A Microcomputer Procedure to Analyze Axle Load Limits and Pavement Damage Responsibility

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The development of rational guidelines for the posting of load limits in Pennsylvania is presented. A theoretical analysis was conducted to evaluate the effect of axle loads under a variety of conditions that considered various load magnitudes and configurations for different pavement thicknesses and material properties. It was found that axle configuration (i.e., single-, tandem-, and triple-axle assemblies) did not significantly affect pavement response, provided that the load per tire remained the same. A performance model based on present serviceability index was developed that related pavement performance to calculated subgrade strain. In order to accommodate Pennsylvania's deflection-measuring equipment, a procedure was developed that determines the subgrade strain from measurements taken with either the road rater or the falling weight deflectometer. A microcomputer program was written that incorporates the new procedure and includes a default traffic stream that is typical of secondary roads. The program generates information concerning predicted years to failure for different load limits. In addition, simple charts were developed to allow engineers to conduct a load-limit analysis in the absence of deflection measurements and to determine pavement damage responsibility for different axle loads. Results of an example application of the procedure indicate more damage responsibility for heavy loads on thin pavements than on thick pavements, as would be expected. However, cost allocation based on marginal pavement damage can be misleading if the initial cost of construction is not considered. The load-limit analysis procedure presented in this paper can be a valuable tool in the evaluation of axle load limits and axle damage responsibility.

Every state has specified the maximum legal load limit for a single axle, for a tandem axle, and for maximum gross vehicle weight (GVW). Often, however, roads do not have adequate structural capacity to carry axle loads at the legal load limit for all or part of the year. In the spring when the ground is thawing, these pavements have significantly reduced bearing capacity. In addition, for many roads the expense of importing non-frost-susceptible materials is prohibitive. To deal with this problem, many legal codes allow for the posting of load limits below the state's legal maximum.

This reduction (posting) of legal load limits on roads during the spring-thaw period is employed in 17 U.S. states and Canadian provinces *(1)*. Some of the states employ deflection-measurement equipment to determine when the road is in its worst condition. The Washington State Department of Transportation (WSDOT) uses load restrictions that are based primarily on experience and, occasionally, on either Benkelman beam or falling weight deflectometer (FWD) surface deflection measurements. Alaska has developed quantitative methods of establishing load restrictions based on measurements of pavement surface deflections. Most states use experience and judgment to determine the appropriate posted load limits for spring thaw conditions.

In Pennsylvania, the use of load-limit posting goes beyond the seasonal load restrictions employed by some states. The reason is that the Commonwealth of Pennsylvania is responsible for 44,000 miles of roadway, approximately two-thirds of which are classified as collector or local roads. In most states such lower volume roadways would be the responsibility of local government agencies. Because many of the secondary roads have a structural capacity that is inadequate to carry heavy loads without extensive maintenance, Pennsylvania has the authority to post load limits during any time of the year. Currently the state has a uniform, load-restriction policy: when load limits are imposed, they are always set at 10 tons GVW.

A major factor in the consideration of axle load limits on a particular roadway is the cost associated with the pavement deterioration caused by each vehicle. For occasional overloads, permits can be purchased. Similarly, if vehicles heavier than the posted limit use the road for an extended period of time, proper bonds may be required. At present, both types of fee are determined on the basis of experience.

The posting of load limits on the basis of GVW poses a fundamental problem. The load from the vehicle is transmitted through the axle tires, and the load applied by each tire depends on the number of tires per axle. Tandem and triple axles have more tires than have single axles, so they can carry a heavier load while putting as much stress on the pavement as a lighter-loaded single axle. Because the performance is related more accurately to axle loads and axle types than to GVW, the posting of load limits should be based on a maximum load for a given axle type.

The objective of this research project was to develop a rational and comprehensive guideline for the posting of load limits. The procedure had to be capable of evaluating the load-carrying capacity of pavements and of determining the appropriate damage cost to be assigned to heavy vehicles. The research effort resulted in the development of a comprehensive procedure for the evaluation of axle load limits. This procedure, which was developed for a microcomputer, uses deflection measurements from either a road rater or an FWD to determine the expected pavement life for different axle load limits. In addition, the program determines the percentage of

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total damage resulting from each axle load, so that estimates of damage responsibility can be made. For cases in which the user does not have deflection-measurement information, simple figures were developed to provide the engineer with results for typical pavement conditions.

REVIEW OF CURRENT PRACTICE

Load-Limit Posting Practices in Pennsylvania

The establishment of truck-axle weight restrictions below the legal load limits is authorized by Section 4902 of the Pennsylvania Motor Vehicle Code. Under this law, Commonwealth and local authorities may impose restrictions on the weight or size of vehicles allowed to operate on a particular route whenever it is determined that, without such restrictions, excessive damage may occur to the road. Section 4902 also authorizes Commonwealth and local authorities to issue permits allowing the movement of vehicles that exceed the limits of size and weight, and to require sufficient security to cover the cost of repairing the pavement damage caused by the movement of heavy vehicles. The procedure for bonding the roadway is usually as follows:

1. The operator who wishes to haul amounts in excess of the posted load limit notifies the state department of transportation;
2. The department inspects the roadway, so that future damage (caused primarily by the operator) will be recognized;
3. The operator posts a bond, indicating the obligation to maintain the road in a suitable condition; and
4. The department periodically inspects the road for operator compliance.

