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Factorial Study of Relations Between Pavement Cost and Legal Axle Loads

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Results are presented of a study conducted to estimate lifetime costs for flexible pavements as a function of legal axle-load limits by using an improved version of the VESYS IIM computer program. VESYS IIM was modified to include capabilities for (a) seasonal characterizations of pavement materials, (b) a discretized representation of axle-load distribution, and (c) predictions of low-temperature cracking. A literature survey and a laboratory testing program were combined to produce definitions of the variations in permanent deformation parameters as important material characteristics vary seasonally with the environment. These data and other information and experience were applied to produce input data that would yield realistic performance predictions. A factorial of 64 solutions was obtained by using the input data and the improved version of VESYS IIM to study the effects of truck traffic for four levels of legal axle-load limits, two levels of traffic, two levels of pavement-section thickness, and four environmental zones. When failures were predicted, an overlay was applied and a new solution obtained until a pavement life of at least 20 years was attained. Initial and overlay costs were estimated, and these costs, for 20 years of pavement service, were related to legal axle-load limits. Estimated costs for 20 years of pavement service were considerably increased by increasing legal axle loads, and estimated cost increases were more severe for the northern than for the southern environmental zones of the United States.

Significant efforts are under way to evaluate the effects on pavement performance and maintenance costs of the increasing levels of traffic being imposed on U.S. highway systems. The results of one study in this overall effort are reported here.

This study was conducted by using an improved version of the Federal Highway Administration computer program VESYS IIM for predicting pavement distress and performance (1, 2). Briefly, VESYS IIM consists of a set of mechanistic models that are uniquely integrated for use in analyzing the structural integrity and performance of flexible highway pavements. The working hypothesis for the VESYS model assumes that all responses of the pavement can be stated in terms of the geometry of the pavement structure, the physical properties of the material layers, and the effect of climate and load on these properties. The material properties can be characterized for primary response behavior as linear elastic and/or linear viscoelastic, and temperature and stress in the appropriate layers are accounted for.

Laws of cumulative damage exist for several distress mechanisms that cause pavement damage. These laws are formulated from observations of the distress behavior of the materials. The serviceability of a pavement is hypothesized to be represented by the linear accumulation of the distress parameters (cracking, rutting, and roughness), which can be expressed similarly as the American Association of State Highway and Transportation Officials definition of present serviceability index (PSI).

More precise verification of the model was necessary in this study than had previously been attained (3-6). However, such precise verification requires more realistic measurement of traffic and environmental effects. To account for these effects, the program was modified to include all the capabilities of VESYS IIM plus capabilities for (a) seasonal characterizations of stiffness and permanent deformation properties of materials, (b) a discretized representation of axle-load distribution for more accurate axle-load characterization, and (c) predictions of low-temperature cracking (1). This new version of VESYS (currently called VESYS A) is believed to provide greatly improved predictions of rutting, slope variance, PSI, and expected life.

Verification of the modified program and its associated sets of input data was accomplished by comparing predicted distress and performance with measured values from four sections of the AASHO Road Test, four sections from the Brampton Test Road, and data available for sections of I-80N in Utah and I-10 in Florida. This verification effort involved an iterative procedure that required exercising the model to arrive at predictions, comparing the predictions with measured performance, analyzing differences to assess their cause, and making rational modifications to problem input where they were indicated to sharpen up the predictions. The only revisions made to input values were those that could be justified through analysis.

Once the modified VESYS IIM subsystem had been verified and rational material, traffic, and environmental characterizations established, a factorial of 64 solutions was developed in order to arrive at a basis for establishing relations between cost and legal axle load. This factorial included four levels of legal axle load {80, 89, 98, and 107 kN [18 000, 20 000, 22 000, 24 000 lbf (18, 20, 22, and 24 kip)]}, two levels of pavement section called thin and thick, two levels of truck traffic called low and high, and four different environmental zones, including wet-freeze, dry-freeze, wet/no freeze, and dry/no freeze. The solutions were run as a full factorial of 64. The environmental zones were represented by conditions at a section of I-80 in Illinois for wet-freeze, a section of I-80N in Utah for dry-freeze, a section of I-10 in Florida for wet/no freeze, and a section of I-20 in Texas for dry/no freeze.

DEVELOPMENT OF REALISTIC INPUT DATA

Modifications to the computer program were accompanied by a rather detailed study to determine (a) how the permanent deformation characteristics of the surface asphalt concrete, base material, and subgrade materials vary seasonally with variations in density, moisture content, stress, and temperature; (b) what the axle-load distributions might be expected to be in the event of higher legal axle-load limits; (c) how the layer stiffnesses could be expected to vary seasonally in view of freeze-thaw conditions, temperature, moisture content, density, and stress; (d) what low-temperature model should be incorporated into the VESYS system and how to obtain the necessary input values; (e) what pavement temperatures should be assigned for the various environmental zones to be considered; and (f) how moisture content varies in base and subgrade layers.

To develop a general range of input data on the permanent deformation characteristics of materials subjected to seasonal changes of temperature and moisture, a factorial test series was run in the laboratory. A total of 18 tests were run for a typical asphalt concrete, and duplicate tests were run for three levels of stress and three levels of temperature. Each test was continued for 100 000 cycles of loading. A typical silty clay was similarly tested at three levels of moisture content and three levels of density. The test procedures and results are described in detail by Rauhut and Hordahl (7).

One of the most important decisions in a study of the effects of increased legal axle loads is what the resulting axle-load distribution may be. Accordingly, the axle-load distributions selected were arrived at after careful study of the work of Winfrey and others (8) and Whiteside and others (9), correspondence with agencies that represent the trucking industry, and study of W-4 tables from a number of states, including those that have relatively high limits on legal axle loads. The resulting axle-load distributions expected for the four legal axle-load limits considered are given in Table 1. It can be reasonably argued that more overloaded trucks than the 0.5 percent shown operate on U.S. highways and evade weighing, but only data from weight measurements are available. A higher incidence of heavily loaded trucks would, of course, result in a higher rate of damage.

