensity of a freezing or thawing season. A more thorough description of Mn/DOT's policy on using the FI and TI is given elsewhere [22]. The FI (Equation 3) is defined as the positive cumulative deviation between 0^oC and the mean daily air temperature for successive days. The TI (Equation 4) is the positive cumulative deviation between the mean daily air temperature and a reference thawing temperature for successive days.

$$FI = \Sigma(0^oC - T_{mean}) \qquad (3)$$

where T_{mean} = mean daily temperature, $^oC = 1/2(T_1 + T_2)$, and

T_1 = maximum daily air temperature, ^oC,

T_2 = minimum daily air temperature, ^oC.

$$TI = \Sigma(T_{mean} - T_{ref}) \qquad (4)$$

where T_{ref} = reference freezing temperature that varies with the date, ^oC.

Pavement Condition Surveys

Pavement condition surveys are typically used to quantify the current distress level of the surface layer. The primary purposes are to determine if the structure is in need of rehabilitation and to track the change in condition. Past and present surveys were compared to determine the magnitude of change that occurred due to traffic and climatic effects.

A Mn/DOT manual explains the procedure for rating pavement surface layers [23]. This procedure calculates the pavement quality index (PQI) (Equation 5). The SR is on a scale of 0 –

4 and the PSR is on a scale of 0 – 5. This results in a PQI ranging from 0 – 4.5. AASHTO classifies roadways with a PQI of 2.5 as being "Fair" and in need of some form of rehabilitation. The PQI trigger value for Mn/DOT is 2.8 or less.

$$PQI = \sqrt{SR \bullet PSR} \qquad (5)$$

where PQI = pavement quality index,

SR = surface rating, and

PSR = present serviceability rating.

The SR is the sum of the percent occurrence of pavement distresses, such as cracking, rutting, raveling, patching, spalled and faulted joints, cracked or broken panels, and D-cracking. The PSR is a subjective rating completed by citizens, whom rate 120 roadway sections for ride quality from very good to very poor. PSR for pavement in Minnesota is calculated from IRI measurements correlated to the citizens' ratings.

Deflection Testing

FWD testing was conducted at three sites along the pilot study corridor and at the Mn/ROAD to quantify the seasonal changes in the structural capacity. The deflection data were measured in the fall and winter on the pilot study route, and during the spring at Mn/ROAD. The deflection data were used in EVERCALC version 5.0 [22, 24] to backcalculate the flexible pavement layer moduli. In this analysis, 9 sensors (spacing shown in Table 7) were used from the 40-kN (9,000 lbs.) drop, the plate radius was 15 cm, and the software was allowed to calculate the depth to a rigid layer with a modulus of 345 MPa (50 ksi). The load transfer efficiency was used to compare deflections measured from the PCC site near the Ada West piling station.

Deflections measured from the bituminous over concrete (BOC) site near Halstad were used to compare the seasonal change in BOC pavement stiffness.

Table 7. FWD sensor spacing.

Sensor Number	Spacing, mm (in)
1	0
2	203 (8)
3	305 (12)
4	457 (18)
5	610 (24)
6	914 (36)
7	1219 (48)
8	1524 (60)
9	1829 (72)

A saturated soil layer exists at the Mn/ROAD site that has an effect on the backcalculated layer moduli. It was found that the depth to this saturated layer is variable depending on the time of year and location of the pavement structure at Mn/ROAD [25]. Therefore, the depth to a saturated soil layer is calculated each time the backcalculated modulus is determined.

Measured Strains from Mn/ROAD

To observe seasonal changes in the measured strain levels of a low volume road (LVR), strain data were collected from the LVR at Mn/ROAD. The truck used at the Mn/ROAD facility is a 5-axle tractor-trailer combination that is loaded to 356 kN (80,000 lbs.) on one lane for four days a week, and 454 kN (102,000 lbs.) on the other lane the fifth day of each week. The data collected for this study was from the heavy lane.

The strains were measured from transverse and longitudinal embedded strain gage (TE and LE, respectively) sensors located at the bottom of the HMA layer. Strain data were collected from test section 30 on the following dates:

- October 21, 1998,
- December 23, 1998,
- March 3, 1999,
- March 17, 1999,
- March 31, 1999, and
- April 28, 1999.

The last date corresponds to the last day of SLR in central and southern Minnesota. The sensors were LE4, LE5, TE4, TE5 and TE6, which are located in the outer wheel path of the heavier loaded lane of test section 30. Using Equation 1 with strain data from test section 30 is particularly useful because strain, modulus, percent asphalt cement, and percent void data are available. The volumetric information from test section 30 is:

V_b = percent volume of asphalt cement = 5.9% for test section 30, and

V_v = percent volume of air voids = 8.2% for test section 30.

Summary

A pilot study was conducted in northern Minnesota in which a sugar beet hauling company was permitted to increase the winter load limit for 6-axle tractor-trailer combinations for a defined period of time. The route used in the pilot study was monitored for pavement structural data, traffic loads, and environmental conditions. Frost and thaw depths were monitored and used to define the increased winter load limit period. The surface condition of the roads used in the pilot study were rated before and after the increased load period to measure changes due to the increased load limits. The structural capacity of the roads was estimated using the falling weight deflectometer (FWD) and strain data were collected from Mn/ROAD. Finally, a simple analysis was performed to determine the feasibility of allowing higher winter load limits based on the information collected during this pilot study.

CHAPTER FOUR

RESULTS OF PILOT STUDY

Overview of the Pilot Study

A pilot study was conducted to investigate the effects of increasing the winter weight limits. The calendar of events was as follows:

- September, 1998 Falling weight deflectometer tests conducted on TH 200.
- October, 1998 Frost and temperature sensors installed in the shoulder of TH 200 near milepost 7 to monitor frost and thaw conditions of the roadway.
- November, 1998 Falling weight deflectometer tests conducted on TH 9.
- December 21, 1998 Frost and temperature measurements show two feet of frost in the pavement structure, which gives the green light for the study to begin.
- January 20, 1999 Actual beginning of the pilot study, Ada North, Ada West & Midway Piling Stations.
- February 6, 1999 Thaw begins. Frost and temperature measurements and forecasted temperatures show that thaw is occurring. Pilot study ends. Transporter resumes hauling at normal legal load limits.
- February, 1998 Falling weight deflectometer tests conducted on pilot study route.
- September and November 1999, September 2000. Additional frost and temperature sensors are installed in Wright, Lyon, Olmsted and St. Louis counties to aid in spring load restriction placement and removal.

Safety and Accident Prevention Measures

To ensure the safety of the drivers and the public, vehicle inspections were increased during the study. Drivers inspected the vehicles daily rather than weekly and the annual North American Standard Truck Inspection Procedure Level I, was done before and after the pilot study was conducted. The results of the Level I inspections were informative because these are very thorough and reveal many items found defective. Nineteen vehicles were inspected at the factory garage and all repairs were made immediately at the garage. Defective items included inoperable lamp, air leak in brake hose/tube, torn mud flap, and brake out of adjustment.

Truck Traffic Loads During Pilot Study

Typically the transporters monitor truck weight at the factory and weigh one vehicle from the fleet of 18 trucks on each rotation. The rate increased during this study to two trucks per 18 and the data is shown in Tables 8 and 9. The average weight was near 416 kN (93,500 lbs.) GVW, however the standard deviation was sometimes large, ± 20 kN (± 4,750 lbs.). This range of weights was partially due to the changing density of the sugar beets as they froze. The company used this information to improve its ability to keep the trucks within the legal limit. The local Department of Public Safety was also involved in monitoring the vehicle weights and historical records revealed good compliance by this company.

Table 8. Weight and frequency of trips data from Midway piling station.

Date	Average, kN (lbs.)	St. Dev, kN (lbs.)	% var. from 416 kN (93,500 lbs.)	Vehicle Count Per Day	% Vehicles Checked For Weight (Goal = 10%)
1/25/99	415 (93,389)	5 (1,169)	0.1%	127	11%
1/26/99	383 (86,084)	26 (5,804)	7.9%	49	10%
1/27/99	412 (92,615)	16 (3,596)	0.9%	51	20%
1/28/99	410 (92,214)	13 (2,828)	1.4%	67	30%
1/29/99	NA	NA	NA	81	NA
1/30/99	415 (93,306)	4 (899)	0.2%	80	13%
1/31/99	NA	NA	NA	57	NA
2/1/99	414 (93,188)	15 (3,410)	0.3%	84	6%
2/2/99	416 (93,488)	13 (2,859)	0.0%	64	16%
2/3/99	415 (93,273)	10 (2,171)	0.2%	92	9%
2/4/99	417 (94,838)	7 (1,562)	-1.4%	86	12%
2/5/99	411 (92,455)	7 (1,605)	1.1%	108	9%
			Total Trips =	946	

Table 9. Weight and frequency of trips data from Ada North piling station.