Even though the procedure requires a significant amount of manpower from the department to be implemented, there are some offsetting benefits to the department. For example, the operators will typically contract out the required maintenance work on their own, thereby reducing the amount of maintenance work required by department forces. Also, as each operator is financially responsible for his own road, he is more careful to monitor his truck loads and reduce hauling when the pavement is in a condition with poor bearing capacity.

In Pennsylvania, the maintenance districts enforce a 10-ton gross vehicle weight limit for posted roads. Chapter 15 of the Pennsylvania Department of Transportation (PennDOT) *Maintenance Manual* establishes a uniform, statewide policy on hauling in excess of posted load limits *(2)*. This load-limit specification was selected on the basis of engineering judgment and experience. Most posting in the districts is done on a permanent (year-round) basis, although seasonal posting of some routes is practiced.

Although the establishment of load restrictions on the basis of gross vehicle weight is convenient from the standpoint of implementation, it is fundamentally incorrect. The load from a vehicle is transmitted through the axle tires, and the number of tires per axle significantly affects the loads transmitted to the pavement. Consequently, pavement response is more directly related to the tire loads imposed on the pavement surface than to gross vehicle weight. It is therefore more rational to determine load limits on the basis of axle loads and number of tires per axle.

DEVELOPMENT OF LOAD-LIMIT ANALYSIS PROCEDURE

Analysis of Axle Loads and Configurations

An important objective of this project was the analysis of the effect of axle-load distribution on pavement response. This analysis was conducted by examining theoretical solutions of a linear-elastic, pavement-analysis computer program called BISAR *(3)*. With this program the effect of changing load magnitude or load configuration for a variety of pavement conditions could be evaluated in a practical and rational way.

A three-layer pavement structure (surface, base, and subgrade) was selected for the analysis because it is representative of typical pavements for secondary roads in Pennsylvania. Three different levels (associated with low, medium, and high values) were chosen for various pavement parameters (surface thickness, surface modulus, base thickness, base modulus, and subgrade modulus). Because of the importance of load magnitude in this study, five different levels were selected for this variable. The levels of all variables were selected with equal differences between levels in order to satisfy certain criteria in the statistical analysis of the data. The values chosen for the different factor levels (Table 1) represented a broad range of pavement and loading conditions, and include the range of surface and base thicknesses typically found in Pennsylvania. The possible combinations of all values of all factors (a full factorial) result in 3^5 times 5, or 1,215 observations for each axle configuration. The pavement surface deflections, the horizontal strain at the bottom of the asphalt concrete layer, and the vertical strain at the top of the subgrade were calculated for all of the factorial combinations. These pavement-response variables were determined for single-, tandem-, and triple-axle configurations.

A detailed analysis of the pavement-response study is reported elsewhere *(4, 5)* and is too long to repeat here. It was found that axle configuration (i.e., single-, tandem-, and triple-axle assemblies) did not significantly affect theoretical pavement response, provided that the load per tire remained the same. It was therefore decided to use load per tire as the principal factor in developing a load-limit analysis procedure.

Following the analysis of axle loads, a performance model based on present serviceability index (PSI) was developed that related pavement performance to calculated subgrade strain. The performance is given by

$$\begin{aligned}\log_{10} N_X = {} & 4.508 - 436.992\,(\varepsilon_{sg}) + 0.092\,(H_2 + H_3) \\ & + 0.141\,(\mathrm{PSI}_i * \mathrm{TSI}) - 0.014\,[\mathrm{TSI}(H_1 + H_2 + H_3)] \\ & + 3.382 \log_{10}(H_1 + H_2) - 0.319 \log_{10} \\ & [(\mathrm{PSI}_i * H_2) + 1] - 1.987 \log_{10}(\mathrm{TSI} * H_1) \\ & - 0.299H_2 - 0.00018P + 0.041\,(H_1 * H_2)\end{aligned}$$

$$R^2 = 0.758 \quad \mathrm{SEE} = 0.283 \quad N = 568 \text{ observations} \qquad (1)$$

where

N_X = number of applications of axle load X,
ε_{sg} = maximum subgrade vertical strain,
H_1 = surface layer thickness (in.),
H_2 = base layer thickness (in.),

TABLE 1 LEVELS OF VARIABLES USED IN THE STUDY

Variable	Levels	Units
Load (all dual tires)		
(a) Single Axle	6; 12; 18; 24; 30	kips
(b) Tandem Axle	12; 24; 36; 48; 60	kips
(c) Triple Axle	18; 36; 54; 72; 90	kips
Surface Thickness -T1	1; 5.5; 10	inches
Surface Modulus -E1	80×10^3; 540×10^3 1000×10^3	psi
Granular Base Thickness - T2	3; 9; 15	inches
Granular Base Modules - E2	10×10^3; 40×10^3 70×10^3	psi
Subgrade Modules - E3	3×10^3; 10×10^3 17×10^3	psi

H_3 = subbase layer thickness (in.),
PSI_i = initial present serviceability index,
TSI = terminal serviceability index, and
P = load per tire (lb).

