Research Report
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TRUCK DESIGN AND USAGE RELATED TO HIGHWAY PAVEMENT PERFORMANCE

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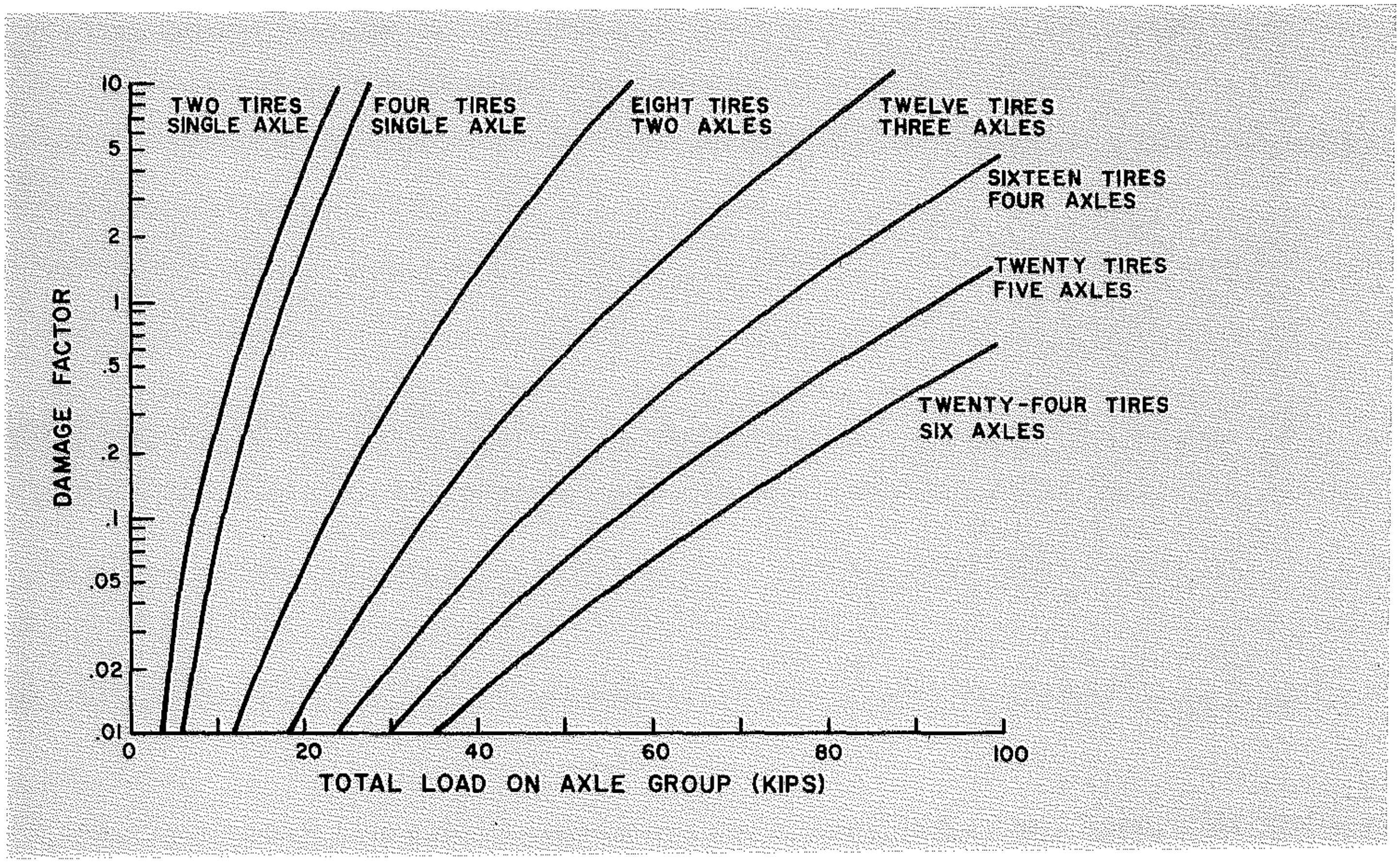


Figure 1. Variation of Damage Factor for Selected Axle Groups as Load on Axle Group Is Changed.

