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Evaluation of Increased Truck Size and Mass on Pavement Life and Design Thickness

R. G. Hicks, R. D. Layton, and Steve Glover, Department of Civil Engineering, Oregon State University

The results are presented of an analytical study that evaluated the effects of increased vehicle size and mass on pavement life and thickness. The techniques are applicable primarily to relatively new or reconstructed pavements; however, an approach is also presented that shows how they can be used to evaluate the effect on pavements that have been in service for several years. An increase in legal single-axle loads from 80 to 110 kN [18 000 to 24 000 lbf/in^2 (18 to 24 kips)] or in tandem-axle loads from 140 to 200 kN [32 000 to 44 000 lbf/in^2 (32 to 44 kips)], could result in a loss of pavement life of up to 80 percent if applied to the existing system. The incremental thickness for new construction or reconstruction associated with the heavier trucks would require a maximum of 65 mm (2.5 in) of surfacing material. Truck configuration can also substantially affect the number of equivalent 80-kN axle loadings. The incremental thickness for new or reconstructed pavements associated with the different truck configurations can amount to approximately 40 mm (1.5 in) of surfacing material.

With the changing and growing demands on today's technology, there has arisen the need to evaluate the impact of increasing the sizes and masses of vehicles. The U.S. transportation system must be responsive to any change in vehicle dimensions. An evaluation of the effects of changed vehicle sizes on the highway system requires an analysis of the effect of increased vehicle loads on pavement performance.

The objective of this paper is to evaluate, by using analytical techniques, the effects of increased vehicle loads on pavement life and pavement thickness. The techniques developed apply to relatively new or reconstructed pavements. Additional work is under way to evaluate the effects of increased loads on pavements that have been in service for several years.

The axle loadings used are within the range forecast in the U.S. government 1980 goals report (1); i.e., single-axle loads of up to 115 kN (26 kips) and tandem-axle loads of up to 200 kN (44 kips). Results of this study are in three forms:

1. An estimate of the reduction in life of existing pavements if no change in current maintenance practices occurs,
2. An estimate of the additional pavement thickness that will be required to maintain the level of service under present legal loads, and
3. An evaluation of the relative pavement damage

Figure 1. Flow diagram for evaluation of reduction in life of existing pavements caused by increased vehicle mass.

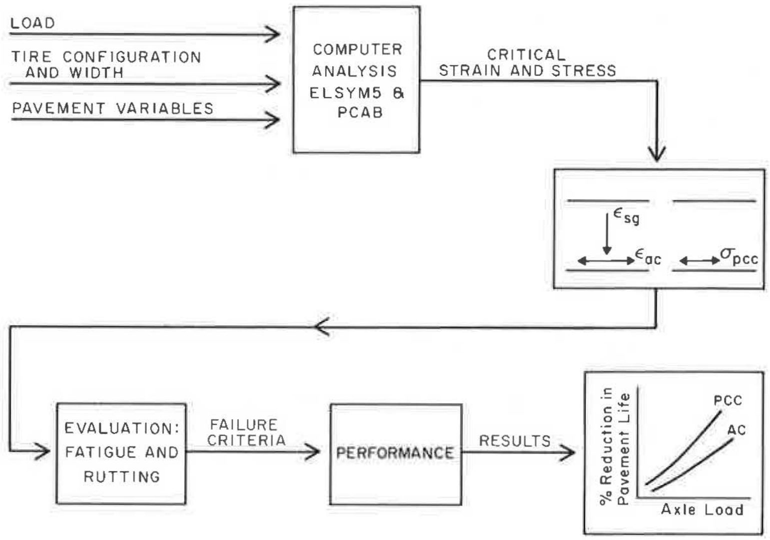
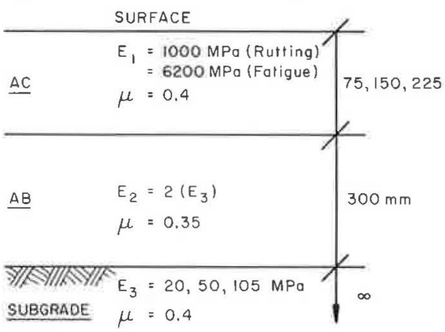
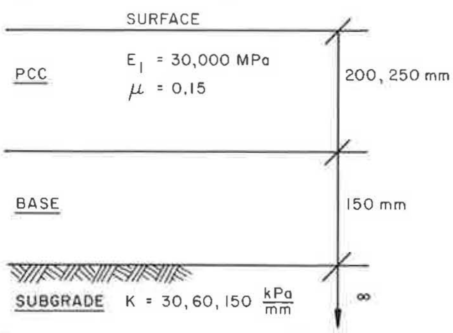


Figure 2. Schematic of flexible layered pavement.