In order to accommodate Pennsylvania's deflection-measuring equipment, a procedure was developed that estimates the subgrade strain directly from deflection measurements taken with either the road rater or the FWD. In the development of the procedure, theoretical displacements for the road rater and FWD loading conditions were determined from multilayer linear elastic theory *(4, 6)*. For the road rater, a loading frequency of 25 Hz and a peak-to-peak displacement of 0.1 in. were assumed in the calculation of theoretical surface displacements. These assumed values for frequency and peak-to-peak displacement result in a peak-to-peak force of 500 lb and are those normally used by PennDOT when road rater deflection measurements are taken. Theoretical displacements were determined at four different positions corresponding to the four sensors of the road rater, which are spaced at 1-ft intervals.

For the FWD, a load level of 9,000 lb, applied through a circular plate of 5.9-in. radius, was assumed in the computation of theoretical surface displacements. The displacements were determined at seven different positions, corresponding to the seven sensors of the FWD, assuming a 1-ft spacing between sensors.

The theoretical displacements calculated by BISAR for the road rater and FWD loading conditions, and for each combination of layer moduli and thickness included in the factorial study presented earlier, were subsequently correlated with theoretical strain values associated with various axle loads and axle configurations. The regression equations obtained are given in Table 2.

FRAMEWORK FOR ESTABLISHING LOAD RESTRICTIONS

With the development of the strain versus deflection relationships and the formulation of a strain-based performance model, a rational framework for evaluating load restrictions was developed (see Figure 1). In the load-limit analysis procedure, deflection measurements taken with either the road rater or the FWD are used to estimate subgrade compressive strains caused by various axle loads in the traffic stream. The axle-load distribution provided by the pavement engineer is converted to an equivalent, tire-load distribution, and the number of allowable applications for each tire load present in the traffic stream is determined from the performance model. By going through a procedure in which the cumulative pavement damage is successively calculated as tire loads of increasing magnitude in the traffic stream are considered, a curve such as that shown in Figure 2 can be constructed. The determination of load limits for posting can then be made by specifying a minimum time that a road must remain in service before rehabilitation is allowed.

The curve shown in Figure 2 will vary depending on pavement structural condition and on the characteristics of the traffic stream for the road segment under consideration. In the procedure, pavement structural condition is evaluated from deflection measurements. The traffic distribution must be provided by the pavement engineer. Unfortunately, this information is usually not available or is not collected on a regular basis, particularly for secondary roads. These types of roads are the ones that are most often posted in Pennsylvania. Consequently, efforts were made during the study to define typical traffic distributions for secondary roads, information that can be used in the absence of actual data.

TABLE 2 RELATIONSHIPS FOR ESTIMATING SUBGRADE COMPRESSIVE STRAIN FROM DEFLECTION MEASUREMENTS

$$\begin{aligned}\log_{10}(\varepsilon_{zz})_{x,FWD} = {} & -4.273 + 0.433 \log_{10}(W_1 - W_2) \\ & +0.560 \log_{10}(W_1 + 2W_2 + 2W_3 + W_4) \\ & -1.799 \log_{10}(H_1+H_2) + 0.912 \log_{10}(P_{tire})_X \\ & +0.122 \sqrt{H_1} + 0.285 \sqrt{H_2}\end{aligned}$$

$R^2 = 0.9715$ SEE = 0.088 N = 3645 obs

$$\begin{aligned}\log_{10}(\varepsilon_{zz})_{x,RR} = {} & -2.784 + 0.498 \log_{10}(W_1 - W_2) \\ & +0.477 \log_{10}(W_1 + 2W_2 + 2W_3 + W_4) \\ & -0.948 \sqrt{H_1} + H_2 + 0.9121\log_{10}(P_{tire})_X \\ & +0.097 H_1 + 0.673 \sqrt{H_2}\end{aligned}$$

$R^2 = 0.9703$ SEE = 0.090 N = 3645 obs

where

$(\varepsilon_{zz})_{X,FWD}$ = vertical compressive strain at top of subgrade due to tire load X, computed using FWD measured deflections

$(\varepsilon_{zz})_{x,RR}$ = vertical compressive strain at top of subgrade due to tire load X, computed using Road Rater measured deflections

W_i = measured deflection at the i^{th} sensor of the deflection device used, inches

H_1 = surface layer thickness, inches

H_2 = base layer thickness, inches

$(P_{tire})_X$ = tire load, lb

SEE = standard error of estimate

DETERMINATION OF TYPICAL TRAFFIC DISTRIBUTIONS

PennDOT was contacted to determine the availability of data on axle-weight distribution for secondary roads. For these classes of roads, it was found that PennDOT has data on traffic counts broken down by vehicle type but very little information on vehicle axle-weight characteristics. Collection of axle-weight data is mainly done on the primary routes (Interstate and principal arterials), but very little information is gathered on the secondary routes (minor arterials and local roads).

However, W-3 tables for the 1982 to 1984 period for local roads were obtained from PennDOT. These tables were based on survey data from three survey stations located on secondary roads in the state. The tables provide information on average vehicle weights by type of vehicle and for both loaded and empty conditions. Additional information was obtained from a truck-weight case study conducted by FHWA in a year-long study in 1980 to 1981 *(7)*.