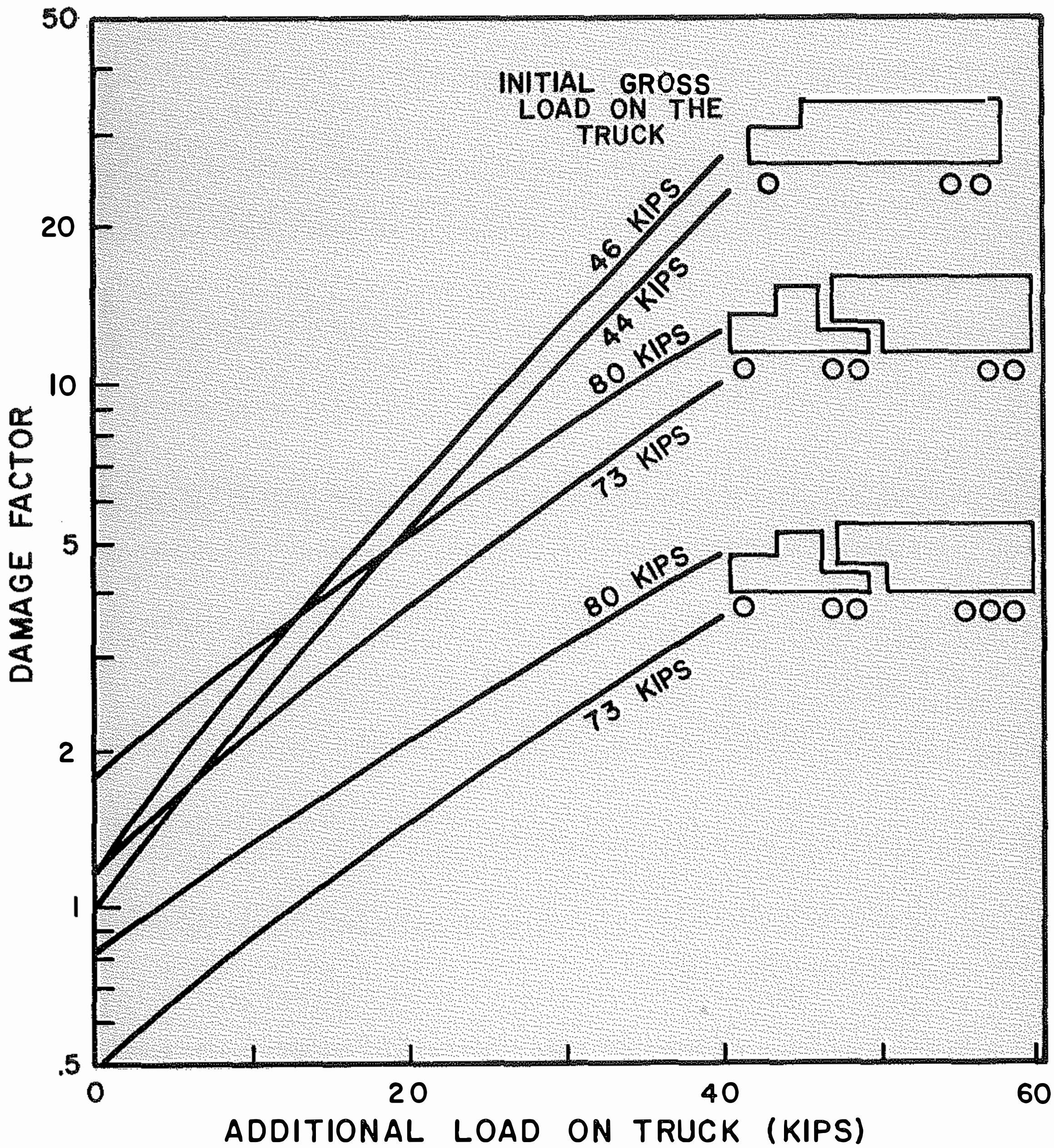


Figure 2. Increase in Damage Factor for Selected Vehicles as Load on Truck Is Increased.

