Comprehensive Truck Size and Weight (TS&W) Study

Phase 1-Synthesis

Pavements

and

Truck Size and Weight Regulations

Working Paper 3

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By

Battelle Team
505 King Avenue
Columbus, Ohio 43201-2693

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Phase 1—Synthesis

Working Paper 3—Pavements and TS&W Regulations

1.0 Technical Relationships of Policy Consequence Concerning Pavements[1]

1.1 Background

Pavement-related effects of changes in truck size and weight regulations include the following:

- Increased traffic loadings require thicker pavements which, in turn, increase the construction cost of pavements. There are, however, considerable economies of scale in designing new pavements for higher traffic loadings. In the AASHTO pavement design procedures used by many states, a given percentage increase in traffic loadings can be accommodated by a much smaller increase in pavement thickness and costs. For example, increasing a rigid pavement from 9 to 10 inches in depth will approximately double the traffic loadings that can be accommodated by the pavement.

- For existing pavements, increases in traffic loadings would affect pavement rehabilitation costs in two ways. First, an increase in traffic loadings would shorten the time interval to the next resurfacing. Moving resurfacing expenditures nearer to the present would increase the real cost for resurfacing because of the time value of money. If the funds required to resurface highways sooner were not available to highway agencies, pavement condition would worsen and, as discussed below, highway users would be subjected to added cost and discomfort. Second, at the time resurfacing is required, higher traffic loadings would either increase overlay thickness or require more frequent resurfacing in the future. However, for asphalt pavements, milling the rough surface can delay the need for resurfacing.

- Costs for routine maintenance might also be affected by changes in traffic loadings. A pavement in new or very good condition requires relatively little expenditure for maintenance. As pavement condition worsens, however, expenditures for activities such as filling cracks and patching potholes increase. The effect of an increase in traffic on costs for routine maintenance

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[1] Much of this discussion is drawn from TRB Special Report 225, *Truck Weight Limits: Issues and Options*. That study, which was published in 1990, included an extensive review of the literature on pavements in relation to TS&W policy.

would be relatively insignificant if resurfacing programs were expanded so that there was no change in times between overlays and terminal serviceabilities. However, if resurfacing programs were not expanded, the maintenance workload could be much greater than it was before the increase in traffic.

- If traffic loadings are increased and highway agencies do not increase pavement-related expenditures to compensate for the increase, then pavement condition will deteriorate, in turn forcing users to travel over worse roads. Changes in pavement condition affect highway users by increasing vehicle repair cost and decreasing speed and fuel economy. Driver and passenger comfort are also affected by pavement condition, although there is no generally accepted way to quantify these effects. Further, highway users may suffer time delays during pavement resurfacing, reconstruction, rehabilitation, and maintenance. Such user costs should be included in a life cycle cost analysis of every major investment in pavements.

1.2 Truck Characteristics Affecting Pavements

(a) Axle Weights

Load equivalence factors measure the relative effects of different types of loadings on pavements. Pavement engineers generally use the concept of an equivalent single-axle load (ESAL) to measure the effects of axle loads on pavement. By convention, an 18,000-pound single axle is 1.00 ESAL. The ESAL values for other axles express their effect on pavement wear relative to the 18,000-pound single axle. Stating, for example, that a given vehicle on a given type of pavement is 3.0 ESALs means that one pass by the vehicle has the same effect on the pavement as three passes by an 18,000-pound single axle.

The American Association of State Highway Officials (AASHO) Road Test conducted in the 1950s provided sets of ESAL values for single and tandem axles on various types of pavements. In 1986, the Road Test results were extended by the American Association of State Highway and Transportation Officials (AASHTO) to provide load-equivalence factors for tridem axles (AASHTO 1986). The load-equivalence factors vary sharply with weight, following roughly a fourth-power relationship. On both flexible and rigid pavements, the load-equivalence factor for a 20,000-pound single axle is about 1.5 because $(20/18)^4$ is approximately equal to 1.5. Thus, 100 passes across a pavement by a 20,000-pound axle would have the same effect on pavement life as 150 passes by an 18,000-pound axle.

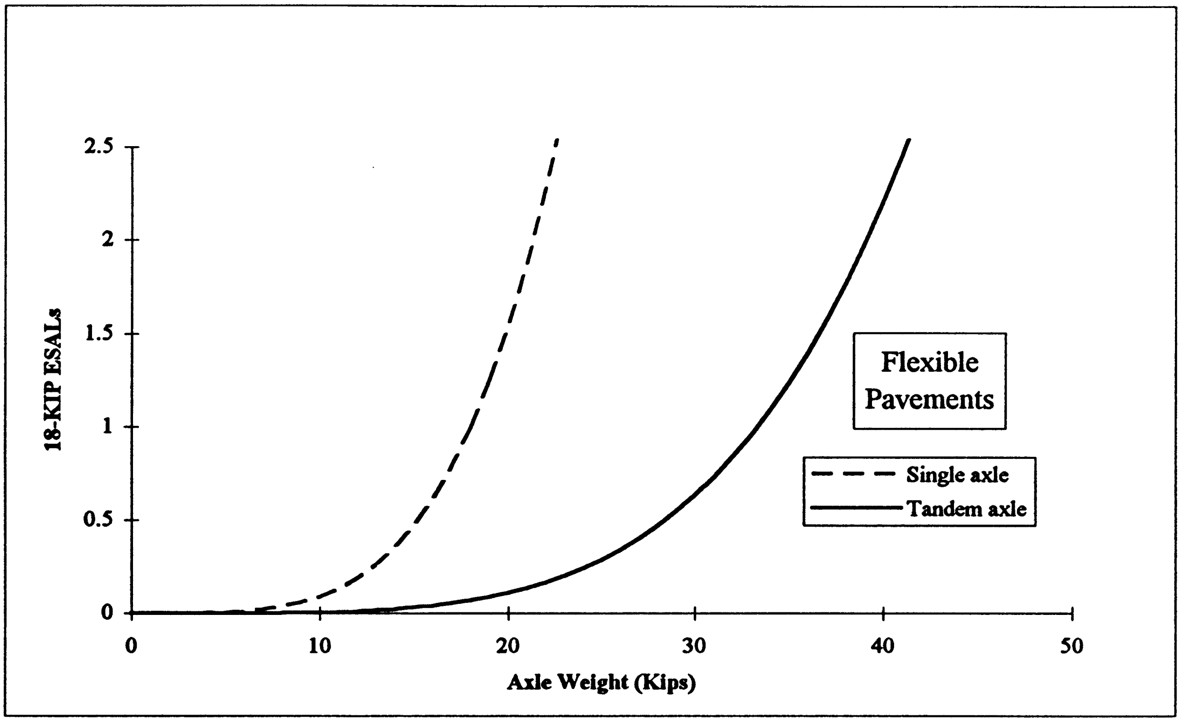
AASHTO provides separate sets of ESAL values for flexible and rigid pavements. The principal difference between the flexible and rigid pavement ESAL values is that tandem axles were found to have a greater effect on rigid pavements (Exhibit 1). For example, a 34,000-pound tandem axle is about 1.1 ESALs on flexible pavement and about 2.0 ESALs on rigid pavements.

The effect of a given vehicle on pavements can be estimated by calculating the number of ESALs for each axle and summing to get total ESALs for the vehicle (Exhibit 2). However, a comparison of vehicles in terms of ESALs would not account for the fact that vehicles with higher weights, assuming more axles, require fewer trips to transport the same amount of freight, thereby offsetting part of the additional pavement wear caused by increased weight. To circumvent this problem, vehicles can be compared in terms of ESALs per unit of freight carried (Exhibits 3 to 6).

Because of the fourth-power relationship from the AASHO Road Test, ESALs increase sharply with vehicle weight. The number of axles is also important: other things being equal, a vehicle with more axles has less effect on pavements. Thus, a nine-axle combination vehicle carrying 110,000 pounds has much less effect on pavements than a five-axle combination vehicle carrying 80,000 pounds.

Average ESALs per ton of payload were examined by Fekpe and Clayton under different assumptions about enforcement. They found ESALs per ton of payload to be lower for a six-axle combination with a rear tridem than for a conventional five-axle combination. They also found lower ESALs for seven- and eight-axle doubles than for five- and six-axle tractor-semitrailers.