The same distributions of truck traffic in time were used for all legal axle loads, which implies an increase in megagrams with increasing legal limits on axle loads. An alternative approach could have been decreases in traffic with increases in axle-load distributions to maintain constant megagrams, but this was the less severe condition and the relative realism of either extreme is moot.

PAVEMENT DISTRESS AND PERFORMANCE PREDICTIONS

Since the reporting of the performance predictions for all 64 solutions would require a great deal of space, typical plots for 80- and 107-kN legal axle loads are shown in Figures 1-4. One figure for each environmental zone has been included; both low- and high-traffic cases and some variation in pavement section are also shown.

Study of distress and performance predictions for the entire factorial indicated the following:

1. Expected increases in cracking and rutting with increased traffic and increased axle loads were predicted. The magnitudes of predicted cracking damage and rut depths were less for thick than for thin pavements.
2. Predicted "failures" were caused by cracking in all environmental zones, except for the quite warm wet/no freeze environment represented by Florida. Overlays for the wet/no freeze environment were necessitated by excessive rutting and consequent loss of serviceability.
3. Cracking failures occurred much more rapidly in the colder wet-freeze and dry-freeze environments than in the dry/no freeze environment represented by Texas. Low-temperature cracking also added to the higher levels of fatigue cracking in the colder climates and affected the shapes of the cracking curves with time. (The nature of the fatigue equation is such that the curve tends to become horizontal as it approaches 1000 m^2 cracked/1000 m^2, but the linear addition of the low-temperature cracking causes it to reach [illegible] before the curve approaches the horizontal.)
4. PSI remained relatively high where cracking necessitated use of an overlay since serious rutting did not have time to develop (see Figure 1 for an example).
5. Although the expected increase in incidence of higher axle loads for higher axle limits is numerically minor, it can be seen that failures are predicted considerably earlier for the higher legal axle-load limits than for the usual 80-kN limit. In fact, twice as many cases (8:4) of legal axle-load limits of 98 and 107 kN required two overlays than the corresponding 80-kN case. This results, of course, from the increased rate of damage caused by the higher axle loads.

COST EVALUATIONS AND RELATION BETWEEN COSTS AND LEGAL AXLE LOADS

It was originally intended that cost estimates would be performed in terms of present worth, but the unpredictable variability in time of interest rates and of differential inflation, plus the fact that interest rates and inflation rates have been similar and off-setting in recent years, resulted in a decision to base cost estimates on 1977 costs for both initial construction and subsequent overlays. This means, in effect, that present worth is based on assumption of a zero discount rate. The probability of inaccuracy, however, is no higher than it would be were we to attempt to predict these rates in time.

One of the very difficult decisions made during the research effort was how to meaningfully express the relations between costs and legal axle loads. One type of cost that must be considered is the total cost of maintaining 20 years of acceptable pavement service. Although it is meaningful, this cost does not discriminate with much sensitivity between the real costs of operating real pavements that are certainly not to be abandoned after 20 years. As can be seen later, the same number of overlays may suffice for several axle-load distributions, although the relative distresses and performances may differ. Consequently, it was decided that "value of remaining pavement life" or "salvage value" beyond 20 years should also be included as a part of the analysis and presentation. It was also apparent that the costs of maintaining an existing pavement in service under increased axle-load distributions were at least as important as the costs of building and maintaining new pavements under various axle-load distributions.

From the many types of costs that might have been used in this comparative study, four were selected:

1. Total cost, which consists of the initial construction costs and costs of necessary overlays to maintain satisfactory service for 20 years;
2. Average annual cost, which is calculated by dividing the total cost by the total life of the pavement;
3. Total cost of overlays, or the cost for the overlays necessary to attain 20 years of satisfactory service (the same as total cost less initial construction cost); and
4. Average annual cost for overlays, or the total cost of overlays divided by the life of the pavement after the first overlay.

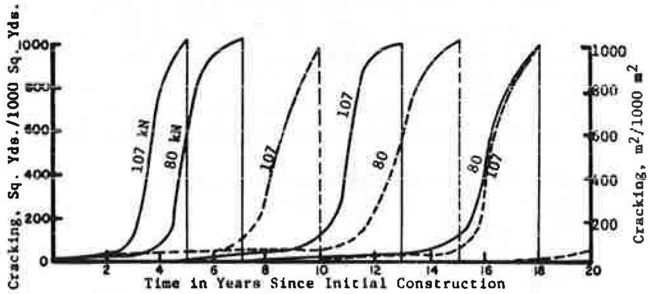
Table 1. Axle-load distribution (percentage of total representing the four legal axle-load limits studied).

Axle-Load Range (kN)	Axle-Load Distribution (%)			
	80 kN	89 kN	98 kN	107 kN
9-18	7.5	5.8	2.5	2.0
18-27	11.2	9.7	9.2	8.1
27-35	15.4	14.9	15.5	13.6
35-44	30.8	27.7	23.8	23.2
44-53	11.1	13.9	16.9	17.8
53-62	8.1	9.1	10.5	11.3
62-71	11.5	11.6	12.5	13.1
71-80	3.9	5.3	6.1	7.1
80-89	0.4	1.4	1.9	2.2
89-98	0.1	0.4	0.6	1.0
98-107	-	0.1	0.2	0.2
107-115	-	0.1	0.2	0.2
115-124	-	-	0.1	0.2

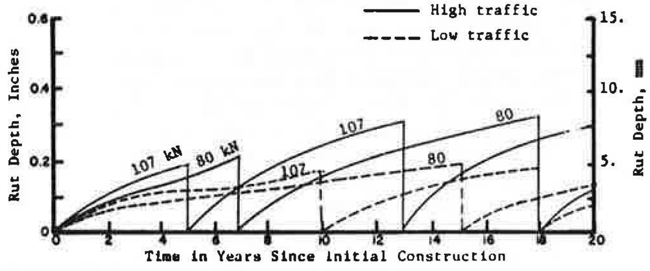
Notes: 1 kN = 224.8 lbf.
Fifty-two percent of the total number of axles were found to be tandem axles, and one set of two axles in tandem was considered as 2.25 single axles instead of 2.0 to approximate equivalency between tandem and single axles.