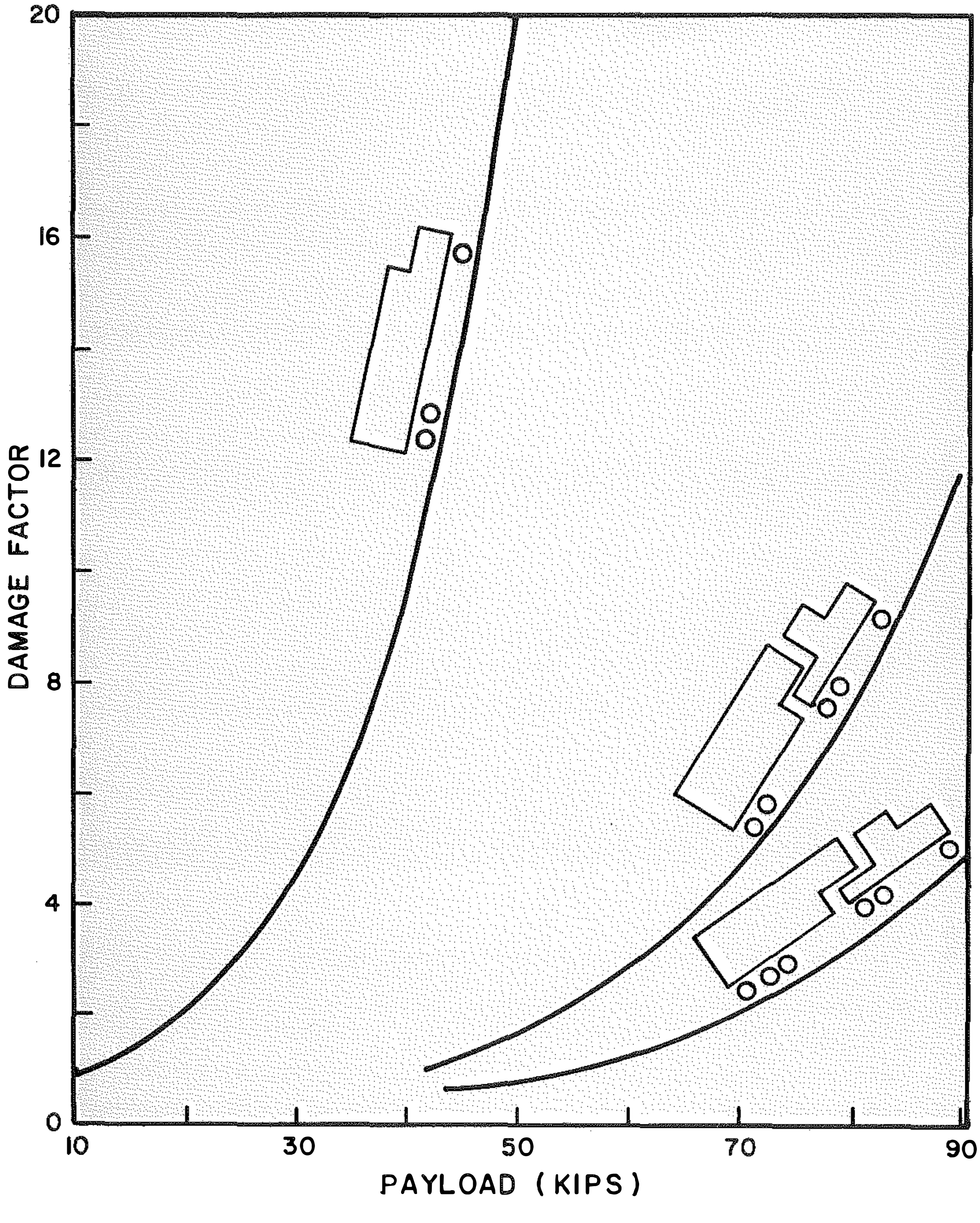
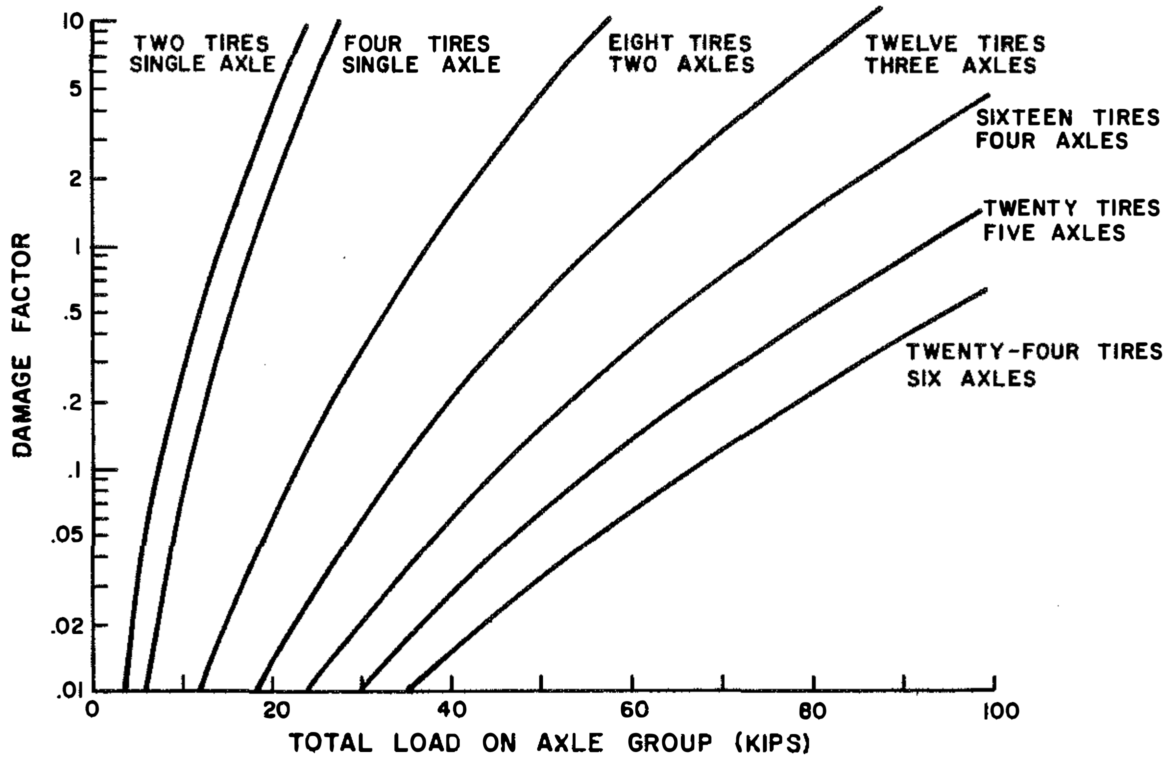