Date	Average, kN (lbs.)	St. Dev, kN (lbs.)	% var. from 416 kN (93,500 lbs.)	Vehicle Count per Day	% Vehicles Checked For Weight (Goal = 10%)
1/20/99	NA	NA	NA	41	NA
1/21/99	405 (91,113)	21 (4,751)	2.5%	93	11%
1/22/99	418 (93,988)	11 (2,433)	-0.5%	110	12%
1/23/99	423 (95,002)	9 (2,005)	-1.6%	134	7%
1/24/99	419 (94,140)	2 (439)	-0.7%	28	11%
			Total Trips =	406	

ESALs were used to compare the effects of tandem and tridem axles on flexible and rigid pavement structures, Tables 10 and 11 respectively. The comparisons made in these tables are between the current standard load limit for a tandem axle, 151 kN (34,000 lbs.), and three increased winter weight limits: a tandem axle at 169 kN (38,000 lbs.), a tridem axle at 198 kN (44,500 lbs.) and a tridem axle at 227 kN (51,000 lbs.). The tables show that the damage to both flexible and rigid pavements is more severe for a tandem axle loaded to 169 kN (38,000 lbs.) than for the tridem axles at 198 kN (44,500 lbs.) or 227 kN (51,000 lbs.). In other words, the increase in gross vehicle weight (GVW) from 356 kN (80,000 lbs.) to 416 kN (93,500 lbs.) or 445 kN (100,000 lbs.) was less detrimental than the increase from 356 kN (80,000 lbs.) to 391 kN (88,000 lbs.) for the described axle configurations. This is reasonable since the load on tridem axles is more spread out across the pavement when compared to tandem axles. This is also shown later in this report during the discussion of theoretical pavement response data.

Table 10. Increase in ESALs for flexible pavement due to increased winter load limits.

Gross Vehicle Weight, lbs.	Axle Configuration	Axle Weight, kN (lbs.)	Increase in ESALs	Overall Increase in ESALs for Truck
80,000	2 Tandems	151 (34,000)	0.0%	0.0%
88,000	2 Tandems	169 (38,000)	51.4%	46.9%
93,500	Tandem Tridem	165 (37,000) 198 (44,500)	37.8% -27.5%	4.7%
100,000	Tandem Tridem	165 (37,000) 227 (51,000)	37.8% 21.2%	26.9%

Table 11. Increase in ESALs for rigid pavement due to increased winter load limits.

Gross Vehicle Weight, lbs.	Axle Configuration	Axle Weight, kN (lbs.)	Increase in ESALs	Overall Increase in ESALs for Truck
80,000	2 Tandems	151 (34,000)	0.0%	0.0%
88,000	2 Tandems	169 (38,000)	53.8%	51.2%
93,500	Tandem Tridem	165 (37,000) 198 (44,500)	39.6% -4.9%	16.5%
100,000	Tandem Tridem	165 (37,000) 227 (51,000)	39.6% 61.0%	47.8%

Frost and Thaw Monitoring

The depth of solid frost needed to allow an increase in the gross vehicle weight was estimated to be 150 mm (6 in.) into the subgrade layer. It was assumed that the occurrence of daily freeze-thaw cycles at the top of the frozen layer would be negligible.

Freezing Index and Frost Depth

Since frost and temperature data were available at test sites in Norman County and Mn/ROAD, a comparison was made between the FI computed from average daily air temperature data and the measured frost depth. Greater FI values correspond to colder temperatures. The FI and average daily air temperature versus the date are shown in Figures 6 and 7 for Mn/ROAD and Norman County, respectively.

There is a broad range of FI values that correspond to the frost depth, Table 12. Test sections 24 and 27 at Mn/ROAD were used because they represent similar thin pavement designs and the subgrade material is different between the three sections. Mn/ROAD test section 24 has a sandy subgrade with a design R-value of about 70, Mn/ROAD test section 27 has a subgrade with a design R-value of about 12, and the pilot study site has a fine-grained subgrade with an unknown R-value.

Many observations can be seen in the data shown in Table 12. First, there was approximately 305 mm (12 in.) of frost depth when the FI reached nearly 36 to 38^{o}C-days. Second, test section 27 required more days with cooler temperatures to reach 455 mm (18 in.) of frost depth when compared to test section 24 and the Norman County site. This may be due to differences in moisture content, however this information was not available. The third observation concerns the large difference in FI values when the frost reached 610 mm (24 in.) for the three pavement sections. This may be a consequence of intermittent frost and thaw that occurred at the Norman County site in November prior to the more permanent frost, which occurred in December. There are a number of variables that could cause these differences including geography, temperature history, pavement layer materials, and moisture content. These variables need to be considered when predicting the frost depth from average daily air temperature.

Table 12. FI, ^{o}C-days, and approximate frost depth for Mn/ROAD test sections 24 and 27 and Norman County, 1998.

Site	305 mm (12 in.)	455 mm (18 in.)	610 mm (24 in.)	915 mm (36 in.)
Test section 24 – sandy subgrade	36 ^{o}C-days	55 ^{o}C-days	86 ^{o}C-days	220 ^{o}C-days
Test section 27 – fine-grained subgrade	36 ^{o}C-days	72 ^{o}C-days	99 ^{o}C-days	330 ^{o}C-days
Pilot Study in Norman county – fine-grained subgrade	38 ^{o}C-days	59 ^{o}C-days	160 ^{o}C-days	331 ^{o}C-days

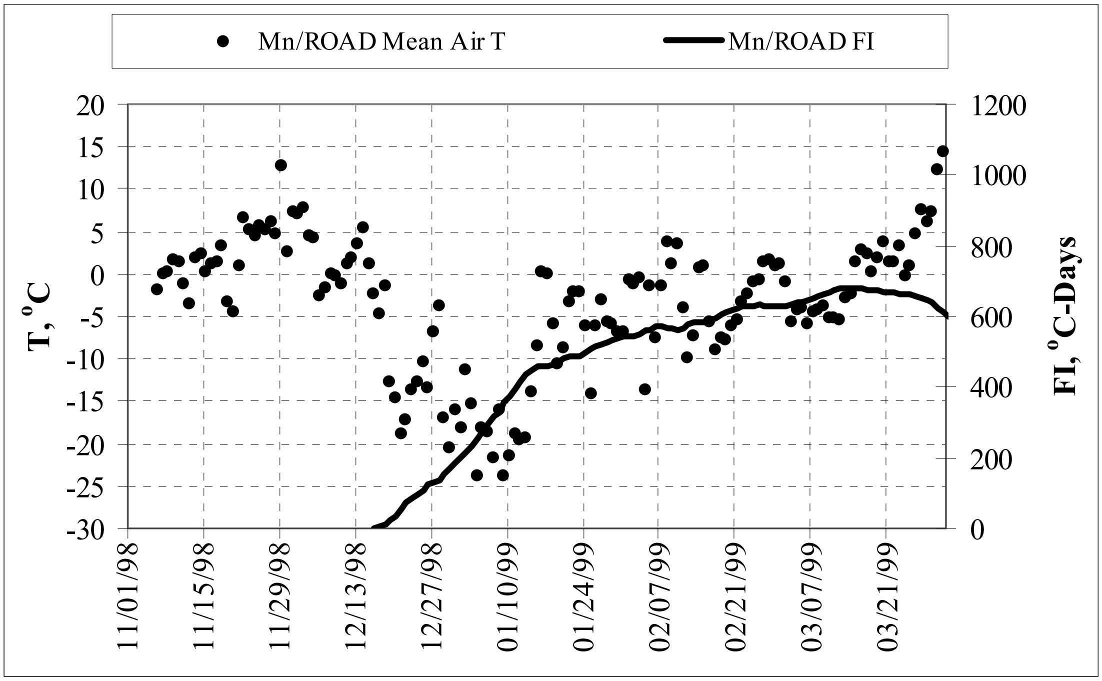

Figure 6. Mean air temperature and FI for Mn/ROAD, 1998 - 1999.