Two recent studies have raised questions about the fourth power relationship between axle weight and pavement wear. In *Road Work: A New Highway Policy*, Small, Winston, and Evans present the results of their reanalysis of data from the AASHTO Road Test. Their analysis show a somewhat less steep relationship between pavement life and axle load—closer to a third-power law than the fourth-power law conventionally used to approximate the original AASHTO findings. Similar results are reported by Irick and ARE Inc. in their 1989 study for the Trucking Research Institute (TRI). The TRI Executive Summary notes that "the study refutes the existence of a universal fourth power law of pavement damage. Rather than a fourth power relationship, ARE found significant



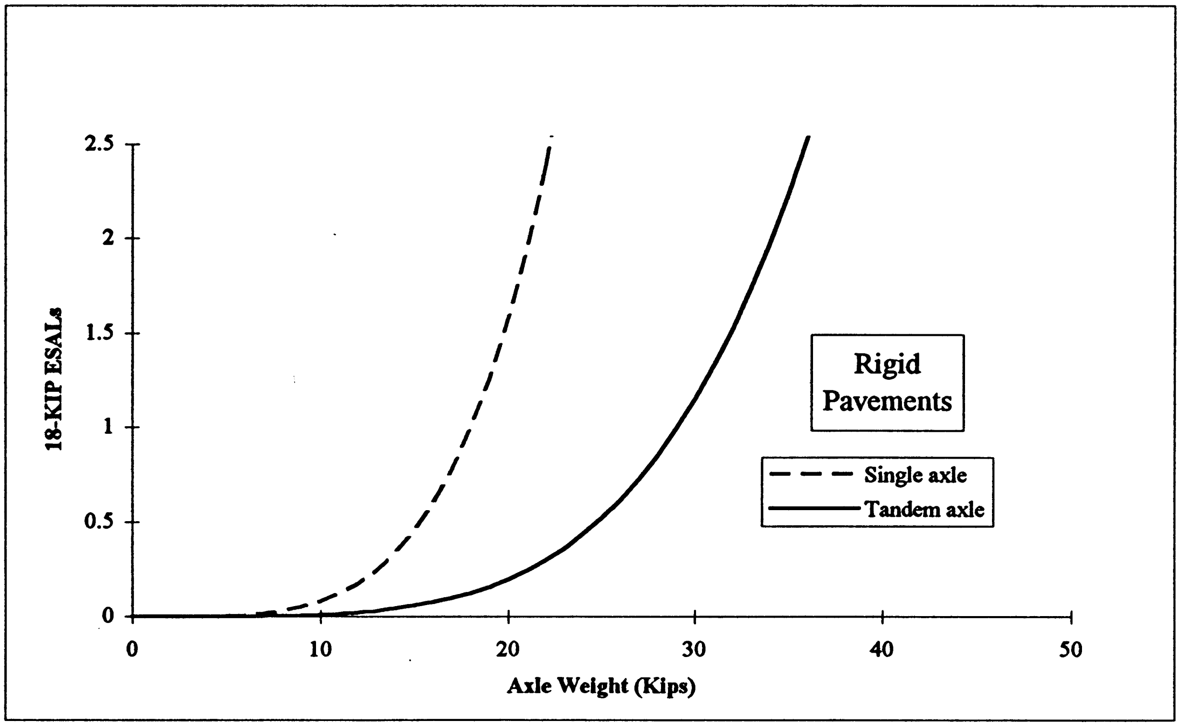
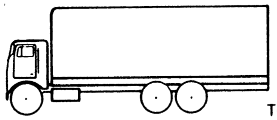


Exhibit 1 Axle load effects on pavements: top, flexible pavements (structural number 5, terminal serviceability = 2.5); bottom, rigid pavements (slab thickness = 10, terminal serviceability =2.5) (AASHTTO 1986).

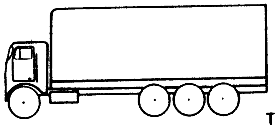
Exhibit 2 Equivalent single-axle loads for various vehicles.

(a) Three-Axle Single-Unit Truck



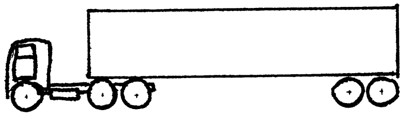
			Total
Weight (lb 000s)	16	32	48
ESALS			
Flexible	0.62	0.86	1.48
Rigid	0.60	1.50	2.10

(b) Four-Axle Single-Unit Truck



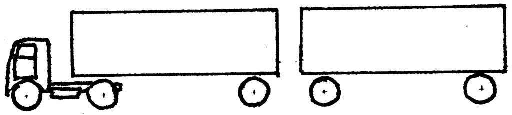
			Total
Weight (lb 000s)	16	40	56
ESALs			
Flexible	0.62	0.49	1.11
Rigid	0.60	1.18	1.78

(c) Five-Axle Tractor-Semitrailer (3-S2)



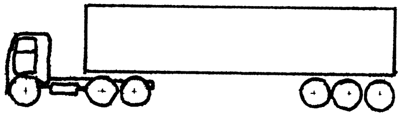
				Total
Weight (lb 000s)	12	34	34	80
ESALs				
Flexible	0.19	1.09	1.09	2.37
Rigid	0.17	1.95	1.95	4.07

(d) Five-Axle Double (2-S1-2)



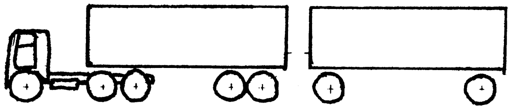
						Total
Weight (lb 000s)	9	20	19	16	16	80
ESALs						
Flexible	0.06	1.51	1.24	0.62	0.62	4.05
Rigid	0.05	1.58	1.26	0.60	0.60	4.09

(e) Six-Axle Tractor-Semitrailer (3-S3)



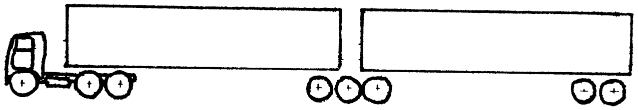
				Total
Weight (lb 000s)	12	34	42	88
ESALs				
Flexible	0.19	1.09	0.60	1.88
Rigid	0.17	1.95	1.45	3.57

(f) Seven-Axle Double (3-S2-2)



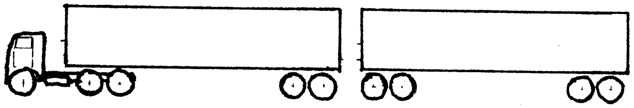
						Total
Weight (lb 000s)	9	31	30	16	15	101
ESALs						
Flexible	0.06	0.75	0.66	0.62	0.48	2.57
Rigid	0.05	1.31	1.14	0.60	0.46	3.56

(g) Eight-Axle B-Train Double (3-S3-2)



					Total
Weight (lb 000s)	12	34	42	34	122
ESALs					
Flexible	0.19	1.09	0.60	1.09	2.97
Rigid	0.17	1.95	1.45	1.95	5.52

(h) Nine-Axle Double (3-S2-4)



						Total
Weight (lb 000s)	12	33	28	28	28	129
ESALs						
Flexible	0.19	0.97	0.50	0.50	0.50	2.66
Rigid	0.17	1.71	0.85	0.85	0.85	4.43