Note: 1 mm = 0.04 in and 1 MPa = 145 lbf/in^2.

Figure 3. Schematic of rigid pavement.



Note: 1 mm = 0.04 in, 1 MPa = 145 lbf/in^2, and 1 kPa/mm = 3.45 lbf/in^3.

caused by various truck combinations carrying a given amount of payload.

Finally, an approach is presented to illustrate the incremental maintenance and rehabilitation costs associated with the use of larger and heavier vehicles.

ANALYSIS OF REDUCTION IN LIFE

The two basic types of pavements, flexible and rigid, were evaluated by using elastic-layer theory (2) and the Portland Cement Association (PCA) method (3) respectively. The approach used to compute the reduction in pavement life for given increases in axle loads is shown in Figure 1. The axle loads used range from 80 to 110 kN (18 to 24 kip) for single axles and from 140 to 200 kN (32 to 44 kip) for tandem axles.

Flexible Pavements

The pavement system used for flexible pavement is shown in Figure 2. A wide range of pavement properties were used in the analysis to simulate poor, average, and good subgrades. The flexible pavement is made up of three layers: asphalt concrete, base, and subgrade. Each layer is described by a modulus of elasticity and Poisson's ratio.

The distress criteria used in this analysis limit the horizontal tensile strain (ϵ_{ac}) in the asphalt concrete layer as a measure of fatigue and the vertical compressive subgrade strain (ϵ_{sg}) as a measure of rutting. Of all the limiting strain criteria available, the Shell failure criterion (4) given below was chosen for use (1 mm/mm = 1 in/in).

Fatigue: No. of Load Applications	Fatigue: ϵ_{ac} (mm/mm)	Rutting: Load	Rutting: ϵ_{sg} (mm/mm)
10^5	2.3×10^{-4}	10^4	1680×10^{-6}
10^6	1.45×10^{-4}	10^5	1050×10^{-6}
10^7	9.2×10^{-5}	10^6	650×10^{-6}
10^8	5.8×10^{-5}	10^7	420×10^{-6}

Rigid Pavements

The pavement systems analyzed for rigid pavements are shown in Figure 3. The portland cement concrete pavement sections consist of three layers: concrete slab, base, and subgrade. The subgrade properties range between poor and good.

The engineering properties required for the evaluation are the modulus of subgrade reaction (K) of the subbase and the modulus of rupture of the concrete slab. The K-values used ranged from 15 to 90 kPa/mm (50 to 300 lbf/in^3). The modulus of rupture has been selected at 4750 kPa (690 lbf/in^2), a common figure for concrete pavements.

The distress criterion used to evaluate rigid pavements is that of fatigue. Two methods have been used to relate stress to pavement fatigue failure—the Vesic equation (5) and the PCA stress ratio (6) are the most common failure criteria. The stress ratio criteria operates on the premise that any ratio greater than 0.51, between the actual pavement stress and the modulus of rupture, will result in a reduction of pavement life. However, if the stress ratio is 0.50 or less, then there is no reduction in pavement life. This restriction on pavements that have low stress levels led to the selection of the Vesic equation as the fatigue criterion for rigid pavements:

$$N_f = K(MR/\sigma)^4 \quad (1)$$

where

σ = tensile concrete stress (kPa),
MR = rupture modulus (kPa),
K = empirical constant, and
N_f = number of equivalent 80-kN axle repetitions to failure.

Computer Analysis

Evaluation of existing flexible pavements was accomplished by using the computer program entitled ELSYM5 (2), developed at the University of California, Berkeley. Inputs for this computer program are

1. Pavement characteristics,
2. Tire configurations,
3. Tire properties (i.e., pressure, contact area, and contact radius), and
4. Applied axle load (from 140 to 200 kN for tandem axles and from 80 to 110 kN for single axles).

The tire properties used are given below (1 kN = 225 lbf, 1 m^2 = 1549 in^2, 1 kPa = 0.145 lbf/in^2, and 1 mm = 0.04 in).

Axle Load (kN)	Wheel Load (kN)	Contact Area (m^2)	Pressure (kPa)	Contact Radius (mm)
80	20	0.0325	620	100
90	22.5	0.0325	680	100
100	25	0.0325	750	100
110	27.5	0.0325	820	100

Outputs of the program used in this analysis involved the critical strains found in the surface layer (the fatigue) and those in the subgrade (the rutting).

