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16. Abstract

This summary report describes the field data and analysis techniques used to evaluate the effect of winter ground freezing on WSDOT pavement structures during two thaw periods. Six field test sites were selected in District 2 for deflection testing and in situ instrumentation as well as materials sampling.

The results show that a principal mechanism which necessitates load restrictions for some of the WSDOT pavement structures is the weakened condition of the base course during thawing periods. Presented in the report is a single revised load restriction table and criteria to use in determining the time and location for establishing load restrictions.

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A RESEARCH SUMMARY REPORT

THE EVALUATION OF FROST RELATED EFFECTS ON PAVEMENTS

by

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Prepared by the
Washington State Transportation Center
and the
University of Washington

for the

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

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STUDY CONCLUSIONS

1. Approximately 11 of Washington's 39 counties (about one-third) can be expected to experience frost related pavement damage each year. These counties are located in Districts 2, 5 and 6. However, similar damage can occur in essentially any county in the state for severe winter conditions.

2. For the field test sites studied which normally require seasonal load restrictions, the "strength" of the base course (measured by resilient modulus) varied more than the subgrade (the opposite of what is normally expected). In fact, the subgrade moduli are relatively stable throughout the year (except when frozen). The base course weakness is due to excessive moisture available during the thawing period. The excessive moisture in the base course is exacerbated by either a still frozen subgrade and/or a low permeability subgrade soil (i.e., a water drainage path is temporarily reduced or eliminated).

3. A multilayered elastic analysis computer program along with WSDOT Falling Weight Deflectometer pavement deflection data was used to characterize the materials in the pavement layers for each test site with time. Criteria were developed which essentially reduce the allowable loads for a "summer" condition to equivalent loads during the critical period ("spring thaw"). Based on this analysis for the more critical test sites, a reduction in legal loads of about 60 percent is required and a single load restriction table was developed. The proposed load restriction values generally range between those contained in the two load restriction tables currently used by WSDOT.

4. A criterion was developed which can be used to determine <u>when</u> load restrictions should be initiated on a pavement structure requiring such

limitations (the criterion does not identify which pavements require load restrictions). The criterion is based on thawing degree - days (Thawing Index) and can be readily used by the WSDOT Maintenance Offices which record daily high and low temperatures. Both field data and an analytical procedure suggest the critical period will approach this condition after a Thawing Index of 25°F-days. Further, the pavement section will be in a critical condition after accumulating 50°F-days of thawing weather. These results show that only a modest amount of thawing weather can place a pavement into a critical condition. Site specific deflection data is the single "best" criterion to use in assessing the need for load restrictions but deflection data can be expensive to obtain and difficult to get at the needed time. A temperature based criterion is the next best alternative (and by far the least expensive and quickest to obtain). However, if summer and spring thaw pavement surface deflections are available, a preliminary criterion is that pavement sections with spring thaw surface deflections 50 percent or more higher than summer are candidates for load restrictions.

5. The length of the load restriction application period is, as one would expect, site specific. For the test sites studied in District 2, the most probable critical period date generally fell within a two week range (last week of February through the first week of March). Further, once the critical period is reached, it appears that about two weeks (at a minimum) is required for the pavement structure to overcome some of the low stiffness condition associated with the critical period.

INTRODUCTION

WSDOT District personnel throughout the State of Washington are faced with the recurring problem of weakened pavement structures during the spring thaw. One option available to reduce the pavement deterioration which can occur during this time period is load restrictions for truck traffic. Maintenance personnel generally know where spring thaw weakened pavement sections are located but there is a natural reluctance to apply load restrictions until certain they are needed. Severely weakened pavement structures can be essentially destroyed in one day by truck traffic. Thus guidance as to <u>when</u> to apply load restrictions should be helpful. Specifically when load restrictions are used, several questions arise such as:

1. Which pavement sections require load restrictions?
2. When should load restrictions be applied and removed?
3. Are the present WSDOT load restrictions (developed in 1952) adequate and, if not, how should they be revised?

These questions have been discussed within WSDOT and from this two recent studies were conducted.

The first study was performed by WSDOT personnel in District 1 primarily on various SR 20 pavement test sites in Western Washington [1]. The limited information from this study illustrated the elusive nature of the problem. Western Washington pavement conditions are difficult to quantify due to the brief but occasionally severe temperatures resulting in frozen pavement structures followed by rapid thawing. The second study [2] was a joint activity between the University of Washington Department of Civil Engineering, Washington State Transportation Center, WSDOT Materials Laboratory and WSDOT District 2. The contents of this research summary report are based primarily on the study noted as Reference 2.

RESEARCH OBJECTIVES

The objectives of the reported research were, in general, to address the previously stated questions (primarily Questions 2 and 3). More specifically the objectives were to:

1. Measure the variation of base and subgrade moisture contents, frost depths, and pavement deflections for several WSDOT pavement test sites in District 2.
2. Develop procedures to utilize easily obtained data to predict <u>when</u> load restrictions should be applied on a given pavement structure.
3. Determine if the current WSDOT load restriction tables are adequate and, if not, a suitable revision.

To accomplish these objectives, the following activities were accomplished during 1982-1984:

1. Collect data at several test sites including:
   - (a) frost depth,
   - (b) moisture contents of base and subgrade,
   - (c) soil temperatures,
   - (d) pavement surface deflections using the WSDOT Falling Weight Deflectometer (FWD), Benkelman Beam and extensometers permanently buried in the pavement structure.
2. Collect weather data.
3. Obtain pavement samples.

Overall, the study results can be used by maintenance personnel to better assess when load restrictions are needed, how long to enforce them, and what magnitude of restrictions to use.

THE PROBLEM

The frost related structural effects on pavements can be separated into two separate but related processes:

1. frost heaving resulting from accumulation of ice in the pavement layers (primarily base and subgrade) during the freezing period, and
2. weakening of the pavement structure when thawing temperatures occur (weakening mainly due to excessive moisture from melting ice and/or surface infiltration).

The conditions necessary for frost heave to occur include:

1. subfreezing temperatures,
2. water, and
3. frost susceptible soil (mainly silts and silty soils).

Remove any of the above conditions and pavement related frost effects will be eliminated or at least minimized.

Heaving

Frost heaving of soil is caused by crystallization of ice within the larger soil voids and a subsequent extension to form continuous ice lenses, layers, veins, or other ice masses. An ice lens grows in thickness in the direction of heat transfer until the water supply is depleted or until freezing conditions no longer support further ice crystallization. Ice segregation occurs primarily in soils containing fine particles (i.e. "frost susceptible"). Clean sands and gravels are non-frost susceptible. Frost susceptible soils are mainly silts and clays. Figure 1 illustrates the formation of ice lenses in a frost susceptible soil.