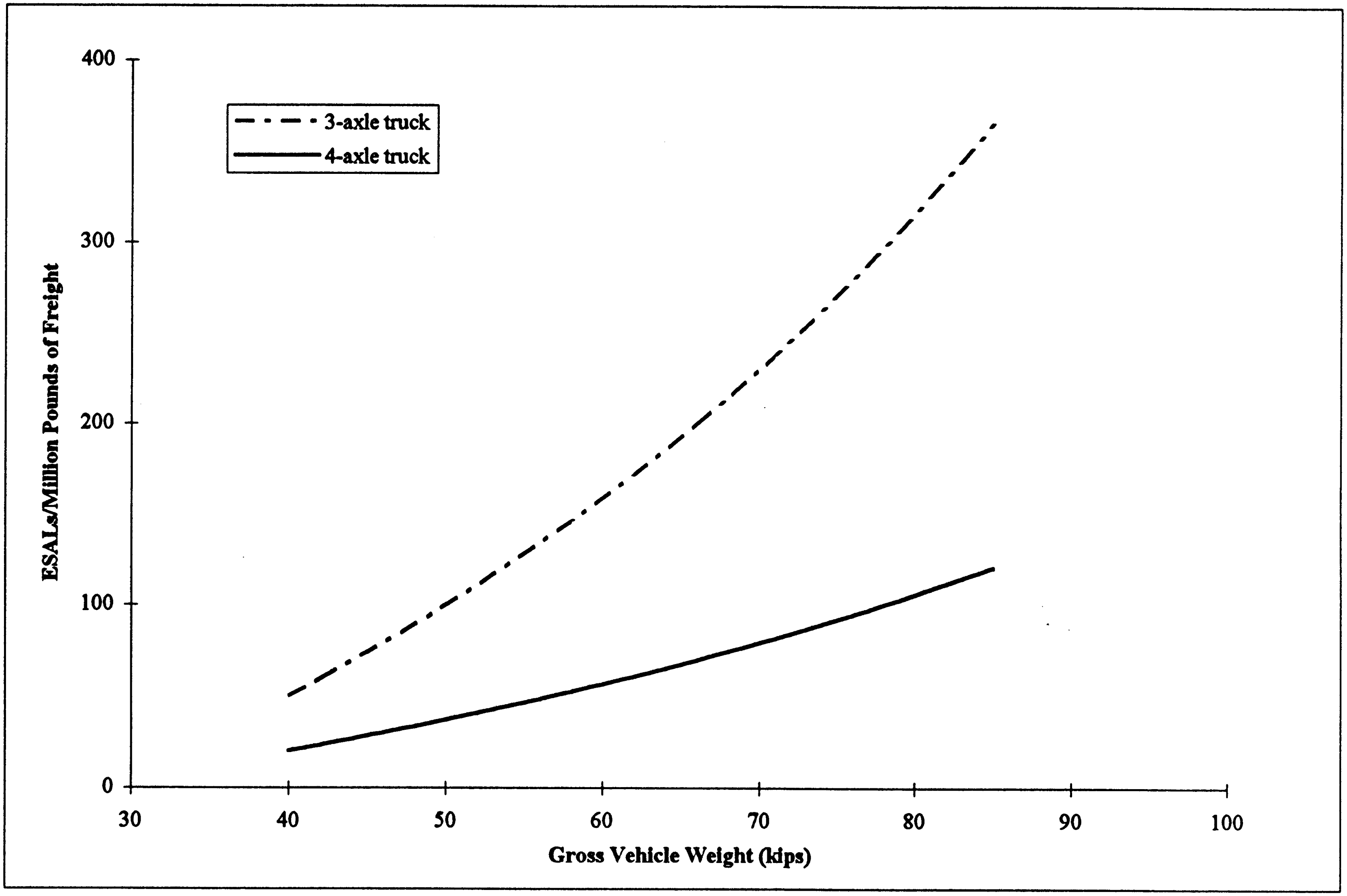


Exhibit 3 ESALs per million pounds of freight on flexible pavements: three- and four-axle trucks.
Source: TRB staff estimates developed using AASHTO load-equivalence factors (AASHTO 1986).

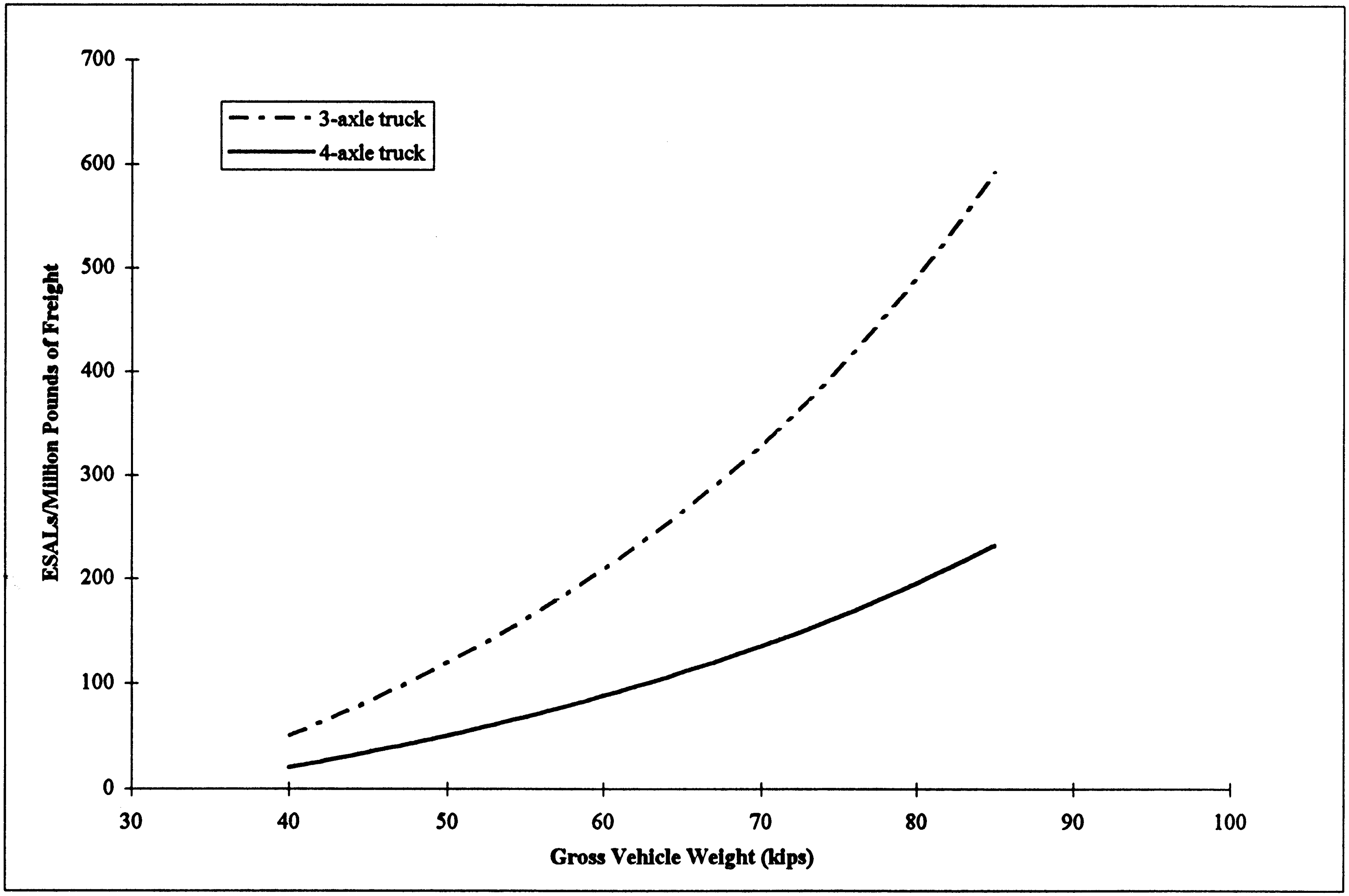


Exhibit 4 ESALs per million pounds of freight on rigid pavements: three- and four-axle trucks.
Source: TRB staff estimates developed using AASHTO load-equivalence factors (AASHTO 1986).

