Ratios of Pavement Damage to User Fees

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An important decision that state legislatures are charged with is the apportionment of highway user fees among the various weight classes of vehicles. Departments of transportation must provide supporting and convincing data for these legislative decisions. Currently, the most rational basis for setting user fees is the prediction of pavement damage by using the AASHTO 1986 pavement design equations. Axle load equivalency charts are prepared from the AASHTO 1986 Design Manual equations for determining the damage to rigid and flexible pavements by single-, tandem-, and triple-axle loads from 2 to 90 kips. Tables present the ratios of pavement damage (according to these equations) to road user charges for different classes of vehicles in two states having among the lower and higher road user fees in the country. The method for computing ratios of pavement damage to user fees for these two states provides a fast and convenient means for all states to evaluate and adjust their road user fees for each class of vehicle.

Heavy axle loads shorten pavement life. In order to allocate user fees, load effects must be quantified. This paper addresses the question: "Are road user revenues proportioned equitably among various weights of vehicles according to the pavement damage which they cause?" Axle load equivalency charts are prepared from the AASHTO 1986 Design Manual (*1*) equations that relate the damage to rigid and flexible pavements by single-, tandem-, and triple-axle loads from 2 to 90 kips. Tables compare the ratios of pavement damage, according to these equations, to road user charges for different classes of vehicles in two states having among the lower and higher road user fees in the country.

AASHO ROAD TEST EQUIVALENCY FACTOR EQUATIONS

The AASHO Road Test equivalency factor equations (*2*) were extended by the AASHTO 1986 Design Manual, Appendix MM (*1*), to include the following:

1. Single-axle, maximum load to 50 kips;
2. Tandem-axle, maximum load to 90 kips;
3. Triple-axle, maximum load to 100 kips;
4. Equivalency factors for terminal serviceability index (p_t) between 2 and 3; and
5. Rigid pavements—equivalency factors for slabs up to 14 in. thick.

For flexible pavements, these equations are

$$\log\left(\frac{w_{tx}}{w_{t18}}\right) = 6.1255 - 4.79 \log (L_x + L_2) + 4.33 \log L_2 + \frac{G_t}{\beta_x} - \frac{G_t}{\beta_{18}} \tag{1}$$

$$G_t = \log \frac{4.2 - p_t}{2.7} \tag{2}$$

$$\beta_x = 0.4 + \frac{0.081\,(L_x + L_2)^{3.23}}{(\mathrm{SN} + 1)^{5.19} L_2^{3.23}} \tag{3}$$

where

w_{tx} = total number of applications of a given axle load x;
w_{t18} = equivalent number of applications of the standard 18-kip axle load;
L_x = load on one single, tandem, or triple axle (kips);
L_2 = axle code (1, 2, or 3 for single, tandem, or triple axle, respectively);
SN = structural number;
p_t = terminal serviceability index, which relates various indicators of pavement distress to overall surface quality; and
β_{18} = value of β_x when L_x is equal to 18 and L_2 is equal to 1.

For rigid pavements, the equations are

$$\log \frac{w_{tx}}{w_{t18}} = 5.9081 - 4.62 \log (L_x + L_2) + 3.28 \log L_2 + G_t\left(\frac{1}{\beta_x} - \frac{1}{\beta_{18}}\right) \tag{4}$$

$$G_t = \log \frac{4.5 - p_t}{2.7} \tag{5}$$

$$\beta_x = 1.0 + \frac{3.63(L_x + L_2)^{5.2}}{(D + 1)^{8.46}\, L_2^{3.52}} \tag{6}$$

where D is the slab thickness (in.). For both flexible and rigid pavements, the equation for translating w_{tx} into w_{t18} is

$$w_{t18} = \frac{w_{tx}^2}{w_{tx} - 1} \tag{7}$$

According to AASHTO (*2*), there is considerably more uncertainty in extending the equations to triple axles than in extending them to higher loads on single and tandem axles.

AXLE LOAD EQUIVALENCY CHARTS

In order to permit rapid estimates of pavement damage by different vehicle classes, Equations 1–7 were programmed in Fortran for preparing the load equivalency charts shown in Figures 1a–1f. The program source code is given in the ap-