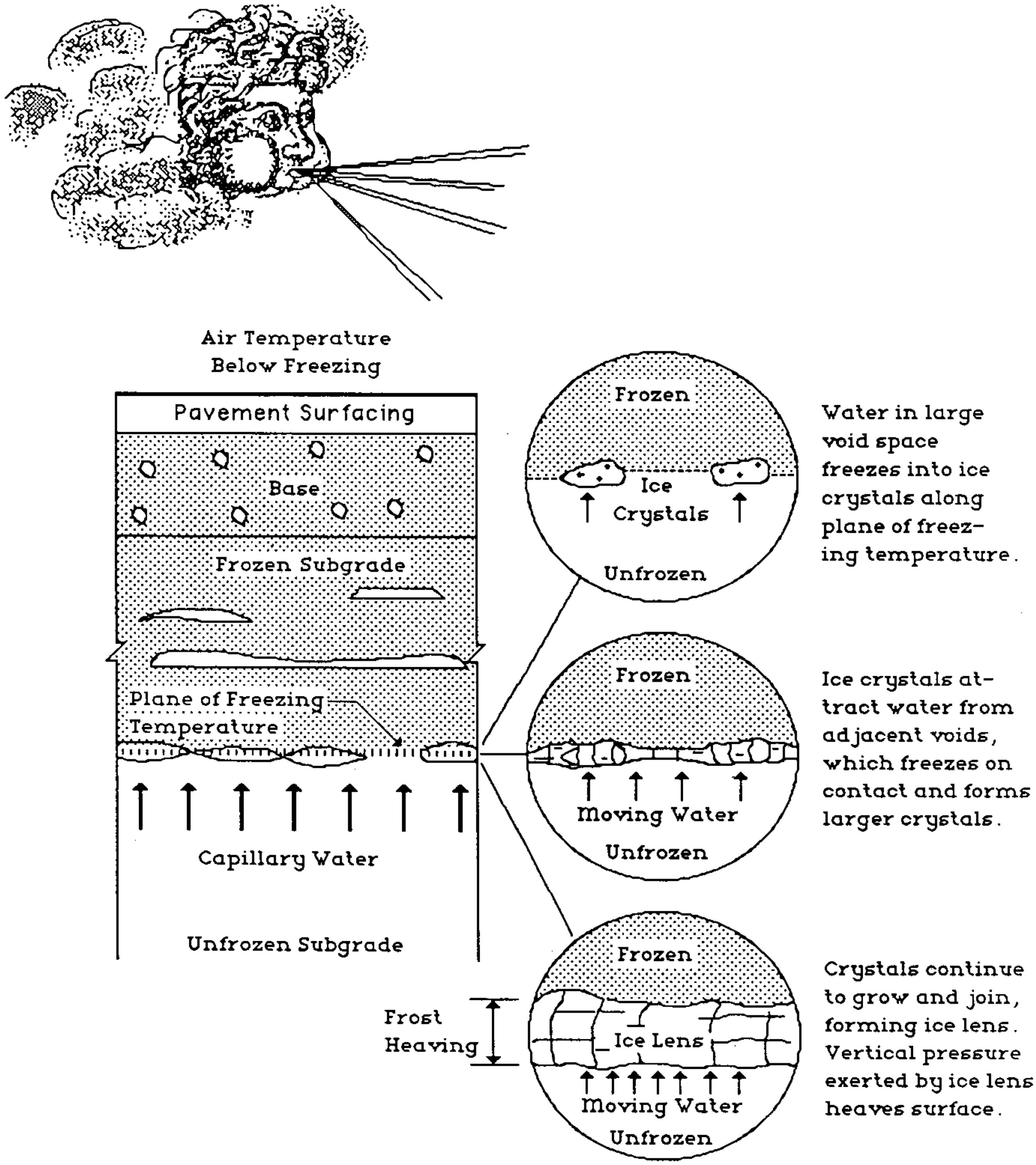

Figure 1. Formation of Ice Lenses in a Pavement Structure.

In general, it is difficult to totally eliminate heave, thus the objective is to reduce its magnitude and make it more uniform. An occasional problem for a number of WSDOT routes is differential heave which is likely to occur at locations such as:

1. abrupt transitions from cut to fill with groundwater close to the surface,
2. where subgrades change from clean sands and/or gravels to silty frost susceptible materials,
3. where excavation exposes water-bearing strata,
4. culverts frequently result in abrupt differential heaving due to different backfill material or compaction and the fact that open buried pipes change the thermal conditions (i.e., remove heat from the surrounding soils resulting in more frozen soil - analogous to an air conditioning duct).

Thawing

Pavement thawing can proceed from the top downward, or from the bottom upward, or both. How this occurs depends mainly on the pavement surface temperature. During a sudden spring thaw, melting will occur almost entirely from the surface downward. This type of thawing leads to extremely poor drainage conditions. The frozen soil beneath the thawed layer can trap the water released by the melting ice lenses so that lateral and surface drainage are the only paths the water can take.

Loss of pavement strength (or load capacity) during the spring thaw period (or other thawing periods occurring during the winter months) is one of the most serious problems associated with frost action. The usual pattern of pavement seasonal strength variation includes (usually) a significant increase from "normal" summer-fall conditions during the winter months when the pavement structure (including at least part of the subgrade) is frozen. Thawing can produce a rapid decrease in pavement strength below the summer-fall conditions followed by a gradual recovery over a period of weeks. Figure 2 is used to illustrate this process of strength variation by use of pavement surface deflections (higher deflections represent a weaker pavement structure).

FIELD STUDY

SITE SELECTION

District 2 was chosen for the location of all the field pavement test sites. Several criteria were used in selecting the sites resulting in the following pavement locations (each 500 ft. long):

SR 97, Milepost 184

SR 2, Milepost 117

SR 2, Milepost 160

SR 172, Milepost 2

SR 172, Milepost 21

SR 174, Milepost 2

These locations are shown in Figure 3.