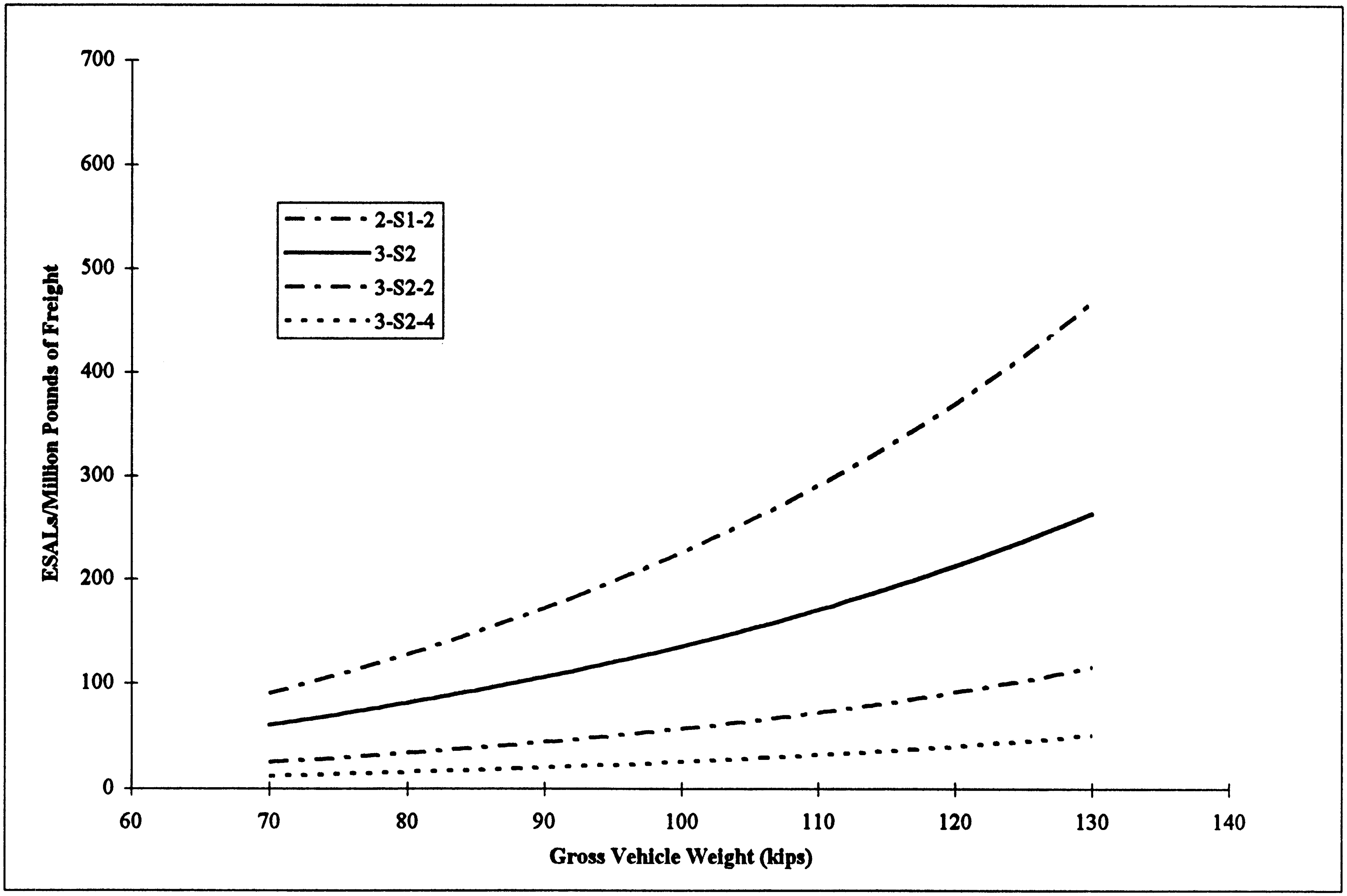


Exhibit 5 ESALs per million pounds of freight on flexible pavements: 3-S2, 2-S1-2, 3-S2-2, and 3-S2-4 trucks
Source: TRB staff estimates developed using AASHTO load-equivalence factors (AASHTO 1986).

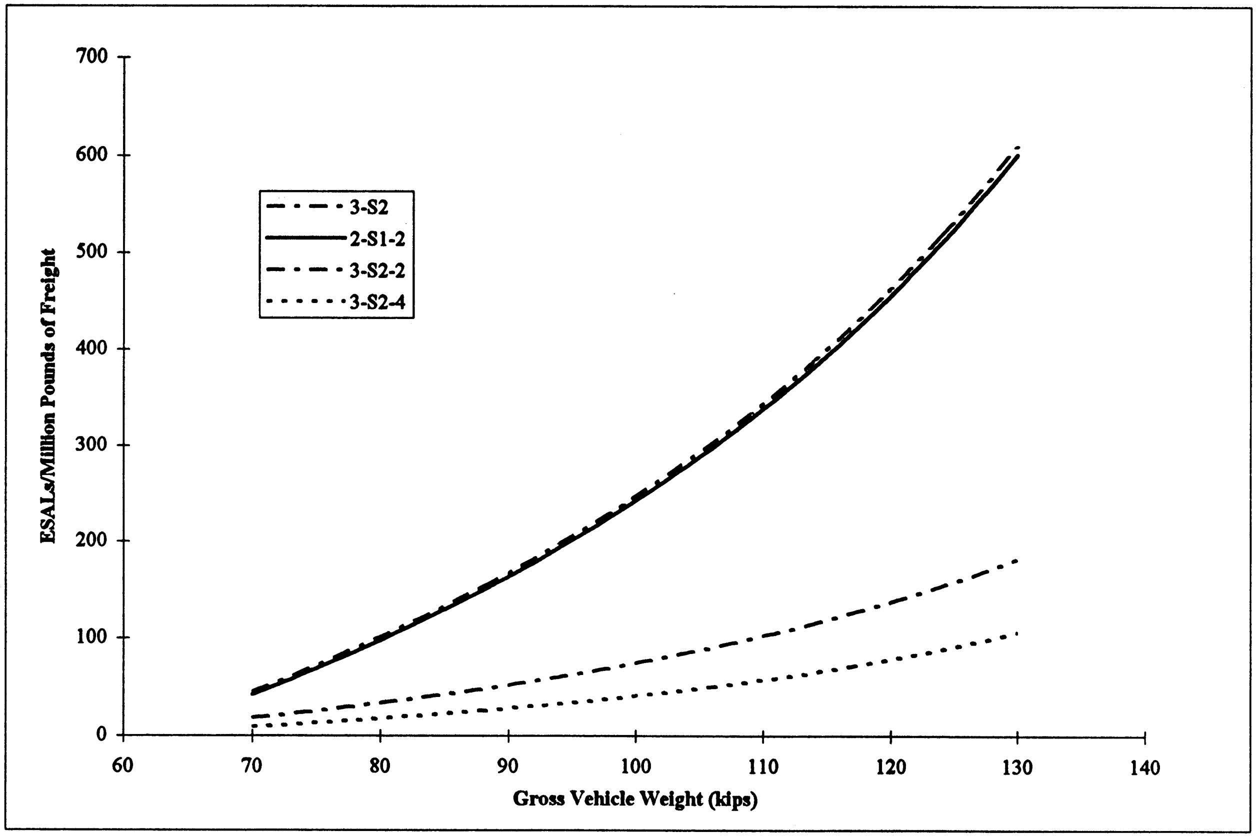


Exhibit 6 ESALs per million pounds of freight on rigid pavements: 3-S2, 2-S1-2, 3-S2-2, and 3-S2-4 trucks
Source: TRB staff estimates developed using AASHTO load-equivalence factors (AASHTO 1986).

scatter in the data depending upon pavement type, pavement thickness, and the type of distress being analyzed. Damage functions were generally found to be less than the fourth power, lying somewhere in the range of the second or third power in most cases."

The increase in pavement costs per added ESAL mile can vary by several orders of magnitude depending upon pavement thickness, quality of construction, and season of the year. Thinner pavements are much more vulnerable to traffic loadings than thicker pavements. Pavements are much more vulnerable to traffic loadings during spring thaw in areas that are subject to freeze-thaw cycles. The literature provides widely varying estimates of the marginal pavement cost per ESAL mile. The 1982 *Final Report on the Federal Highway Cost Allocation Study* estimated efficient pavement damage charges by functional system ranging from 8.7 cents per ESAL mile on rural Interstates to 69.1 cents per ESAL mile on local urban highways. In contrast, Hutchinson and Haas estimated the marginal pavement damage costs for a pavement with 500,000 annual ESALs as 2 cents per ESAL kilometer (3.3 cents per ESAL mile).

Deacon (1988) developed a model using the AASHTO pavement design and performance equations to estimate the changes in pavement rehabilitation costs resulting from increases or decreases in pavement loadings. In this model, each pavement section to be analyzed is described in terms of its thickness, base traffic loadings, and other design and environmental variables such as resilient modulus and drainage coefficient. The model then calculates the remaining life of the existing pavement and the annualized cost of all future resurfacings under base traffic and a ten percent increase in base traffic. The model indicated that there is surprisingly little variation in the additional cost associated with a ten percent increase in loadings under a very broad range of traffic and environmental conditions. Thus, when viewed in terms of cents per ESAL mile, pavement costs are much higher on low traffic roads than on high traffic roads. Very similar results are presented in Hutchinson and Haas. They show average and marginal costs per ESAL on highways with 500,000 to 2,000,000 ESALs per year. The cost per ESAL on highways designed for 500,000 ESALs per year is almost four times as great as the cost per ESAL on highways designed for 2,000,000 ESALs per year. One practical implication of this finding is that a policy which causes heavy trucks to shift from highways with thicker pavements to highways with thinner pavements can have adverse pavement cost impacts. An example of such a policy would be having more permissive axle-weight limits off the National Highway System (NHS), since this policy would encourage trucks with high axle weights to shift from the NHS to non-NHS highways.

(b) Tire Characteristics

Tires mounted on the AASHO Road Test trucks were representative of those in use in the late 1950s: they were of bias-ply construction with inflation pressures of 75 to 80 pounds per square inch (psi). Since then, bias-ply tires have been replaced with radial tires and inflation pressures have increased. A study by Bartholomew (1989) summarized surveys of tire pressure conducted in seven states from 1984 to 1986 and found that 70 to 80 percent of the truck tires used were radials and that average tire pressures were about 100 psi. As a result of these and similar studies, concern has been raised about the possibility of accelerated pavement wear, particularly rutting, as a result of increased tire pressure.