All results for existing pavements are expressed in the form "percentage reduction in pavement life versus applied axle loads." To obtain the pavement life, each strain value from the computer program output is transformed into an N_f-value (Figure 4). The final form of percentage reduction in pavement life is merely the percentage difference in repetitions. An example of this computation is

$$\text{Reduction in pavement life (\%)} = [(N_{ff} - N_f)/N_{ff}] \times 100 \quad (2)$$

where

N_{ff} = number of axle repetitions of 80-kN axle and
N_f = number of equivalent axle repetitions of some axle load greater than 80 kN.

This evaluation of pavement life is a comparison between applied axle loads and does not take account of the amount of payload moved or the distance traveled.

The procedure for evaluating reduction in life of rigid pavements is similar to that used for flexible pavements. The computer program entitled PCAB, developed by PCA (3) was used in analyzing the applied axle loads. Inputs for PCAB, as in ELSYM5, are variables that describe the pavement and soil engineering properties. Outputs of the PCAB program are in the form of critical stresses and, as for flexible pavements, a relationship between stress and equivalent 80-kN repetitions to failure exists. Final results are shown in Figure 5.

Figure 4. Procedure for transforming stress and strain into equivalent 80-kN repetitions.

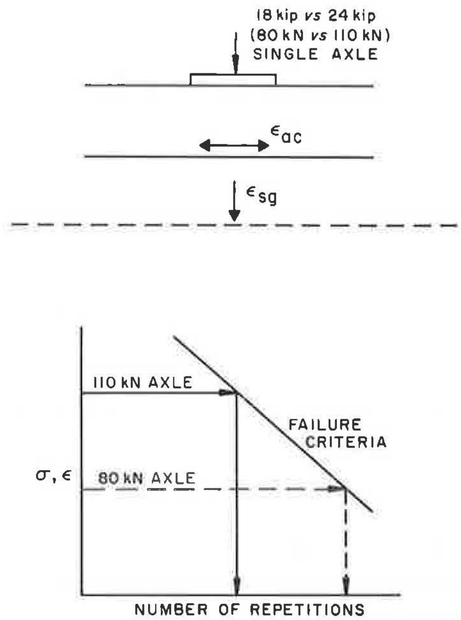
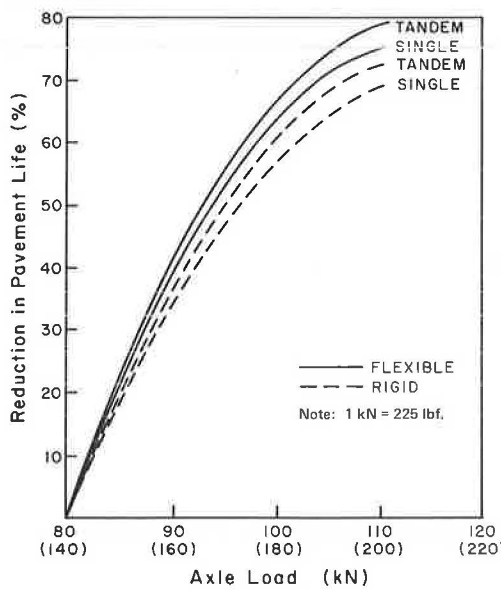


Figure 5. Reduction in life of pavement: theoretical equivalencies.



The percentage reduction in life was the same for all combinations of surface thickness and subgrade type considered and all distress criteria used, but these trends may not hold for different combinations of pavement geometrics and distress criteria. The decrease in pavement life is quite severe, ranging up to 80 percent.

For comparison, the American Association of State Highway and Transportation Officials (AASHTO) wheel-load equivalencies (SN = 3 and D = 9) were also used to compute reduction in pavement life. The results shown in Figures 6 and 7 are similar to the theoretical relationships developed and shown in Figure 5. Because of

Figure 6. Reduction in life of rigid pavement: AASHTO equivalencies.