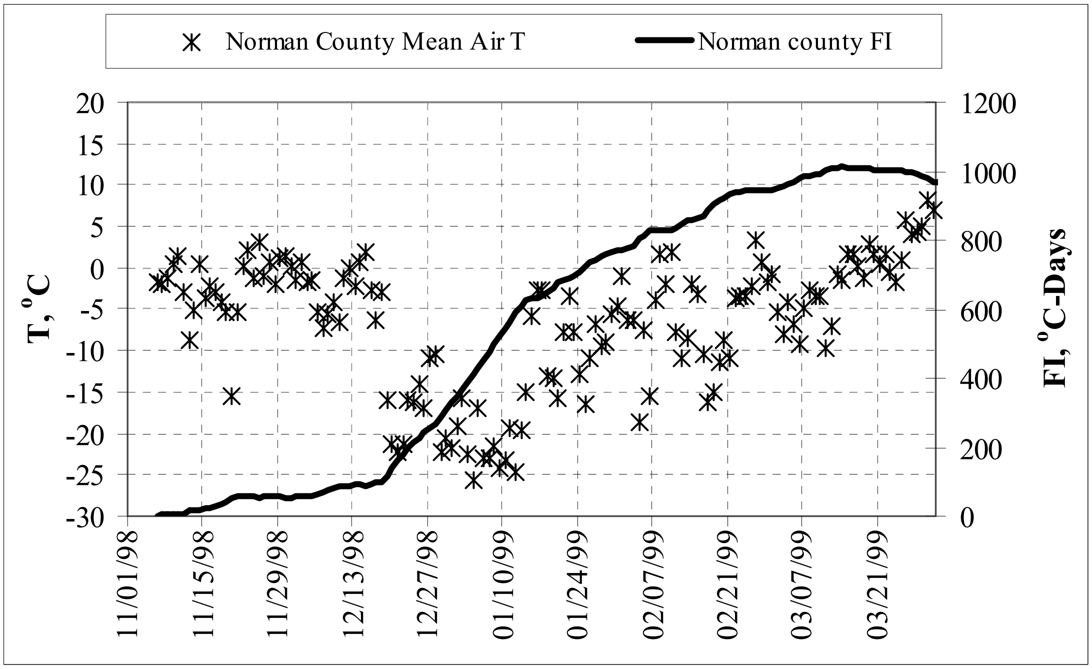

Figure 7. Mean air temperature and FI for Norman county, MN, 1998 - 1999.

Thawing Index and Spring Thaw

Temporary freeze-thaw events are typical in Minnesota and the spring of 1999 was no exception. Mn/DOT's policy is to place SLR once the TI reaches 15°C-days and the forecast calls for thawing to continue. Once SLR are placed, they remain for a period of 8 weeks. SLR began in the northern zone on March 18 and on March 3 for the other zones. Figure 8 (interpreted from the WM and TC data) and Figure 9 show that 305 mm (12 in.) of the base layer thawed by March 17, 1999 when the TI reached 23°C-days, thus SLR were placed in a timely fashion.

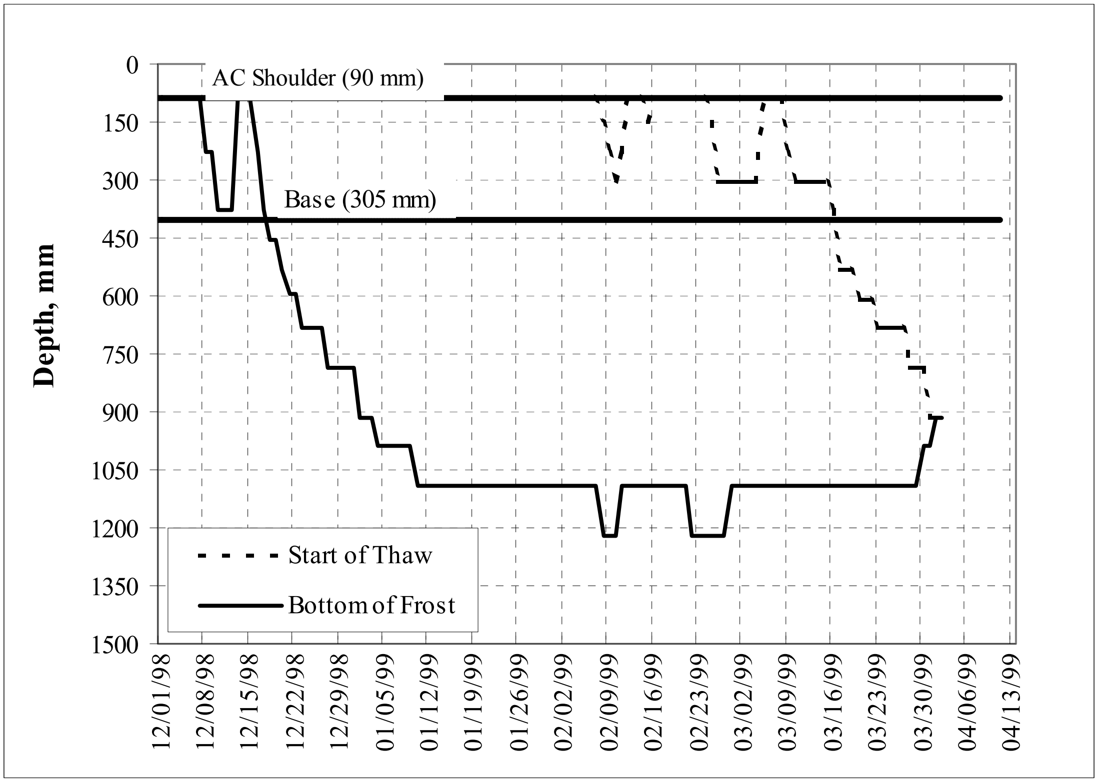

Figure 8. Frost and thaw depth in TH200 near Ada, MN in the winter and spring of 1999.

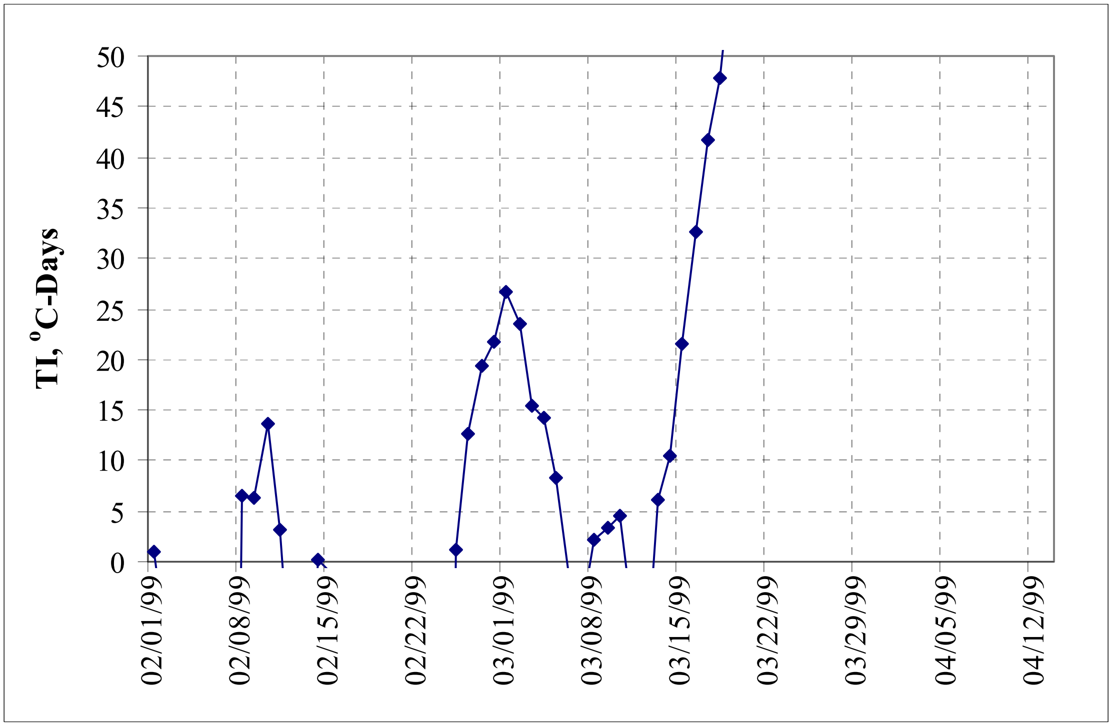

Figure 9. Cumulative TI for Ada, MN in the winter and spring of 1999.

Results of Pavement Layer System Monitoring

Condition Survey Results

Condition surveys were performed on all three pavement sections to determine if the condition of the pavement deteriorated with an increase in winter loads. The condition surveys were performed on the three pavement sections in the fall (November 3, 1998) and the winter (February 10, 1999). These surveys were similar to the past condition surveys conducted by Mn/DOT and are shown in Table 13.

Table 13. Current condition surveys of three test sites.