Higher tire pressure reduces the size of the tire "footprint" on the pavement, so that the weight of the wheel is distributed over a smaller area. The increased pressures hasten the wear of flexible pavements, increasing both the rate of rutting and the rate of cracking. During highway operations, the rolling of the tire results in a temperature rise that in turn causes the inflation pressure to increase. Inflation pressures of hot tires can be 10 to 20 psi greater than pressures of cold tires for bias-ply and 5 to 15 psi greater for radials (Sharp 1987). Results from other studies (Southgate and Deen 1987; Bonaquist et al. 1988a, 1988b) suggest that, for 20,000-pound single axles on thicker pavements characteristic of major highways, an increase in tire pressure from 75 to 100 psi increases pavement wear by about 15 percent. Taken together, these results suggest that, other things being equal, pavement wear effects of hot tires are 3 to 12 percent greater than pavement wear effects of cold tires.

The AASHTO load-equivalency factors strictly apply only to axles supported at each end by dual tires. Recent increase in steering-axle loadings and more extensive use of single tires on load-bearing axles have precipitated efforts to examine the effect on pavement wear of substituting single for dual tires. Both standard and wide-based tires have been considered. Past investigations of the pavement wear effects of single versus dual tires have found that single tires induce more pavement wear than dual tires, but that the differential wear effect diminishes with increases in pavement stiffness, in the width of the single tire, and in tire load.

Gillespie (1993) found that a steering axle carrying 12,000 pounds with conventional single tires is more damaging to flexible pavement than a 20,000-pound axle with conventional dual tires. He states further that "road damage from vehicles currently operating at the 80,000-pound gross weight limit would be decreased approximately 10 percent by modifying road use laws to favor a load distribution of 10,000 pounds on the steering axle with allowance for 35,000 pounds on tandems." Without disputing Gillespie's assessment of the relative pavement costs for steering axles and tandems at different weights, it should be noted that weight-limited five-axle tractor-semitrailers usually have steering axle weights below 11,000 pounds (even though truck weight limits would allow 12,000-pound steering axles). Hence, the practical effect of Gillespie's suggested change in limits for most weight-limited trucks would be to increase tandem axle weights without a compensating decrease in steering axle weights.

Bauer (1994) summarized several recent studies on the effects of single vs. dual tires:

- "Smith (1989), in a synthesis of several studies dealing with the roadway-tire relationship, evaluated at 1.5 on average the relationship of the damage caused by wide base single assemblies and that caused by traditional dual tire assemblies with identical loading at the axle.

- Sebaaly and Tabataee (1992) found rutting damage ratios between wide base and dual tire assemblies varying between 1.4 and 1.6. This was a study carried out at the University of Pennsylvania on two coatings, with 2 types of axle (single and tandem) and four sizes of tire (two dual mounted and two wide based).

- Bonaquist (1992), reporting on results obtained from a study carried out on the road simulator of the Turner-Fairbank Highway Research Center at McLean (Virginia), on two types of roadway, using a dual tire assembly with 11 R 22.5 and a wide base with 425/65 R 22.5, indicates rutting damage ratios varying from 1.1 to 1.5, depending on the layers of the roadway."

In summary, Bauer states that the wide-base single tire would seem to cause around 1.5 times more rutting than the dual tire on roadways that do not possess good resistance qualities to rutting. However, Bauer also noted that one of the wheels in a dual tire assembly is frequently overloaded due to the road. He noted that the average overload for a dual wheel causes an increase in rutting similar to that which exists between a wide-base single and a dual tire assembly, so that the real advantage of dual tire assemblies is therefore undoubtably lower than the theoretical advantage with which they are attributed.

Conflicting results were reported by Akram et. al. They used multidepth deflectometers to estimate the damage effects of dual versus wide base tires. Deflections measured at several depths within the pavement under dual and wide-base single tires were used to calculate average vertical compressive strains. The Asphalt Institute subgrade limiting strain criteria were then used to estimate the reduction in pavement life that will occur by using the wide-base single tires in place of duals. At a speed of 55 miles per hour and equivalent axle loading, they found that the wide-base single tires (trailer axle) reduced the anticipated pavement life by a factor of between 2.5 to 2.8 over that predicted for standard dual tires.

Molenaar, Huurman, and Naus examined the combined effects of tire pressure and super single versus dual wheel tires on rutting. They found a roughly ten-fold increase in rutting for a super-single with a tire pressure of 1.00 MPa as compared with a dual tire with a tire pressure of 0.60 MPa.

Although it is undoubtedly true that, other things being equal, single tires have more adverse effects on pavements than dual tires, it appears likely that past investigations have overstated the adverse effects of single tires by neglecting two potentially important effects: unbalanced loads between the two tires of a dual set and the effect of randomness in the lateral placement of the truck on the highway.

Unbalanced loads between the tires of a dual set can occur as a result of unequal tire pressures, uneven tire wear, and pavement crown. As with unequal loads on axles within a multiaxle group, pavement wear increases as the loads on the two dual tires become more unbalanced.

The second neglected factor, sometimes termed "wander," is the effect of randomness in the lateral placement of trucks within and sometimes beyond lane boundaries. Less perfect tracking is beneficial to pavement wear: the fatiguing effect is diminished because the repetitive traffic loads are distributed over wider areas of the pavement surface. Because the greater overall width of dual tires naturally subjects a greater width of pavement to destructive stresses, wander is expected to have a smaller beneficial effect for dual than for single tires. Once rutting begins, however, tires—especially radial tires—tend to remain in the rut, thereby greatly reducing the beneficial effects of wander for both single and dual tires.

TRB's Truck Weight Study undertook a special analysis to examine the importance of loading imbalances and wander as part of its examination of vehicle characteristics affecting pavement wear (Deacon 1988b). Two types of pavement wear were considered: surface cracking due to fatigue and permanent deformation or rutting in the wheel tracks. Fatigue was found to be more sensitive to the difference between single and dual tires than rutting, and was selected as the basis for pavement wear comparisons.

Both balance and unbalanced dual-tire loads were considered. In the unbalanced case, one of the tires carried a 5 percent greater-than-average load and the other carried a 5 percent less-than average load. Wander was described by a normal probability distribution. In the absence of definitive field data, three standard deviations were considered: 4, 6, and 8 inches. For these values, approximately 99 percent of truck operations would track within a 2-, 3-, and 4-foot pavement width, respectively.

Analysis of these data showed that taking wander into account reduced the adverse effects of single tires on pavement wear, but that these effects were still significant (Exhibit 7). Without wander, the ESAL equivalent for an 18,000-pound axle with single tires was estimated to be 2.23. When wander with a standard deviation of 8 in. is assumed, the ESAL equivalent drops to 1.31. At least for the ±5 percent case considered in this study, the effects of imbalance in dual-tire sets on ESALs were found to be very small relative to the effect of wander.

Research summarized by the Midwest Research Institute (MRI) also suggests that dynamic loadings are a consideration in assessing the relative merits of wide-base single vs. dual tires. MRI notes that "the dynamic component of pavement loading arises from vertical movements of the truck caused by surface roughness. Thus, peak loads are applied to the pavement that are greater than the average static load. Gyenes and Mitchell report that the magnitude of the added dynamic components was earlier thought to increase road damage over that of the static loading alone by 13 percent to 38 percent, according to research reported by Eisenmann.

"Many recent studies have pointed out the fallacy in the earlier work, which assumed that the dynamic component of loading was distributed uniformly over the pavement in the direction of travel. What those researchers found, instead, is that the dynamic component is very localized. Because it arises from pavement surface irregularities, the dynamic loading is spatially correlated with these irregularities. Indeed, signs of pavement damage are typically localized, at least initially.