Tables provided by FHWA showing the distribution of gross vehicle weights among the various axles were used, together with the data available on average gross vehicle weights, to establish distributions of axle loadings for secondary routes. The axle-load distributions were converted to equivalent tire-load distributions by dividing each axle load by the appropriate number of tires per axle. Figures 3 and 4 show cumulative distributions for tire loads as determined from PennDOT data on local roads. Figure 3 shows the tire-load distribution for loaded vehicles, while Figure 4 shows the distribution when

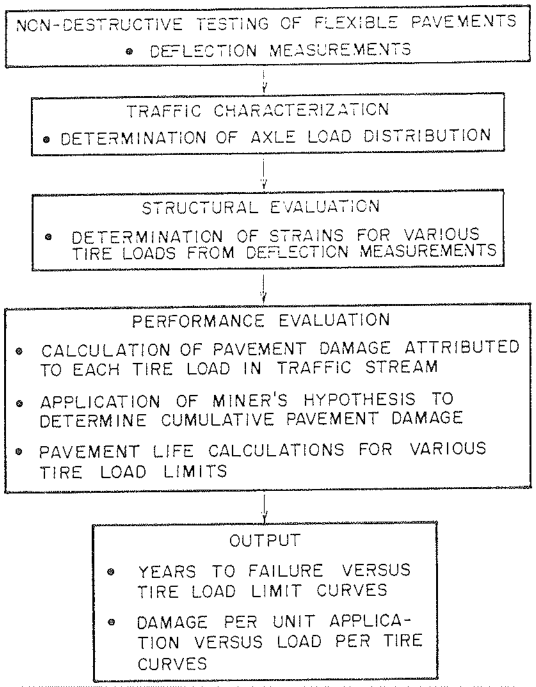

FIGURE 1 Rational framework for evaluating load restrictions.

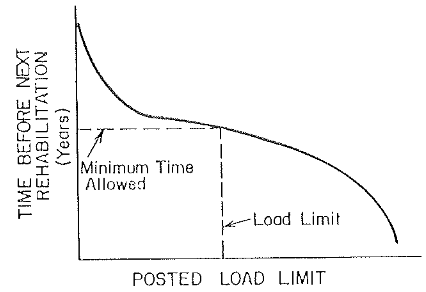

FIGURE 2 Selection of load limit based on minimum time to next rehabilitation.

both empty and loaded vehicles are considered. A load-limit analysis of both distributions showed that the results were similar because the predicted pavement performance was dominated by the loaded vehicles—information that appeared in both distributions. In the absence of site-specific traffic survey data, the cumulative, tire-load distribution given in Figure 3 is provided as a default in the load-limit analysis procedure. However, the pavement engineer is cautioned not to use the default load distributions indiscriminately because they may be significantly different from the actual traffic conditions. Actual truck traffic count and weight surveys for characterizing the traffic stream are strongly recommended.

In the load-limit analysis procedure, the given traffic volume, annual average daily traffic (AADT) remains constant as different load limits are considered. For example, in reference to Figure 3, if the AADT is set at 1,000 vehicles/day, and a load limit of 4,000 lb/tire is being considered, the procedure will distribute the 1,000 vehicles/day according to the load-distribution figure for loads less than or equal to 4,000 lb. This is a simplifying assumption that does not consider a shift in the load-distribution curve for different load limits. However, if the user has information concerning the shifted, load-distribution curve, this information can be input directly and used in the procedure.

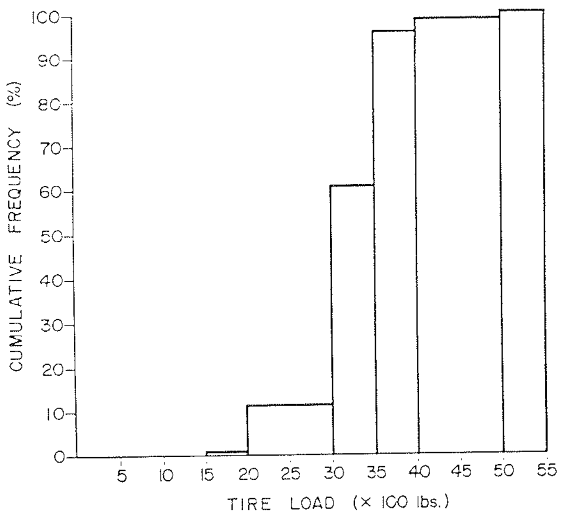

FIGURE 3 Cumulative tire-load distribution (loaded vehicles).

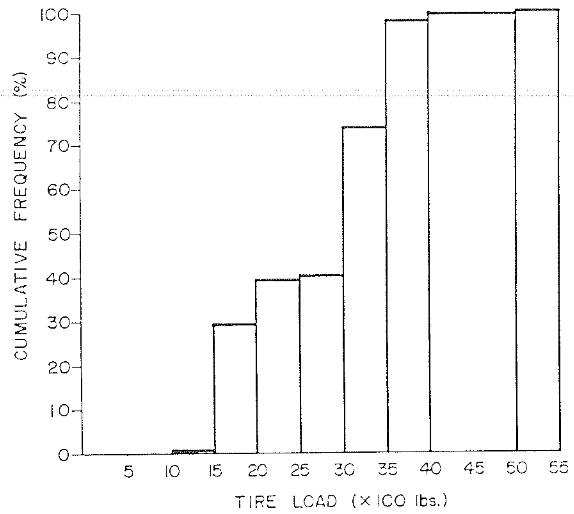

FIGURE 4 Cumulative tire-load distribution (loaded and empty vehicles).

DEVELOPMENT OF A COMPUTER PROGRAM AND GENERAL CHART FOR LOAD-LIMIT ANALYSIS

The load-limit analysis procedure discussed here has been implemented in a computer program. The program is interactive and is suitable for use on a microcomputer.

