nology, particularly in the formulation of the case study data, execution of the simulation model, and analyses of results.

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REFERENCES

1. Highway Statistics 1979. FHWA, 1979.
2. Who Pays for Highways: Is a New Study of Highway Costs Allocation Needed? Congressional Budget Office, Washington, DC, Sept. 1978.
3. T.K.F. Wong and M.J. Markow. Allocation of Life-Cycle Highway Pavement Costs. FHWA, Sept. 1982.
4. M.J. Markow and B.D. Brademeyer. Modifications of EAROMAR: Final Technical Report. FHWA, June 1981.
5. Highway Capacity Manual. HRB, Special Rept. 87, 1965.
6. AASHTO Interim Guide for Design of Pavement Structures--1972. American Association of State Highway and Transportation Officials, Washington, DC, 1974.
7. Final Report on the Federal Highway Cost Allocation Study. FHWA, May 1982.

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Methodology for Evaluating Increase in Pavement Maintenance Costs That Result From Increased Truck Weights on Statewide Basis

BENJAMIN COLUCCI-RIOS AND ELDON J. YODER

When this study was made, Indiana's weight limits for trucks were 18 000 lb on a single axle, 32 000 lb on a tandem axle, and 73 280 lb gross vehicle weight (GVW). The federal limits for the Interstate system and other primary roads were 20 000 lb on a single axle, 34 000 lb on a tandem axle, and 80 000 lb GVW. The objective of this study was to evaluate what the effects would be on pavement maintenance costs if Indiana's weight limits were increased to those of the federal limits. The methodology that was developed to evaluate the increase in load limits from 73 280 to 80 000 GVW is described. The road-life records of the Indiana Department of Highways were searched and pavement sections were evaluated by using these data coupled with truck weight information from the weight stations and soil and performance data available from previous studies. A total of 301 pavement sections were selected for evaluation. The types of pavements evaluated included continuously reinforced concrete, jointed reinforced concrete, asphalt, and concrete pavements overlaid with asphalt. The pavement sections were evaluated according to functional classification. The pavements were further divided on a regional basis so that climatic effects would be evaluated as well. Cost estimates were presented in dollars per lane mile per year and dollars per year for Interstates, primary roads (U.S. and state routes carrying more than 4000 vehicles/day), and secondary roads (U.S. and state routes carrying less than 4000 vehicles/day).

The Federal-Aid Highway Act of 1956 established the maximum weight limits for the Interstate system, which at that time were 18 000 lb on a single axle, 32 000 lb on a tandem axle, and 73 280 lb gross vehicle weight (GVW) (1). Since some states already permitted loads in excess of those specified by the Act, a grandfather clause was included to protect them from this Act (2).

After the 1973 energy crisis, the Federal-Aid Highway Act of 1974 raised the federal weight limits to 20 000 lb on single axles, 34 000 lb on tandem axles, and 80 000 lb GVW. At the time of this study, in 1978, nine states in addition to Indiana still maintained the 1956 weight limits. These states, known as "barrier states," lie in the midwestern part of the United States.

This paper presents the methodology used in this study to estimate the effect of increased truck weights on the service life of pavements, specifically on pavement maintenance costs.

The study was limited to evaluation of added load-related costs on the state system of Indiana highways, including Interstates and U.S. and state routes. This report deals with maintenance costs alone and does not consider changes in economic benefits that might result if weight laws were changed.

GENERAL BACKGROUND

Although pavement maintenance may be required for many reasons, including material breakdown and climatic effects, the number of heavy-load applications in terms of 18 000-lb equivalent single axle loads (ESALs) is a primary factor that causes pavement deterioration for a given set of conditions. Figure 1 shows the conceptual relationship between present serviceability index (PSI) and pavement life for a typical road that is exposed to an increase in load limits. It is to be noted that a change in load has an effect on pavement serviceability. If loads heavier than originally anticipated in the design are applied, the pavement will deteriorate more rapidly with two net effects. First, routine maintenance costs will increase and, second, the life of the pavement may decrease. On the other hand, if the pavement is designed for the newer and heavier loads, the change in serviceability will be essentially the same as that of the original pavement.

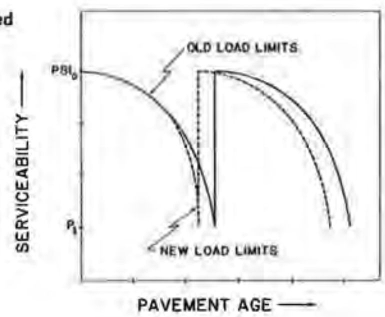
METHODOLOGY DESCRIPTION

The methodology adopted in this study to evaluate the effect of increased truck weights on pavement maintenance costs is shown in Figure 2 and is summarized as follows (3,4):

1. Collect data on pavement characteristics, traffic, soil type, climate, and unit costs;
2. Determine the total 18 000-lb ESALs under the existing and proposed load limits;
3. Predict the expected life cycle of all pavement sections (this includes predicting the time at which resurfacing is required as well as the thickness of overlay required);
4. Estimate future routine and major maintenance needs for all pavement sections;
5. Estimate total increase in maintenance costs for each year of the analysis period based on the difference of old and new load limits; and
6. Present the results in terms of equivalent uniform annual cost (EUAC).