Distress/ Rating	Ada North, 1997		Ada West Site, 1998		Halstad Site, 1998	
	Length	% Area	Length	% Area	Length	% Area
IRI, mm/km	0.57	-	1.21 to 1.27	-	2.54 to 2.67	-
PSR	4.1	-	3.5	-	2.3	-
SR	3.8	-	3.8	-	2.5	-
PQI	3.9	-	3.6	-	2.4	-
SLT, m	94.5	62%	-	-	143.3	94%
SET, m	-	-	-	-	45.7	30%
SLL, m	18.3	12%	-	-	36.6	24%
CRA, m	-	-	18.3	12%	-	-
MUL, m	-	-	-	-	23	15%
Avg. Rut, mm	-	-	-	-	6	23%

The results show that while low severity cracks will be more visible in the winter when the pavement surface layer contracts due to the colder weather, there was no noticeable increase in the amount or severity level of distresses already prevalent in the pavement prior to this study. The Halstad BOC site received the most loads and the longest duration without any changes in the distress level of the section. The onset of D-cracking at the Ada West PCC site was noted, however this was not an effect of the increased winter loads. Finally, some of the fatigue cracks at the Ada North HMA site were more prevalent to the eye since the cooler temperatures caused the asphalt cement in the mix to contract.

Pilot Study Route Backcalculated Layer Moduli

The backcalculated layer moduli show a significant increase in structural capacity when the pavement is frozen. The test section near the Ada North piling station is the only flexible pavement test section. The backcalculated layer moduli are shown in Figures 10, 11, and 12 for the HMA, aggregate base, and subgrade layers, respectively. The deflections were small enough in the winter (on the order of 30 microns) that the maximum backcalculated layer moduli needed to be limited. These maximum layer moduli limits were as follows for the HMA, base, and subgrade layers: 14,000 MPa (2030 ksi), 5500 MPa (800 ksi), and 3500 MPa (500 ksi), respectively.

Deflection testing was done in the fall and winter on September 3, 1992, November 25, 1998 and February 9, 1999 for the Ada North site. It is shown in Figures 10, 11 and 12 that the highest stiffness of the three dates is on February 9, 1999, in which the pavement is frozen to a depth of at least 1.2 m (4 ft.). These figures show slight spatial variation in the modulus change between the stations tested.

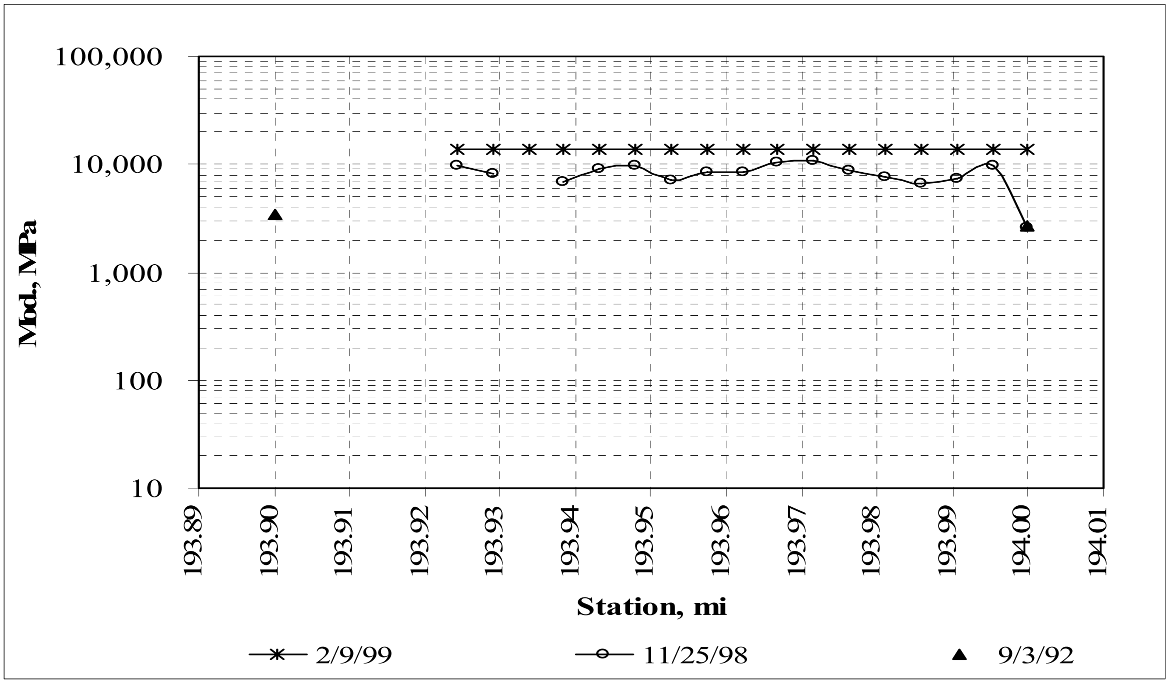

Figure 10. Backcalculated HMA layer moduli of Ada North site (#3).

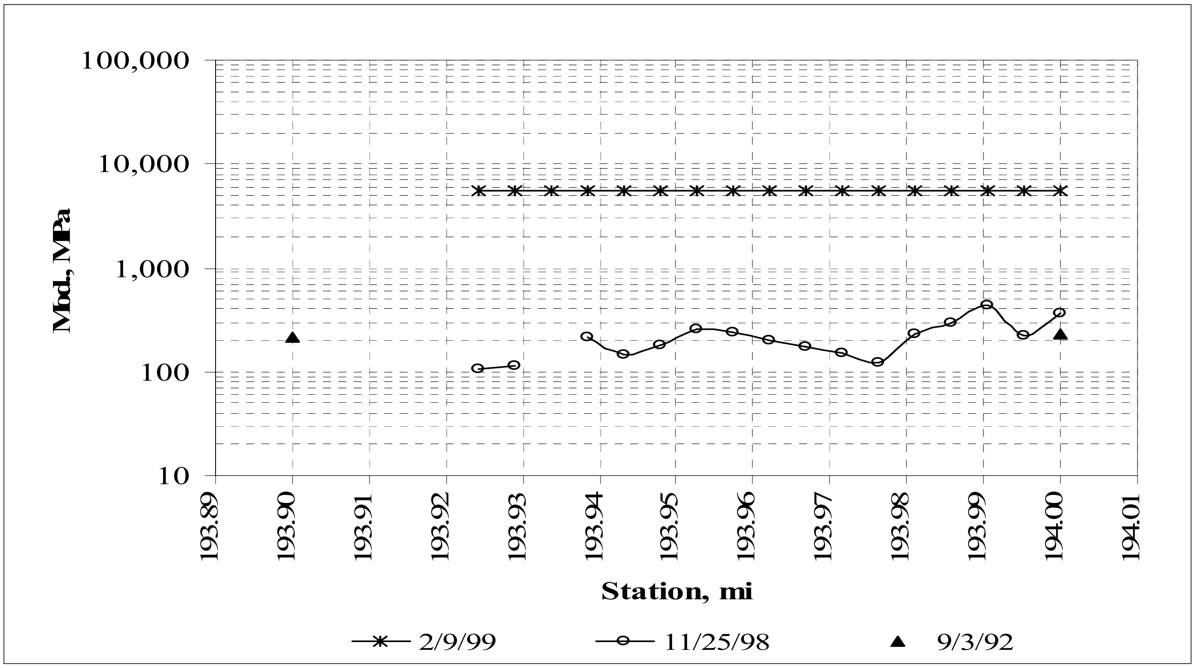

Figure 11. Backcalculated aggregate base layer moduli of Ada North site (#3).