Total cost and average annual cost include initial construction costs and therefore relate to relative costs for new pavements subjected to truck traffic that represents different legal axle loads, whereas the other two types of costs relate in an approximate fashion to major maintenance costs for existing pavements that are subjected to different legal axle loads. Total cost, average annual cost, and total cost of overlays appear to be rather straightforward and their relation to real situations direct. The cost type termed average annual cost of overlays is not as direct but does give a measure of sorts for relating axle loading to the cost of maintaining pavement serviceability. Other cost terms can be defined and considered for existing pavements, but none have any more general applicability. Both average annual cost and average annual cost of overlays bring the value of the remaining pavement life after 20 years of service into consideration.

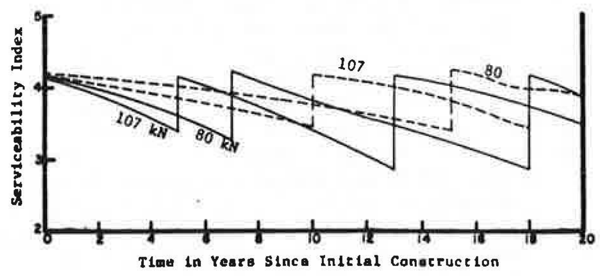
Figure 1. Predicted pavement performance under high and low traffic volumes for wet-freeze environment and thin pavement.



a. Cracking vs. time

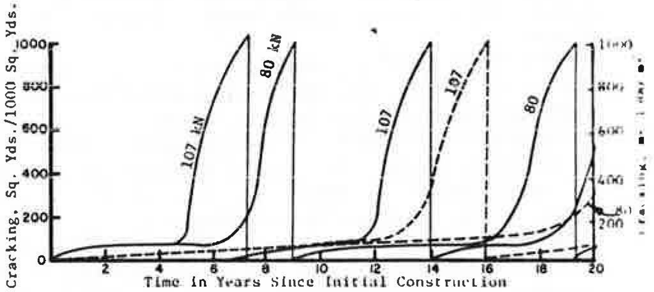


b. Rut depth vs. time

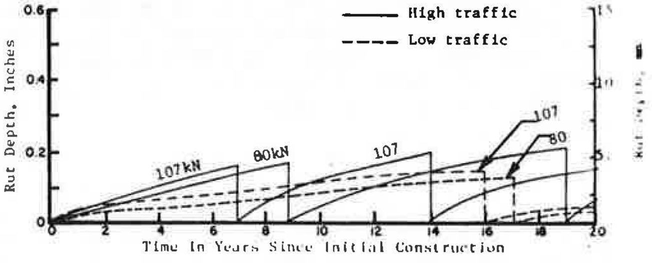


c. Serviceability Index vs. time

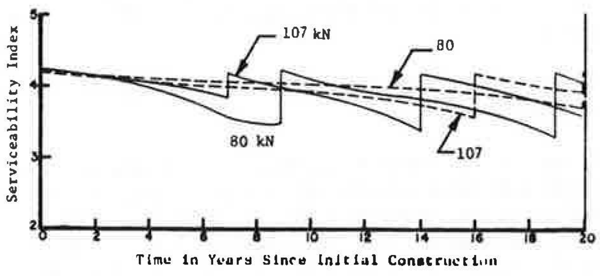
Figure 2. Predicted pavement performance under high and low traffic volumes for dry-freeze environment and thick pavement.



a. Cracking vs. time

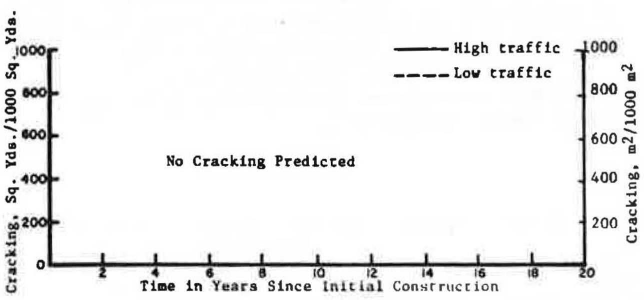


b. Rut depth vs. time

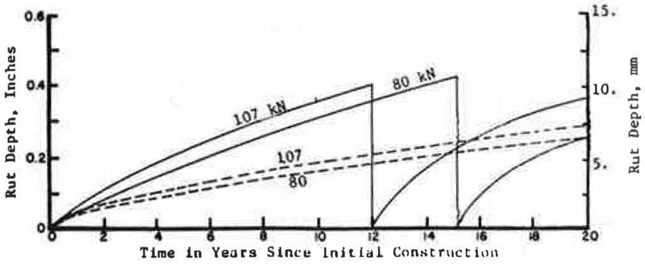


c. Serviceability Index vs. time

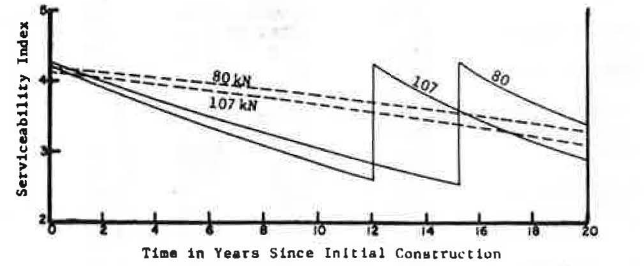
Figure 3. Predicted pavement performance under high and low traffic volumes for wet/no freeze environment and thick pavement.