The NULOAD computer program was used for determining the effects of increased truck weights on pavement performance and relating them to maintenance and rehabilitation costs (5,6).

Figure 1. Effect of increased load limits.



DESCRIPTION OF DATA USED

The information required to analyze the effects of increased truck weights on pavement maintenance costs can be classified into the following areas:

1. Road-life data,
2. Highway classification,
3. Pavement type,
4. Soil type,
5. Truck-weight data (traffic data),
6. Climate data, and
7. Routine and major maintenance cost data.

Road-Life Data

The road-life records of the Indiana Department of Highways (IDOH) consist of two standard forms that provide information in the following broad categories (7):

1. Design and construction features,
2. Bridges,
3. Construction costs,
4. Location,
5. General description of improvement, and
6. Retirements of improvement.

The above information is available for each route of the state highway system. The following information was obtained from the road-life records for this study:

1. Pavement type,
2. Pavement thickness,
3. Pavement age,
4. Layer components,
5. Construction costs, and
6. Last time of major improvement.

The computer program for this study uses the

Figure 2. Methodology to determine effect of new legal load limits.

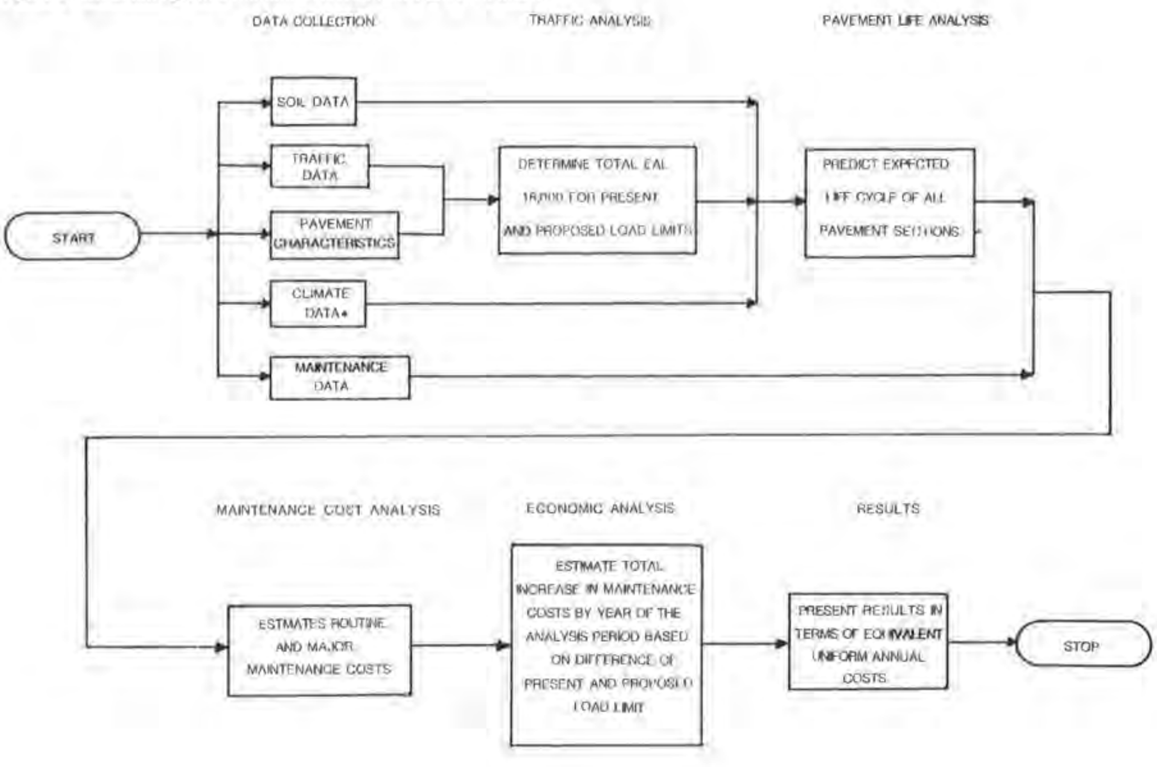


Table 1. Pavement design information.

Design Parameter	Value Adopted
Flexible Pavement	
Structural coefficient[a]	
a_1	0.44
a_2	0.14
a_3	0.11 (north and central Indiana) 0.14 (southern Indiana)
Initial PSI	4.2 (Interstate, primary, and secondary)
Terminal PSI	2.5 (Interstate and primary) 2.0 (secondary)
Analysis period	20
Regional factor	1.0 (southern Indiana) 1.1 (central Indiana) 1.5 (northern Indiana)
Soil-support value	See Table 2
Layer thickness	Road-life records
Rigid Pavement	
Modulus of rupture at 28 days (third-point loading)	700 psi
Working stress in concrete	525 psi
Modulus of elasticity	4 000 000 psi
Modulus of subgrade reaction	Correlation with CBR (prior to 1943) (see Table 2) 300 pci (after 1943)
Concrete thickness	Road-life records

[a] $SN = a_1D_1 + a_2D_2 + a_3D_3$.

Table 2. Soil-support values and modulus of subgrade reaction for major soil units of Indiana.