DATA COLLECTION

Field data were collected at the six test sites over a 15 month period beginning in January 1982, with special emphasis on the spring thaw period. The following data were collected:

1. pavement surface deflection using the FWD and/or Benkelman Beam,
2. extensometer readings,

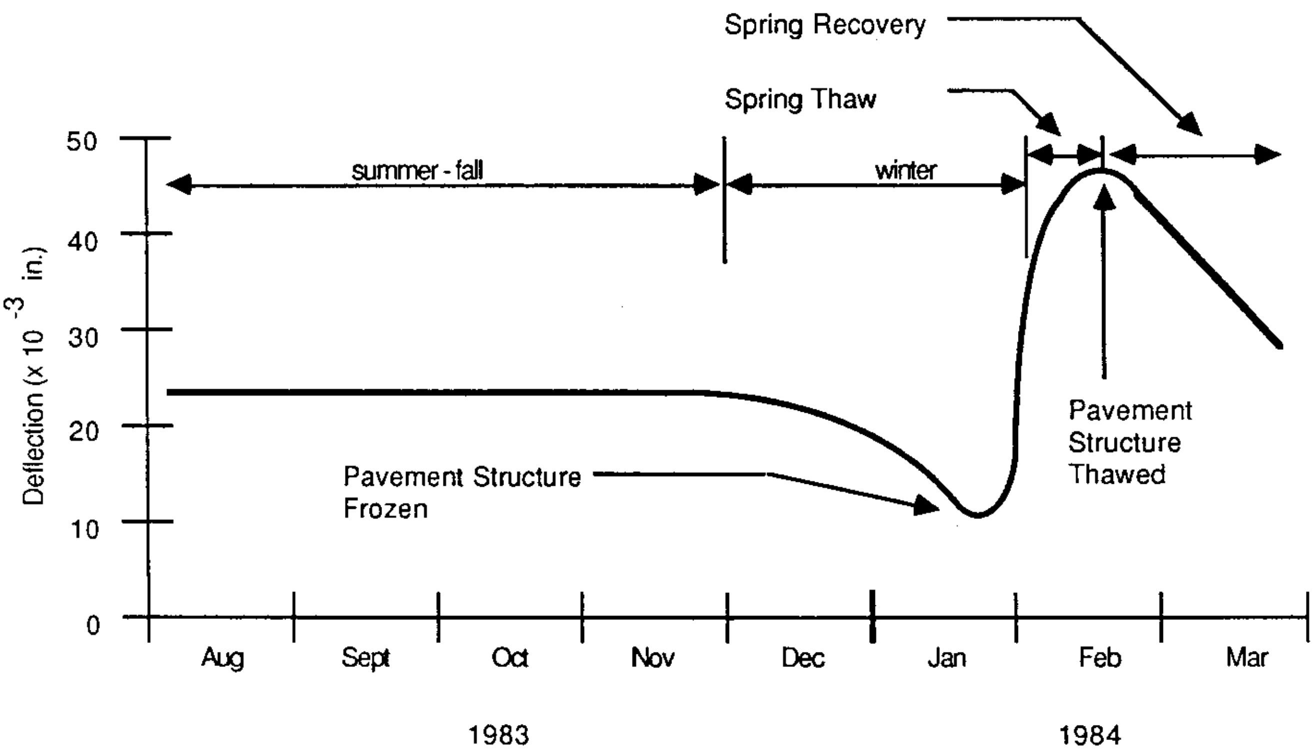

Figure 2. Pavement Deflections Illustrating Seasonal Pavement Strength Changes (SR172 - District 2).

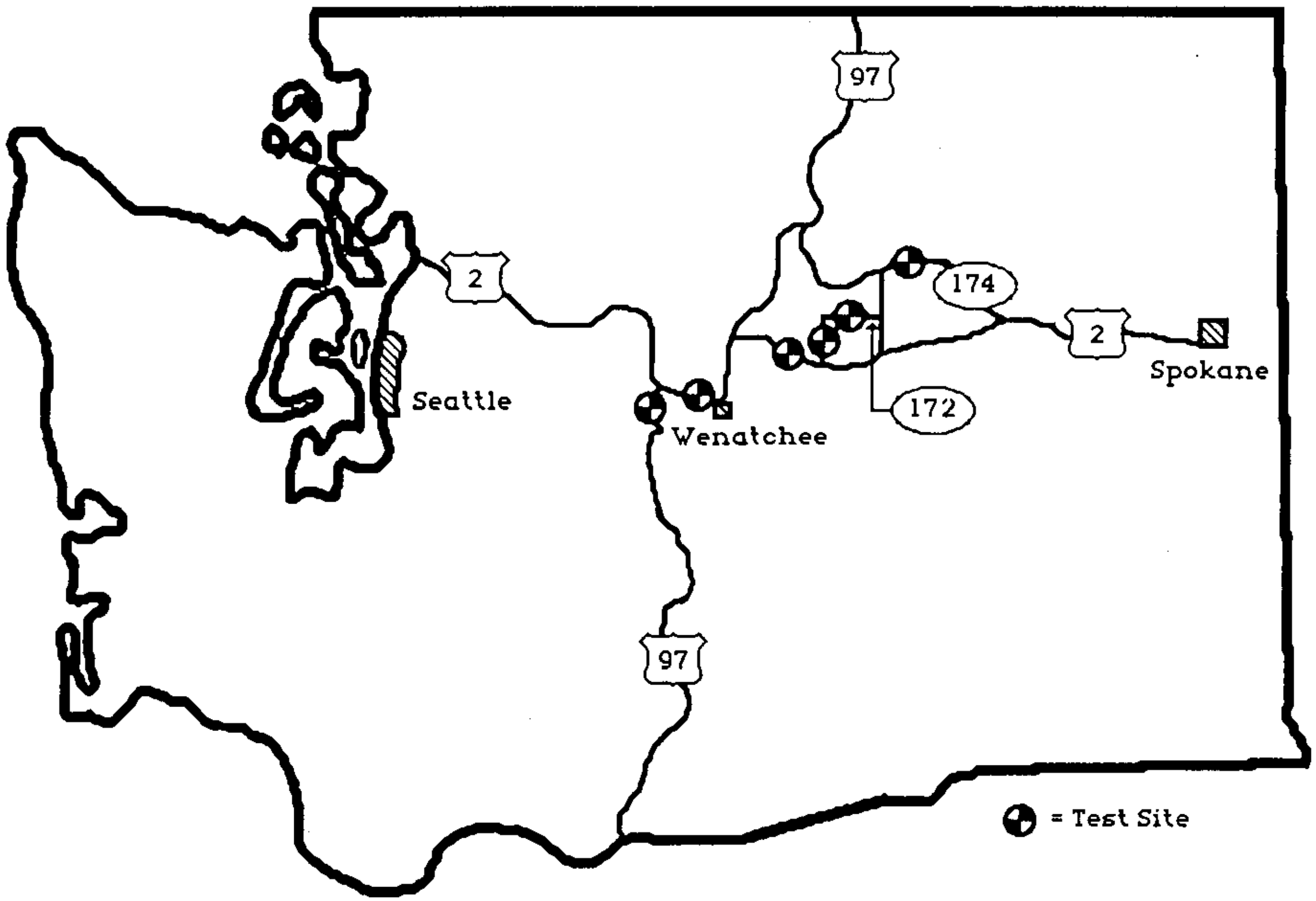

Figure 3. Location of Field Test Sites.

3. pavement surface temperature,
4. base and subgrade temperature,
5. soil moisture content, and
6. depth of frost penetration.

All of the above test data were not collected for all six sites and some of the instrumentation performed marginally. Details are provided in Reference 2.