"Because of the localized nature of the dynamic loading, its severity is much greater than thought earlier. Gillespie et al. estimate that damage due to the combination of static and dynamic loading can be locally two to four times that due to static loading. Von Becker estimates that the combined loading produces a "shock factor" from 1.3 to 1.55, depending upon suspension characteristics. applying the fourth power law would translate these figures

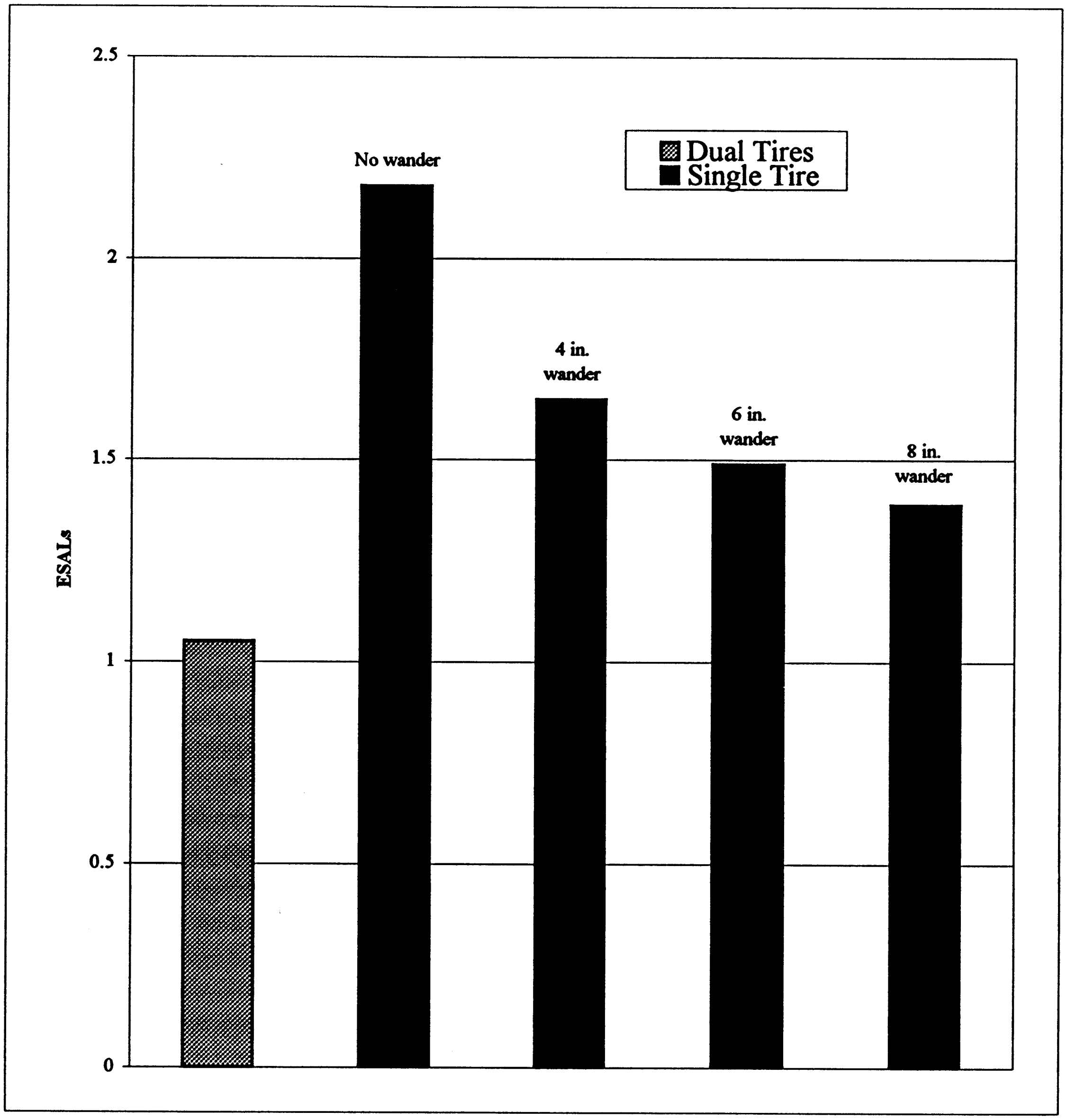


Exhibit 7 Effects of single tires on pavements for 18,000-lb single axles (wander is in standard deviations)
Source: TRB, Truck Weight Limits: Issues and Options, Special Report 225

into relative damage estimates ranging from 2.8 to 4.8 time s the static loading damage. Gyenes and Mitchell suggest impact factors of 1.3 to 1.5, for relative damage estimates of 2.8 to 5.1."

Midwest Research Institute noted further that "parallel research has shown that a wide base tire, having only two sidewalls, is much more flexible than a pair of dual tires with four sidewalls. This flexibility means that the tire absorbs more of the dynamic bouncing of the truck, so less of the dynamic load is transmitted to the pavement."

In summarizing their assessment of wide-base tires, MRI states that "taking all of these findings into consideration suggests that the relative damage potential is much less than commonly believed, and conceivably the wide- base tires might be less damaging than duals."

(c) Suspension Systems

As a heavy truck travels along the highway, axle loads applied to the pavement surface fluctuate above and below their average values. The degree of fluctuation depends on factors such as pavement roughness, speed, radial stiffness of the tires, mechanical properties of the suspension system, and overall configuration of the vehicle. On the assumption that the pavement wear effects of dynamic loads are similar to those of static loads and follow a fourth-power relationship, increases in the degrees of fluctuation increase pavement wear. For example, a 22,000-pound load followed by an 18,000-pound load has 1.06 times the effect of two 20,000-pound loads. Rough estimates of the effects of suspensions assuming that the pavement wear effects of dynamic loads follow a fourth-power relationship support a finding by the Organization for Economic Cooperation and Development (OECD 1982) that reduction in dynamic effects due to improved suspension systems might reduce pavement wear effects by about 5 percent.

Rakheja and Woodrooffe investigated the role of suspension damping in enhancing the road friendliness of a heavy vehicle using a quarter-truck model to estimate the loads transmitted to the pavement by a tire. In this model, suspension effects are represented using a sprung mass, an unsprung mass, and restoring and dissipative effects due to suspension and tire. The tire is modeled assuming linear spring rate, viscous damping, and point contact with the road. They found that an increase in linear suspension damping tends to reduce the dynamic load coefficient and the dynamic tire forces, factors which are related to road wear. They conclude that linear and air spring suspensions with light linear damping offer significant potentials to enhance the road friendliness of the vehicle with a slight deterioration in ride quality.

Sousa, Lysmer and Monismith investigated the influence of dynamic effects on pavement life for different types of axle suspension systems. They calculated a Reduction of Pavement Life (RPL) index of 19 percent for torsion suspensions, 22 percent for four leaf suspensions, and 37 percent for walking beam suspensions (an ideal suspension would have RPL of 0). Similar results were found by Peterson in a study for Road and Transport Association of Canada: under rough roads at 80 kph (50 mph), air bag suspensions exhibited dynamic loading coefficients (DLC) of 16 percent, spring suspensions had a DLC of 24 percent, and rubber spring walking beam suspensions had a DLC of 39 percent. Problems with walking beam suspensions were also noted Gillespie et. al., who stated that on rough and moderately rough roads, walking-beam suspensions without shock absorbers are typically 50 percent more damaging than other suspension types.

(d) Axle Spacing

Two primary load effects on flexible pavement performance are rutting and fatigue. For rutting, bringing axles closer together is unlikely to significantly affect the critical stresses and pavement performance. Thus, the effect of a tandem axle on rutting is expected to be identical to the cumulative effects of the two single axles of which it is composed. For fatigue, when widely separated loads are brought closer together, the stresses they impart to the pavement structure begin to overlap and they cease to act as separate entities. While the maximum deflection of the pavement surface continues to increase as axle spacing is reduced, maximum tensile stress at the underside of the surface layer (considered to be a primary cause of fatigue cracking) can actually decrease as axle spacing is reduced. However, effects of the overlapping stress contours also include increasing the duration of the loading period. Thus, the beneficial effects of stress reduction are offset to some largely unknown degree by an increase in the time or duration of loading. In short, the net effect of changes in axle spacing on pavement wear is complex and highly dependent on the nature of the pavement structure.

Hajek and Agarwal studied the influence of spacing on pavement damage associated with dual and triple axles on thick flexible pavements (SN=5.7). They examined six different measures related to pavement damage and two different axle spacings each for tandems and tridems. For the pavements studied, AASHTO load equivalence factors indicate that two 10,000 kilogram single axles would have the same effect as a tandem axle weighing 21,600 kilograms. For tandems with a 1.0 meter spacing, Hajek and Agarwal found that lower tandem weights would have the same effect: ranging from 14,900 kilograms to 20,600 kilograms depending on the damage measure used. For the pavements studied, AASHTO load equivalence factors indicate that three single axles weighing 10,000 kg. would have the same effect as a tridem axle weighing 34,300 kg. For tridems with a 2.0 meter spacing (from the first to third axle), Hajek and Agarwal found that lower tridem weights would have the same effect, ranging from 20,300 kg. to 31,000 kg. Based on these results, they concluded that the AASHTO ESAL values appear to understate the damaging effect of dual and triple axles in comparison to single axles.