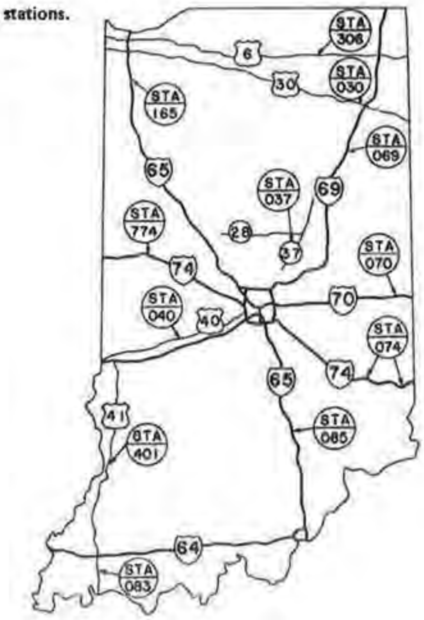
Major Soil Unit	Soil-Support Value (S)	Modulus of Subgrade Reaction (K)
Water transported		
Porous substrata (sands and gravel)	6.8	350
Sands (except Kankakee sands)	6.2	250
Kankakee sands	5.6	220
Lake beds	4.0	150
Ice transported		
Young drift till plains (silty clays), moraines	4.9	180
Areas of sand, gravel, and eskers	6.3	260
Old drift silts and silty clays	5.0	180
Wind transported		
Sand: some water-deposited sand areas include windblown sands	6.0	240
Loess—silt	5.3	200
Residual		
Limestone, interbedded limestone and shale, limestone, sandstone, and shale	4.9	180
Sandstone and some shale, interbedded shale and sandstone	5.1	190

structural design equations that were developed at the road test of the American Association of State Highway Officials (AASHO). Table 1 shows the values used in this study for both flexible and rigid pavements.

Highway Classification Used

Three road categories were considered in this study--Interstate, primary, and secondary. The distinc- tion between primary and secondary roads was based primarily on average daily traffic (ADT). Primary roads were U.S. and state routes with ADT > 4000 vehicles/day. Secondary roads were U.S. and state routes with ADT < 4000 vehicles/day. The Indiana traffic-flow map was used to determine the ADT of each of the pavement sections included in the sample (8).

Figure 3. Weigh stations.



Pavement Types Evaluated

For the purpose of this study the pavements encountered on the state highway system were classified into four major design categories as follows:

1. Flexible,
2. Jointed reinforced-concrete pavements (JRCP),
3. Continuously reinforced concrete pavements (CRCP), and
4. Overlay (asphalt over concrete).

Flexible pavements included an asphalt surface on a nonstabilized base and subbase on the natural subgrade and full-depth asphalt pavements.

JRCP are concrete pavements without an overlay and with joints (typically spaced at 40-ft intervals). In some cases plain pavements were placed in this category, but these were minimal since the older plain pavements have been overlaid.

CRCP are pavements without joints and that contain continuous steel.

Overlay pavements are concrete pavements with an appreciable amount of asphaltic concrete.

The actual classification of each pavement section was made after a search of the road-life records in the Planning Division of IDOH.

Soil Types Evaluated

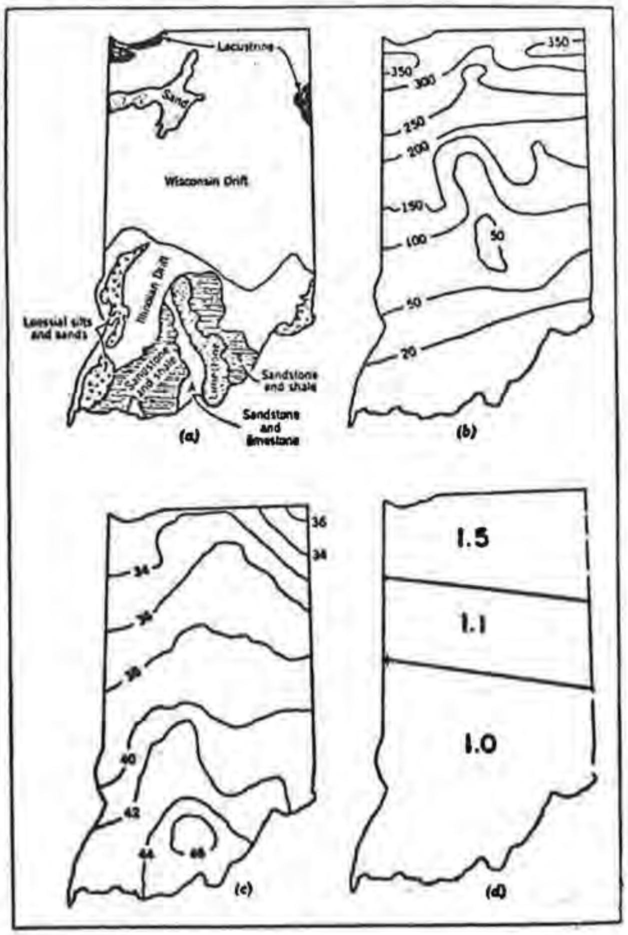
For the purpose of this study, the soils encountered in Indiana within the state highway system were classified into 11 design units as shown in Table 2. The classification of these soils was extracted from the engineering soil parent material map of Indiana (9).

The AASHTO design method requires the soil-support value as the measure of subgrade strength under flexible pavements and the modulus of subgrade reaction under rigid pavements. These design values are also tabulated in Table 2. The modulus of subgrade reaction was obtained from correlations with the soil-support value and the California bearing ratio (CBR) (10).