RESULTS

CRITERION FOR WHERE AND WHEN TO APPLY LOAD RESTRICTIONS

A basic objective addressed in the study was when to establish load restrictions on a specific highway (assuming that load restrictions for a specific pavement are necessary). A criterion based on deflection measurements provides certainty as to the need for load restrictions.

Maximum pavement surface deflections (at a "standard" 9000 lb. FWD load) gathered on the test sites which normally require load restrictions suggest that the "critical period" surface deflections are about 50 percent or more higher than "summer" deflections. Further, the winter "frozen" condition deflections were about 10 to 40 percent less than summer deflections. Overall, a preliminary "rule-of-thumb" is that a pavement section with spring thaw surface deflections of about 50 percent or higher than typical summer deflections is a candidate for load restrictions (maintenance personnel judgment is very important - the above stated criterion should only be used as a "guide"). A better criterion would be based on the complete deflection basin but use of such information awaits further field data and analysis.

At least for the near future, it is impossible for WSDOT deflection equipment and/or personnel to be at all the necessary locations during the critical months of January, February, and March. An alternative approach is to use temperature data to estimate the depth of thaw in a pavement structure and hence if it is near or in the "critical period".

Temperature data were obtained from local WSDOT Maintenance Offices and used to calculate Thawing Indices (TI) which represent the cumulative number of degree - days above a reference temperature for a specified period of time (i.e., a measure of the severity and duration of the thawing period following seasonal freezing weather conditions). A possibly more familiar index is Freezing Index (FI) which is commonly used to characterize the severity and duration of below freezing temperatures during the winter months (also cumulative degree - days). Figure 4 shows Design Freezing Index (three coldest winters out of the last 30) for Washington State.

Such data as shown in Figure 4 illustrate the colder portions of the state such as the north central and eastern areas which represent about 50 percent of the state. Freezing and Thawing Indices go hand-in-hand. The colder the area, the deeper the ground will freeze which increases the probability of frost heaving and eventually thaw weakening. For example, the following freezing depths will occur in typical subgrade soils underneath pavements for various Freezing Indices:

Freezing Index	Estimated Depth of Freezing Beneath a Pavement (rounded to the nearest foot)	
(°F-day)	(Gravels)	(Silts)
500	3	2
1000	5	3
1500	6	3
2000	7	4

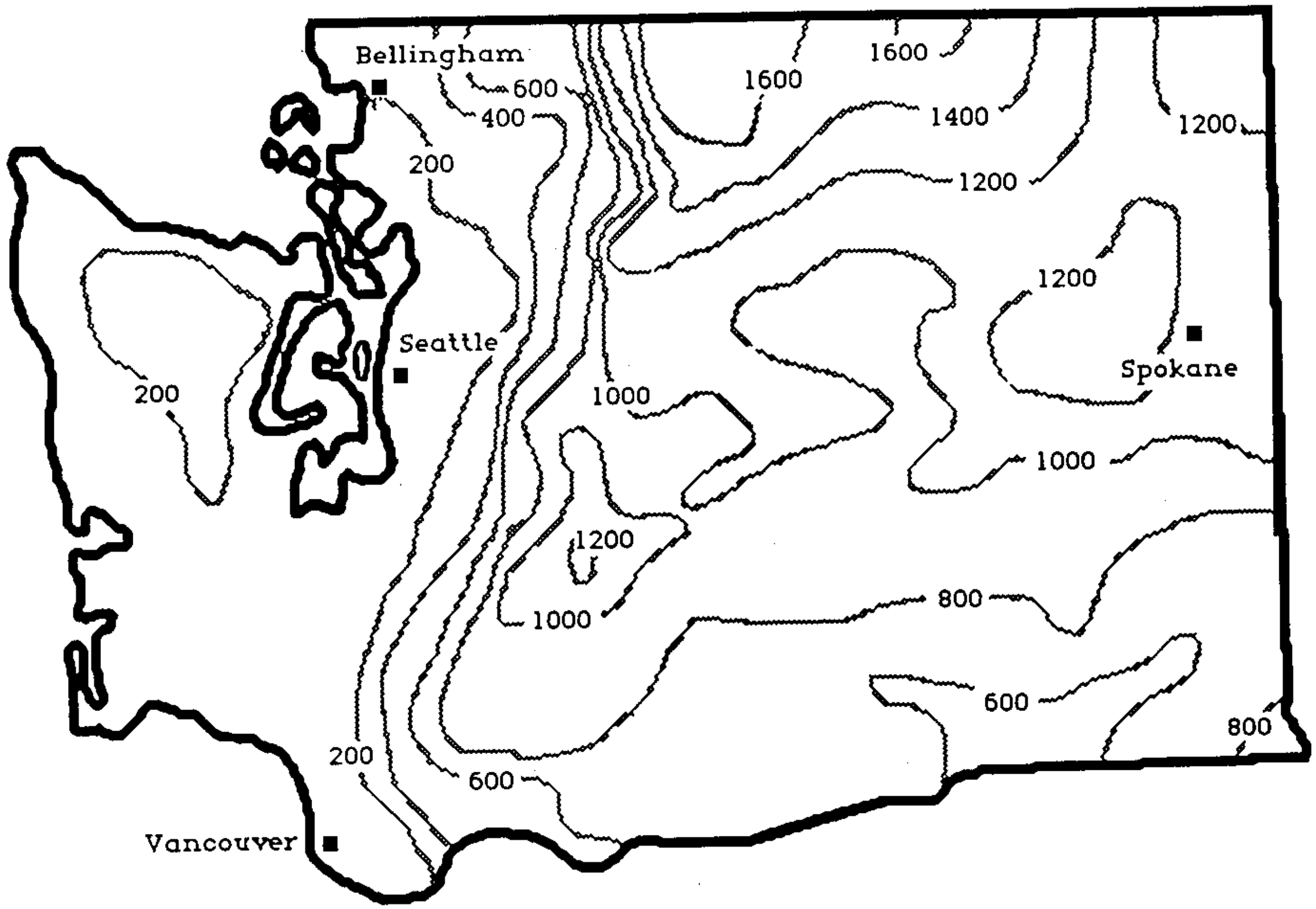

Figure 4. Design Freezing Index Contour Map for Washington State

The above illustrates two basic facts:

1. granular soils have greater depths of freezing than silts (however the material properties for gravels change the least from a frozen to a thawed condition), and
2. during severe winters, depending on local soil conditions, depths of freeze in much of Washington will range from about two to six feet.

If a Design Freezing Index of 1000°F-days is used to describe those parts of the state more likely to experience frost related pavement damage (a freezing depth of about three to five feet), the following counties would be included (located in either Districts 2, 5, or 6):

1. Chelan
2. Douglas
3. Ferry
4. Grant
5. Kittitas
6. Lincoln
7. Okanogan
8. Pend Oreille
9. Spokane
10. Stevens
11. Yakima

In other words, about 30 percent of Washington State counties can be expected (depending on local soil and moisture conditions) to be affected by frost action (though not necessarily every winter). However, for severe winter conditions, essentially <u>any</u> county in the state can experience frost related damage.