a. Cracking vs. time

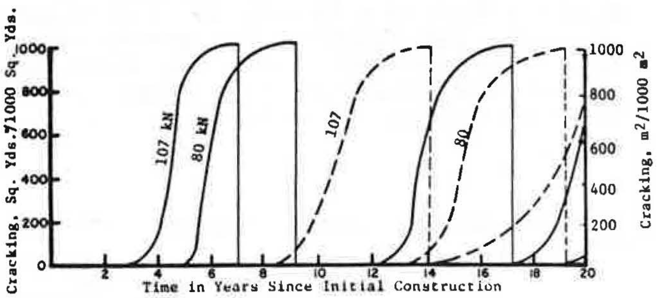


b. Rut depth vs. time

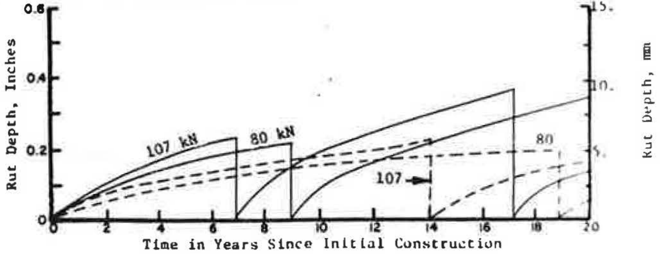


c. Serviceability Index vs. time

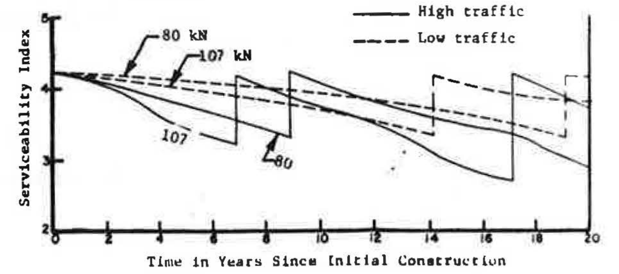
Figure 4. Predicted pavement performance under high and low traffic volumes for dry/no freeze environment and thin pavement.



a. Cracking vs. time



b. Rut depth vs. time



c. Serviceability Index vs. time

Table 2. Predicted pavement life and pavement age when overlaid, by legal axle load: low traffic volume.

		Age (years)							
		Thin Section				Thick Section			
Environmental Zone	Age Category	80 kN	89 kN	98 kN	107 kN	80 kN	89 kN	98 kN	107 kN
Wet-freeze	At first overlay	15	13	11	10				19
	At second overlay				18				
	Life of system[a]	25	22	20	28E	26	23	21	33
Dry-freeze	At first overlay	12	10	9	8			17	16
	At second overlay		18	16	15				
	Life of system[a]	21	28E	24E	22E	23	20	30E	27E
Wet/no freeze[b]	Life of system[a]	29	28	26	25	37	35	34	33
Dry/no freeze[c]	At overlay	19	17	15	14				
	Life of system[a]	32	28	25	24	31	27	25	23

Note: E = estimated.
[a] As repaired to serve at least 20 years. [b] No overlays. [c] Single overlay.

Table 3. Predicted pavement life and pavement age when overlaid, by legal axle load: high traffic volume.

		Age (years)							
		Thin Section				Thick Section			
Environmental Zone	Age Category	80 kN	89 kN	98 kN	107 kN	80 kN	89 kN	98 kN	107 kN
Wet-freeze	At first overlay	7	6	5	5	11	10	9	8
	At second overlay	18	16	14	13			18	17
	Life of system[a]	29E	27E	24E	21E	24	21	29E	27E
Dry-freeze	At first overlay	6	5	5	4	9	8	8	7
	At second overlay	15	13	12	11	19	17	15	14
	Life of system[a]	25E	23E	21E	20E	30E	28E	25E	22E
Wet/no freeze	At first overlay	11	11	10	10	15	13	11	11
	At second overlay			18	18				
	Life of system[a]	21	20	25E	24E	28	26	25	24
Dry/no freeze	At first overlay	9	8	7	7	15	13	11	11
	At second overlay			18	17				
	Life of system[a]	23	20	30E	28E	30	26	22	21

Note: E = estimated.
[a] As repaired to serve at least 20 years.

The total costs for the 64 combinations of conditions studied can be developed by taking the appropriate initial cost ($8.05 for a thin or $10.37 for a thick pavement section) and adding to that the cost of the overlays. Tables 2 and 3 indicate the number of overlays and the point in time at which they were used. Their thicknesses and costs were as follows (2):

1. Pavements for all environmental zones except wet/no freeze received 7.6-cm (3-in) overlays at $4.25/m² ($3.55/yd²) for low traffic and 10.2-cm (4-in) overlays at $5.65/m² ($4.71/yd²) for high traffic.
2. Five-centimeter (2-in) overlays at $2.85/m² ($2.39/yd²) were placed on pavements in the wet/no freeze environmental zone.

Table 4. Pavement cost by legal axle load: low traffic volume.