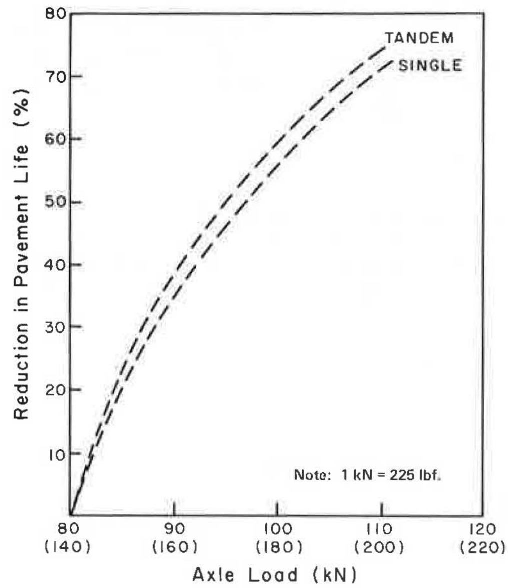
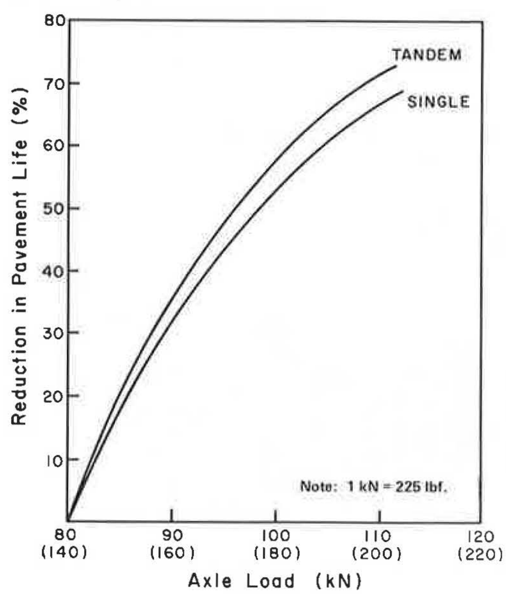


Figure 7. Reduction in life of flexible pavement: AASHTO equivalencies.



these similarities, the remainder of the analysis in this paper is based on the AASHTO thickness design procedure (5).

INCREMENTAL THICKNESS ANALYSIS

Constant Axle Repetitions Approach

The AASHTO thickness design method was used to calculate the incremental thicknesses for flexible and rigid pavements, as shown in Figure 8, by using the standard sections shown in Figure 9. The soil-support factor was varied from poor to good and three equivalent 80-kN axle repetitions were selected to represent light, medium, and heavy traffic. The complete list of the inputs used in the analyses is given below (1 kN = 225 lbf).

Figure 8. Approach used to determine incremental thickness associated with increased vehicle size and mass.

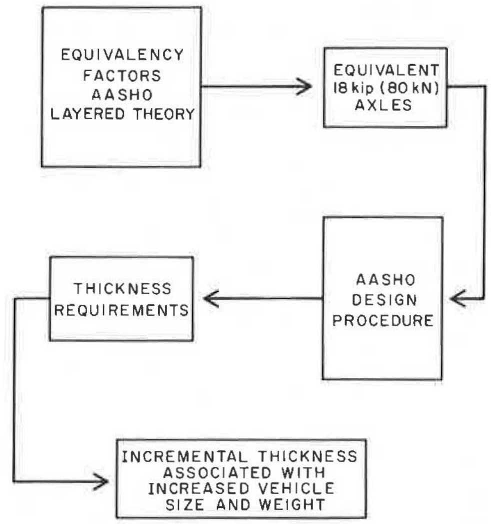
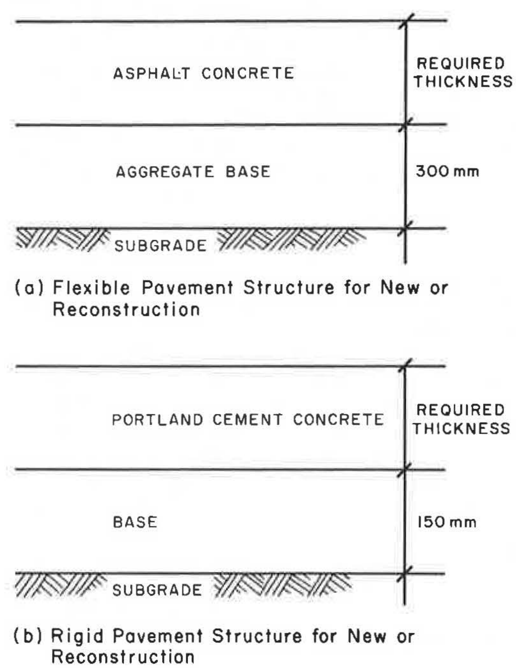


Figure 9. Pavement sections used in incremental-thickness analysis.



Note: 1 mm = 0.04 in.