Large Freezing Indices are required to achieve large depths of freezing; however, relatively small Thawing Indices are required to thaw enough of the pavement structure to cause a "critical condition". Based on the study results (2) and a recently completed report funded by the FHWA (3), it was recommended that WSDOT tentatively adopt a Thawing Index of 25°F-days to indicate pavement structures approaching a "critical condition" (using a reference temperature of 29°F to calculate Thawing Index) and a Thawing Index of 50°F-days for pavements in a "critical condition". Clearly, the pavement structure, subgrade soils, and winter temperature history will influence such criteria; however, WSDOT District Maintenance personnel in the various maintenance offices record high/low daily temperatures for other purposes each winter. Now this same information can be used as a rule-of-thumb to assess the need for load restrictions.

Figure 5 is a proposed datasheet which can be used in maintenance offices to record measured high/low daily temperatures which in turn can be used to assist in calculating Thawing Index. The figure also is used to illustrate the use of "typical" data. The example shows that recording of daily high/low temperatures (Columns 3 and 4) started on February 18 and was discontinued on March 9. The average daily temperature was calculated and is shown in Column 5. The daily contribution to Thawing Index was obtained by subtracting 29°F from the average daily temperature and recorded in Column 6. Finally, the cumulative Thawing Index is shown in Column 7 and was obtained by summing the positive daily Thawing Index contributions from Column 6. The example shows that on March 4 the Thawing Index reached exceeded 25°F-day and on March 8 passed 50°F-day. Thus, the critical condition should be expected to start on about March 4 and be "critical" by March 8 (keep in mind that

Day	Date	Measured Daily Temperature (°F)		Average Daily Temperature °F $\left(\frac{High + Low}{2}\right)$	Daily Thawing Index = Ave. Daily Temp. -29° F (°F - day)	Sum of Daily Thawing Index
		High	Low			
(Col. 1)	(Col. 2)	(Col. 3)	(Col. 4)	(Col. 5)	(Col. 6)	(Col. 7)
1	Feb 18	31	19	25	-4	-
2	Feb 19	30	18	24	-5	-
3	Feb 20	29	19	24	-5	-
4	Feb 21	29	21	25	-4	-
5	Feb 22	28	16	22	-7	-
6	Feb 23	29	19	24	-5	-
7	Feb 24	33	21	27	-2	-
8	Feb 25	32	20	26	-3	-
9	Feb 26	34	22	28	-1	-
10	Feb 27	40	30	32	+3	3
11	Feb 28	42	32	32	+3	6
12	Mar 1	44	34	35	+6	12
13	Mar 2	42	30	34	+5	17
14	Mar 3	42	32	35	+6	23
15	Mar 4	44	32	37	+8	31
16	Mar 5	42	30	36	+7	38
17	Mar 6	40	28	34	+5	43
18	Mar 7	43	27	35	+6	49
19	Mar 8	44	32	38	+9	58
20	Mar 9	50	30	40	+11	69
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Figure 5. Form for Calculating Thawing Index with Example Data.

local site specific conditions can be different and that the illustrated calculations and criteria are for "general" conditions).

CRITERION FOR DURATION OF LOAD RESTRICTIONS

The most probable critical period start date for the test sites studied generally fell within a two week range (last week of February through the first week of March). Further, once the critical period is reached, it appears that about two weeks (at a minimum) is required for the pavement structure to overcome some of the low stiffness condition associated with the critical period. However, such conditions are quite site specific as one would expect. At best, once load restrictions are applied, the two week load restriction application period is only suggested as a rule-of-thumb. The "best" method to determine the continuing need for load restrictions (or lack of) is the use of the Falling Weight Deflectometer (or in general any kind of pavement surface deflections).

MAGNITUDE OF LOAD RESTRICTIONS

The Falling Weight Deflectometer and two computer programs were used to evaluate the two currently used WSDOT load restriction tables and develop a new single table. First, in situ material properties for various times during the study period were determined based on the deflection data followed by calculation of the pavement structure response to various tire sizes and wheel loads.

The primarily material property estimated was the resilient modulus for each pavement layer at each test site (resilient modulus is analogous to a "modulus of elasticity"). An interesting trend noted for SR 2, MP 160 was that the base course modulus decreased about 41 percent from the August 1983 (summer condition) to March 1984 (spring thaw) but the subgrade modulus on both dates were about the same. The maximum observed decrease in modulus from summer to spring thaw conditions was 78 percent. For all test sites (except SR 2, MP 117 which exhibited extensive fatigue cracking and was actually weaker during the summer months), the base course modulus was reduced by an average of 52 percent and the subgrade modulus about 23 percent from summer to spring thaw conditions. This is a significant finding in that the loss of strength during the spring thaw for pavements not designed for the condition is normally attributed to the subgrade soils. Actually the design and associated drainage conditions for base courses can be as significant (or more so) as the subgrade soils. Such data suggest that stabilized base courses (in those areas where they can be economically constructed) merit consideration.

A second computer program was used to evaluate various tire sizes and loads to estimate the pavement response at various times of the year (specifically summer and spring thaw conditions). The following pavement responses were calculated:

1. pavement surface deflection
2. horizontal strain at the bottom of the bituminous bound layer,
3. vertical strain at the top of the base course, and
4. vertical strain at the top of the subgrade.

These pavement responses are illustrated in Figure 6.

The spring thaw loads were calculated which would result in the same deflections and strains as the summer condition. Clearly, the loads so calculated were lower than the summer case. The pavement response which governed the spring thaw allowable load (or equivalent) varied but generally