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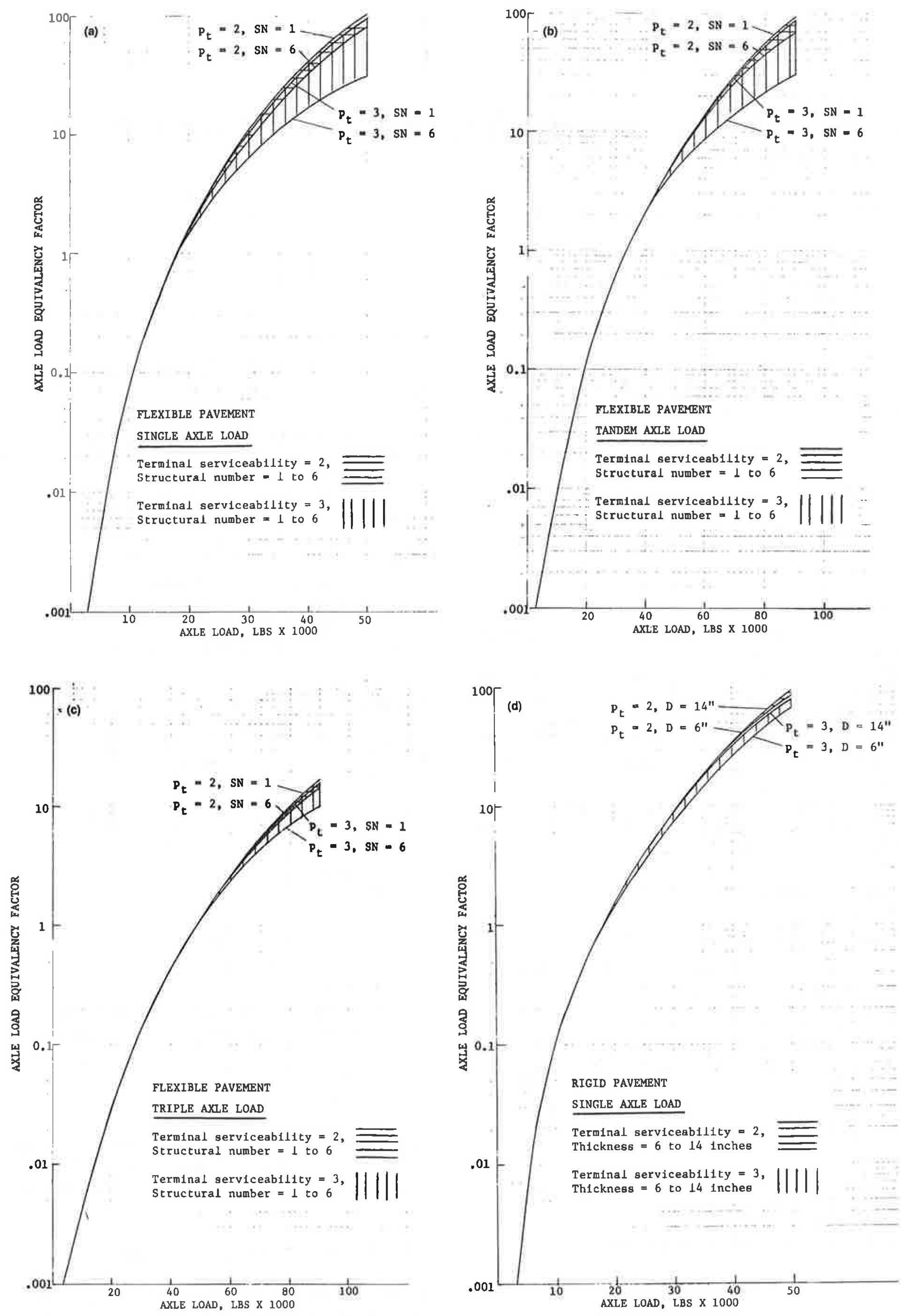