No. of Load Repetitions	No. of Equivalent 80-kN Repetitions for Increased Axle Load		
	90 kN	100 kN	110 kN
Flexible pavements			
1 x 10^5	1.49	2.17	3.09
1 x 10^6	1.49	2.17	3.09
1 x 10^7	1.49	2.17	3.09
Rigid pavements			
1 x 10^5	1.57	2.34	3.36
5 x 10^6	1.57	2.34	3.36
2 x 10^7	1.57	2.34	3.36

[Note: The following are assumed—For flexible pavements, regional factor = 1.0; soil-support factor (ss) =

3, 5, or 10; and terminal serviceability index = 2.5 and for rigid pavements, modulus of elasticity = 30 GPa (4 350 000 lbf/in²); flexural strength = 4750 kPa (690 lbf/in²); subgrade modulus = 30, 60, or 150 kPa/mm (100, 200, or 300 lbf/in³); and terminal serviceability index = 2.5.] The results are given as incremental thicknesses (i.e., the differences between an 80-kN axle design thickness and the higher axle-load design thickness are shown in Table 1). As expected, the incremental thicknesses increase as the axle loads increase, to maximum values of about 65 mm (2.5 in) for flexible pavements and 50 mm (2 in) for rigid pavements. This analysis, however, assumes a fixed number of axle applications for any increase in axle loads. In actuality, any increase in axle loads would probably reduce the number of axle repetitions, because payloads would increase. Therefore, the incremental thicknesses shown in these tables should be considered maximum values for new or reconstructed pavements.

Constant Payload Approach

The above approach assumes a fixed number of axle repetitions, which does not account for the reduction in number of axle loads that might result from increased payload capacity. An alternative approach, shown in Figure 10, was also used, which attempts to treat this change in payload. Nine different truck configurations were selected to represent the majority of truck combinations in use today (10). The total number of 80-kN axle loads required to transport a payload of 150 000 Mg (100 000 000 tons) was determined by using AASHTO wheel-load equivalencies. To obtain these descriptive axle repetitions, it is necessary to know the payload per equivalent 80-kN axle of each truck combination. Figure 11 summarizes the payload transported per 80-kN axle for the various truck combinations. The configuration designation gives the number of axles on each unit of the tractor-trailer combination, beginning at the tractor, and also identifies the type of truck (S implies semi-trailer and T implies tanker).

The total number of 80-kN axles needed to transport the 150 000-Mg (100 000 000-ton) payload are given in Figure 12. Truck combinations giving the smallest number of equivalent 80-kN axles cause the least pavement distress. For this study, the 3S-2 truck combination was chosen as the standard for comparison. Figure 13 shows the difference in equivalent 80-kN axle repetitions between the standard combination and the other truck combinations considered. From these data, the AASHTO method was used to compute additional pavement thicknesses. As can be seen in Table 2, the various truck combinations affect the thickness of highway pavements, but the effects are quite small. The results are similar to those reported in the Utah study (8).

Both methods, constant axle repetitions and constant payload, involve oversimplification. However, the best model for the evaluation of the consequences of increased vehicle masses and their respective payload capacities is the constant payload approach. For better and more refined results, further analysis of truck combinations and their effects on pavements must be performed.

IMPLEMENTATION

If the rate of pavement deterioration and the quantity of pavement improvements required are known, the pavement cost for increased vehicle masses can be determined for any pavement section. Of the two methods,

Figure 10. Equal payload approach.

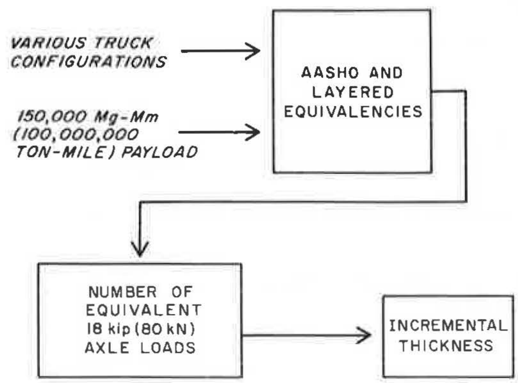


Figure 11. Histogram of payload per equivalent 80-kN (18-kip) axle for various truck combinations.

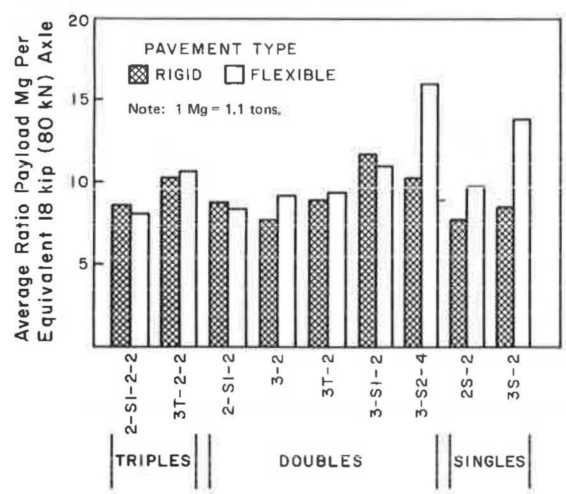


Table 1. Incremental thickness of pavement for increased axle loads.