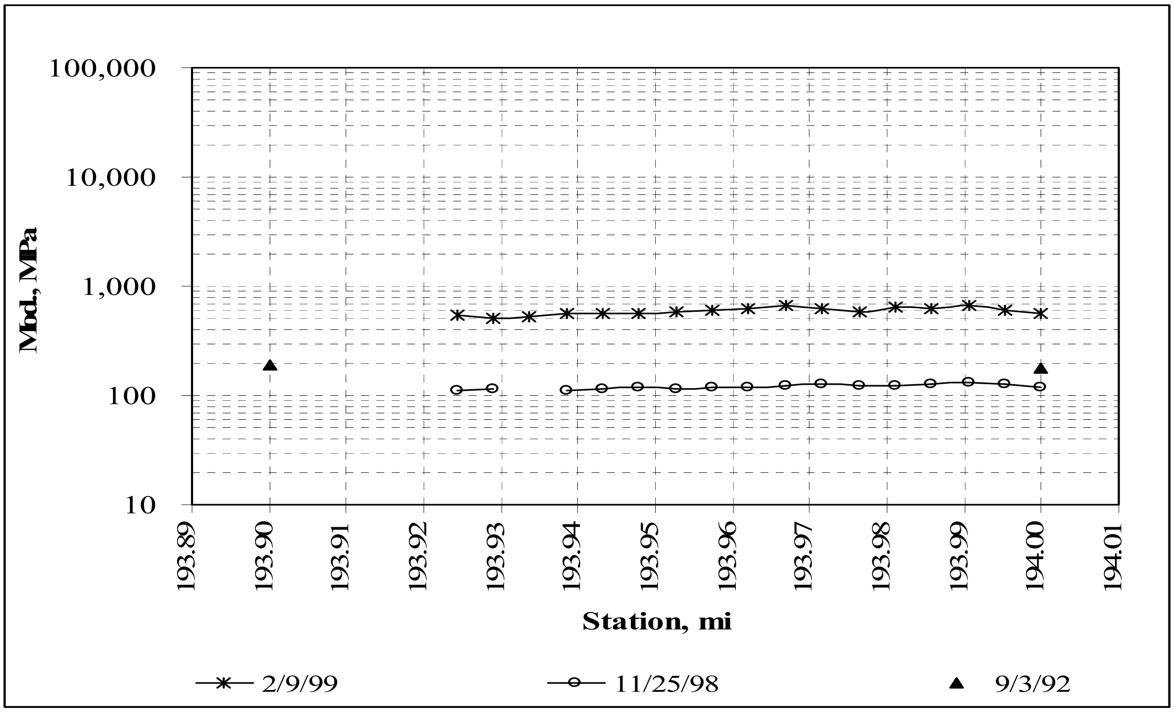

Figure 12. Backcalculated subgrade layer moduli of Ada North site (#3).

The deflection data for the Ada West site is shown in Figure 13. The load transfer efficiency (LTE) at the joints of the Ada West site increased in the winter, not because of improved interlock at the undoweled joints, but because the underlying base layer was frozen. The FWD became inoperable at the Halstad site and the winter deflections were not measured.

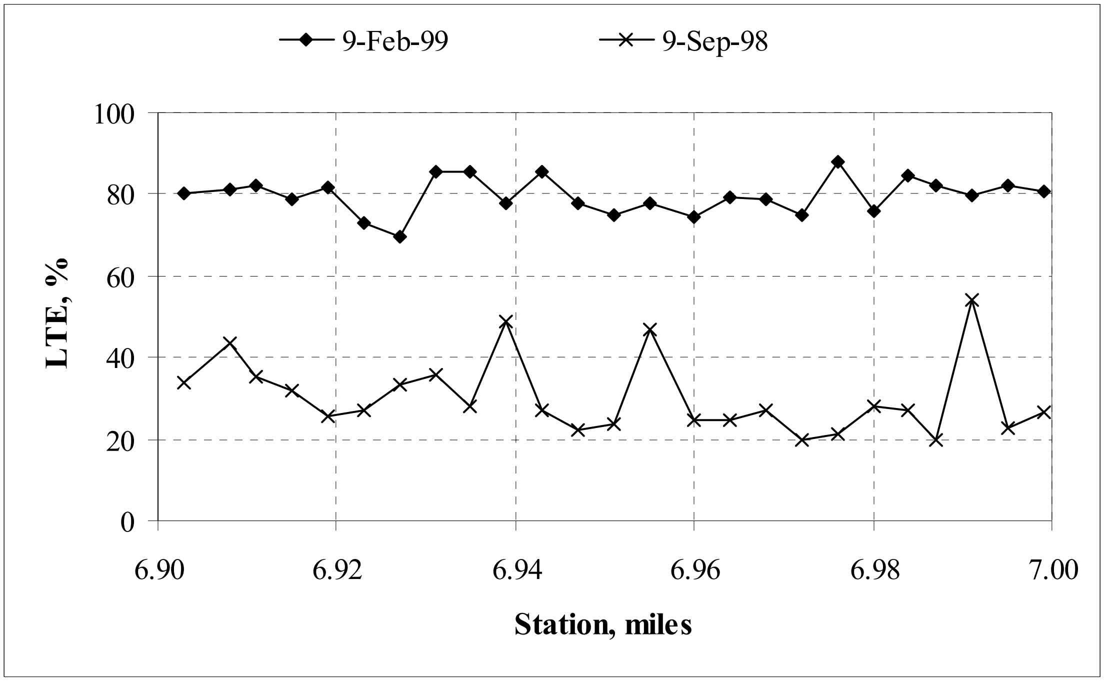

Figure 13. Load transfer efficiency at the Ada West site, undoweled PCC.

Mn/ROAD Backcalculated Layer Moduli

Similar seasonal trends in the backcalculated flexible pavement layer moduli are shown in Figure 14 for test section 30 at Mn/ROAD. Typical layer moduli values are seen in the fall, a distinct increase in the pavement layer moduli occurs in the winter and a significant decrease during the spring-thaw period. The base and subgrade layer moduli slowly recover during the summer to typical fall values. The decrease in the HMA layer moduli in the summer is caused by increased temperature.

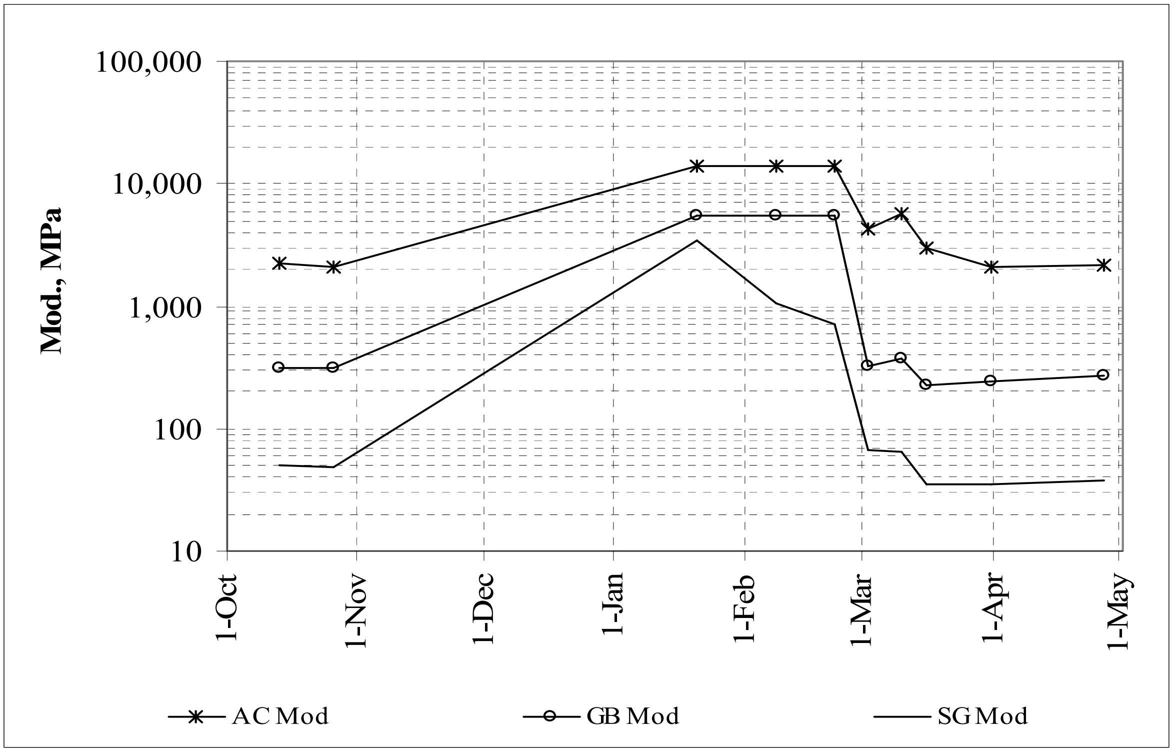

Figure 14. Test section 30 backcalculated layer moduli, fall 1998 – spring 1999.

Mn/ROAD Strain Data Results

It is shown in Figure 15 that the strain measured at the bottom of the HMA layer decreases significantly when the pavement structure is frozen. The strain levels are between 80 and 250 microstrain (με) in October and decrease between 10 and 20 με with the occurrence of two feet of frost in December. The strains begin to increase in March with the thawing of the pavement structure and reach strain levels between 150 and 500 με at the end of April, coinciding with increasing daily temperatures.