FIGURE 1 *(continued on next page)*

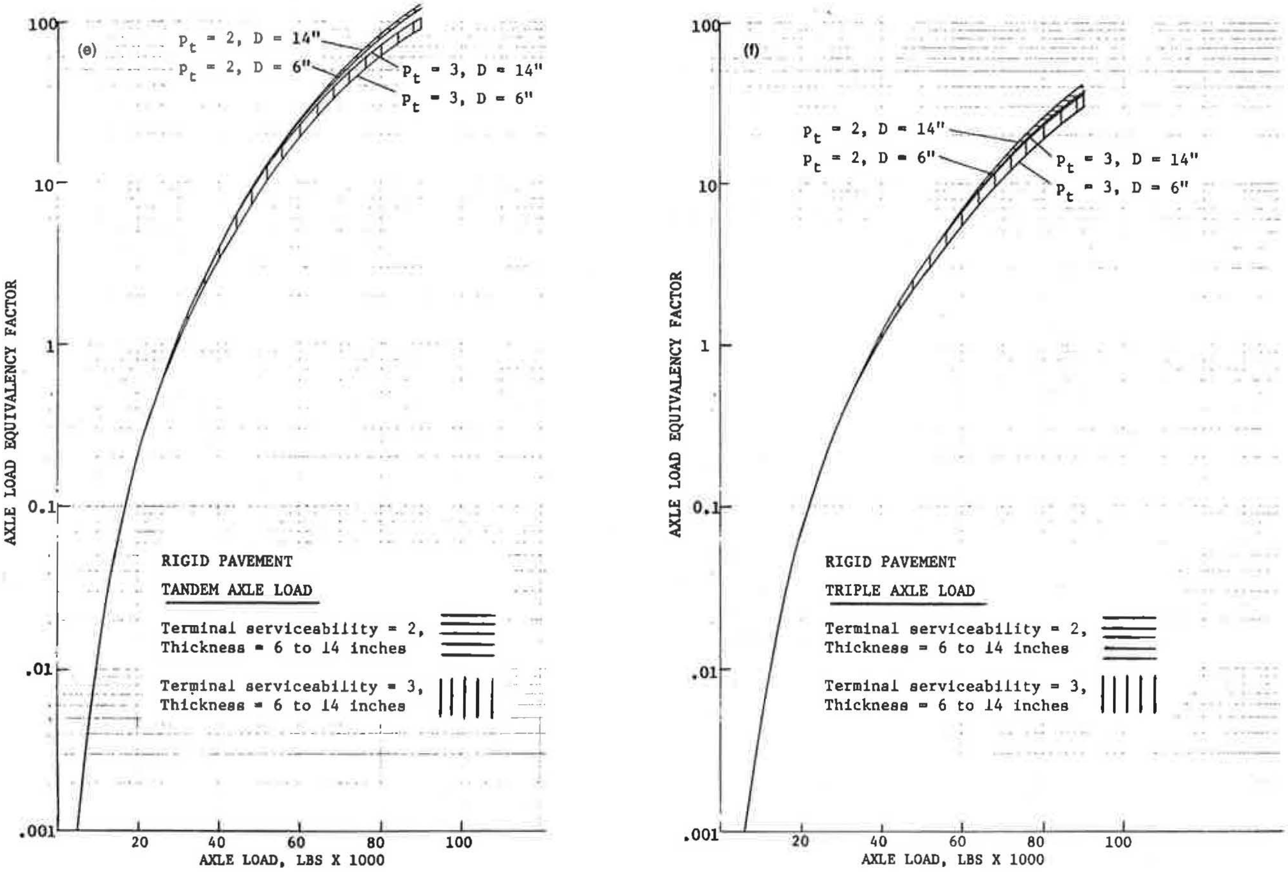

FIGURE 1 Axle load equivalency factors: (a) single-, (b) tandem-, and (c) triple-axle loads on flexible pavements; and (d) single-, (e) tandem-, and (f) triple-axle loads on rigid pavements.

pendix. Figures 1a–1c show the ratio between the number of axle loads and the number of 18-kip single-axle loads that do equivalent damage to a flexible pavement as a function of axle load for single, tandem, and triple loadings for pavements having SN between 1 and 6. Figures 1d–1f show the ratio between number of axle loads and number of 18-kip single-axle loads that do equivalent damage to a rigid pavement as a function of axle load for single, tandem, and triple loadings for D between 6 and 14 in. The following examples illustrate use of the equivalency charts.

Example 1

How many passes of a 30-kip single-axle load cause the same damage as 1,000 passes of an 18-kip single-axle load on a flexible pavement having SN of 4 and p_t of 2?

Solution

Interpolating Figure 1a for single-axle loads on a flexible pavement with L_x = 30 kips, SN = 4, and p_t = 2, yields $w_{tx}/w_{t18} \approx 10.1$. 1,000/10.1 = 99 passes.

Example 2

How many passes of a 50-kip tandem-axle load cause the same damage as 1,000 passes of an 18-kip single-axle load on a 10-in. rigid (concrete) pavement having a terminal serviceability of 2.5?

Solution

Interpolating Figure 1e for tandem-axle loads on rigid pavements with L_x = 50 kips, D = 10 in., and p_t = 2.5, yields $w_{tx}/w_{t18} \approx 9.5$. 1,000/9.5 = 105 passes.

The AASHTO (*1*) measure of pavement quality is the present serviceability index (PSI), a composite number that relates various indicators of pavement distress to overall surface quality. Pavement distress appears as roughness, rutting, cracking, faulting, blowups, potholes, etc. The distress indicators possess a degree of objectivity, but the overall rating is necessarily subjective. For simplicity, the AASHTO 86 design method assumes that an equivalent single-axle load (ESAL) of 18 kips causes a unit damage to pavement and a unit reduction in surface quality, both of which are constant over the pavement life (*1*).

Example 3

This example (*3*) illustrates how changes in gross vehicle weight (GVW), weight distribution, and axle arrangement affect pavement life.

A 60-kip tractor-semitrailer is used for the base case. This vehicle is a type that can be replaced by a twin-trailer truck. Assumed design values for the AASHTO load-equivalency factors are p_t = 2.5, D = 9 in., and SN = 3.

1. Base Case of 60-kip Tractor-Semitrailer (Figure 2a).

Pavement Type	ESALs by Axle or Axle Group: 1 Single	2 Tandem	3 Tandem	Total
Flexible	0.10	0.52	0.27	0.89
Rigid	0.07	0.79	0.37	1.23

2. Base plus 6 kips, with weight distribution between front and rear tandem axles unchanged, adjusted for 9 percent fewer trips (Figure 2b). Because of the higher payload, the vehicle will require 0.91 as many vehicle-miles to deliver the same load as the lighter truck.