Axle Load (kN)	Subgrade	Flexible Pavements (a_1 = 0.44): Light (10^5 loads)	Flexible: Medium (10^6 loads)	Flexible: Heavy (10^7 loads)	Rigid Pavements: Light (10^5 loads)	Rigid: Medium (5×10^6 loads)	Rigid: Heavy (2×10^7 loads)
90	Poor	16.3	21.3	23.1	8.4	16.0	18.0
100		33.8	41.4	45.7	16.8	31.5	36.1
110		50.5	59.4	66.5	25.1	46.0	53.1
90	Fair	10.4	19.1	21.3	10.9	16.5	18.3
100		21.3	38.4	41.7	20.6	32.5	36.3
110		32.0	56.1	60.2	29.2	47.0	53.1
90	Good			11.2		19.3	18.8
100			1.0	22.9		52.1	54.4
110			8.1	34.5			

Incremental Thickness (mm)

Note: 1 mm = 0.04 in and 1 kN = 225 lbf.

Figure 12. Number of AASHTO equivalent axles for constant payload.

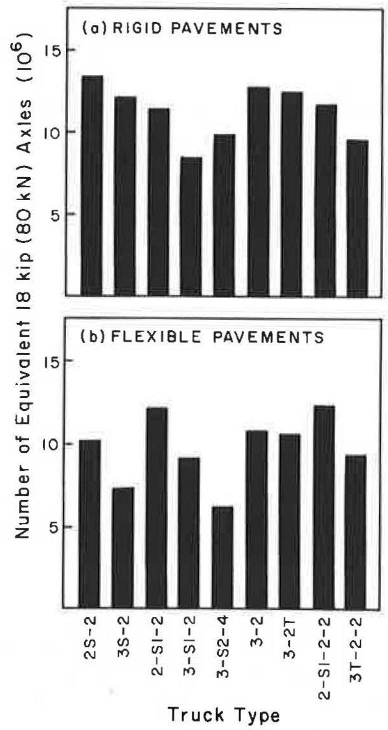
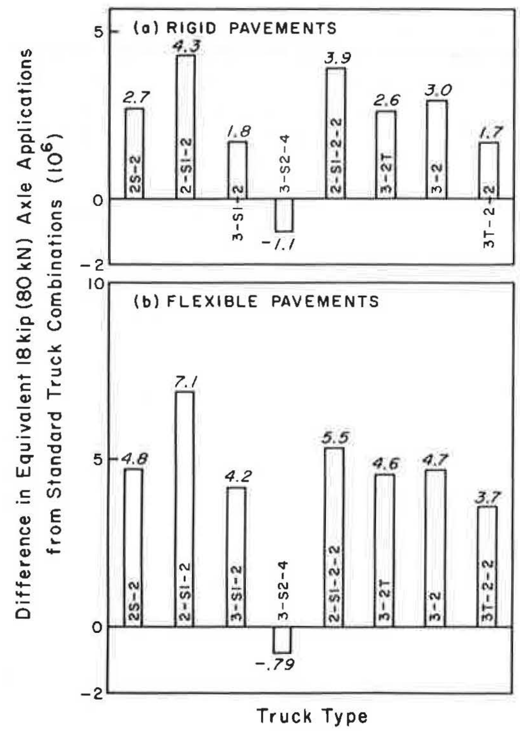


Figure 13. Difference in equivalent 80-kN (18-kip) axles between truck combinations and standard truck.

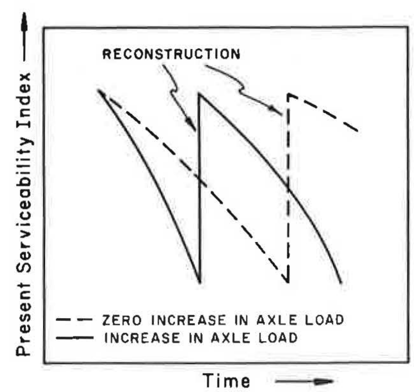


the one that uses constant axle repetitions represents the maximum rate of reduction in pavement life and the maximum incremental thicknesses needed. Figures 14 and 15 represent the probable conditions for a pavement for no change in legal loads and for one that has an increase in legal loading. If there are no changes in maintenance strategies when loads are increased, accelerated pavement deterioration can be expected. Although pavement-life reduction appears severe for any great increase in vehicle size, the needed rehabilitation for new or reconstructed highways is not unreasonable, according to analysis by using the AASHTO design procedure.