Traffic Data

Traffic data were obtained from the weigh stations opened in Indiana during the 1977 truck weight study (see Figure 3). These data were used along with the

Figure 4. Distribution of soils, rock, and climate in Indiana: (a) soils and rock, (b) mean freezing index (degree-days), (c) mean rainfall (inches/year), and (d) AASHTO regional zones.



AASHTO equivalency factors to calculate the 18 000-lb ESALs necessary for the analysis.

Since these traffic data correspond mainly to the Interstate system and some U.S. routes, a correction factor was applied to the original traffic data in order to provide a traffic distribution to the primary and secondary roads included in this study. These correction factors were obtained from the federal National Highway Inventory and Performance Study (NHIPS) report (11). A truck factor of 6 percent was used for the primary system and 4 percent for the secondary system.

Geographical Area

In this study, geographical area was considered to take into account the different climatic conditions from the ones encountered at the AASHO Road Test.

The following steps were undertaken to analyze the effect of climate on load-related costs:

1. The pavements in the state were stratified on a regional basis from north to south.
2. A correction factor was assigned to each of the regions in order to take into account climatic variations. These correction factors were developed in satellite research studies across the United States for the AASHO Road Test. The values used in this study were 1.5 for northern Indiana, 1.1 for central Indiana, and 1.0 for southern Indiana.

The final division of the state into three geographical regions was possible due to the unique relationships among soil type, freezing index, and rainfall as shown in Figure 4, which shows (a) a generalized distribution of the soils and rocks in the state, (b) freezing index, and (c) average rainfall contour lines for the state. It can be readily noted that soils as well as rainfall and freezing index distribute in a north-to-south direction.

The southern boundary of the northern region extends on a line from just north of Kentland in Newton County through Monticello in White County north of Marion and Grant County and north of Portland in Jay County. The southern boundary of the central region extends from a line just south of Newport in Vermillion County through a point north of Franklin in Johnson County and from there north of Lawrenceburg in Dearborn County.

Truck Types Evaluated

Six different types of trucks were evaluated in this study. These are shown in Figure 5 along with the old and new load limits of each truck.

The equivalency factors developed at the AASHO Road Test were used to convert the axle-load distributions of these trucks into 18 000-lb ESALs. These equivalency factors have been tabulated in many textbooks as a function of pavement thickness, magnitude of axle load, and terminal serviceability of the facility (12). Typical ESALs for the trucks considered in this study are shown in Figure 5 for a 10-in concrete pavement and a terminal serviceability of 2.5 for both present and proposed load limits.

SELECTION OF PAVEMENT SECTIONS

Two statistical techniques were used in this study for the selection of specific pavement sections. These were random and stratified sampling.

Random Sampling

This technique consisted of constructing an x-y coordinate chart that assigned a unique location to each area in Indiana. Numbers were then generated by using a standard table of random numbers. Two numbers were generated at the same time, which gave a specific location in the state. If there was a section of road within a 2-mile radius of that point, it was taken as one section of the sample. However, if there was no section, that location was dropped and another pair of numbers were generated.

Some 300 pavement sections were selected for evaluation by using the sampling technique discussed above. For each pavement section all the information described in previous paragraphs was recorded. Each section of road was a construction contract section that averaged 5 miles in length.

Strata Analysis

Strata analysis consisted of dividing the states into regions or zones, depending on the number of factors considered to be significant throughout the evaluation process. The procedure is commonly used when it is desirable to make certain that there is an adequate number of sections of each of the influencing factors under study; in addition, it helps in minimizing the variance within each influencing factor.

In this study the states were divided according to geographical area, pavement type, and functional classification. Soil type and traffic data were

Figure 5. Characteristics of trucks evaluated in this study.

	EAL Per Truck		Practical Maximum Gross Weight, lbs.	
	Old Load Limits	New Load Limits	Old	New
 2D	1.08	1.76	27,280	32,000
 3A	1.58	2.13	41,280	46,000
 2-S1	2.08	3.34	45,280	52,000
 2-S2	2.58	3.71	59,280	66,000
 3-S1	2.58	3.7	59,280	66,000
 3-S2	3.08	4.08	73,280	80,000

Table 3. Number of specific pavement sections included in study.

	Northern Area			Central Area			Southern Area		
		U.S. and State Roads			U.S. and State Roads			U.S. and State Roads	
Type of Pavement	Interstate	ADT >4000	ADT <4000	Interstate	ADT >4000	ADT <4000	Interstate	ADT > 4000	ADT <4000
CRCP	1	2	-	10	-	-	2	4	-
JRCP	17	1	1	15	3	3	4	2	2
Overlay concrete	4	24	15	3	17	14	7	14	16
Flexible	-	4	21	-	3	26	2	6	59

included but in a qualitative manner in the geographical classification. This technique proved to be efficient since it helped in recognizing the regions (strata) where there were not enough Interstate sections.

In summary, of the original 300 pavement sections, 256 were used, since the data of the remaining 44 sections were not available on the road-life records of IDOH. An additional 45 Interstate sections were selected for evaluation, since it was felt that any increase in load limits would be reflected more on the Interstate system. These highways now have the highest number of ESAL repetitions in the state (see Table 3).