Pavement Type	ESALs by Axle or Axle Group: 1 Single	2 Tandem	3 Tandem	Total × 91%	Percent Above Base
Flexible	0.11	0.77	0.39	1.16	30
Rigid	0.08	1.26	0.58	1.75	42

3. Base case with twin-trailer truck axle arrangement, GVW and weight distribution unchanged (Figure 2c). Assume that the axle arrangement is changed to five single axles, the usual twin-trailer truck arrangement.

Pavement Type	ESALs by Axle or Axle Group: 1 Single	2 Single	3 Single	4 Single	5 Single	Total	Percent Above Base
Flexible	0.10	0.38	0.37	0.20	0.20	1.25	40
Rigid	0.07	0.32	0.32	0.15	0.15	1.01	−18

4. Effect of combination of higher weight, less uniform weight distribution, and different axle arrangement, adjusted for 9 percent fewer trips (Figure 2d).

Pavement Type	ESALs by Axle or Axle Group: 1 Single	2 Single	3 Single	4 Single	5 Single	Total × 91%	Percent Above Base
Flexible	0.11	0.86	0.50	0.34	0.17	1.70	91
Rigid	0.08	0.84	0.45	0.28	0.12	1.61	31

In this case, the cumulative effect of higher weight, less uniform weight distribution, and a different axle arrangement is greater than the sum of the individual changes. This result occurs because changes to weight distribution and axle arrangement alter the incremental impact of the added 6 kips of weight as well as the impact of the original 60 kips. Also, dividing a tandem axle unevenly between the two single axles to match typical weight distributions of twins increases the effect on pavement wear. Table 1 presents the four-axle loading effects.

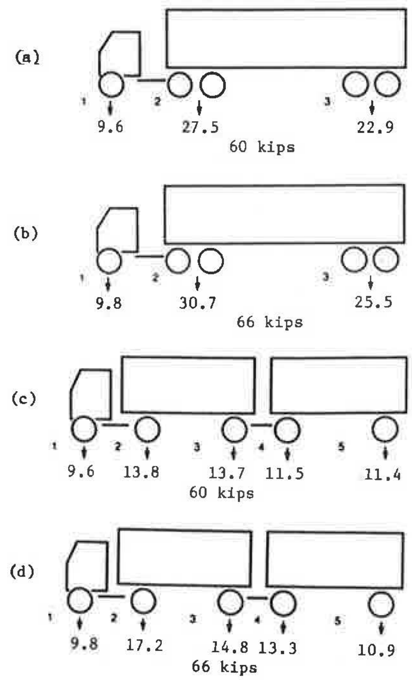

FIGURE 2 Axle arrangements and weights (*3*).

OBSERVATIONS REGARDING LOAD EQUIVALENCIES

Effects of Axle Weight, Pavement Thickness, and Terminal Serviceability Index

The AASHTO 86 (*1*) equations indicate that load equivalency factors increase approximately with the fourth power of axle load. For example, the load equivalency on rigid pavement for a 12-kip load is 0.19, whereas for a 20-kip axle it is 1.51 (Figure 1d). Thus the 20-kip load is 8 times as damaging as the 12-kip load, i.e. $(20/12)^4$, and should arguably pay approximately 8 times as much per vehicle-mile in highway revenue. The power term varies only slightly with structural number (SN), pavement thickness (D), and terminal serviceability index (p_t) (Figures 1a to 1f).

State Revenues

State road-user taxes are of three major types, the most important being fuel taxes and fees incidental to fuel taxes. The second type, motor vehicle revenues, consists of motor vehicle registration and related fees, some of which are not paid annually, e.g., title fees and drivers' license fees. The third type includes vehicle-mile, ton-mile, and axle-mile taxes.

The assignment of pavement costs has a major effect on the overall cost assignments to different vehicle classes. Not only is pavement cost the largest component of highway dollars, there is a greater variation in the relative cost responsibilities of vehicles of different weights than for any other component of highway costs. FHWA (*4*) gives 1987 road user taxes and property taxes levied on vehicles of various weights by each state to provide a planning tool for highway administrators and legislators concerned with highway user fees. A

TABLE 1 SUMMARY OF FOUR-AXLE LOADING EFFECTS (*3*)

	Flexible Pavement		Rigid Pavement	
Case	Total ESALs	Percent Increase Over Base	Total ESALs	Percent Increase Over Base
1. 60 kip tractor-semitrailer	0.89	–	1.23	–
2. 66 kip semi, 9% fewer trips	1.16	30	1.75	42
3. 60 kip twin	1.25	40	1.01	−18
4. 66 kip twin, 9% fewer trips	1.70	91	1.61	31

total of 14 vehicles were used to illustrate the range and magnitude of state taxes (Figure 3): 3 passenger cars, 5 single-unit trucks, 5 vehicle combinations, and 1 motorcycle (*4*).