Environmental Zone	Type of Cost	Type of Section	Cost ($/m²)			
			80 kN	89 kN	98 kN	107 kN
Wet-freeze	Total	Thin	13.87	13.87	13.87	18.12
		Thick	12.40	12.40	12.40	16.65
	Average annual cost	Thin	0.55	0.63	0.69	0.64
		Thick	0.48	0.54	0.58	0.50
	Total for overlays	Thin	4.24	4.24	4.24	8.49
		Thick	0	0	0	4.24
	Average annual cost for overlays	Thin	0.43	0.46	0.46	0.46
		Thick	0	0	0	0.30
Dry-freeze	Total	Thin	13.87	18.12	18.12	18.12
		Thick	12.40	12.40	16.65	16.65
	Average annual cost	Thin	0.66	0.64	0.75	[illegible]
		Thick	0.54	0.62	0.55	[illegible]
	Total for overlays	Thin	4.24	8.49	8.49	[illegible]
		Thick	0	0	4.24	[illegible]
	Average annual cost for overlays	Thin	0.46	0.46	0.56	[illegible]
		Thick	0	0	0.32	[illegible]
Wet/no freeze	Total	Thin	9.63	9.63	9.63	[illegible]
		Thick	12.40	12.40	12.40	[illegible]
	Average annual cost	Thin	0.33	0.34	0.37	[illegible]
		Thick	0.33	0.36	0.37	[illegible]
	Total for overlays	Thin	0	0	0	0
		Thick	0	0	0	0
	Average annual cost for overlays	Thin	0	0	0	0
		Thick	0	0	0	0
Dry/no freeze	Total	Thin	13.87	13.87	13.87	13.87
		Thick	12.40	12.40	12.40	12.40
	Average annual cost	Thin	0.43	0.49	0.55	0.57
		Thick	0.39	0.45	0.49	0.54
	Total for overlays	Thin	4.24	4.24	4.24	4.24
		Thick	0	0	0	0
	Average annual cost for overlays	Thin	0.32	0.38	0.43	0.43
		Thick	0	0	0	0

Note: 1 m² = 1.196 yd²

Table 5. Pavement cost by legal axle load: high traffic volume.

Environmental Zone	Type of Cost	Type of Section	Cost ($/m²)			
			80 kN	89 kN	98 kN	107 kN
Wet-freeze	Total	Thin	20.89	20.89	20.89	20.89
		Thick	18.03	18.03	23.67	23.67
	Average annual cost	Thin	0.72	0.77	0.87	[illegible]
		Thick	0.75	0.86	0.81	[illegible]
	Total for overlays	Thin	11.26	11.26	11.26	11.26
		Thick	5.63	5.63	11.26	11.26
	Average annual cost for overlays	Thin	0.51	0.54	0.59	0.70
		Thick	0.43	0.51	0.56	0.59
Dry-freeze	Total	Thin	20.89	20.89	20.89	20.89
		Thick	23.67	23.67	23.67	23.67
	Average annual cost	Thin	0.84	0.91	0.99	1.04
		Thick	0.79	0.85	0.94	1.07
	Total for overlays	Thin	11.26	11.26	11.26	11.26
		Thick	11.26	11.26	11.26	11.26
	Average annual cost for overlays	Thin	0.60	0.64	0.70	0.70
		Thick	0.54	0.56	0.66	0.75
Wet/no freeze	Total	Thin	12.48	12.48	15.34	15.34
		Thick	15.26	15.26	15.26	15.26
	Average annual cost	Thin	0.60	0.62	0.61	0.63
		Thick	0.55	0.58	0.61	0.63
	Total for overlays	Thin	2.86	2.86	5.72	5.72
		Thick	2.86	2.86	2.86	2.86
	Average annual cost for overlays	Thin	0.29	0.32	0.38	0.40
		Thick	0.21	0.24	0.24	0.24
Dry/no freeze	Total	Thin	15.26	15.26	20.89	20.89
		Thick	18.03	18.03	18.03	18.03
	Average annual cost	Thin	0.67	0.76	0.69	0.74
		Thick	0.60	0.69	0.82	0.86
	Total for overlays	Thin	5.63	5.63	11.26	11.26
		Thick	5.63	5.63	5.63	5.63
	Average annual cost for overlays	Thin	0.40	0.46	0.49	0.54
		Thick	0.37	0.43	0.51	0.56

Note: 1 m² = 1.196 yd².

The cost estimates developed in this manner are given as total cost in Table 4 for low truck traffic and in Table 5 for high truck traffic. The other three types of costs are also given in Tables 4 and 5.

All the basic data are now tabulated. Costs are now considered in relation to legal axle loads in terms of new pavements (initial construction costs are considered) and existing pavements (only overlay costs are considered).

COST RELATIONS FOR NEW PAVEMENTS

A review of Tables 4 and 5 shows that, for a given climatic region, total cost is independent of the legal

Table 6. Normalized pavement cost by legal axle load: low traffic volume.

Environmental Zone	Type of Cost	Type of Section	Normalized Cost[a]			
			80 kN	89 kN	98 kN	107 kN
Wet-freeze	Total	Thin	1.00	1.00	1.00	1.31
		Thick	1.00	1.00	1.00	1.34
	Average annual cost	Thin	1.00	1.14	1.25	1.17
		Thick	1.00	1.13	1.23	1.05
	Total for overlays	Thin	1.00	1.00	1.00	2.00
		Thick	1.00	1.00	1.00	-[b]
	Average annual cost for overlays	Thin	1.00	1.08	1.08	1.08
		Thick	1.00	1.00	1.00	-[b]
Dry-freeze	Total	Thin	1.00	1.31	1.31	1.31
		Thick	1.00	1.00	1.34	1.34
	Average annual cost	Thin	1.00	0.98	1.14	1.25
		Thick	1.00	1.15	1.03	1.14
	Total for overlays	Thin	1.00	2.00	2.00	2.00
		Thick	1.00	1.00	-[b]	-[b]
	Average annual cost for overlays	Thin	1.00	1.00	1.21	1.31
		Thick	1.00	1.00	-[b]	-[b]
Wet/no freeze	Total	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost	Thin	1.00	1.02	1.10	1.15
		Thick	1.00	1.06	1.09	1.12
	Total for overlays	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost for overlays	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
Dry/no freeze	Total	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost	Thin	1.00	1.14	1.28	1.33
		Thick	1.00	1.15	1.24	1.35
	Total for overlays	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost for overlays	Thin	1.00	1.19	1.33	1.33
		Thick	1.00	1.00	1.00	1.00

[a] Normalized by dividing all values by the corresponding 80-kN legal axle-load costs.
[b] Intermediate since the divisor is zero.