The program requires deflection measurements made with either the road rater or the FWD. Information on tire-load distribution, if available, can also be entered in the program. Otherwise, the default tire-load distribution presented in Figure 3 is used for the load-limit analysis. Output from the program includes a plot of the years to failure versus load per tire curve, and a plot of the inverse of the number of allowable applications before failure ($1/N_f$) versus load/tire. Figures 5, 6, and 7 illustrate sample program output. Figure 6 is used to evaluate

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DATE  03/24/86

DISTRICT NO.     2                      BEGINNING JOB STATION        0011+00
COUNTY   14                             ENDING JOB STATION       0013+25
LEGISLATIVE ROUTE NO.    L 135          MAINTENANCE CLASS     A
WHEEL PATH    1                         LANE        RIGHT

DEFLECTION DEVICE USED IS ROAD RATER
NUMBER OF DEFLECTION BASINS TAKEN IS  10

      TIRE LOAD DISTRIBUTION
  TIRE LOAD   DAILY APPLICATIONS
     500.00        100.00
    1500.00         70.00
    2500.00         40.00
    3500.00         30.00
    4500.00         28.00
    5000.00         30.00

TOTAL DAILY LOAD APPLICATIONS (BOTH DIRECTIONS) =      298.00000000
BASIN STATION INDEX FOR LOAD LIMIT ANALYSIS      3
BASIN STATION ID    0011+50
LAYER 1 THICKNESS      3.00
LAYER 2 THICKNESS      4.00
CURRENT PSI    3.50
TERMINAL SERVICEABILITY INDEX    1.50
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FIGURE 5 Sample output from LOADLIM (data on tire-load distribution) entered as inputs.

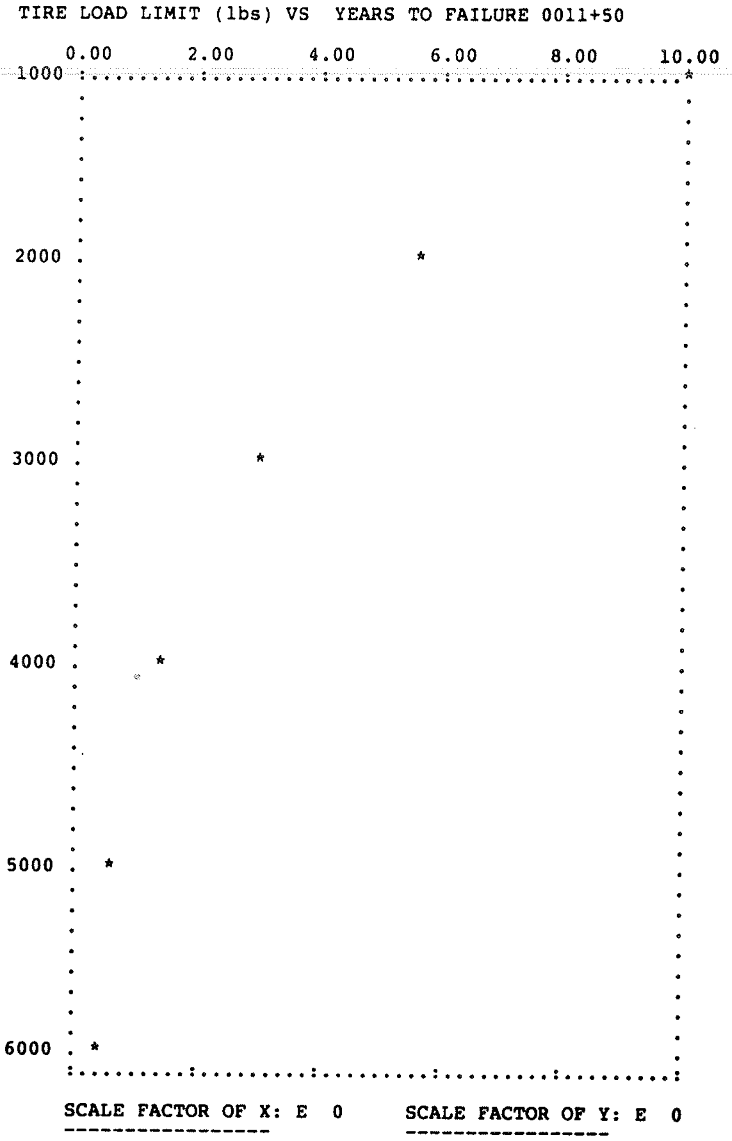

FIGURE 6 Sample output from LOADLIM: Plot of load per tire versus number of years to failure.

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TIRE LOAD LIMIT (lbs) VS  1/Nf           0011+50

    0.00      5.00     10.00     15.00     20.00     25.00     30.00
1000 :*........:.........:.........:.........:.........:.........:...
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6000 .                                                              *
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     SCALE FACTOR OF X: E  0     SCALE FACTOR OF Y: E -5
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FIGURE 7 Sample output from LOADLIM: Plot of load per tire versus damage per unit load application.

the sensitivity of pavement design life to load limit. As illustrated in Figure 2, the user may have a desired minimum time before rehabilitation and can determine the load limit appropriate for that time to failure. Figure 7 indicates the fraction of total damage caused by one load application of an axle with a given load per tire. This figure can be used to determine damage responsibility for different axle loads and is discussed in more detail in the next section. The program also creates a file called DEF.OUT (Figure 8) containing the deflection measurements entered by the user and a plot of Sensor 1 deflections versus station index. This plot is generated if three or more deflection basin measurements are entered by the user.