The federal taxes on gasoline, vehicles, and tires were excluded, as was the annual use tax on vehicles over 55,000 lb gross weight. These are uniform throughout the nation and would not affect comparisons among states. Local taxes other than property taxes were also excluded; the registration fees and motor fuel taxes imposed by counties and cities were beyond the scope of the study (*4*).

In order to avoid the complex situations that would be encountered in computing taxes on vehicles in Interstate op-

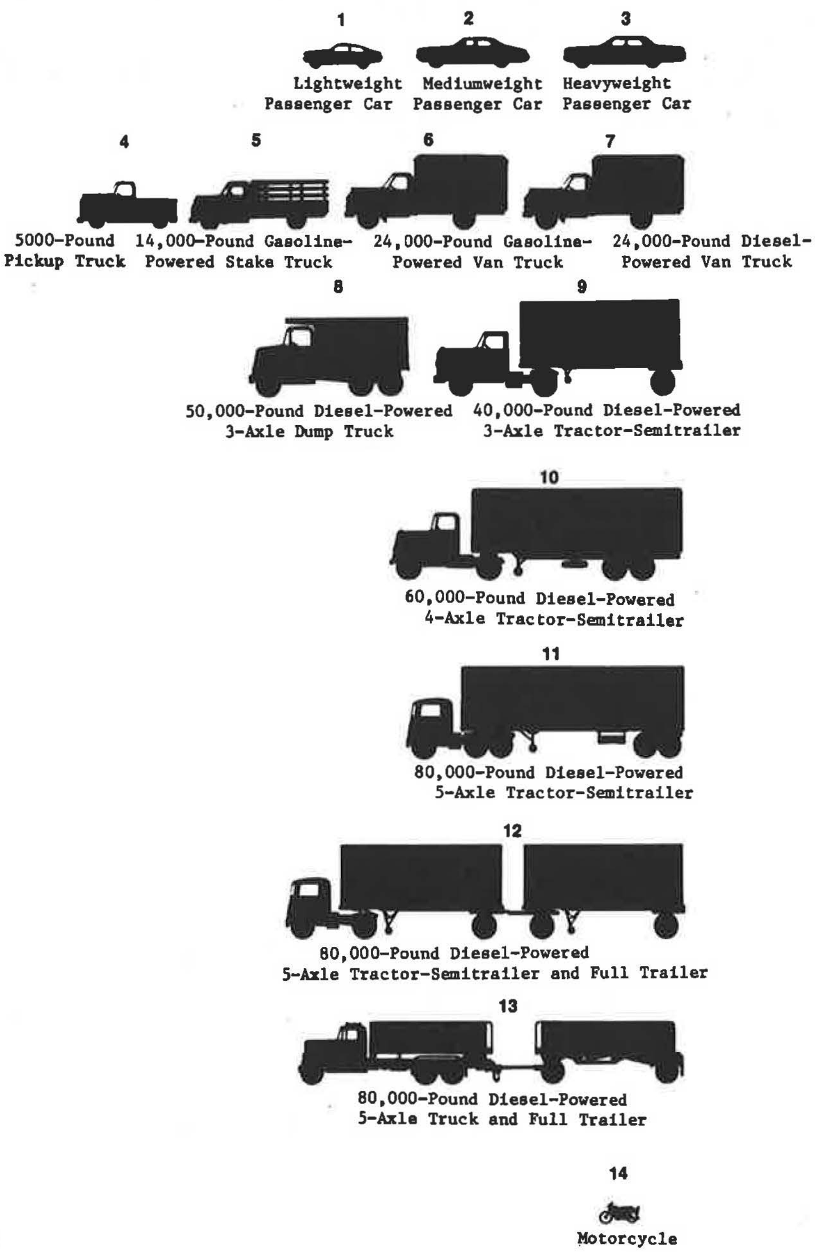

FIGURE 3 Vehicle classifications for a state revenue study (*4*).