TRUCK WEIGHT DISTRIBUTION ANALYSIS

Axle-Load Distribution

The axle-load distribution has been used for many years in the analysis of truck weight data, specifically to determine the 18 000-lb ESAL per truck. In addition, it provides useful information relative to the number of axles weighed in excess of the legal weights. The tables contain the necessary information to analyze the axle-load distribution of each vehicle class being considered in this study. Figure 6 shows the cumulative axle-load distribution of the 3-S2 truck observed during the 1977 truck weight study for both single and tandem axles. It is to be noted first that about 7 percent of the tandem axles weighed were in excess of the current load limits. Second, about 93 percent of the single axles weighed less than 12 000 lb.

The primary reason for using this statistical tool is the great variety of vehicles weighed in any one axle configuration type at any station and on any road system. With this method each type of truck can be analyzed separately according to the magnitude of load being carried. The steepness of the curves is in most cases the characteristic of interest.

GVW Distribution

Figure 7 shows the cumulative GVW distribution for the three trucks that most commonly traveled on Indiana highways at the time of this investigation. These were the 2-S1, 2-S2, and 3-S2 trucks. It can be readily noted that about 11 percent of the 3-S2 trucks weighed were in excess of the existing load limits of 73 280 lb. On the other hand, only about 1 percent of the 2-S1 and 2-S2 trucks were in excess of the AASHTO load limits of 45 280 and 59 280 lb.

Shifting Procedure for New Load Limits

The new load limits were analyzed by using the shifting procedure reported by Whiteside and others (13). Essentially, the axle-load distributions of any truck as well as the GVW distribution under the current load limits are basically shifted to the right in order to evaluate the effect of legal load limits on future truck weight distributions. The new axle-load and GVW distributions were determined by using the ratio of the practical maximum gross weight of each vehicle class. Practical maximum gross weight is defined here as the sum of the individual axle legal weights. The front or steering-axle weight was set at a reasonable amount consistent with that class of vehicle and what past roadside weighing has shown to be normal.

Although this method is statistically feasible, the truth is that it is very doubtful that an increase in the legal load limits on Indiana highways would accelerate an immediate shift to higher loads.

Figure 6. Cumulative axle-load distribution of 3-S2 truck under old load limits (rural Interstates).

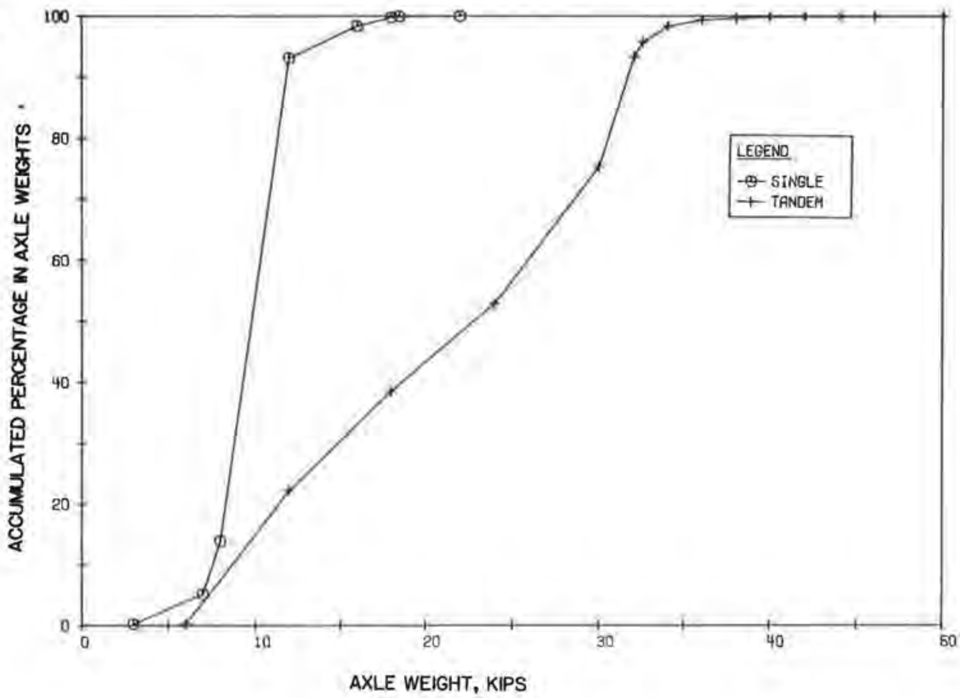
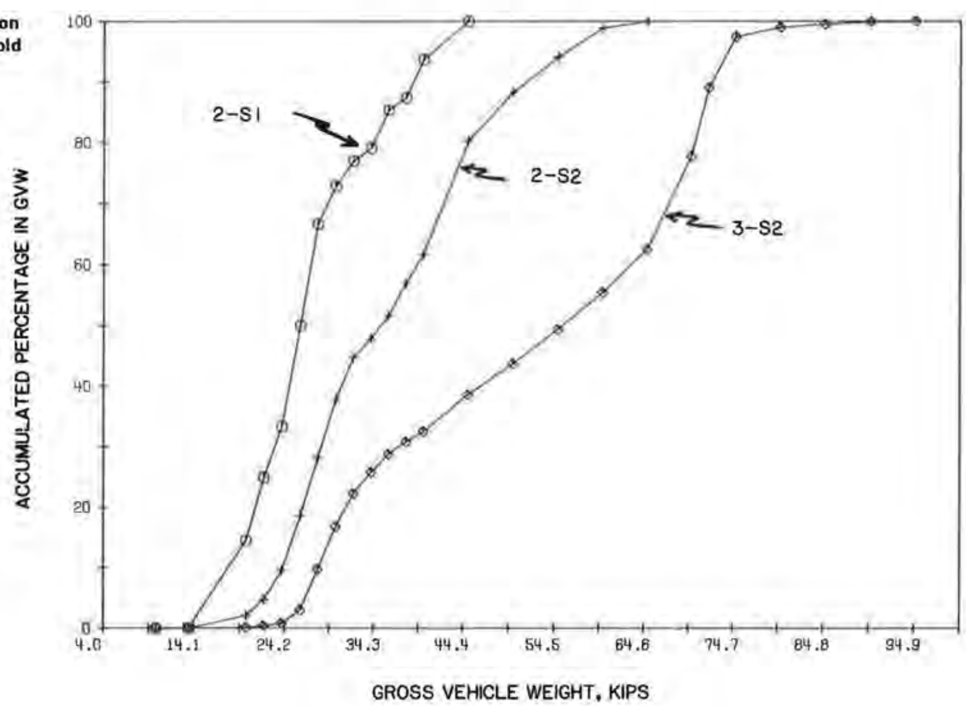