Inasmuch as deflection data may not always be available to the pavement engineer, a chart (Figure 9) has been prepared that allows load limits based on a qualitative evaluation of pavement structural condition to be determined. In the development of the chart, the assumed values of larger moduli and thicknesses for medium- and poor-quality pavements were characterized as follows:

	Pavement Condition	
Variable	*Medium*	*Poor*
Asphalt-layer modulus (psi)	300,000	150,000
Base modulus (psi)	35,000	15,000
Subgrade modulus (psi)	6,500	3,000
Surface-layer thickness (in.)	3.5	1.5
Base thickness (in.)	5.0	4.0

The tire-load distribution assumed is that presented in Figure 3.

The general chart and the computer program form a complete package, which allows the pavement engineer to conduct

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DATE  03/24/86

DISTRICT NO.    2                        BEGINNING JOB STATION        0011+00
COUNTY   14                              ENDING JOB STATION    0013+25
LEGISLATIVE ROUTE NO.   L 135            MAINTENANCE CLASS     A
WHEEL PATH   1                           LANE        RIGHT

DEFLECTION DEVICE USED IS FWD
NUMBER OF DEFLECTION BASINS TAKEN IS  10


          PLOT OF MAXIMUM DEFLECTION VS. STATION NO.

            0.00      1.00      2.00     3.00
           1 :........*:.........:.........:.....
           2 .         *                        .
           3 .     *                            .
           4 .     *                            .
           5 .                        *         .
           6 .                                  *
           7 .          *                       .
           8 .            *                     .
           9 .          *                       .
          10 .          *                       .

    SCALE FACTOR OF X: E  0      SCALE FACTOR OF Y: E -2
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                              SENSOR DEFLECTION (inches)
INDEX  STATION ID    DEF #1     DEF #2     DEF #3     DEF #4
-----  ----------   --------   --------   --------   ---------
  1     0011+00     0.008760   0.006004   0.003327   0.001693
  2     0011+25     0.010276   0.007717   0.004705   0.002756
  3     0011+50     0.005787   0.004941   0.003622   0.002559
  4     0011+75     0.005906   0.005000   0.003740   0.002717
  5     0012+00     0.025236   0.016752   0.008031   0.003661
  6     0012+25     0.034724   0.020669   0.008189   0.002795
  7     0012+50     0.010787   0.007835   0.004744   0.002795
  8     0012+75     0.013484   0.009311   0.005236   0.002835
  9     0013+00     0.010709   0.007717   0.004724   0.002795
 10     0013+25     0.010709   0.007677   0.004764   0.002894
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FIGURE 8 Sample listing of DEF.OUT file.

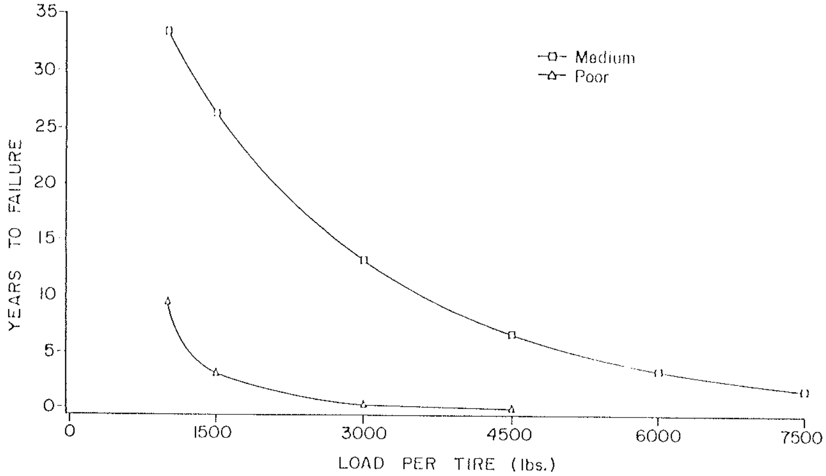

FIGURE 9 Chart for establishing load restrictions based on a qualitative evaluation of pavement structural condition.

a rational evaluation of load restrictions both with and without deflection data. The collection of deflection and traffic data is recommended, however, because the data would permit a better evaluation of the effect of different load-limit policies.

DETERMINING PAVEMENT DAMAGE RESPONSIBILITY FOR DIFFERENT AXLE LOADS

Methodology

For a variety of reasons, it sometimes becomes necessary to determine the amount of pavement damage resulting from a given axle load. This is often difficult because the AASHTO load-equivalence factors are not sensitive to the effect of different pavement structures *(8)*. In this project, a procedure was developed for estimating the amount of damage for which each vehicle is responsible.

The principal factor involved in determining damage responsibility is the expected number of applications to failure for each axle load. As the concept of cumulative damage (Miner's Rule) is used in the performance algorithm, if a pavement is expected to carry 100,000 applications of a light vehicle before failing, then each application of that vehicle consumes 1/100,000 of the pavement life (or 0.001 percent). However, if only 1,000 applications of a heavy vehicle are required to make the same pavement fail, then each heavy vehicle application consumes 1/1,000 (or 0.1 percent) of the pavement life. By multiplying the percentage of pavement damage per vehicle application by the actual number of applications, the total damage caused by that vehicle can be determined.