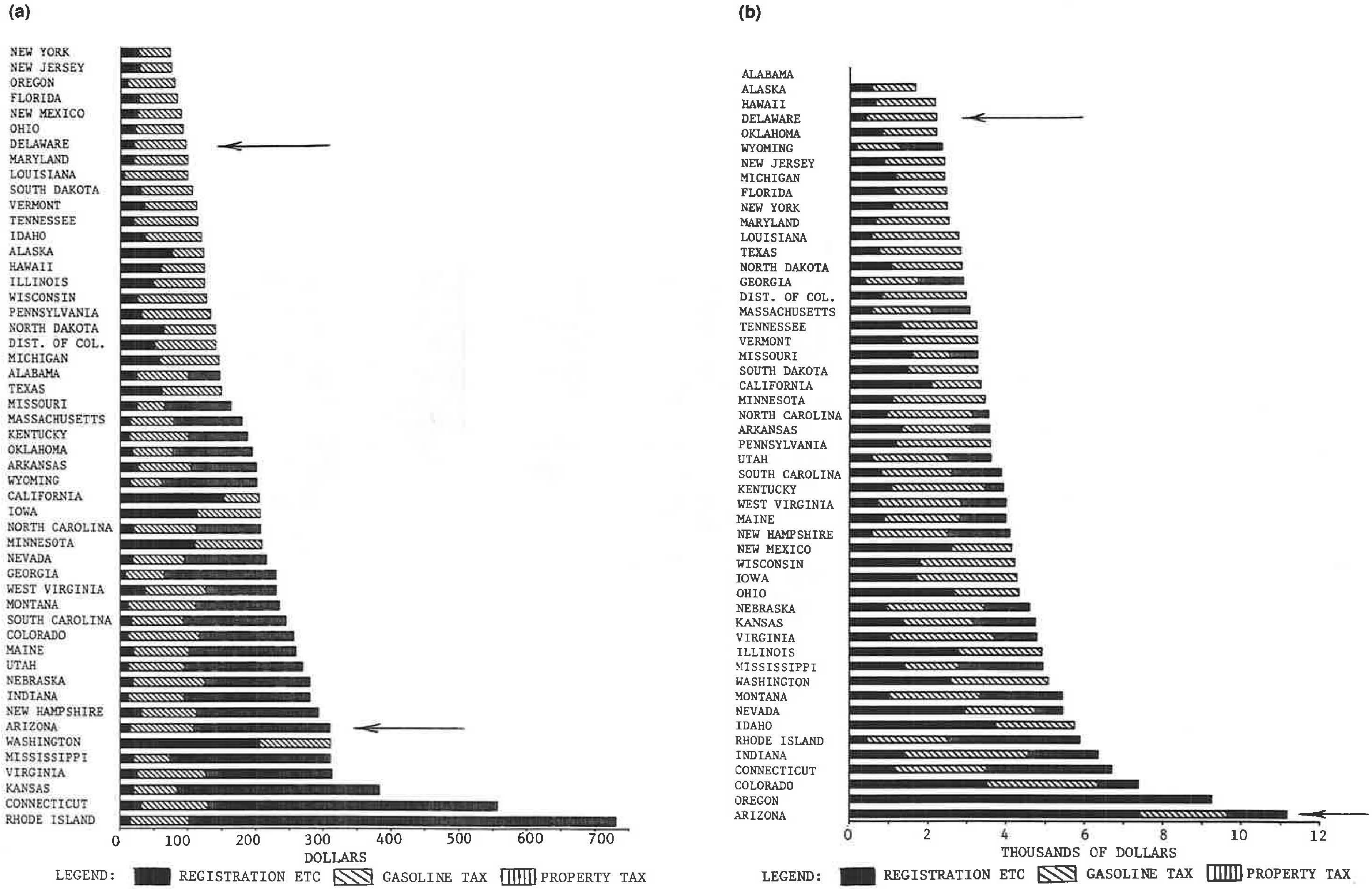

FIGURE 4 State road-user and property taxes: (a) on a medium passenger car (No. 2), (b) on an 80,000-lb diesel five-axle tractor-semitrailer and full trailer combination (No. 12) in private use (*4*).

eration, intrastate operation was specified. Without this stipulation, the study would have needed to (a) include the additional taxes and fees applicable only to Interstate carriers, and (b) consider an almost infinite variety of circumstances, including various state reciprocity and proration agreements.

Although property taxes on motor vehicles have no direct relation to the amount of highway use and in most states are not available for highways, they are closely related to registration fees and make up such a large portion of the total taxes on motor vehicles in some states that they were included in Figure 4 to obtain equitable comparisons (*4*).

Examples of Road-User Revenue Assessments

This section explores the question: "How equitably are road user revenues in two states, Delaware and Arizona, representing low and high total road-user fees, proportioned among the various weights of vehicles according to the pavement damage which they cause?"

By dividing Delaware's and Arizona's total user revenues provided by FHWA (*4*), for each class of vehicle by the vehicle-miles per year from Table 1, used for estimating this revenue, then dividing the result by the ESAL for that vehicle class, the ratios of pavement damage cost to user fee presented in the right-hand columns of Tables 2 and 3, for Delaware and Arizona, respectively, are obtained. Tables 2 and 3 relate to only pavement damage cost, through the ESAL ratings. They do not include other highway costs, such as user costs, congestion delay, air pollution, noise, highway administration, etc. Notice that the interpretation of the right column of Table 2, for Vehicle Class 9, for example, is not that it should pay 846 times as much per mile as Vehicle Class 1 pays, to equalize fees for pavement damages, but that it should pay 846 times what it presently pays if fees for Vehicle Class 1 remained the same.

The effect of overload provisions in state laws may also be of interest. Although Table 2 presents three-axle trucks (Vehicle Class 8) carrying 50 kips, a provision in Delaware law, for example, permits up to 70 kips for three-axle trucks carrying construction or agricultural products, for an additional fee of $100 per year. This allowance for added weight at the added cost increases the ratio presented in the right-hand column of Table 2 for Vehicle Class 8 from 2,035 to 2,035(10.0 ESAL/3.7)($806/$906) = 4,893.