Figure 7. Cumulative GVW distribution of 2-S1, 2-S2, and 3-S2 trucks under old load limits (rural Interstates).



In many cases, trucks may "cube out" before higher axle load results. Furthermore, it would probably decrease the number of trucks necessary to transport a particular commodity, and, as a consequence, the number of load repetitions will decrease. On the other hand, higher load limits will result in heavier loads on trucks, which increases the ESAL for a particular truck.

Figure 8. Cumulative GVW distribution of 3-S2 truck for old and new load limits (shifting procedure).

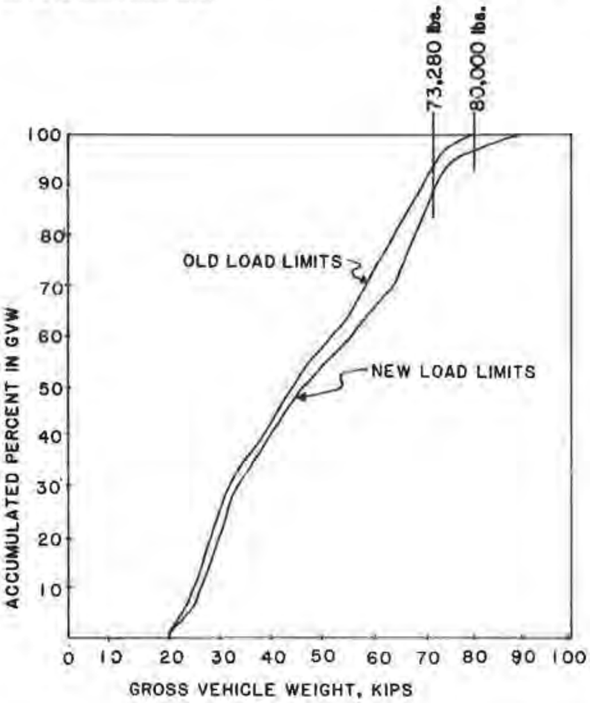


Figure 8 shows a typical shift of the GVW distribution of the 3-S2 truck by using the shifting procedure described above. As expected, the GVW distribution shifted toward higher loads. This results in additional payload carried per truck, and if the same types of trucks are used with higher loads, the life cycle of the pavements exposed to these loads will decrease because the damage per loaded truck increases exponentially as the payload increases linearly. In any case, the method gives the decisionmaker a tool to compare incremental damage due to a particular increase in load limits.

MAINTENANCE COSTS CONSIDERED

In this study the term "maintenance" refers only to those maintenance functions directly related to the pavement structure. Two types of maintenance operations were considered--routine and major maintenance.

Routine Maintenance

Routine maintenance is defined as the correction of pavement distress as it occurs at irregular time intervals. It includes all types of patching and sealing, repair of blow-ups, and all other operations related to the pavement structure during its life cycle. In this study, routine maintenance was estimated by using prediction models developed by Butler (14).

Major Maintenance

Major maintenance is defined as resurfacing of the pavement in order to bring the road surface back to its original, constructed condition. End-of-period maintenance done prior to the application of an overlay, such as patching, resurfacing, and wedging of rutted sections or removal of badly deteriorated pavements, is also included in this category.

Table 4. Range in increased pavement maintenance costs (resurface only).

	Area			
Type of Road	Northern	Central	Southern	System Total
Dollars per Lane Mile per Year				
Interstate	458.81-727.34	447.30-764.94	420.18-968.13	458.98-811.26
Primary	354.08-584.28	533.54-829.04	377.22-600.72	425.01-655.17
Secondary	234.68-494.60	261.29-682.77	204.87-374.31	212.14-489.92
Thousands of Dollars per Year				
Interstate	600.07-951.29	967.40-1654.38	491.31-1132.02	2129.64-3764.18
Primary	880.28-1452.57	939.92-1460.49	748.79-1192.44	2649.33-4084.04
Secondary	819.07-1726.23	1052.32-2749.79	857.78-1567.21	2482.99-5734.27

Table 5. Range in increased pavement maintenance costs (resurface plus routine maintenance).