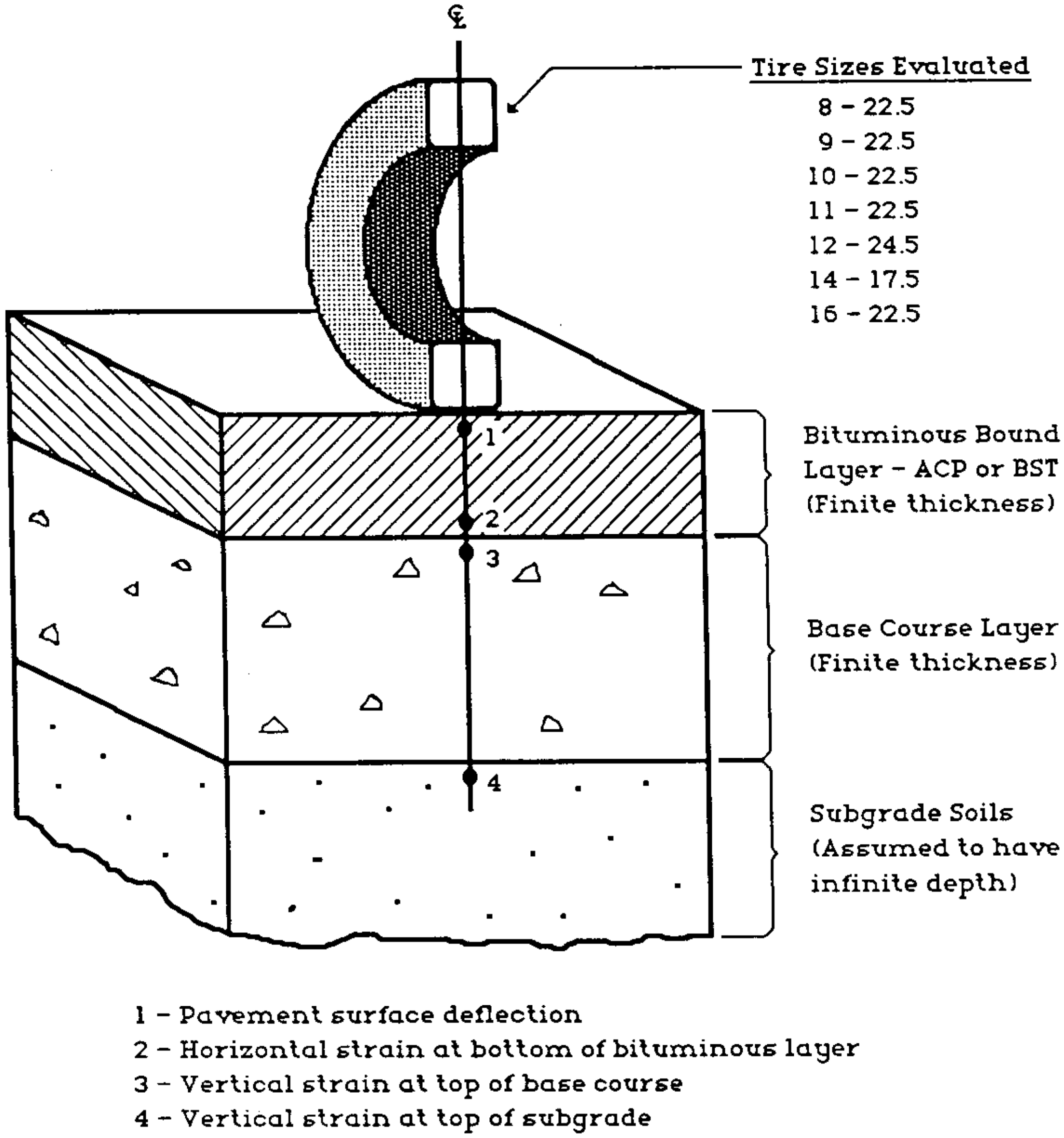

Figure 6. Pavement Response Locations Used in Evaluating Load Restrictions.

were either the pavement surface deflection or vertical strain at the top of the base course as shown in Table 1.

Table 1 further illustrates the allowable spring thaw load and critical criterion for each tire size and test site. The low volume routes such as SR 172 and SR 174 (500-800 ADT) clearly have the largest reduction in allowable loads. Based on this type of analysis, the actual load restrictions could be varied for each site; however, from a practical standpoint, this is not enforceable. If load restrictions are needed for a specific pavement structure, then only one or two levels of restrictions should be considered. From the analysis a spring thaw period allowable load of about 40 percent of summer allowable for all tire sizes appears reasonable (a 60 percent reduction). Interestingly, the corresponding allowable spring period loads from the analysis fall within the range of the current WSDOT load restrictions (refer to Table 2). Figures 7, 8, and 9 can be used to illustrate the differences between the maximum allowable axle loads (non-thaw conditions), the proposed spring load restrictions, current WSDOT emergency load restrictions, and current WSDOT severe emergency load restrictions as a function of tire size (these figures are based on the recently revised RCW 46.44.042 which provides for an allowable tire load of 600 lb. per in. width). Figure 7 was prepared for single axles with single tires, Figure 8 for single axles with dual tires, and Figure 9 for tandem axles with dual tires. In general, the proposed tire load restrictions resulting from the study result in axle loads which fall between those allowed by the two currently used WSDOT load restriction tables. Specifically, steering axles (single axle - single tires) could go to 7,600 lbs. (16 in. tire) under the proposed load restrictions as opposed to a maximum of 6,000 lbs. under the currently used severe emergency load restrictions.

Table 1. Summary of the Critical Criteria and Corresponding Spring Allowable Load for Each Tire Size Modeled.

Tire Size	Site	Critical Criterion for Each Site (1)	Spring Allowable Load (lbs)	% of Maximum Legal Load
8-22.5	SR 97, MP 183.48	δ	3,775	79
	SR 2, MP 117.38	ε_t	5,200	108
	SR 2, MP 159.6	ε_{VB}	3,670	76
	SR 172, MP 2.0	δ	1,820	40 (critical)
	SR 172, MP 21.4	ε_{VB}	2,400	50
	SR 174, MP 2.0	ε_{VB}	3,130	65
9-22.5	SR 97, MP 183.48	δ	4,325	80
	SR 2, MP 117.38	δ	5,460	101
	SR 2, MP 159.6	ε_{VB}	4,190	78
	SR 172, MP 2.0	δ	2,180	40 (critical)
	SR 172, MP 21.4	ε_{VB}	2,730	51
	SR 174, MP 2.0	ε_{VB}	3,490	65
10-22.5	SR 97, MP 183.48	δ	4,900	82
	SR 2, MP 117.38	δ	6,230	104
	SR 2, MP 159.6	ε_{VB}	4,600	77
	SR 172, MP 2.0	δ	2,400	40 (critical)
	SR 172, MP 21.4	ε_{VB}	2,750	46
	SR 174, MP 2.0	ε_{VB}	3,700	62
11-22.5	SR 97, MP 183.48	δ	4,875	74
	SR 2, MP 117.38	δ	6,770	103
	SR 2, MP 159.6	ε_{VB}	4,990	76
	SR 172, MP 2.0	δ	2,450	37
	SR 172, MP 21.4	ε_{VB}	2,290	35 (critical)
	SR 174, MP 2.0	ε_{VB}	3,850	58
12-24.5	SR 97, MP 183.48	δ	6,300	88
	SR 2, MP 117.38	δ	8,550	119
	SR 2, MP 159.6	ε_{VB}	6,180	86
	SR 172, MP 2.0	δ	3,800	53
	SR 172, MP 21.4	ε_{VB}	3,600	50 (critical)
	SR 174, MP 2.0	ε_{VB}	4,780	66
14-17.5	SR 97, MP 183.48	ε_t	6,020	72
	SR 2, MP 117.38	δ	9,380	112
	SR 2, MP 159.6	ε_{VB}	6,020	72
	SR 172, MP 2.0	δ	4,400	52
	SR 172, MP 21.4	ε_{VB}	3,460	41 (critical)
	SR 174, MP 2.0	ε_{VB}	4,670	56
16-22.5	SR 97, MP 183.48	ε_t	5,990	62
	SR 2, MP 117.38	δ	11,100	116
	SR 2, MP 159.6	ε_{VB}	6,760	70
	SR 172, MP 2.0	δ	4,680	49
	SR 172, MP 21.4	ε_{VB}	3,320	35 (critical)
	SR 174, MP 2.0	ε_{VB}	4,780	50

(1) δ = pavement surface deflection
ε_t = horizontal tensile strain at the bottom of the bituminous bound surface layer
ε_{VB} = vertical strain at the top of the base course

Table 2. Comparison of the Current and Proposed Load Restrictions.