Table 7. Normalized pavement cost by legal axle load: high traffic volume.

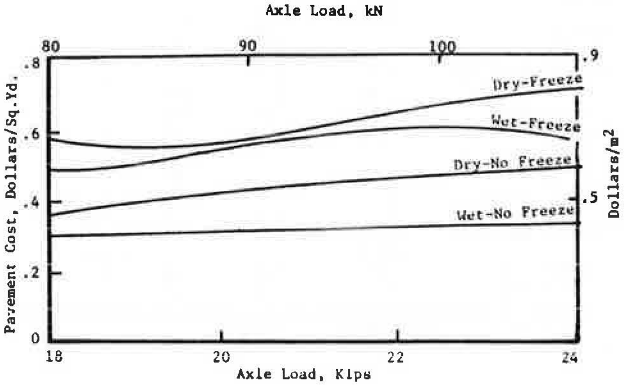
Environmental Zone	Type of Cost	Type of Section	Normalized Cost[a]			
			80 kN	89 kN	98 kN	107 kN
Wet-freeze	Total	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.31
	Average annual cost	Thin	1.00	1.07	1.21	1.45
		Thick	1.00	1.14	0.87	1.02
	Total for overlays	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	2.00	2.00
	Average annual cost for overlays	Thin	1.00	1.05	1.16	1.37
		Thick	1.00	1.19	1.31	1.39
Dry-freeze	Total	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost	Thin	1.00	1.09	1.19	1.25
		Thick	1.00	1.07	1.27	1.36
	Total for overlays	Thin	1.00	1.00	1.00	1.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost for overlays	Thin	1.00	1.08	1.18	1.18
		Thick	1.00	1.04	1.22	1.40
Wet/no freeze	Total	Thin	1.00	1.00	1.23	1.23
		Thick	1.00	1.00	1.00	1.00
	Average annual cost	Thin	1.00	1.05	1.03	1.08
		Thick	1.00	1.08	1.12	1.17
	Total for overlays	Thin	1.00	1.00	2.00	2.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost for overlays	Thin	1.00	1.12	1.33	1.42
		Thick	1.00	1.11	1.11	1.11
Dry/no freeze	Total	Thin	1.00	1.00	1.37	1.37
		Thick	1.00	1.00	1.00	1.00
	Average annual cost	Thin	1.00	1.15	1.05	1.12
		Thick	1.00	1.15	1.36	1.43
	Total for overlays	Thin	1.00	1.00	2.00	2.00
		Thick	1.00	1.00	1.00	1.00
	Average annual cost for overlays	Thin	1.00	1.15	1.21	1.32
		Thick	1.00	1.16	1.39	1.52

[a] Normalized by dividing all values by the corresponding 80-kN legal axle-load costs.

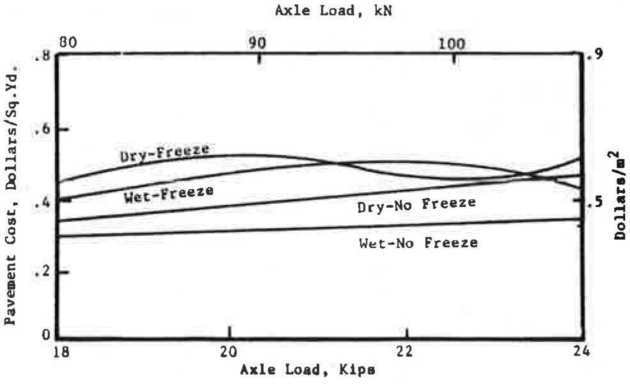
Table 8. Mean values of pavement costs, by legal axle load, normalized by dividing by 80-kN axle-load costs.

	Normalized Cost			
Cost Item	80 kN	89 kN	98 kN	107 kN
Total				
All thin pavements	1.00	1.04	1.12	1.16
All thick pavements	1.00	1.00	1.05	1.12
All low traffic volumes	1.00	1.02	1.09	1.14
All high traffic volumes	1.00	1.04	1.09	1.16
Wet-freeze environment	1.00	1.00	1.08	1.12
Dry-freeze environment	1.00	1.00	1.00	1.23
Wet/no freeze environment	1.00	1.08	1.16	1.16
Dry/no freeze environment	1.00	1.00	1.06	1.06
All pavements	1.00	1.02	1.08	1.14
Average annual costs				
All thin pavements	1.00	1.08	1.16	1.22
All thick pavements	1.00	1.12	1.15	1.20
All low traffic volumes	1.00	1.10	1.17	1.20
All high traffic volumes	1.00	1.10	1.14	1.23
Wet-freeze environment	1.00	1.12	1.14	1.18
Dry-freeze environment	1.00	1.07	1.16	1.23
Wet/no freeze environment	1.00	1.01	1.03	1.04
Dry/no freeze environment	1.00	1.05	1.09	1.13
All pavements	1.00	1.10	1.15	1.21

Figure 5. Average annual pavement cost by environment and legal axle load: low traffic volume.