	Area			
Type of Road	Northern	Central	Southern	System Total
Dollars per Lane Mile per Year				
Interstate	589.61-821.56	594.97-878.15	487.40-983.81	563.32-888.80
Primary	307.54-658.92	699.79-858.16	471.54-649.79	490.84-713.88
Secondary	301.57-543.49	433.62-747.34	273.11-446.47	313.20-543.76
Thousands of Dollars per Year				
Interstate	771.15-1074.52	1286.78-1899.23	569.91-1150.35	2632.33-4123.98
Primary	764.57-1638.13	1232.79-1511.79	936.01-1289.84	3059.68-4450.01
Secondary	1052.53-1896.87	1746.37-3099.84	1143.50-1869.34	3665.85-6364.44

Table 6. Estimated increased annual pavement maintenance costs for Indiana.

	Increased Costs ($000 000s)	
Type of Road	Resurface Only	Resurface Plus Routine Maintenance
Interstate	2.95	3.38
U.S. and state routes		
ADT >4000 (primary)	3.37	3.75
ADT <4000 (secondary)	4.11	5.02
Total	10.43	12.15

ECONOMIC COST PREDICTION DATA

Unit-cost information is needed for the different maintenance activities on a given pavement section. These include unit cost of asphalt concrete, granular material, patching, crack sealing, base and surface repair, and blow-up repair. The unit cost of these materials as well as typical maintenance costs were obtained from the Catalog of U.P.A. Prices for Roads and Bridges prepared by IDOH (15). These cost figures were given in terms of 1978 dollars.

The additional input parameters that affect economic predictions are (a) the interest rate used for economic analysis and (b) the length of the analysis period. A 20-year analysis period was used in this study.

Since changes in legal load limits will produce maintenance costs at different periods of time, it is necessary to convert these costs to equivalent costs at the same time basis. This is the reason interest rates are used in engineering economic analysis. In this study the routine maintenance and overlay costs were converted into an EUAC. A conservative interest rate of 6 percent was used in the economic analysis.

INCREASED PAVEMENT MAINTENANCE COSTS

The cost range presented here includes estimates of the added routine maintenance costs and resurfacing costs that would be required when the weight limits in Indiana were increased from 73 280 to 80 000 lb gross. These cost changes are directly attributed to load changes.

Tables 4 and 5 show the estimated increased pavement costs with and without routine maintenance. For practicality, these cost estimates are presented in two forms: total increase in maintenance costs per lane mile per year and total increase in maintenance costs per year. These estimates are based on a confidence level of 90 percent. The increase in maintenance costs for pavements in the state of Indiana can be expected to range between $10.43 million and $12.15 million annually (in 1978 dollars) as shown in Table 6.

SENSITIVITY ANALYSIS

A sensitivity analysis is the process by which a given variable is changed while the other factors are kept constant. This is done to check how sensitive the variable of interest is, which in this case is the increased pavement maintenance costs.

In this study a sensitivity analysis was performed on the price of asphalt concrete to check its effect on increased pavement maintenance costs. The prices of asphalt concrete used in this analysis were $20.00, $22.50, $25.00, $30.00, and $40.00/ton in place. From this analysis, it was found that resurfacing costs are directly related to asphalt-concrete prices. Routine costs, on the other hand, do not vary linearly with asphalt prices since the costs include many maintenance activities exclusive of overlay.

SUMMARY AND CONCLUSIONS

This paper describes the methodology that was used by the state of Indiana in evaluating the effect of increased truck weights on pavement maintenance costs. The factors as well as the assumptions used in this study were briefly discussed. Routine as well as major maintenance were covered along with the cost information necessary to perform the analysis.

Cost estimates were presented in dollars per lane mile per year and in dollars per year for Interstates and primary roads (U.S. and state routes carrying more than 4000 vehicles/day) and secondary roads (U.S. and state routes carrying less than 4000 vehicles/day).

The results of this study have indicated that both routine and major maintenance will increase if larger loads are permitted on Indiana highways.

In summary, an increase in truck weight limits from 73 280 to 80 000 lb gross will cause an increase in pavement maintenance costs for the total state mileage to range between $10.43 million and $12.15 million annually (in 1978 dollars). Statistically speaking, this estimate is based on a 90 percent confidence level.

County roads were not considered in this study, since factual information relating the pavement thickness and truck weights on the statewide county system is not available.