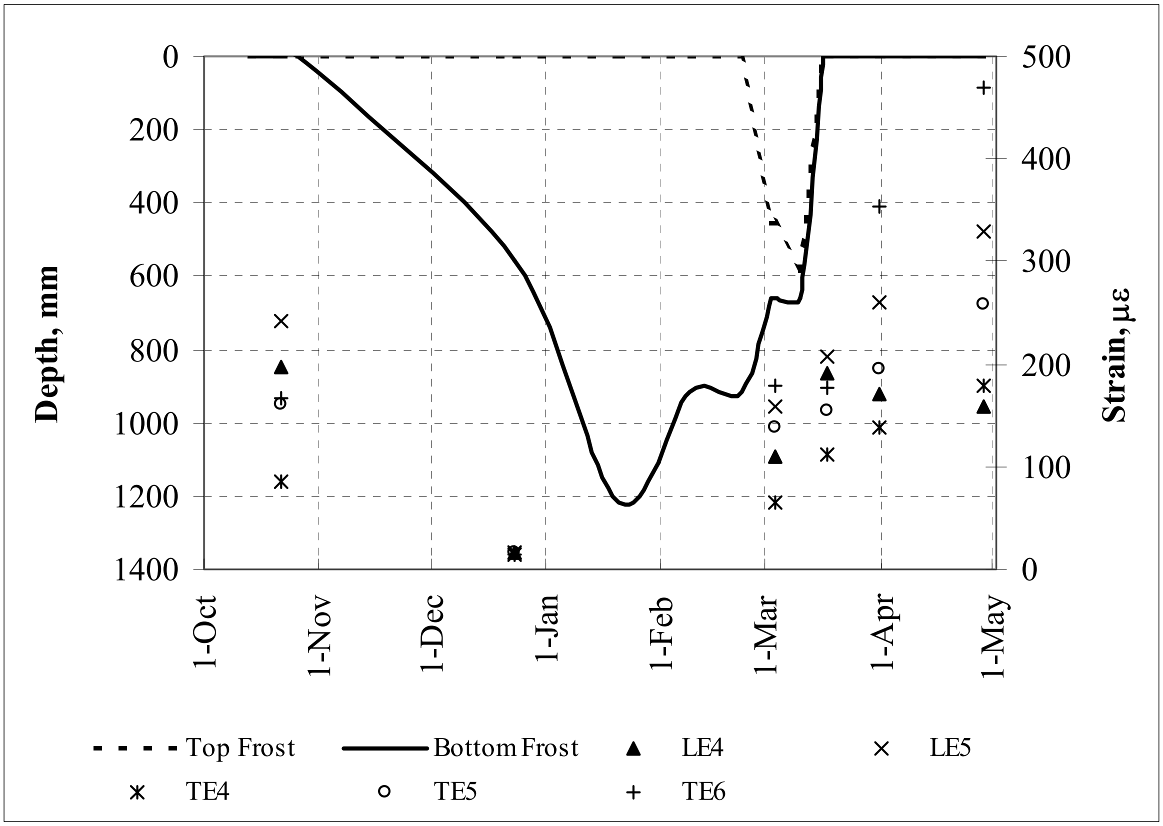

Figure 15. Frost depth and strain amplitude data from test section 30, 1998 – 1999.

Flexible Pavement Elastic Response

The maximum tensile strain at the bottom of the HMA in a flexible pavement structure decreases with the use of tridem axles. Strain levels also decrease significantly in the winter when the pavement layers are frozen. The theoretical strain at the bottom of the HMA layer is shown in Table 14. The comparison made in Table 14 is between the maximum tensile strain at the bottom of the HMA layer due to the current weight limit allowed throughout the year, 356 kN (80,000 lbs.) and the three proposed increased winter weight limits: 391 kN (88,000 lbs.), 416 kN (93,500 lbs.), and 445 kN (100,000 lbs.). The use of tridem axles weighing 198 kN (44,500 lbs.) actually decreases the strain level. The tridem loaded to 227 kN (51,000 lbs.) will cause similar strain levels when compared to a tandem at 151 kN (34,000 lbs.). A similar analysis is shown in Table 15 for the maximum vertical strain on the top of the subgrade layer.

Table 14. Theoretical increases in winter and spring microstrain, bottom of the HMA layer.

Gross Vehicle Weight, kN (lbs.)	Axle Configuration	Axle Weight, kN (lbs.)	$\varepsilon_{\text{Winter}}$	Increase in Winter Strain	$\varepsilon_{\text{Spring}}$	Increase in Spring Strain
356 (80,000)	2 Tandems	151 (34,000)	85	-	168	-
391 (88,000)	2 Tandems	169 (38,000)	93	8.5%	183	8.9%
416 (93,500)	Tandem Tridem	165 (37,000) 198 (44,500)	91 77	6.4% -9.8%	180 151	6.7% -10.2%
445 (100,000)	Tandem Tridem	165 (37,000) 227 (51,000)	91 85	6.4% 0.0%	180 168	6.7% 0.0%

Table 15. Theoretical increases in winter and spring microstrain, top of the SG layer.

Gross Vehicle Weight, kN (lbs.)	Axle Configuration	Axle Weight, kN (lbs.)	ε_{Winter}	Increase in Winter Strain	ε_{Spring}	Increase in Spring Strain
356 (80,000)	2 Tandems	151 (34,000)	141	0.0%	214	0.0%
391 (88,000)	2 Tandems	169 (38,000)	157	11.5%	239	11.6%
416 (93,500)	Tandem Tridem	165 (37,000) 198 (44,500)	153 122	8.7% -13.2%	233 186	8.7% -13.1%
445 (100,000)	Tandem Tridem	165 (37,000) 227 (51,000)	153 140	8.7% -1.0%	233 213	8.7% -1.0%

Predicted Pavement Fatigue

The measured strain from test section 30 was used in Equation 1 to predict the number of 80-kN (18-kip) ESALs to failure. The HMA layer modulus was estimated using the average daily temperature the day of the test. Table 16 compares the number of cycles to fatigue failure in October to the other test dates. The days when temperatures are below 0^oC allows for approximately 2 to 2400 times more ESALs. In contrast, when temperatures are above 0^oC, Equation 1 predicts an allowance of 1.2 to 3.4 times fewer ESALs.

Table 16. Predicted number of 80kN (18 kip) ESALs to failure, test section 30.

Date	Avg. Microstrain	Est. HMA Modulus, psi	Avg. T, ^oC.	N_f
10/21/98	171	800,000	6.7	86,771
12/23/98	15	1,000,000	-13.6	208,078,163
3/3/99	130	1,000,000	-5.7	175,449
3/17/99	168	1,000,000	2.3	75,311
3/31/99	224	500,000	14.2	53,213
4/28/99	279	500,000	12.5	25,781

North Dakota Pavement Sections & Cooperation

Mn/DOT collaborated with the NDDOT because the final destination of the trucks participating in the pilot study was a factory in North Dakota. NDDOT researchers monitored the surface pavement layer for increased distresses. None were found.

Possible Savings from Increased Winter Load Limits

Two scenarios were analyzed to determine the possible benefit of increasing winter load limits. In these scenarios, one variable is changed and the result compared to the current legal load limit. This was done by comparing the number of days saved during the spring load restriction period. Decreasing the amount of trips taken in the spring benefits the pavement structure and the transporter by increasing the payload and completing transport earlier than scheduled. The first scenario consists of using the same number of trips and the same duration as the pilot study, Tables 17 and 18. The second scenario increases the duration to begin with two feet of frost and end with one foot of thaw depth, Tables 19 and 20.

Table 17. Scenario One: 75 trips per day for 18 days.

GVW, kN (lbs.)	Axles	Estimated Payload, KN (lbs.)	Weight Moved, million kN (lbs.)
356 (80,000)	5	231 (52,000)	0.312 (70.20)
391 (88,000)	5	267 (60,000)	0.360 (81.00)
378 (85,000)	6	245 (55,000)	0.330 (74.25)
391 (88,000)	6	258 (58,000)	0.348 (78.30)
416 (93,500)	6	282 (63,500)	0.381 (85.73)
431 (97,000)	6	298 (67,000)	0.402 (90.45)
445 (100,000)	6	311 (70,000)	0.420 (94.50)

Table 18. Scenario One, fewer trips needed during SLR for piling stations in pilot study.

Weight Comparisons, kN (kips) and Number of Axles		Difference in Weight Moved, million kN (lbs.)	Difference in Number of Trips	Difference in Number of Spring Load Restriction Days
391 v 356 (88 v 80)	5 v. 5 axles	48 (10.8)	208	3
416 v 391 (93.5 v 88)	6 v. 6 axles	33 (7.4)	143	2
416 v 391 (93.5 v 88)	6 v. 5 axles	21 (4.7)	91	1
431 v 391 (97 v 88)	6 v. 5 axles	42 (9.5)	182	2
445 v 391 (100 v 88)	6 v. 5 axles	60 (13.5)	260	3
416 v 356 (93.5 v 80)	6 v. 5 axles	69 (15.5)	299	4
431 v 356 (97 v 80)	6 v. 5 axles	90 (20.3)	389	5
445 v 356 (100 v 80)	6 v. 5 axles	108 (24.3)	467	6

Table 19. Scenario Two: 75 trips per day for 67 days.