The percentage of damage responsibility can be converted to cost responsibility by considering the cost of rehabilitating a certain roadway. For example, if the cost of rehabilitating a secondary road is \$50,000/lane mi, and a vehicle is determined to cause 0.0003 percent damage per application, then the cost associated with each application of that vehicle would be

$$\$50{,}000 \times \frac{(0.0003)}{100\%} = \$0.15/\text{mi/vehicle}$$

If the computer program is not used, then Figure 10 can be used to estimate the percentage of damage for an axle with a given load per tire. Curves are provided for two example pavements, one medium-quality and one poor-quality pavement. Details on the assumptions for these pavement examples are given in the preceding section.

Application Examples

To demonstrate the use of the procedure in determining damage responsibility, a load-limit analysis was performed on three sample pavements. The three examples are actual pavement sections that are part of the 1-mi pavement loop of the Pennsylvania Transportation Research facilities at Pennsylvania State University *(9)*. Deflection measurements from the pavement sections were used in the procedure as was also the following thickness information:

	Thickness of Asphalt Concrete (in.)	*Thickness of Granular Base (in.)*
Section 1	5.5	6
Section 2	7.5	6
Section 3	9.5	6

A traffic rate of 2,500 AADT was used in the example, using the default load distribution given in Figure 3.

The results showing the time to failure versus the tire load limit for the three pavement section examples are given in Figure 11. It is interesting to note that the predicted pavement performance for Section 3 is the one affected most by the change in axle load limit. This is due to the fact that Section 1 is probably under-designed for the chosen traffic level and the pavement fails relatively early regardless of the load limit.

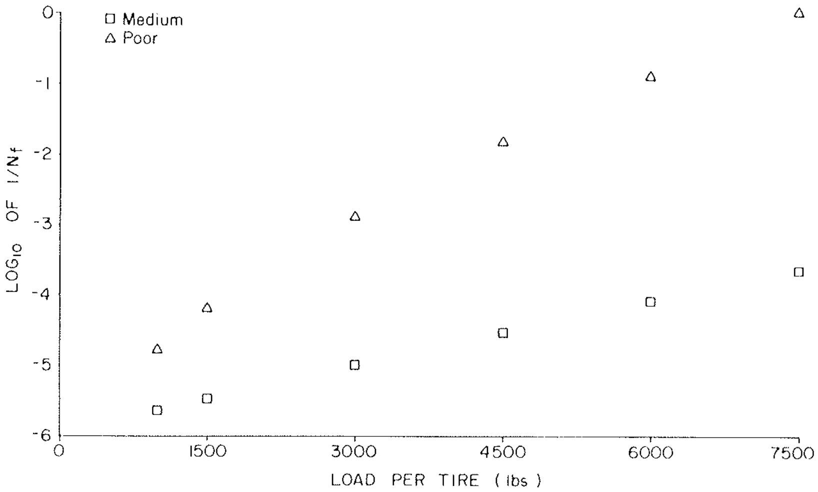

FIGURE 10 Contribution to pavement failure of various tire loads for two example pavement structures.

Of primary interest in this example is the determination of damage responsibility, as shown in Figure 12. The results

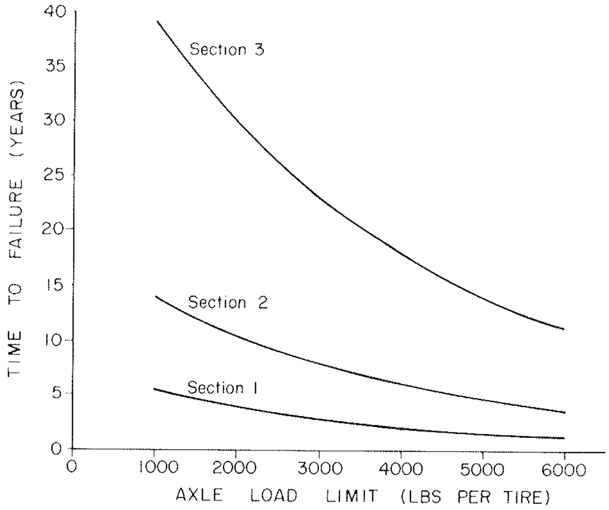

FIGURE 11 Pavement time to failure as a function of tire load limit.

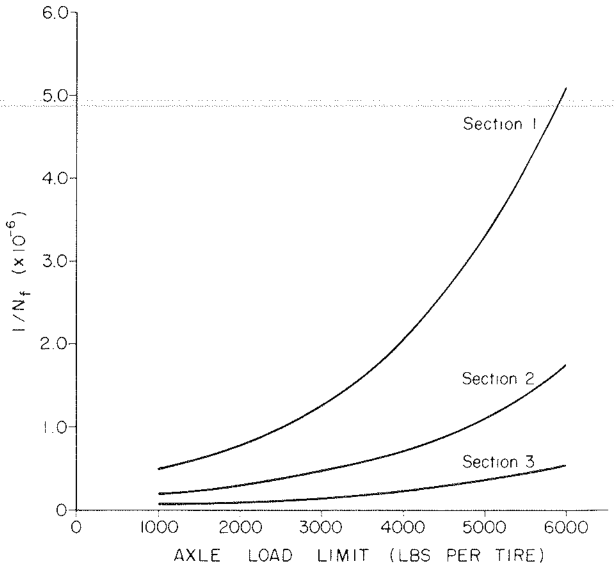

FIGURE 12 Pavement damage responsibility as a function of tire load limit.

indicate that in Section 1 the damage caused by each load application is far more sensitive to the load magnitude than in Section 2 or 3. The marginal damage (rate of increase in pavement damage) is represented by the slope of the curves shown in Figure 12.