(e) Liftable Axles

Billing et. al. investigated the use of liftable axles. They found widespread use of these axles in Canada. For example, a 1988 and 1989 surveys in Ontario and Quebec found 17 and 21 percent (respectively) of trucks on the highways had liftable axles. Truckers frequently adopt liftable axles in response to weight limits under which maximum gross weights are higher for trucks with more axles. Also, trucks with multiple, widely spaced axles have difficulty turning on dry roads. Industry has in some cases resolved this difficulty through the use of liftable axles, which can be raised or lowered by the driver, usually with air pressure. The driver raises a liftable axle when a turn is being made and lowers it when the turn is completed. The axles can also be raised when cruising along the highway to improve fuel consumption and reduce tire wear.

On the negative side, liftable axles make compliance with and enforcement of axle weight limits difficult. There are many concerns about the use of liftable axles and damage to roads and bridges. Improperly adjusted liftable axles can be extremely damaging to pavements. The liftable axle can be adjusted to any level by the driver. If the liftable axle load is too high, the liftable axle is overloaded. If it is too low, other axles may be overloaded (Billing et al). For example, under current Federal limits, a four-axle single-unit truck with a wheelbase of 30 feet can carry 62,000 pounds: 20,000 pounds on the steering axle and 42,000 pounds on the rear tridem. This vehicle would produce approximately 2.1 ESALs on flexible pavements. However, if the first axle of the tridem is a lift axle that is carrying no weight, this vehicle would produce approximately 4.0 ESALs.

(f) Tridems

In a paper prepared for The Association of American Railroads, Hudson and Buttler summarized available information about the effect of tridem axles on pavement damage. They note that no tridem axles were used or observed in the AASHTO Road Test and that "to provide an equivalence value for tridem axles, the developers of the AASHTO [Pavement Design] Guide substituted a dummy variable level of three for 'number of axles' in the AASHTO equation. This methodology is incorrect. Note that the AASHTO equation uses a dummy variable for number of axles, 1 for single, 2 for tandem. This was merely a convenience to permit a regression analysis to be made for variables

> for which there is no quantitative value, such as axle type. Nothing about the original equation suggests that it is possible to create a third level of the dummy variable for tridem axles. Considering the error it is no surprise that many researchers suggest that the true effects of tridem axles is worse than that listed in the AASHTO Design Guide."

In summarizing the literature and results of their own analyses, Hudson and Buttler conclude that, on flexible pavements, a tridem axle set of 38 to 39,000 pounds equally distributed on three axles has the same damaging effect as one 18,000-pound single axle. In sharp contrast, the AASHTO load equivalence factor for a 38 to 39,000-pound tridem on flexible pavements is roughly 0.4. Hudson and Buttler also conclude that, on flexible pavements, the AASHTO load equivalence for tandems also understated, although by much less than the understatement for tridems. Specifically, they conclude that a tandem axle carrying 30 to 32,000 pounds has the damaging effect of one 18,000-pound single axle. The AASHTO load equivalence for a 30 to 32,000-pound tandem is roughly 0.8. On rigid pavements, Hudson and Buttler conclude that a tridem-axle set carrying 36 to 37,000 pounds evenly distributed on three axles has the same damaging effect as one 18,000-pound single axle. The AASHTO load equivalence factor for a 36 to 37,000 pound tridem on rigid pavements is roughly 0.8.

2.0 Policy Implications

2.1 Axle Weight Limits

Increasing axle weight limits will generally result in higher pavement costs, since pavement costs increase sharply with axle weight. However, past studies of truck size and weight limits have generally found that the increase in pavement costs would be much less than the decrease in goods movement costs associated with higher axle weights.

Conversely, reducing axle weight limits (or eliminating grandfather exemptions to federal axle weight limits) would result in lower pavement costs; however, the savings would be much less than the increase in goods movement costs. The *Truck Weight Study* found that the elimination of all grandfather exemptions would reduce pavement costs by $210 million per year. However, the cost of goods movement would be increased by $7,760 million per year if all grandfather exemptions were eliminated.

Several states have special limits on steering axles. The primary reason for these restrictions was concerns about loss of control due to the blow-out of an overloaded steering axle tire; however, the restrictions do provide some pavement cost savings. When viewed just in terms of AASHTO's load-equivalence factors, the savings are very small. However, the actual saving will be greater since steering axles usually have single rather than dual tires, and so the AASHTO factors understate their pavement wear impacts. Gillespie et. al. noted the pavement damage caused by a heavily loaded conventional tire on steering axles. For example, single tires on a steering axle carrying 12,000 pounds can be more damaging in fatigue and rutting to flexible pavement than a 20,000-pound axle with dual tires. They indicate that steering axle weights would have to be reduced to about 11,000 pounds to have the same pavement wear impacts as a 20,000-pound axle with dual tires.

2.2 Bridge Formula

The Bridge Formula limits the weight that can be carried on a group of consecutive axles, based on the number of axles and the distance between the first and last axles in the group. For short, heavy vehicles, such as dump trucks, garbage trucks, and cement mixers, the Bridge Formula controls the amount of weight that can be carried, which in turn affects pavement costs.

The Bridge Formula can also affect axle spacing. However, Gillespie et al noted that damage on flexible pavements is largely insensitive to axle spacing down to the limits dictated by conventional tire diameters and that rigid pavements actually benefit from stress interactions between axles and produce less fatigue with closely spaced axles.

2.3 80,000-Pound GVW Cap

The elimination of the 80,000-pound limit on gross vehicle weight would cause a shift of freight from conventional five-axle tractor-semitrailers to combinations with six or more axles and would also result in some diversion of freight from rail to truck, since elimination of the GVW cap would reduce the cost of shipping high-density freight by truck. The first effect would reduce pavement costs, since pavement cost per million tons of freight is less for trucks with six or more axles than for trucks with five axles. The second effect would increase pavement costs. The *Truck Weight Study* examined a scenario that would eliminate the 80,000-pound cap (with no other changes in TS&W limits) and found that these two effects approximately offset one another, so that there would be no significant increase or decrease in pavement costs under this scenario. However, if states also increased length limits, along with the elimination of the GVW cap, more freight would be diverted from rail, which could increase pavement costs.

2.4 Policies to Encourage Tridems

When viewed using the AASHTO load-equivalence factors, combinations with tridem axles generally have much lower pavement costs per ton of freight carried than conventional five axle combinations. As shown in Exhibit 2, a six-axle tractor-semitrailer with a rear tridem carrying 88,000 pounds produces 1.88 ESALs on flexible pavements and 3.57 ESALs on rigid pavements. The corresponding ESAL values for a conventional five axle tractor-semitrailer carrying 80,000 pounds are 2.37 (flexible) and 4.07 (rigid). Assuming tare weights of 28,000 and 29,500 pounds for the five- and six-axle combinations, ESALs per ton of payload for the trucks shown in Exhibit 2 are as follows:

	ESALs per million pounds of payload	
	Flexible pavement	Rigid pavement
5-axle tractor-semi	46	78
6-axle tractor-semi	32	61

However, much of the pavement benefits shown in the above table disappear if load equivalence factors consistent with Hudson and Buttler's findings (discussed above in Section 1.2.f) are assumed. Specifically, for flexible pavements, the reduction in ESALs per million pounds of payload would drop from 14 to roughly 4. For rigid pavements, the reduction in ESALs per million tons of payload would drop from 17 to roughly 11. Thus, if Hudson and Buttler's conclusions are correct, it appears that there are still pavement cost savings to be realized by promoting a shift to tridems. However, these savings are far less than would be anticipated using the AASHTO load equivalence factors.

2.5 Weight Limits Per Unit of Tire Width

The majority of states restrict the weight that can be carried on a tire based on its width. The limits range from 550 pounds per inch (in Alaska, Mississippi, and North Dakota) to 800 pounds per inch (in Indiana, Massachusetts, New Jersey, New York, and Pennsylvania). Such restrictions result in lower pavement costs; however, the size of the pavement cost savings (either in absolute terms or in relation to the increase in goods movement costs also resulting from these restrictions) have not been estimated.

2.6 Turner Trucks

In 1984, former Federal Highway Administrator Francis Turner proposed a new approach to truck size and weight regulation. The objective of this new approach, which became known as the Turner Proposal, was to reduce pavement wear caused by truck traffic while simultaneously improving the productivity of freight transportation. Truck operators would gain productivity through higher allowable gross weights, but would add extra axles to their vehicles to reduce the weights carried on individual axles.