GVW, kN (lbs.)	Axles	Estimated Payload, kN (lbs.)	Weight Moved, Million kN (lbs.)
356 (80,000)	5	231 (52,000)	1.16 (261.30)
391 (88,000)	5	267 (60,000)	1.34 (301.50)
378 (85,000)	6	245 (55,000)	1.23 (276.38)
391 (88,000)	6	258 (58,000)	1.30 (291.45)
416 (93,500)	6	282 (63,500)	1.42 (319.09)
431 (97,000)	6	298 (67,000)	1.50 (336.68)
445 (100,000)	6	311 (70,000)	1.57 (351.75)

Table 20. Scenario Two, fewer trips needed during SLR for piling stations in pilot study.

Weight Comparisons, kN (kips) and Number of Axles		Difference in Weight Moved, million kN (lbs.)	Difference in Number of Trips	Difference in Number of Spring Load Restriction Days
391 v 356 (88 v 80)	5 v. 5 axles	179 (40.2)	773	10
416 v 391 (93.5 v 88)	6 v. 6 axles	123 (27.6)	531	7
416 v 391 (93.5 v 88)	6 v. 5 axles	78 (17.6)	338	5
431 v 391 (97 v 88)	6 v. 5 axles	156 (35.2)	676	9
445 v 391 (100 v 88)	6 v. 5 axles	224 (50.3)	966	13
416 v 356 (93.5 v 80)	6 v. 5 axles	257 (57.8)	1111	15
431 v 356 (97 v 80)	6 v. 5 axles	335 (75.4)	1450	19
445 v 356 (100 v 80)	6 v. 5 axles	402 (90.5)	1739	23

The number of trips the transporter took during this pilot study was shown in Tables 8 and 9. The average per day was 75 trips at 416 kN (93,500 lbs.) from January 20 through February 5, 1999 (18 days). If the transporter were able to begin transporting from these piling stations when two feet of frost depth was reached (December 21) and continue until a foot of thaw was measured in the pavement structure (February 26), the duration would have lasted 67 days. If the average were still 75 trips per day, then 67 days would result in 5025 vehicle trips at 416 kN (93,500 lbs.).

Data from the transporter reveals that the average number of trips taken during this duration on the 10-ton TH system was 17,300 trips. The total amount of sugar beets harvested in 1998 was 9.80 million metric tons (10.8 million tons) and the total amount moved from the piling stations to the factories was 5.4 million metric tons (6 million tons). This information includes piling stations and factories located in both Minnesota and North Dakota.

Certain assumptions were made in this analysis. The transporter did not reveal the actual empty weight of the vehicles and therefore this was estimated at 125 kN (28,000 lbs.) for the 5-axle vehicles and 133 kN (30,000 lbs.) for the 6-axle vehicles.

Estimated Costs

Permit Fees

Special permits were issued for this study that allowed the transporter to increase the winter load limits of the 6-axle tractor-trailer combinations to 416 kN (93,500 lbs.). The formula to determine the cost of the permits is as follows:

$$\text{Permit fee} = (\#\,\text{trips}) * \left(\frac{\#\,\text{miles}}{\text{trip}}\right) * \left(\frac{\text{damage factor, \$}}{\text{mile}}\right) + (\$36.00 * \#\,\text{trucks}) \qquad (6)$$

For approximately 1350 trips, the final cost of the permits came to $4,840. It was agreed that Mn/DOT would incur this cost in exchange for the transporter's cooperation in this study.

Upgrade Bridges

The primary cost associated with increasing winter load limits is the improvements required for the bridges along the corridors. A truck size and weight study estimated the cost to improve the bridge structures nation-wide to withstand higher GVW would be billions of dollars [20]. The cost to improve the bridge structures along all routes in Minnesota to current standards is estimated at $704 million dollars [16]. This estimate does not include the costs to increase the current winter load limits. It is not stated in these reports whether the bridges will be upgraded to a level at which increased winter load limits would be possible.

Summary

There is a significant increase in pavement stiffness during the winter when the pavement is frozen. The strains and deflections measured during the winter were much less than in the fall and spring. The data also showed that spreading of the load with more axles would reduce pavement strain and cause less damage. A frost depth of 150 mm (6 in.) into the subgrade marked the beginning of the study period and the end occurred when 150 mm (6 in.) of thaw was in the base layer. Condition surveys performed on the pilot study routes did not show an increase in pavement surface distress from the 18-day pilot study, however this is an extremely short period from which to draw conclusions.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

Summary

Increased vehicle loads are allowed on a permit basis depending on the season, vehicle, and roadway. Some states have grandfathered blanket permits that allow an increase in winter load limits to encourage the transport of goods when the stiffness of the pavement structure is greater. This policy is intended to decrease the transport of goods during the spring thaw. In Minnesota, the increased load limits and calendar dates were defined by legislation and not placed according to frost depth.

The objective of this study was to investigate the effects of increasing the winter load limits in Minnesota and to determine a proper method for placing and removing winter load limits. The winter load limit would be set such that a balance is met between: the capacity of the pavement and bridge structures, federal and state legislated axle limits, truck safety issues, and industry needs.

The pilot study was conducted using northern sugar beet haulers that were allowed to increase the winter weight of the 6-axle tractor-trailer combination vehicles from 391 kN (88,000 lbs.) to 416 kN (93,500 lbs.). The northern frost zone was chosen for the study because the frozen period is longer than in the southern zone and because the northern frost zone was allowed to increase winter limits by 10 percent beginning December 1 under the existing law. The increased load limit was chosen to match North Dakota's limit since this was the final destination of the selected route. The Minnesota Department of Public Safety was contacted regarding the permit procedure for the pilot study and enforcement issues.

The depth of the frost and thaw in the pavement structures were measured to determine the dates of the increased load limit period. Indices were used to develop relationships that could predict freezing and thawing. Deflections were measured to model the change in the structural capacity of the pavement during different seasons. Strain data was collected from Mn/ROAD to model a similar increase in the layer stiffness. Finally, condition surveys were done to monitor changes in the surface layer due to the increased load limit.

There are many economic issues that arise from increasing winter load limits. Some economic savings documented in this study would benefit Minnesota's pavement structures and industries. Increased winter load limits would more efficiently use the increased carrying capacity of frozen pavement structures and tractor-trailer combinations. The industry would benefit by increasing its payload per trip. If tridem axles were used in place of tandem axles, the load would be spread out further across the pavement and result in less pavement damage. Also, the increased load limits during the winter would lead to a decrease in the number of trips necessary during the spring if similar total quantities must be transported. This would result in less pavement damage.

Conversely, there are several costs associated with increasing winter weight limits. One of these is the anticipated bridge improvement cost, which was not within the scope of this study but is considered in other studies [18, 19]. Finally, there are several safety related issues associated truck size such as turning, accelerating, and braking that would need to be addressed before a further increase in winter load limits is implemented.

Conclusions

The conclusions from this study are limited in that the transporter was only able to cooperate with the study for 18 days on one test site and 5 days on the other two sites with a total number of trips of 1350. If the transporter had been able to begin December 21, 1998 rather than January 20, 1999, the duration of the study could have been 67 days. The following conclusions were made from the available data:

- The condition surveys conducted showed no visible signs of increased surface distress due to the increase in GVW of 6-axle tractor-trailer combinations from 391 kN (88,000 lbs.) to 416 kN (93,500 lbs.) over the 18 day period.
- There was a significant increase in the structural carrying capacity of the sites as indicated by the decrease in deflections during FWD testing and the reduced strains at Mn/ROAD.
- Tridem axles are expected to cause less damage than tandem axles.
- The frost depth was determined with a reasonable degree of accuracy using thermocouples and Watermark sensors.
- The ability to retrieve data using a modem proved valuable to ensure data was collected remotely and reliably.
- Viable relationships were shown between FI and frost depth and between TI and thaw depth, however specific criteria that would be used for the placement and removal of winter load limits were not determined.
- The costs associated with upgrading the bridges in Minnesota will have a significant influence on how widespread higher winter load limits could be implemented and on the overall cost to change current policy.