a. Thin pavement section

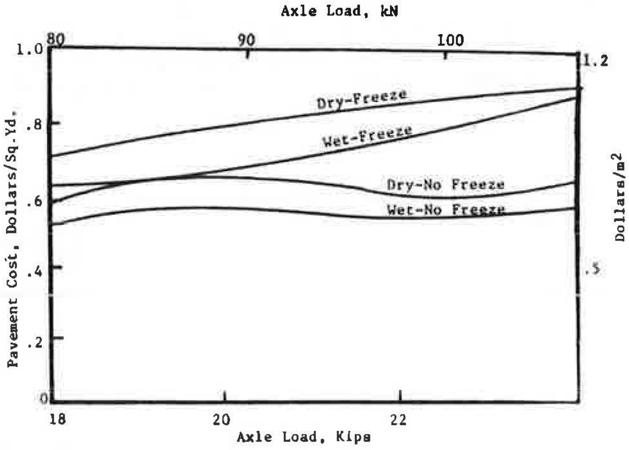


b. Thick pavement section

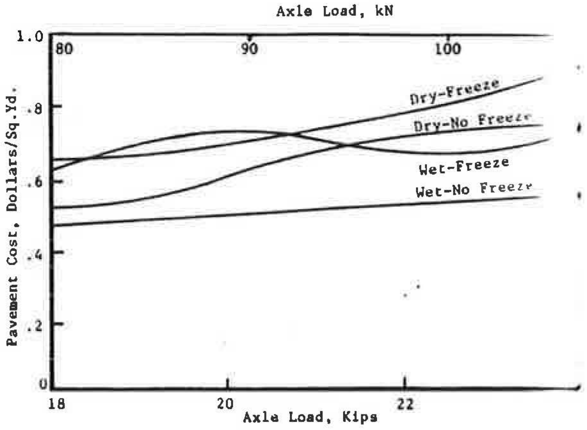
axle load for 9 of the 16 cases considered. This occurred because either the pavement did not require an overlay to reach a 20-year design life or an equal number of overlays were required for each of the legal axle loads considered.

Because of the higher frequency of cracking in colder climates and the lower frequency of overlays required when the failure mode was rutting rather than cracking, costs for thin pavements for the northern environmental zones were higher than those for the sout environmental zones. For thick pavements, the ferences in costs among environmental zones were

Figure 6. Average annual pavement cost by environment and legal axle load: high traffic volume.



a. Thin pavement section



b. Thick pavement section

Another useful way to consider the data devel by normalizing all results given in Tables 4 and dividing each value by its corresponding value f 80-kN legal axle load. These normalized values in Tables 6 and 7, indicate rather directly the i in costs that are produced by increases in legal loads. This information has been summarized tically in Table 8 for new pavements by obtaining values for the various groupings of cases and envi mental zones as well as for all cases combined.

To make it easier to observe trends and identi some unexpected results, average annual cost (probably more meaningful than total cost because siders pavement life after 20 years) from Tables 5 is plotted in Figures 5 and 6. These figures in that average annual costs generally increase as expected with increasing legal axle loads. However apparent anomaly occurs in some cases; see the freeze plot in Figure 5b, where cost is shown de with increasing legal axle load. This is not gener consistent with expectations from field experience partly because accelerating deterioration as moistu percolates through surface cracks into underlying layers and reflection cracking are not modeled by mechanistic models such as VESYS.

Cost decreases with increasing legal axle load because damage predictions necessitate an overlay

Table 9. Mean values of pavement costs for overlays, by legal axle load.

Cost Item	Cost ($/m²) 80 kN	89 kN	98 kN	107 kN
Total for overlays				
All thin pavements	5.46	6.00	7.05	7.59
All thick pavements	3.17	3.17	4.41	4.94
All low traffic volumes	1.59	2.13	2.65	3.72
All high traffic volumes	7.05	7.05	8.45	8.45
Wet-freeze environment	5.28	5.28	6.70	8.81
Dry-freeze environment	6.70	7.76	8.81	8.81
Wet/no freeze environment	1.43	1.43	2.14	2.14
Dry/no freeze environment	3.87	3.87	5.28	5.28
All pavements	4.32	4.59	5.74	6.27
Average annual costs for overlays				
All thin pavements	0.378	0.411	0.454	0.483
All thick pavements	0.195	0.219	0.287	0.354
All low traffic volumes	0.152	0.165	0.222	0.274
All high traffic volumes	0.419	0.465	0.519	0.563
Wet-freeze environment	0.344	0.380	0.406	0.518
Dry-freeze environment	0.400	0.418	0.562	0.613
Wet/no freeze environment	0.125	0.141	0.155	0.161
Dry/no freeze environment	0.275	0.320	0.359	0.383
All pavements	0.286	0.314	0.371	0.418

Table 10. Mean values of pavement costs for overlays, by legal axle load, normalized by dividing by 80-kN axle-load costs.

Cost Item	Normalized Cost 80 kN	89 kN	98 kN	107 kN
Total for overlays				
All thin pavements	1.00	1.10	1.29	1.40
All thick pavements	1.00	1.00	1.39	1.56
All low traffic volumes	1.00	1.34	1.67	2.34
All high traffic volumes	1.00	1.00	1.20	1.20
Wet-freeze environment	1.00	1.00	1.27	1.67
Dry-freeze environment	1.00	1.16	1.32	1.32
Wet/no freeze environment	1.00	1.00	1.49	1.49
Dry/no freeze environment	1.00	1.00	1.36	1.36
All pavements	1.00	1.06	1.33	1.45
Average annual costs for overlays				
All thin pavements	1.00	1.09	1.20	1.28
All thick pavements	1.00	1.12	1.47	1.82
All low traffic volumes	1.00	1.09	1.46	1.80
All high traffic volumes	1.00	1.11	1.24	1.34
Wet-freeze environment	1.00	1.10	1.18	1.50
Dry-freeze environment	1.00	1.05	1.40	1.53
Wet/no freeze environment	1.00	1.12	1.24	1.29
Dry/no freeze environment	1.00	1.17	1.30	1.39
All pavements	1.00	1.10	1.30	1.46

which in turn sufficiently increases predicted pavement life so that its effect in decreasing average annual costs is greater than the increase caused by the added overlay cost. This may well be realistic in a dry climate if reflection cracking can also be controlled, but it may be the exception rather than the rule.