The maintenance of pavements at an acceptable level of service when axle loads are increased is likely to increase rehabilitation costs. The rehabilitation costs associated with any change in loading conditions must be evaluated over the entire roadway system. The rehabilitation of pavements in the highway system is assumed to be spread uniformly over all pavements. This assumes that a fixed percentage of pavements must be rehabilitated each year, for example, 5 percent per year for a 20-year design life. This amounts to

$$\text{Annual pavement rehabilitation costs} = (1/\text{LIFE})(\text{RHB} \times \text{system mileage}) \quad (3)$$

Figure 14. Pavement deterioration and periodic reconstruction for constant repetitions of a standard axle.



where

LIFE = design life of pavements and
RHB = pavement rehabilitation costs per kilometer.

If an increase in loading is allowed, pavement life is reduced. For pavements constructed after the loading in-

Table 2. Incremental thickness for new construction.

Truck Combination	Incremental Thickness (mm)					
	Flexible pavements			Rigid Pavements		
	SS = 3 (poor)	SS = 5 (fair)	SS = 10 (good)	K = 30	K = 60	K = 150
2-S2	17.8	17.8	12.7	2.5	5.1	2.5
2-S1-2	40.6	35.6	15.2	-3.8	-12.7	-5.1
3-S1-2	10.2	12.7	10.2	-8.9	-3.8	-7.6
3-S2-4	-20.3	-5.1	-5.1	12.7	-5.1	-6.4
2-S1-2-2	40.6	35.6	20.3	-3.8	-12.7	-5.1
3-2T	17.8	17.8	12.7	12.7	2.5	12.7
3-2	22.9	25.4	15.2	12.7	2.5	-6.4
3T-2-2	10.2	12.7	10.2	-7.6	-5.1	-6.4

Note: 1 mm = 0.04 in.

crease has been permitted, the annual costs for pavements increase immediately because of the increased thicknesses required.

Existing pavements will experience accelerated deterioration as shown in Figure 16. This figure shows the pavement-deterioration profiles for pavements constructed, or reconstructed, in each year. The pavement deterioration is accelerated after the heavier loads are introduced as shown by the steeper slope of the profiles of the pavements designed for current legal loads, but carrying heavier loads. This can be described analytically:

$$\text{Pavement life} = [(N_{LIFE} - N_{AGE})/N_{NLIFE}]\,(\text{LIFE}) + (N_{AGE}/N_{LIFE})(\text{LIFE}) \qquad (4a)$$

where

- N_{LIFE} = number of repetitions of equivalent 80-kN axles under design loading for normal design life,
- N_{AGE} = number of repetitions of equivalent 80-kN axles that pavement has experienced thus far, and
- N_{NLIFE} = number of repetitions of equivalent 80-kN axles to failure under new loading conditions.

This relationship can also be stated as

$$\text{Pavement life} = (\text{NLIFE}/\text{LIFE})(\text{LIFE} - \text{AGE}) + \text{AGE} \qquad (4b)$$

where

- AGE = pavement age expressed in years and
- NLIFE = pavement life under new loading.

The age is based on the portion of the total design repetitions that have been experienced by the pavement. The new life is calculated from the increased repetitions of equivalent 80-kN axle loads caused by the increased loading. Pavements that have been designed for current legal loads will have varying pavement lives, depending on the age at which the heavier loads are introduced.

The changes in pavement rehabilitation costs are shown in Figure 17. The normal costs are determined based

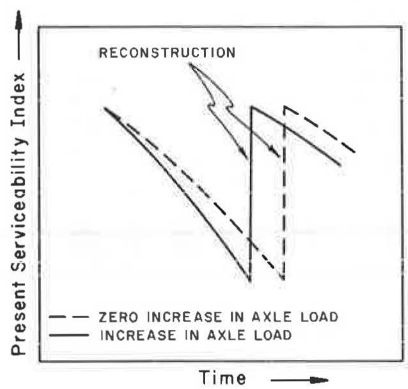


Figure 15. Pavement deterioration and periodic reconstruction for constant payload.