Emergency Load Restriction		Severe Emergency Load Restriction		Proposed Load Restriction	
Tire Width	Gross Load Each Tire (lbs)	Tire Width	Gross Load Each Tire (lbs)	Tire Width	Gross Load Each Tire (lbs)
8 - 22.5	2,250	8-22.5	1,800	8	2,000
9-22.5	2,800	9-22.5	1,900	9	2,200
10-22.5	3,400	10-22.5	2,250	10	2,400
11-22.5 11-24.5	4,000	11-22.5 11-24.5	2,750	11	2,600
12-22.5 12-24.5	4,500	12-22.5	3,000	12	2,900
14-17.5	4,500	14-17.5	3,000	14	3,400
16-22.5	4,500	16-22.4	3,000	16	3,800

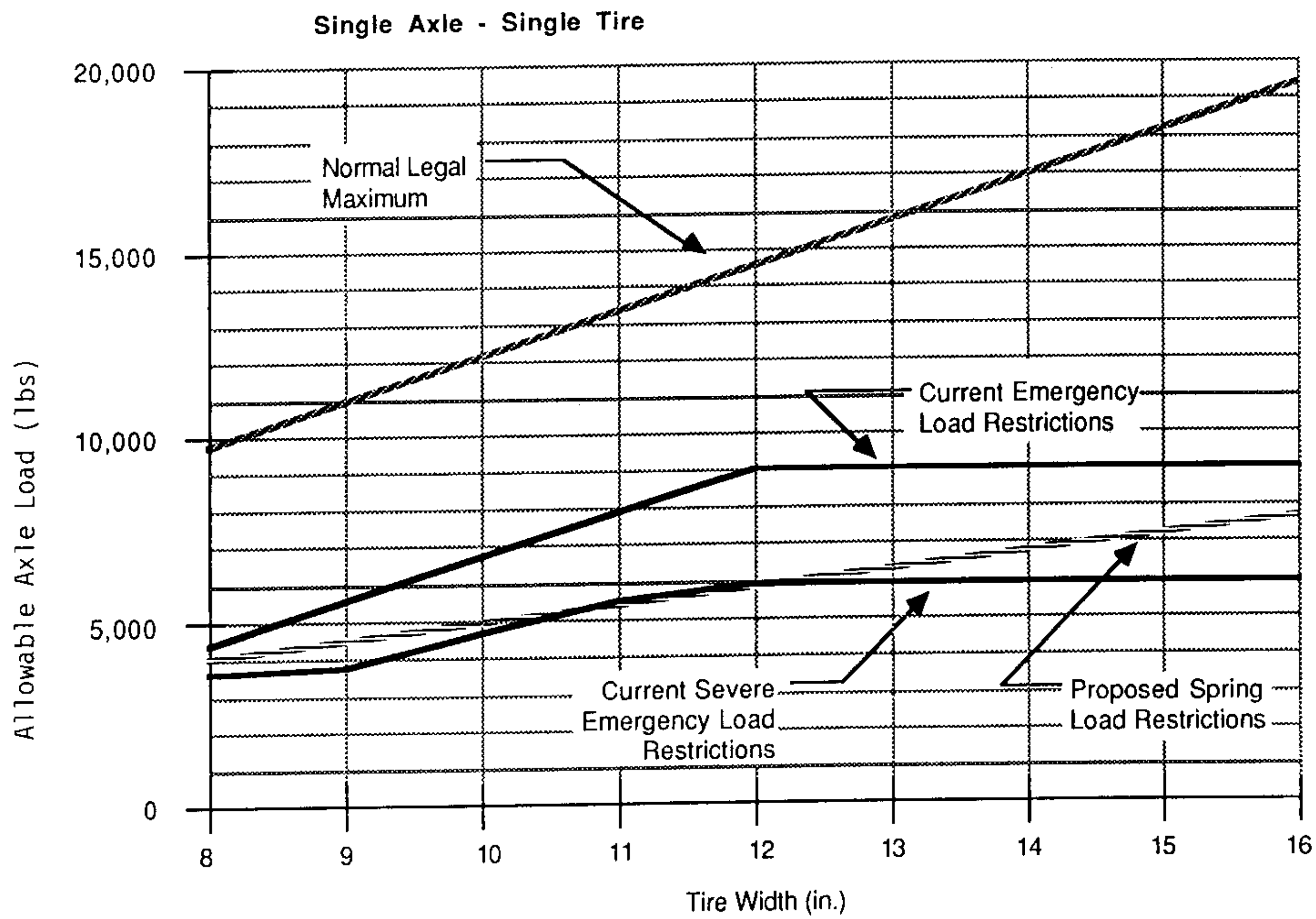

Figure 7. Allowable Axle Loads vs. Tire Width for Single Axles with Single Tires.