REFERENCES

1. Excessive Truck Weight: An Expensive Burden We Can No Longer Support. General Accounting Office, Washington, DC, Aug. 1979.
2. R.J. Hansen Associates. State Laws and Regulations on Truck Size and Weight. NCHRP, Rept. 198, 1979.
3. E.J. Yoder, B. Colucci-Rios, J. Fraczek, and J.A. Skees. Effect of Raising Load Limits on Pavements and Bridges in Indiana. Purdue Univ., West Lafayette, IN, Joint Highway Research Project C-36-73H, Dec. 1979.
4. B. Colucci-Rios and E.J. Yoder. Truck Size and Weight Issues. Presented at the 66th Purdue Road School, Purdue Univ., West Lafayette, IN, March 11-13, 1980.
5. R.F. Carmichael III, F.L. Roberts, P.R. Jordahl, H.J. Treybig, and F.N. Finn. Effect of Changes in Legal Load Limits on Pavement Costs. FHWA, Rept. FHWA-RD-78-98, Sept. 1978.
6. R.F. Carmichael III, F.L. Roberts, and H.J. Treybig. Procedure for Evaluating the Effects of Legal Load Limits on Pavement Costs. TRB, Transportation Research Record 725, 1979, pp. 1-8.
7. Manual of Procedure for Road-Life Records. Long-Range Planning Section, Division of Planning, IDOH, Indianapolis, April 1969.
8. 1975 Traffic Flow Map. IDOH, Indianapolis, 1975.
9. Engineering Soil Parent Material Areas of Indiana. Purdue Univ., West Lafayette, IN, Joint Highway Research Project, map revision from Bull. 87, 1950.
10. E.J. Yoder and M.W. Witczak. Principles of Pavement Design, 2d ed. Wiley, New York, 1975.
11. National Highway Inventory and Performance Study. FHWA, Rept. FHWA-PL-78-006, Dec. 1977.
12. AASHO Interim Guide for Design of Pavement Structures. American Association of State Highway Officials, Washington, DC, 1972.

13. R.E. Whiteside, T.Y. Chu, J.C. Cosby, R.L. Whitaker, and R. Winfrey. Changes in Legal Vehicle Weights and Dimensions: Some Economic Effects on Highways. NCHRP, Rept. 141, 1973.
14. B.C. Butler, Jr. Economic Analysis of Roadway Occupancy for Freeway Pavement Performance and Rehabilitation. FHWA, Rept. FHWA-RD-76-14, 1974.
15. Catalog of U.P.A. Prices for Roads and Bridges. IDOH, Indianapolis, 1973-1979.

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Incremental Cost-Allocation Analysis of Bridge Structures

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Methodologies pertaining to the allocation of costs for bridge superstructure by the incremental design method are developed. Generalized design relations are defined as a function of vehicle classes and are applied to three typical bridge structures. Three alternative allocation methodologies, which depend on the bridge functions, are also defined and applied to determine the cost functions for an entire state building and maintenance program taken over a six-year period. The results from these three methods are then compared for accuracy and amount of work required to implement them into a cost-allocation project.

Cost-allocation studies have traditionally been used to provide a systematic and logical basis for relating highway tax structures to highway program costs. There is no single accepted highway cost-allocation methodology, and the results of these studies often vary widely, depending on the method used. This is because much controversy currently exists as to whether roadway-related construction costs are design or damage related. Regardless of these difficulties, there is no doubt that the proper allocation of costs is an extremely important function that can significantly influence the amount of monies available for a highway program.

The proper execution of a cost-allocation project involves the occasioning of costs to numerous elements contained within any building or maintenance program. Considered in this paper is the methodology for the incremental design and subsequent allocation of costs to the superstructure elements of highway bridges. Although the total cost of such elements is often low as compared with that of other elements of the typical highway program (such as highway reconstruction and drainage), these elements may compose a high percentage of the allocatable costs within the program.

Finally, it is felt that the allocation of costs to bridge structures should potentially be one of the more accurate of any of the highway-related allocation methodologies in that the design process for bridges is well defined and well understood. If inaccuracies do appear in the allocation process for bridge structures, they are attributable to factors aside from the design function. Such factors can include

1. Lack of time to perform a detailed incremental design over the full range of vehicles,
2. Allocation of costs based on a single bridge that is not representative, and
3. Allocation of costs by methods not related to design.

Defined below are those methodologies that have been used to occasion the costs for bridge superstructure elements for an arbitrary set of highway loadings. These methods are applied to the actual highway program in which the results of each are compared.

VEHICULAR LOADINGS

Bridge structures are designed to a standard set of vehicular loadings defined by the American Association of State Highway and Transportation Officials (AASHTO) (1). The loads specified are designated with an H prefix followed by a number that indicates the total weight of the truck in tons for two-axle trucks or with an HS prefix followed by a number that indicates the weight of the tractor in tons for tractor-trailer combinations. These H and HS truck loadings are placed on the spans to simulate the actual vehicles most encountered on the highway system along with the H and HS lane loadings to simulate a series of vehicles. Both the truck and lane loadings are placed on the bridge to produce maximum effects throughout the structure.

The three parameters that influence the level of stress on longitudinal members that compose the bridge superstructure are the gross vehicle weight (GVW), the axle loads, and the spacing between axles. AASHTO (1) specifies a fixed spacing between axles of 14 ft for the H truck and variable limits from 14 to 30 ft for the HS truck. These trucks are to be positioned on the span so as to give maximum stresses and deflections along with the associated lane loadings.

Vehicular Classification

The vehicles that use the Maryland (2) highway system are categorized into seven basic classifications, which can then be broken down by GVW group. A summary of such a classification is given in Table 1 where 59 GVW groups are distributed among the seven basic classes. As can be noted from the table, each GVW group is identified by its design axle loading and spacing.

Hand HS-Truck Correlation

It was first necessary to determine the relationship between the AASHTO Hand HS-truck loadings. This was done by placing each loading type on a series of simple span bridges that ranged from 42 to 400 ft in length, equating the maximum moments at the centerline, and performing the correlations by means of a straight-line least-squares fit.

AASHTO Truck and GVW Correlation

The correlation of the AASHTO truck types with the state GVW system requires that the effect of each of