CONCLUSIONS

The right-hand columns of Tables 2 and 3 present the large disparities between ratios of vehicle ESALs to user fees per vehicle-mile among the 14 vehicle weight classes in the two states, ranging from 0.24 to 3,078 in Delaware and from 0.15 to 1,713 in Arizona. On the basis of the AASHTO design equations, Vehicle Class 7 in Table 3, for example, should pay 408 times what it now pays in road user fees in order to pay its share of pavement damage cost equivalent to that of Vehicle Class 1. This method of pavement damage costing, together with the other components of highway costing (congestion, pollution, etc.) and judgments regarding the values of services provided by the various classes of vehicles, can be used by state legislatures to assess highway user fees.

ACKNOWLEDGMENT

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REFERENCES

1. *AASHTO Guide for Design of Pavement Structures*, Vol. 2. AASHTO, Washington, D.C., 1986.
2. *AASHTO Interim Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1972 (Chapter III revised, 1981).
3. *Special Report 211: Twin Trailer Trucks: Effects on Highways and Highway Safety*. TRB, National Research Council, Washington, D.C., 1986.
4. *Road User and Property Taxes on Selected Motor Vehicles*. FHWA, U.S. Department of Transportation, 1987.

APPENDIX
FORTRAN SOURCE CODE FOR EQUATIONS 1–7

```
REM Axle load equivalency factors
REM Program in two parts. Funct1 is the first three graphs,
REM using Eq. 1. Funct2 is the second three
REM graphs, using Eq. 2.
REM L10 - log base 10 function
DEF FNL10(number) = LOG(number)/LOG(10)
REM INV - inverse log base 10
DEF FNINV(number) = 10^number
REM W1,W2,W3 dummy variables (simplify steps)
M = 19 :REM part of W1. Made it easier to keep track.

Funct1:
  For L2 = 1 to 3 : REM cycle graphs 1 to 3
  Lprint"Eq. 1 Graph L2 =";L2:LPRINT
  REM loop for reading three PT and SN values for each
  graph (Eq 1)
    FOR I = 1 to 3
      READ PT(I)
    NEXT I
    FOR I = 1 to 3
      READ SN(I)
    NEXT I
  REM loop for six LX values (each line)
    FOR I - 1 to 6
      READ LX(I)
    NEXT I
  REM begin data analysis
    FOR K = 1 to 3 :REM loop for PT
      GT1 = (4.2-PT(K))/(4.2-1.5)
      GT = FNL10(GT)
    FOR J = 1 to 3 :REM Loop for SN
```

TABLE 2 ESTIMATED RATIOS OF PAVEMENT DAMAGE COSTS TO USER FEES ON THE BASIS OF FHWA (*4*) VEHICLE USER FEES AND MILEAGE DATA FOR DELAWARE

Vehicle class	DE total user fee	Vehicle miles [1]	(a) User fee per vm	Axle loads, kips [2]	(b) Vehicle ESAL [3]	Ratio $(b/a)10^3$	Ratio, with Class 1=1
1	62	12.5	4.96	2-1.34	.00028	.0564	1
2	96	12.5	7.68	2-2.10	.00064	.0833	1.48
3	103	12.5	8.24	2-2.48	.00080	.0970	1.72
4	96	10	9.60	2-2.50	.00080	.0833	1.48
5	209	12	17.42	4.66,9.32	.0838	4.810	85.3
6	397	15	26.47	8.00,16.0	.702	26.52	470
7	363	15	24.20	8.00,16.0	.702	29.00	514
8	806	25	32.24	10.0,T40.0	3.70	114.8	2035
9	856	30	28.53	8.00,2-16.0	1.36	47.70	846
10	1632	60	27.20	8.58,17.14, T34.28	2.96	108.7	1927
11	2239	80	27.99	8.89,2T35.54	4.86	173.6	3078
12	2201	80	27.51	8.89,4-17.77	3.42	124.3	2204
13	2239	80	27.99	8.89,T35.54, 2-17.77	3.74	133.6	2369
14	19	3.2	5.94	2-0.41	.00008	.0134	0.24

1. Vehicle miles (vm) in thousands

2. T stands for tandem axle. For all 14 vehicle classes, gross weight is assumed to be carried equally by all tires, i.e. single axles with four tires carry twice the weight of single axles with two tires, etc. This assumption under-estimates the pavement damage done by vehicles with unbalanced loads.

3. ESALs from Figs. 1d and 1e for 10 in. rigid pavement with terminal serviceability of 2.5. ESALs will differ somewhat for flexible pavements.