It should be remembered, however, that the modeling limitations mentioned above apply not only to overlays but also to initial construction predictions; that is, pavement life should always be overpredicted if the modeling limitation is serious. Since the predictions do not appear unrealistic for either original pavements or overlays, it can be concluded that the model limitations may not be the primary cause of this apparent anomaly. It may simply mean that an overlay may not only meet an immediate need to maintain service but may also be cost effective. The Florida Department of Transportation has in fact found it cost effective to extend the life of a pavement through a relatively thin overlay when cracking begins at the bottom of the surface layer rather than to apply a thicker overlay after the cracks have propagated to the surface.

A fact that tends to lend credence to the predicted costs is that the axle-load distributions (Table 1) that result from a change in legal axle limit are not very severe. There is no real similarity at all, for instance, in a road test such as the AASHO Road Test, in which an increase in test axle load means that essentially all subsequent traffic has that axle load.

Although it may not be appropriate to claim quantitative accuracy for the predicted costs, it does appear reasonable to expect that all the results will be biased in the same way; the trends would thus be reliable and the cost err, if at all, toward the low side.

To continue with analysis of the cost predictions developed, the following general conclusions can be drawn from the summary values given in Table 8:

1. The total cost for a 20-year service life can be expected to (a) increase as much as 8 percent for an increase in legal axle-load limit from 80 to 89 kN and, on the average, increase 2 percent for all pavements; (b) increase as much as 16 percent for an increase in legal axle-load limit from 80 to 98 kN (depending primarily on pavement thickness and environment) and, on the average, increase 8 percent for all pavements; and (c) increase from 6 to 23 percent for an increase in legal axle-load limit from 80 to 107 kN and, on the average, increase 14 percent for all pavements.

2. The average annual cost (considering the value of remaining pavement life after 20 years) can be expected to (a) increase from 1 to 12 percent for an increase in legal axle-load limit from 80 to 89 kN and, on the average, increase by 10 percent; (b) increase from 3 to 17 percent for an increase in legal axle-load limit from 80 to 98 kN and, on the average, increase by 15 percent; and (c) increase from 4 to 23 percent for an increase in legal axle-load limit from 80 to 107 kN and, on the average, increase by 21 percent.

3. The overall effect of increased axle loads is more severe for thin than for thick pavements and for colder than for warmer climates.

4. Although the effect on damage caused by different levels of truck traffic volume on a pavement section is obvious, the relative costs (or rates of increase in costs) for accommodating traffic at different legal axle limits are not very sensitive to levels of truck traffic.

COST RELATIONS FOR EXISTING PAVEMENTS

The cost types previously described as total costs of overlays and average annual costs of overlays [illegible] an analysis of the effects of increased legal axle-load limits on existing highways because the initial construction costs are not included in the analysis. The mean costs for overlays given in Table 9 were arrived at as previously described for new highways except that initial construction costs were omitted. These values were normalized by dividing by the corresponding 80-kN axle-load costs; the normalized values are given in Table 10.

As would be expected, the percentage increases in overlay costs for increases in legal axle-load limits are much greater when a relatively large fixed initial construction cost is not included. Analysis of the results in Tables 9 and 10 indicates that

1. The predicted overlay costs for the higher legal axle-load limits in the wet/no freeze environmental zone (or warm temperature) represented by Florida I-10 are nominal.

2. As would be expected, the total cost for maintaining the highway is much less for low than for high

traffic volumes, but the percentage increase in total overlay costs with increase in axle loads is much higher for the low-traffic case. For instance, a mean predicted total overlay cost for a 107-kN legal axle load on all low traffic volumes is 2.34 times as much as that for an 80-kN legal axle load as opposed to only 20 percent more for all high traffic volumes.

3. The predicted overlay costs themselves are much higher for northern than for southern environments, but the percentage increases in overlay costs with increasing legal axle load are similar to those for southern highways.

4. The cost of overlaying pavements was logically predicted to be greater for thin than for thick pavements, but the percentage increase in overlay cost with increasing legal axle load was greater for thick pavements.

5. In general, total overlay costs can be expected to increase by about 6 percent for an increase in legal axle-load limit from 80 to 89 kN, 33 percent for an increase from 80 to 98 kN, and 45 percent for an increase from 80 to 107 kN.

6. An increase in legal axle-load limit from 80 to 89 kN increases the average annual cost of overlays about 10 percent, an increase from 80 to 98 kN increases it about 30 percent, and an increase from 80 to 107 kN increases it about 46 percent.

SUMMARY

Relations have been reported between costs for 20 years of acceptable pavement service and established legal single-axle-load limits. These relations are based on distress and performance predicted by a modified version of the VESYS IIM computer program by using the best traffic, environment, and materials characterizations possible in a factorial study of 16 cases with legal single-axle loads of 80, 89, 98, and 107 kN for each.

It is clear that the accuracy of the cost relations depends on the ability of the flexible-pavement structural model to simulate real pavements and on the accuracy of the characterizations of traffic, axle-load distribution, environment, and material input to the model. The modified version of VESYS IIM is certainly one of the most complete mechanistic models of a flexible pavement, but it shares the limitation of most, if not all, other such models in that it does not model reflection cracking or the accelerating deterioration of its structural components as surface cracking progresses and moisture enters the base and subgrade layers nor does it consider loss of stiffness in the asphalt concrete surface caused by cracking or changes in stiffness and viscoelastic properties as the asphalt hardens over time. In addition, distress and performance predictions are very sensitive to materials characteristics. These characteristics are, however, limited to relatively typical materials from several specific locations. Thus, exceptional quantitative accuracy cannot be claimed, but all solutions are subject to the same biases so that the trends established can be expected to be reasonably reliable and the quantitative relations sufficiently accurate to offer valuable insight until the results of other, much more comprehensive, studies are completed.

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