Cost-Allocation Considerations

In cost-allocation procedures where costs are assessed to road users according to their associated damage responsibility, the marginal damage is often used as a method to determine marginal cost for a particular axle load. If this methodology were used with the information from Figure 12, the cost allocation determined from marginal damage would be much higher for Section 1 than for Section 3. This would indicate that heavy trucks operating on thin pavements should be assessed higher costs than the same trucks operating on thick pavements.

However, what is not being taken into consideration in the above methodology is the initial construction cost. Section 3 may have small marginal damage associated with heavy load applications, but Section 3 may have been far more costly to construct than Section 1, so the higher marginal cost of maintenance in Section 1 may be offset by the higher initial cost of Section 3. This emphasizes the fact that total cost, and not simply rehabilitation and user costs, should be considered when determining cost responsibility.

SUMMARY AND CONCLUSIONS

The Commonwealth of Pennsylvania has 44,000 mi of roads under its jurisdiction. About two-thirds of these are secondary roads which, in other states, would be the responsibility of local governments. Because the majority of these roads have pavements with limited structural capacity, the state has the authority to restrict axle loads if it is believed that those axle loads would result in excessive damage to the pavement structure. In Pennsylvania, the posting of load limits below the legal maximum occurs on a year-round basis for some roads, as well as on a seasonal (spring load restriction) basis for others.

The main purpose of this research project was to develop rational guidelines for the posting of load limits in Pennsylvania. To evaluate the effect of axle loads under a variety of conditions, a theoretical analysis was conducted that considered various load magnitudes and configurations for different pavement thicknesses and material properties. In this analysis the effect of subgrade strain was studied, using the elastic-layer program BISAR. It was found that axle configuration (i.e., single-, tandem-, and triple-axle assemblies) did not significantly affect pavement response, provided that the load per tire remained the same.

Following the analysis of axle loads, a performance model based on compressive strain at the top of the subgrade was developed. To accommodate Pennsylvania's deflection-measuring equipment, a procedure was developed that estimates the subgrade strain from measurements taken with either the road rater or the FWD. In this way, the new procedure uses deflection measurements to predict pavement performance for a given level of traffic.

A microcomputer program was written that incorporates the new procedure and includes a default traffic stream that is typical of secondary roads. The program generates information concerning predicted years to failure for different load limits. This enables the user to quantitatively consider the effects of axle load limits on pavement deterioration.

In addition to the microcomputer program, a simple figure was developed to allow engineers to estimate the effects of imposing different load limits in the absence of deflection measurements. A second figure was developed that indicates the portion of the pavement damage that caused by a particular axle load. With this information, the engineer can determine the appropriate charges to be assessed to heavy haulers for permits and bonds.

An example application was presented wherein a load-limit analysis was conducted on three different pavement sections. The analysis indicated more damage responsibility for heavy loads on thin pavements than on thick pavements, as would be expected. However, cost allocation based on marginal pavement damage can be misleading if the initial cost of construction is not considered.

The load-limit analysis procedure presented in this paper can be a valuable tool in the evaluation of axle load limits and axle-damage responsibility.

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REFERENCES

1. B. Connor. *Rational Seasonal Load Restrictions and Overload Permits.* Final Report. Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska, 1980.
2. Pennsylvania Department of Transportation. Weight Restrictions on Highways (Posted Highways). Chapter 15, *Maintenance Manual,* Harrisburg, Pa., Oct. 1985.
3. D. L. De Jong, M. G. F. Peutz, and A. R. Korswagen. *Computer Program BISAR.* External Report. Koninklijke/Shell-Laboratorium, Amsterdam, The Netherlands, 1973.
4. E. G. Fernando, D. R. Luhr, and H. N. Saxena. *Development of Guidelines for Posting Load Limits on Pavements.* PTI Report 8525. Pennsylvania Transportation Institute, University Park, Pa., 1985.
5. E. G. Fernando, D. R. Luhr, and H. N. Saxena. Analysis of Axle Loads and Axle Types for the Evaluation of Load Limits on Flexible Pavements. Paper prepared for presentation at the Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C., Jan. 1987 (in preparation).
6. E. G. Fernando, D. R. Luhr, and D. A. Anderson. *Development of an Overlay Design Procedure for Flexible Pavements.* PTI Report 8416. Pennsylvania Transportation Institute, University Park, Pa., 1984.
7. D. L. Neumann and P. Savage. *Truck Weight Case Study for the Highway Performance Monitoring System.* Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1982.
8. *AASHTO Guide for Design of Pavement Structures: 1986.* American Association of State Highway and Transportation Officials, Washington, D.C., 1986.
9. D. A. Anderson, W. P. Kilareski, and R. F. Bonaquist. *Construction and Operation of the Pavement Durability Research Facility.* PennDOT Research Project 82-11, Vol. 1, PTI Report 8415. Pennsylvania Transportation Institute, University Park, Pa., 1984.

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