TABLE 3 ESTIMATED RATIOS OF PAVEMENT DAMAGE COSTS TO USER FEES ON THE BASIS OF FHWA (*4*) VEHICLE USER FEES AND MILEAGE DATA FOR ARIZONA

Vehicle class	AR total user fee	Vehicle miles	(a) User fee per vm	Axle loads, kips	(b) Vehicle ESAL	Ratio $(b/a)10^3$	Ratio, with Class 1=1
1	165	12.5	13.20	2-1.34	.00028	.0212	1
2	310	12.5	24.80	2-2.10	.00064	.0258	1.22
3	520	12.5	41.60	2-2.48	.00080	.0192	0.906
4	286	10	28.60	2-2.50	.00080	.0280	1.32
5	687	12	57.25	4.66,9.32	.0838	1.464	69.1
6	1115	15	74.33	8.00,16.0	.702	9.444	445
7	1218	15	81.20	8.00,16.0	.702	8.645	408
8	3061	25	122.44	10.0,T40.0	3.70	30.21	1425
9	2670	30	89.00	8.00,2-16.0	1.36	15.28	721
10	4891	60	81.52	8.58,17.14, T34.28	2.96	36.31	1713
11	11012	80	137.65	8.89,2T35.54	4.86	35.31	1665
12	11160	80	139.50	8.89,4-17.77	3.42	24.52	1156
13	11599	80	144.98	8.89,T35.54, 2-17.77	3.74	25.80	1217
14	83	3.2	25.94	2-0.41	.00008	.00308	0.15

```
    B18 = .4 + (.081 *(19)^(3.23))/(SN(J) + 1)^(5.19)
      LPRINT"LinePT,SN :";PT(K)",";SN(J):LPRINT:LPRINT
      LPRINT " LX Wtx/Wt18":LPRINT
      FOR I = 1 to 6 :REM loop for LX
        BX = .4 + (0.81 *(LX(I) + L2)^(3.23))/
        ((SN(J) + 1)^(5.19)*L2^(3.23))
        W1 = FNL10(M)*4.79
        W2 = FNL10(LX(I) + L2)*4.79
        W3 + FNL10(L2)*4.33
        logDpoint = W1-W2 + W3 + GT/BX-GT/B18
        Dpoint = FNINV(logDpoint)
        LPRINT " ";LX(I)" "Dpoint
      NEXT I:REM Cycle to next point LX
      LPRINT:LPRINT:LPRINT
    NEXT J:REM cycle to next SN
  NEXT K:REM Cycle to next PT
NEXT L2

Funct2:
  For L2 = 1 to 3 : REM Cycle graphs 4 to 6
  LPRINT"Eq. 2 Graph L2 =";L2:LPRINT
  REM Loops for reading three PT and D values for each
  graph (Eq 2)
    FOR I = 1 to 3
      READ PT(I)
    NEXT I
    FOR I = 1 to 3
      READ D(I)
    NEXT I
  REM Loop for six LX values (each line)
    FOR I = 1 to 6
      READ LX(I)
    NEXT I
  REM Begin data analysis
    FOR K = 1 to 3 :REM Loop for PT
      GT1 = (4.5-PT(K))/(4.5-1.5)
      GT = FNL10(GT1)
    FOR J = 1 to 3 :REM Loop for D
    B18 = 1 + (3.63*(19)^(5.2))/(D(J) + 1)^(8.46)
      LPRINT"LinePT,D :";PT(K)",";D(J):LPRINT:LPRINT
      LPRINT " LX Wtx/Wt18":LPRINT
      FOR I = 1 to 6 :REM Loop for LX
        BX = 1 + (3.63*(LX(I) + L2)^(5.2))/((D(J) +
1)^(8.46)*L2^(3.52))
        W1 = FNL10(M)*4.62
        W2 = FNL10(LX(I) + L2)*4.62
        W3 = FNL10(L2)*3.28
        logDpoint = W1-W2 + W3 + GT/BX-GT/B18
        Dpoint = FNINV(logDpoint)
        LPRINT " ";LX(I)" "Dpoint
      NEXT I:REM Cycle to next point LX
      LPRINT:LPRINT:LPRINT
    NEXT J:REM Cycle to next D
  NEXT K:REM Cycle to next PT
NEXT L2

REM PT(1,2,3),SN(1,2,3),LX(1,2,3,4,5,6)
REM Graph 1, Eq. 1
DATA 2,2.5,3,2,4,6,2,5,10,20,30,50
REM Graph 2, Eq. 1
DATA 2,2.5,3,2,4,6,10,20,40,50,60,90
REM Graph 3, Eq. 1
DATA 2,2.5,3,2,4,6,20,40,50,60,80,100

REM PT(1,2,3),D(1,2,3),LX(1,2,3,4,5,6)
REM Graph 4, Eq. 2
DATA 2,2.5,3,6,10,14,2,5,10,20,30,50
REM Graph 5, Eq. 2
DATA 2,2.5,3,6,10,14,10,20,40,50,60,90
REM Graph 6, Eq.2
DATA 2,2.5,3,6,10,14,20,40,50,60,80,100
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