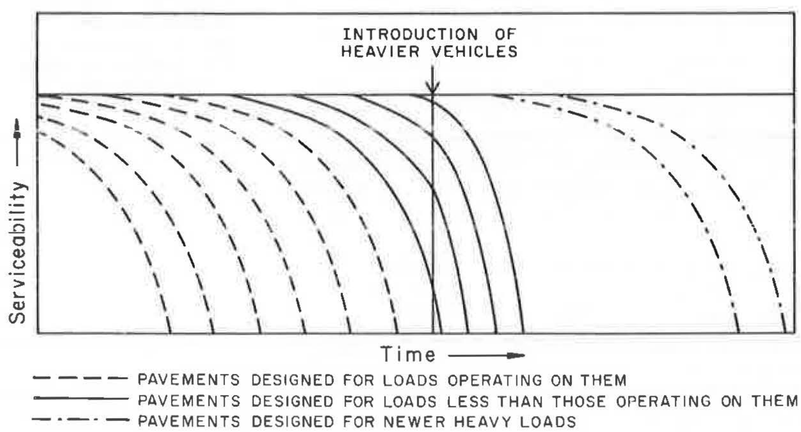


Figure 16. Deterioration profiles demonstrating accelerated wear of pavements caused by operation of heavier than design loads.

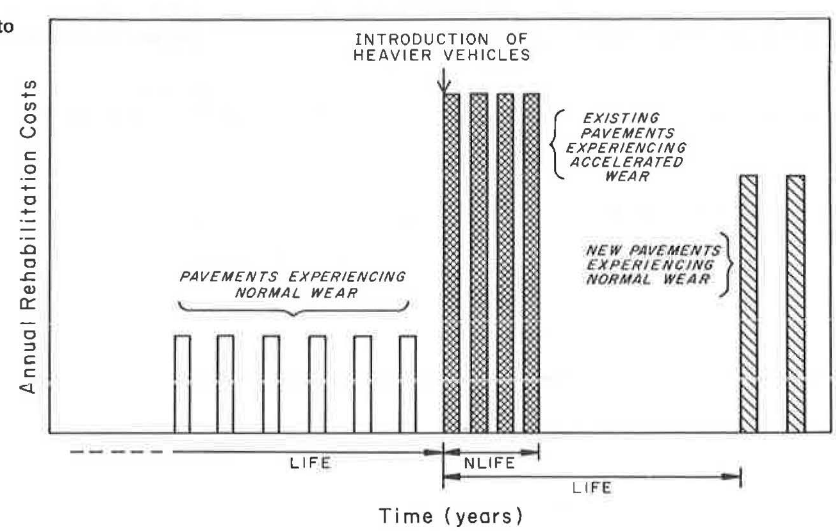


Figure 17. Annual rehabilitation costs due to increased loading.

on a pavement section designed for current legal loads. The rehabilitation costs for pavements that have heavier loading will be greater because the pavement section thickness would be increased. The annual pavement rehabilitation costs might be increased significantly. For example, if the normal pavement life of 20 years is reduced to 5 years by the increased loading, 20 percent, rather than 5 percent, of the pavements will require rehabilitation within each year. Furthermore, the new pavements will require heavier sections to carry the increased loads. This means that the costs of the annual pavement rehabilitation program will be more than quadrupled for 5 years after the heavier loadings are introduced. This also implies that the 6th to 20th years will not require any pavement rehabilitation because all pavements will have been upgraded to new standards by the 6th year. However, the total worth of the costs of pavement rehabilitation under increased vehicle sizes will be much greater than under present legal loads. For the example of a reduction in life of 15 years from a design life of 20 years, the relative present worth of pavement rehabilitation for increased loads will be about 120 percent greater, at an interest rate of 15 percent (11). This includes the incremental thickness required by the larger vehicles, which may be as much as 65 mm for flexible pavements and 50 mm for rigid pavements.

CONCLUSIONS

This paper has presented two approaches to the problem of increased vehicle masses on pavements. One approach is to assume that pavement maintenance will not be changed because of increased vehicle loads. In this case, it is estimated that approximately 80 percent of the pavement life could be lost. The second approach assumes that pavement serviceability must be kept at the present level. Any increase in loads above the present limit will increase pavement rehabilitation and maintenance costs. In this case, pavements newly constructed or reconstructed will require up to 65 mm of additional thickness.

The report also points out that truck configuration can substantially affect the number of equivalent 80-kN axle loads needed to transport a given payload. The incremental thicknesses associated with different truck configurations can range up to approximately 40 mm (1.5 in).

An approach to the calculation of the increased pavement rehabilitation costs associated with an increase in vehicle axle masses has been presented. The accelerated wear that will result from heavier loads may not only increase annual costs, but also significantly increase the pavement funds required in the near term. In view of the limited funds available to highway agencies, it may be difficult to protect and improve the pavements as needed if heavier trucks are permitted.

ACKNOWLEDGMENTS

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