Turner's original proposal was as follows:

- Reduce legal axle loadings to a maximum of 15,000 pounds for single axles and 25,000 pounds for tandem axles
- Allow greater vehicle lengths
- Raise maximum gross weights to as much as 112,000 pounds.

Turner proposed that these limits apply to all trucks, but that when axle weights could not practically be brought down to the indicated maximums, special permits with higher fees be issued.

The Turner Proposal was the subject of an extensive study by the Transportation Research Board, reported in TRB Special Report 227, *New Trucks for Greater Productivity and Less Road Wear: An Evaluation of the Turner Proposal*. That study retained the basic concept of a truck that would be both more productive and less wearing on pavements. However, rather than Turner's mandatory change applying to all trucks (with limited exceptions), it considered a voluntary system in which each truck operator would choose whether to comply with the new weight regulations or to continue to follow the previously existing rules. The study also broadened the scope of its evaluation beyond Turner's original proposal by considering ranges of possible values for axle weights, length limits, and other vehicle characteristics to find trucks that approach optimum overall performance, considering productivity, pavement, bridges, and safety.

The TRB study estimated that if Turner trucks were introduced on a nationwide basis, 23 percent of the freight carried in existing combinations would divert to these trucks. The most popular Turner configuration would be a nine-axle double with 32- to 34-foot trailers carrying 114,000 pounds maximum weight. Key impacts were estimated as follows:

- $2.0 billion per year reduction in freight costs
- Two percent increase in truck freight due to shift from rail. Rail would lose four percent of ton-miles and five percent of gross revenues
- $729 million per year reduction in pavement costs
- $403 million per year increase in bridge costs if all inadequate Interstate and primary bridges and one-quarter of inadequate non-primary bridges are replaced.

2.7 New Approach Proposed by TRB Truck Weight Study

TRB's Truck Weight Study also developed a new approach for regulating the weights of vehicles over 80,000 pounds. Under this approach, the maximum weight carried on any group of axles over 40 feet in length would be given by W in the following formula:

$$W = 1{,}000\,(9L/16 + 72)$$

where L is the length of the axle group in feet. Further, for vehicles with gross weights over 80,000 pounds, maximum axle weights would be limited as follows:

- 15,000 pounds for single axles
- 34,000 pounds for tractor drive tandem axles
- 30,000 pounds for other tandem axles.

The idea behind this new approach was to address some potentially negative pavement, safety, and productivity aspects of the current bridge formula:

- Formula B provides a relatively modest incentive for operating trucks with more axles and consequently less pavement impact. According to the formula, adding an axle increases maximum weight by 4,000 to 6,000 pounds. An additional load-bearing axle on a tractor typically adds 2,700 pounds to empty weight, and an additional load-bearing axle on a trailer typically adds 1,500 pounds to empty weight. Hence, the added payload for an extra axle is less than 3,300 pounds for a tractor axle and less than 4,500 pounds for a trailer axle. Adding an axle generally increases operating costs for fuel and tires and increases costs for new tractors or trailers. For some truckers, the opportunity to carry 4,500 pounds (or less) of additional payload is an insufficient incentive to overcome these cost increases. Increasing the added payload allowed for an extra axle would encourage more truckers to adopt vehicles with more axles.

- If the 80,000-pound limit were eliminated, five-axle doubles could operate under Formula B and current axle weight limits of up to 92,000 pound (assuming a practical maximum steering-axle weight of 12,000 pounds and 20,000 pounds on each of the other four axles). These vehicles perform very poorly in terms of pavement wear per ton of freight carried because they have single rather than tandem axles. In carrying high-density, weight-limited freight, five-axle doubles are less efficient than the LCVs with seven or more axles that currently operate under special permits in western states, so five-axle doubles carry little weight-limited traffic in those states. In eastern states with more restrictive length limits, however, elimination of the 80,000-pound limit with gross weights controlled instead by Formula B would cause some freight to shift from conventional five-axle tractor-semitrailers to five-axle doubles. This shift would adversely affect pavements.

- Formula B provides little incentive to distribute loads evenly among axles. Adding an axle increases maximum permissible weight by 5,000 to 6,000 pounds, even if the axle itself carries no weight. This anomalous feature of the bridge formula can promote the use of non-load-bearing dummy axles. For example, a three-axle dump truck with a wheelbase of 16 feet can carry 48,000 pounds under Bridge Formula B; however, by adding a non-load-bearing dummy axle, this vehicle can operate at 52,500 pounds. Uneven axle weight distributions and the use of dummy axles can worsen pavement wear. For example, a 20,000-pound axle followed by a 10,000-pound axle does 70 percent more damage to pavements than two 15,000-pound axles. Uneven axle weight distribution and the use of dummy axles also degrade vehicle handling and performance, which may have adverse safety consequences.

- Enforcement of the bridge formula can be complex and time consuming, because it involves measuring spacings between individual pairs of axles and applying the formula (usually by use of a table) to different axle groups. Many permanent weigh stations have stripes painted on the pavement to help enforcement officials estimate vehicle lengths. At roadside weight checks with portable scales, however, it is often not practical to test for bridge formula violations.

The new approach would have approximately the same impact on bridges as the current bridge formula, but would help meet the pavement, safety, and enforcement problems outlined above. On the negative side, TRB's Truck Weight Study noted that the equipment and loading practices of many truckers operating vehicles over 80,000 pounds under grandfather exemptions are designed to take advantage of the current federal axle limits. These truckers would be placed at a disadvantage by having to operate under two different sets of limits: current federal limits and the lower limits called for by the new approach. Further, the pavement-related problems with the current bridge formula noted above might be more simply addressed by prohibiting lift axles and limiting five-axle doubles to 80,000 pounds or less.

3.0 Knowledge Gaps and Research Needs

Research is needed to develop improved load-equivalence factors for use in truck size and weight analyses, highway cost allocation studies, and other policy studies. The AASHTO load-equivalence factors that are currently used in most TS&W studies in the U.S. were developed using data from the AASHTO Road Test conducted in the 1950's. Since the primary purpose behind the development of these factors was to provide measures of total traffic loadings for use in pavement design, relatively little attention was paid to the quantifying the relative impacts of different truck characteristics on pavements.

The development of improved load-equivalence factors should address the following issues:

- The relative impacts of single axles, tandem axles, and tridem axles
- The effects of tire type, width, and pressure
- The effects of different types of suspensions
- Axle weight (AASHTO's 4th power relationship vs. the results of recent work by TRI and Brookings).

The research should provide the following:

- The best possible set of load-equivalence factors based on available data
- Some indication of the level of uncertainty associated with these factors
- A plan for how information from ongoing data collection activities (such as SHRP) might be used to update these factors
- Identification of new data collection activities that should be initiated.

Research on load-equivalence factors should build upon recent work by Kenis (1990) and Hudson (1992). Kenis used the VESYS 5 computer program to conduct "computer road tests". After verifying that the program could be used for this purpose, Kenis estimated the damage produced by steering axles at the AASHTO Road Test, in order to quantify the error caused by the fact that these axles were neglected when equivalencies were originally developed. Kenis then used VESYS 5 to estimate equivalence factors for conditions not present in AASHTO Road Test, such as tridem axles. Finally, equations relating pavement deflections and strains to load equivalencies based on cracking and rutting were developed.

Hudson (1992) evaluated alternative "primary response equivalency factor methods". These methods use stresses, strains, and deflections to estimate pavement damage. The research effort included a comprehensive review and evaluation to identify equivalency relationships and select several promising methods. Then, field testing of instrumented pavement sections was conducted to evaluate the selected methods. Hudson concluded that primary pavement response based load equivalency factors are a reasonable method to estimate the equivalent damaging effects of various load parameters, as compared to a standard loading condition. Of the methods tested, the deflection method proposed by

Hutchinson was found by Hudson to be the most viable of the methods that were analyzed in detail.

In addition to better load-equivalence factors, research is needed to identify and assess the potential merit of alternative approaches to regulating tire pressure and other tire characteristics. For each approach identified, the investigation should

- Assess the feasibility and costs of enforcement
- Estimate benefits in terms of reduced pavement costs
- Estimate costs to the trucking industry of complying with the regulations
- Identify and estimate other potentially important benefits and costs.

Consideration should also be given to the development of performance specifications for truck suspension systems to reduce dynamic loading impacts on pavements.

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