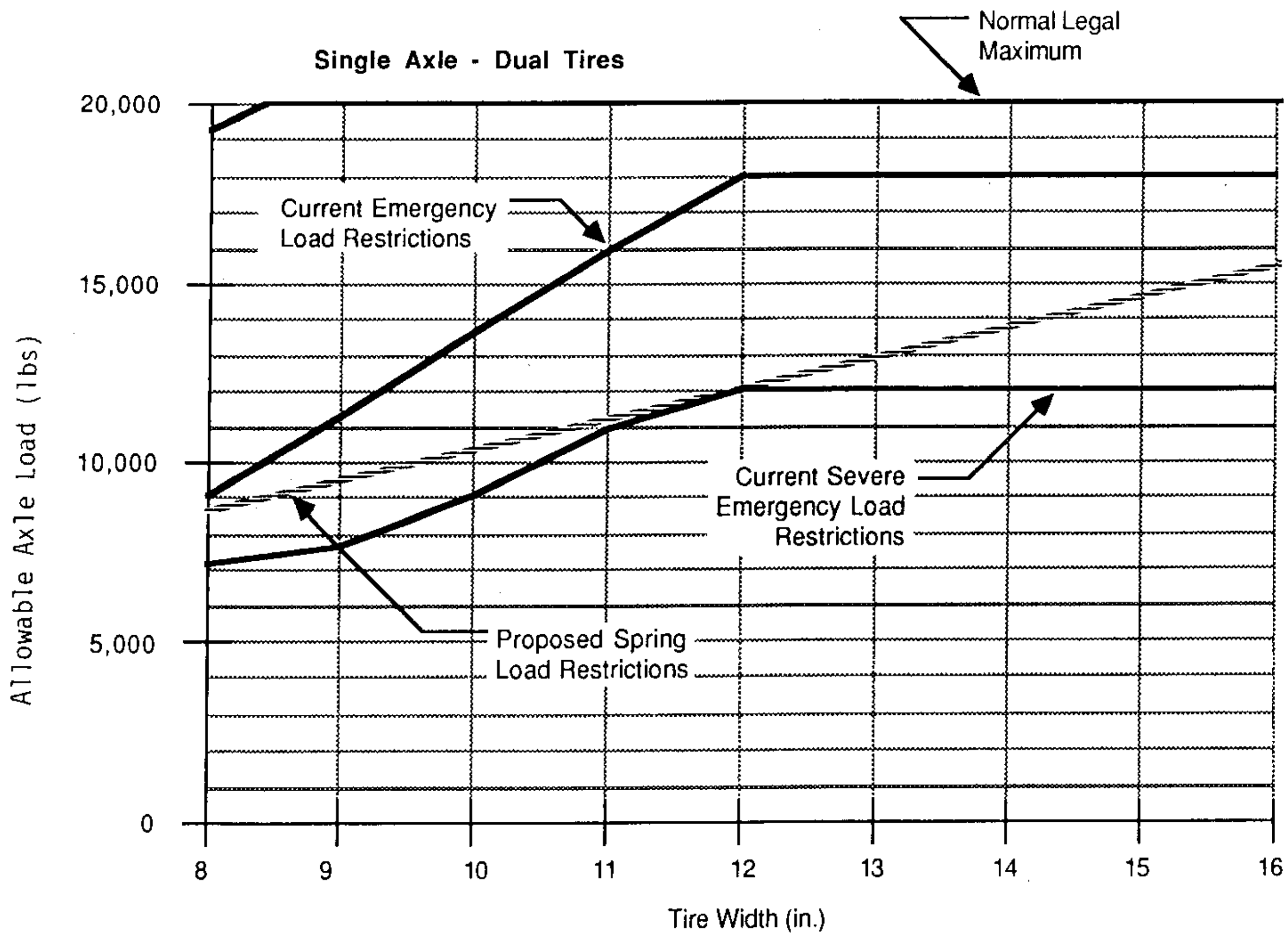

Figure 8. Allowable Axle Loads vs. Tire Width for Single Axles with Dual Tires.

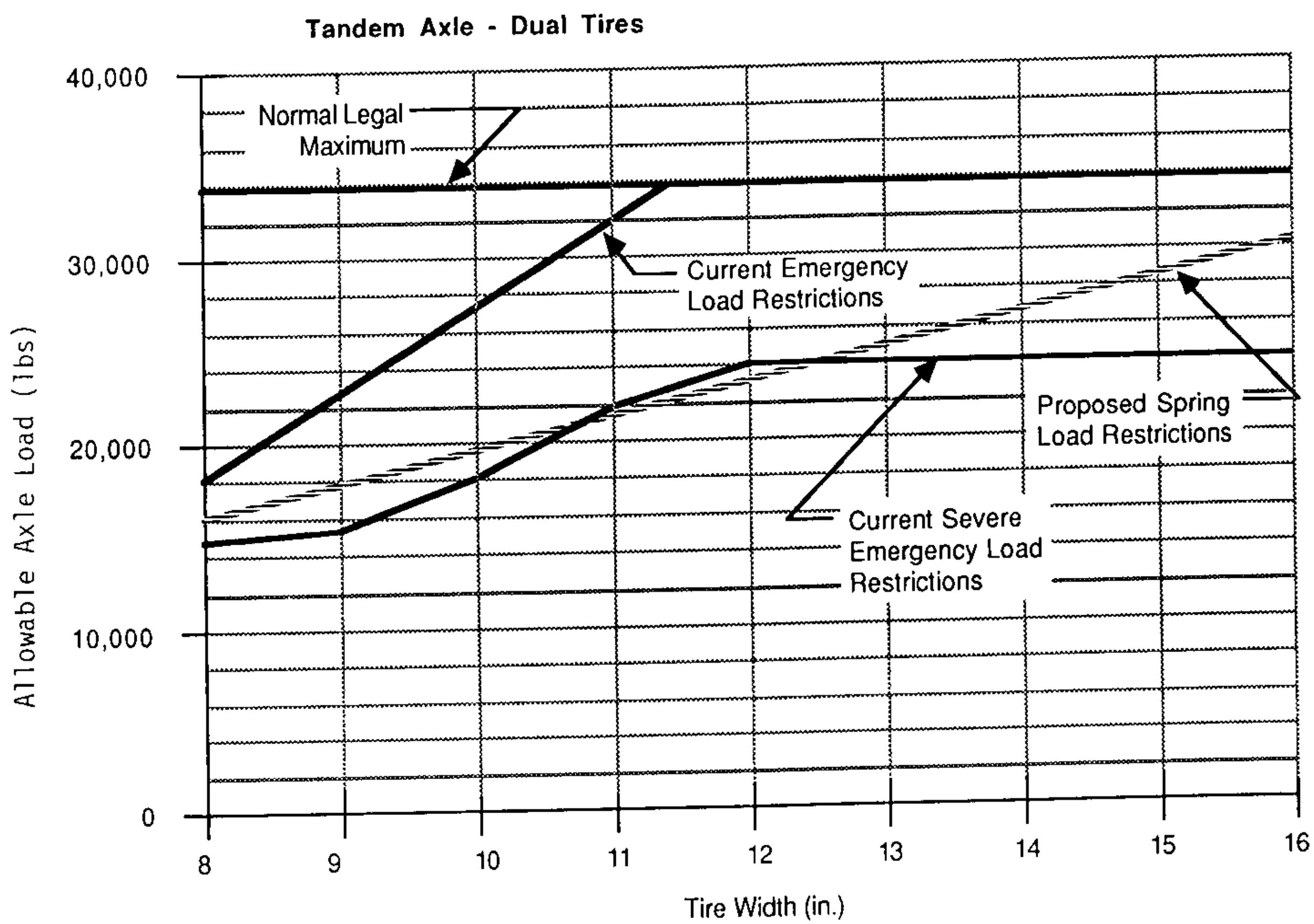

Figure 9. Allowable Axle Loads vs. Tire Width for Tandem Axles with Dual Tires.

Overall, the differences between the proposed load restrictions and those currently used by WSDOT are small and may not merit the effort to change.

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