Recommendations

- It would be useful to determine how much axle weights could be increased during the winter before the pavement structure begins rapid deterioration due to increased brittle fracture or other mechanisms.
- If Minnesota's bridges are of sufficient strength, it would be worthwhile to determine the effects of increasing the GVW throughout the year for vehicles that use tridem axles. Greater use of tridem axles could reduce pavement damage on the state highway system and increase payload.
- It would be beneficial to install more frost and temperature sensors throughout Minnesota to allow more efficient implementation of seasonal load limit policies that maximize economic benefit and manage risk.
- In order to implement an improved method for placing and removing winter load limits, further study is required to develop specific methods that utilize the freezing index and thawing index.

Subsequent Accomplishments and Investigations

- As a result of recommendation three, additional frost and temperature sensors have been installed throughout Minnesota to allow more efficient implementation of seasonal load limit policies. The following six environmental monitoring sites were installed during the fall of 2003:
    1. District 2: Grygula, Minnesota (trunk highway 89 north of Marshall county road 6 [flexible pavement]),
    2. District 2: Cass Lake, Minnesota (trunk highway 2 [flexible pavement]),
    3. District 2: Chippewa National Forest Road 2135 (Cooperative project with Forest Service [aggregate-surfaced road]),
    4. District 4: Otter Tail, Minnesota (trunk highway 78 next to the Otter Tail Lake rest area [flexible pavement]),
    5. District 4: Starbuck/Benson, Minnesota (trunk highway 29 north of Pope county road 10 and 82 [flexible pavement]) and
    6. District 7: Reading (Worthington), Minnesota (trunk highway 266 southeast of Reading [flexible pavement]).

  Figure 5.1 presents a Minnesota map depicting the locations of currently available environmental monitoring sites.

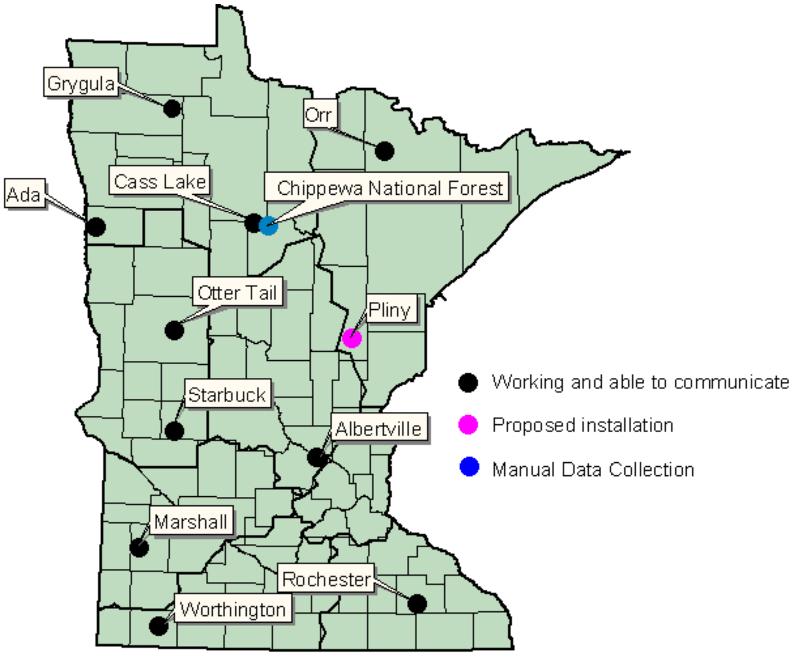

Figure 5.1. Minnesota map of environmental monitoring sites.

- In addition to the installation of added environmental monitoring sites, a task force was established, in 2002/2003, to re-define the frost zone boundaries in hopes of maximizing economic benefits and managing risk in the seasonal load limits policies. As a result of the investigation performed under this task force, spring load restrictions and winter load increases now utilize the same zonal boundaries as defined hereafter (see figure 5.2 for a general depiction of the boundaries):

North Zone Extends south from the Canadian border to a line following and **including**TH 1 at the North Dakota state line east to TH 89, TH 89 south to US 2, US 2 east to TH 33, TH 33 south through Cloquet to I-35, I-35 north to the Carlton/St. Louis county line, and then south on that line to the Wisconsin state line.

North-Central Zone Extends south from the southern limit of the North Zone (TH1 – TH 89 – US 2 – TH 33 – I-35 – Carlton/St. Louis county line – WI state line) to a line following and **including**US 10 from the North Dakota state line east to Motley, TH 210 east to Brainerd, TH 18 east to I-35, I-35 south to TH 48, and then TH 48 east to the Wisconsin state line.

Central Zone	Extends south from the southern limit of the North-Central Zone (US 10 – TH 210 – TH 18 – I-35 – TH 48 – WI state line) to a line following and **including** US 12 from the South Dakota state line to the Hennepin county line.
South Zone	Extends south from the southern limit of the Central Zone (US 12 – Hennepin county line) to the Iowa state line and east to the Metro Zone and then a line following and **including** I-35. This zone includes TH 19 along the southern border of Scott county.
Metro Zone	Minneapolis – St. Paul Twin City Metro Area includes the following counties: Anoka, Carver, Chisago, Dakota, Hennepin, Ramsey, Scott and Washington. This zone does not include TH 19 along the southern borders of Scott and Dakota counties.
Southeast Zone	Extends south from the southern limit of the Metro Zone along, but not including, I-35 to the Iowa state line and east to the Wisconsin state line. This zone includes TH 19 along the southern border of Dakota county.

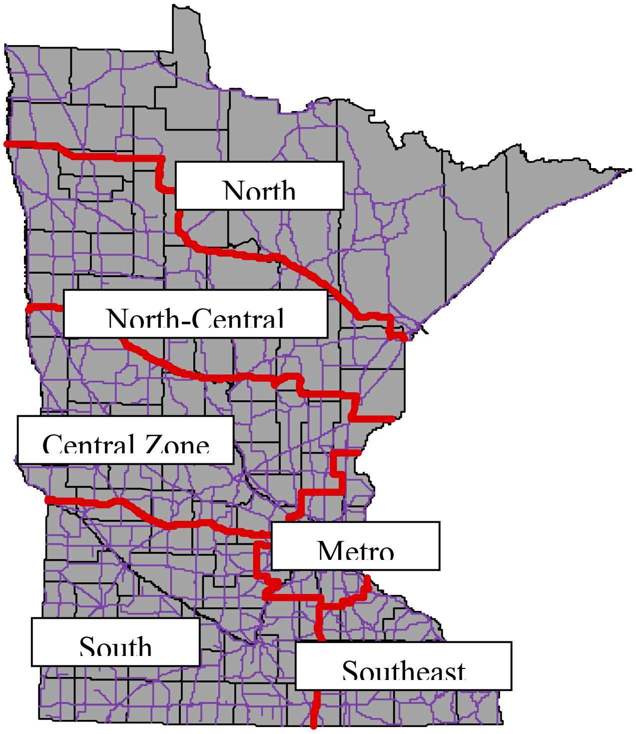

Figure 5.2. Minnesota map illustrating general zone boundary locations.

- An investigation to improve the placement and removal of winter load limits commenced in 2001 as a result of recommendation four. The preliminary model resulting from this investigation is currently being implemented into the seasonal load limit monitoring process. As a result, the start of winter load increases (WLI) are no longer set by fixed calendar dates, but determined for each frost zone using measured and forecasted daily temperatures for several cities within each zone. The criteria used to determine when the WLI will begin is when the cumulative freezing index (CFI) for a zone exceeds 156 C degree days (280 F degree days) based on the 3-day weather forecast, with predicted increases well in excess of 156 C degree days (280 F degree days). The intent is to use the 3-day advance forecast temperatures to ensure that a thawing event is not likely and that future freezing will ensure that the pavement structures will maintain adequate strength to carry larger loads due to increasing frost depth.

In addition to WLI starting date changes, the end of the winter load increase period is no longer tied to the starting date of spring load restrictions or March 7, whichever came first. WLI are not removed during temporary thaw events that are followed by extended freezing periods during the months of December and January, and therefore, are not typically removed prior to February 1. After which time, WLI are removed when the extended forecast predicts daily thawing, as indicated by the cumulative thawing index, and the impending placement of spring load restrictions. See the Mn/DOT Technical Memorandum 03-02-MRR-01 for further details (26).

- The monitoring of seasonal load limit (i.e., winter load increase and spring load restriction) starting and ending dates has been automated using an ORACLE based system. The climatic data currently collected is obtained directly from the National Weather Service via FTP sites. However, work is currently underway to incorporate the Mn/DOT road weather information system (R/WIS) climatic data into the seasonal load limit-monitoring program. Including this data would increase the density and distribution of data points throughout Minnesota; thereby, allowing the dissemination of cumulative freezing and thawing indices via contour maps, in lieu of the current two-dimensional graphs. (It is believed that the contour maps would mitigate confusion, by the users, when interpreting the generated information.)

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