Figure 3. Variation of Damage Factor for Selected Vehicle Types as Payload Is Changed.



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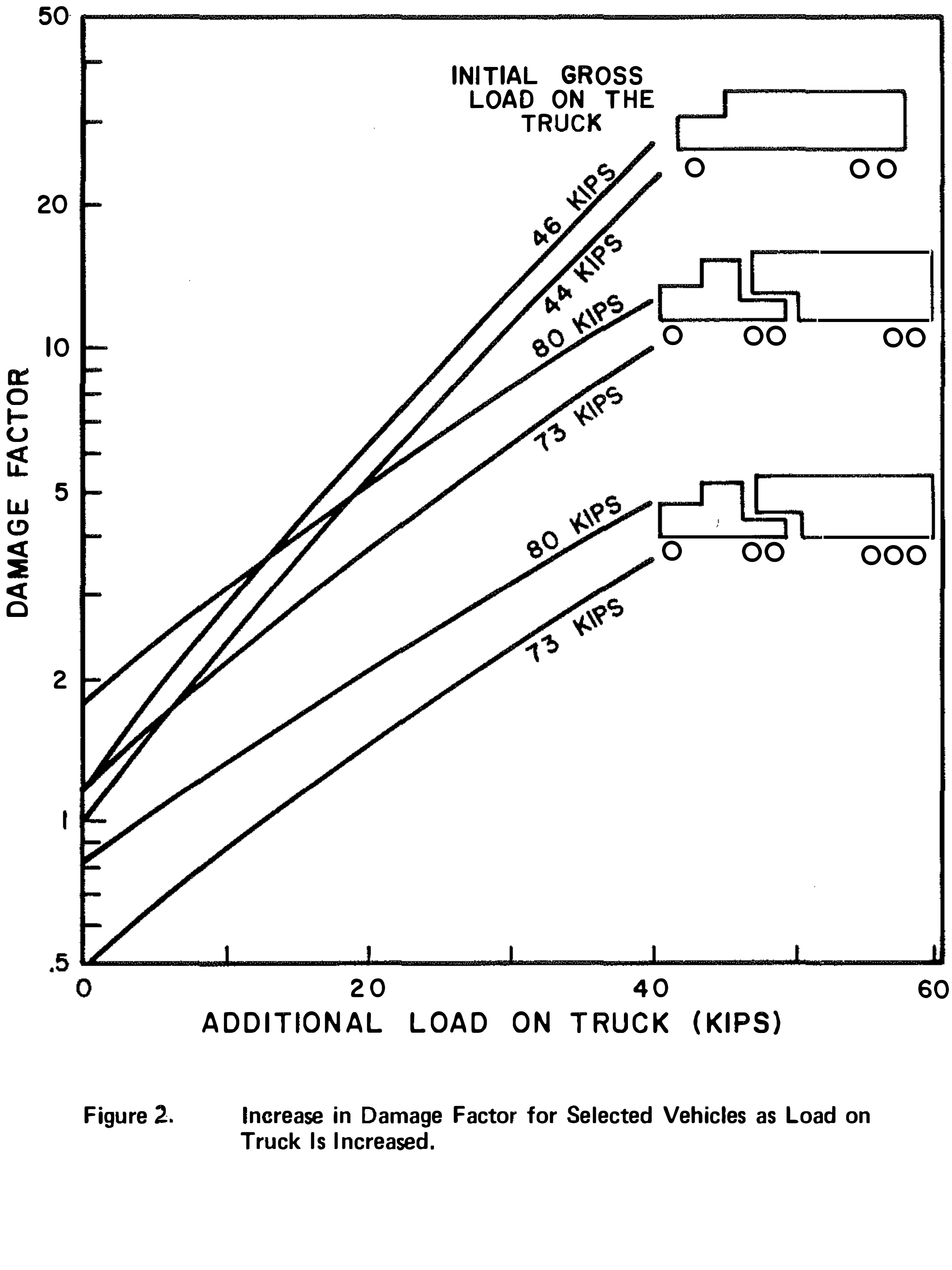

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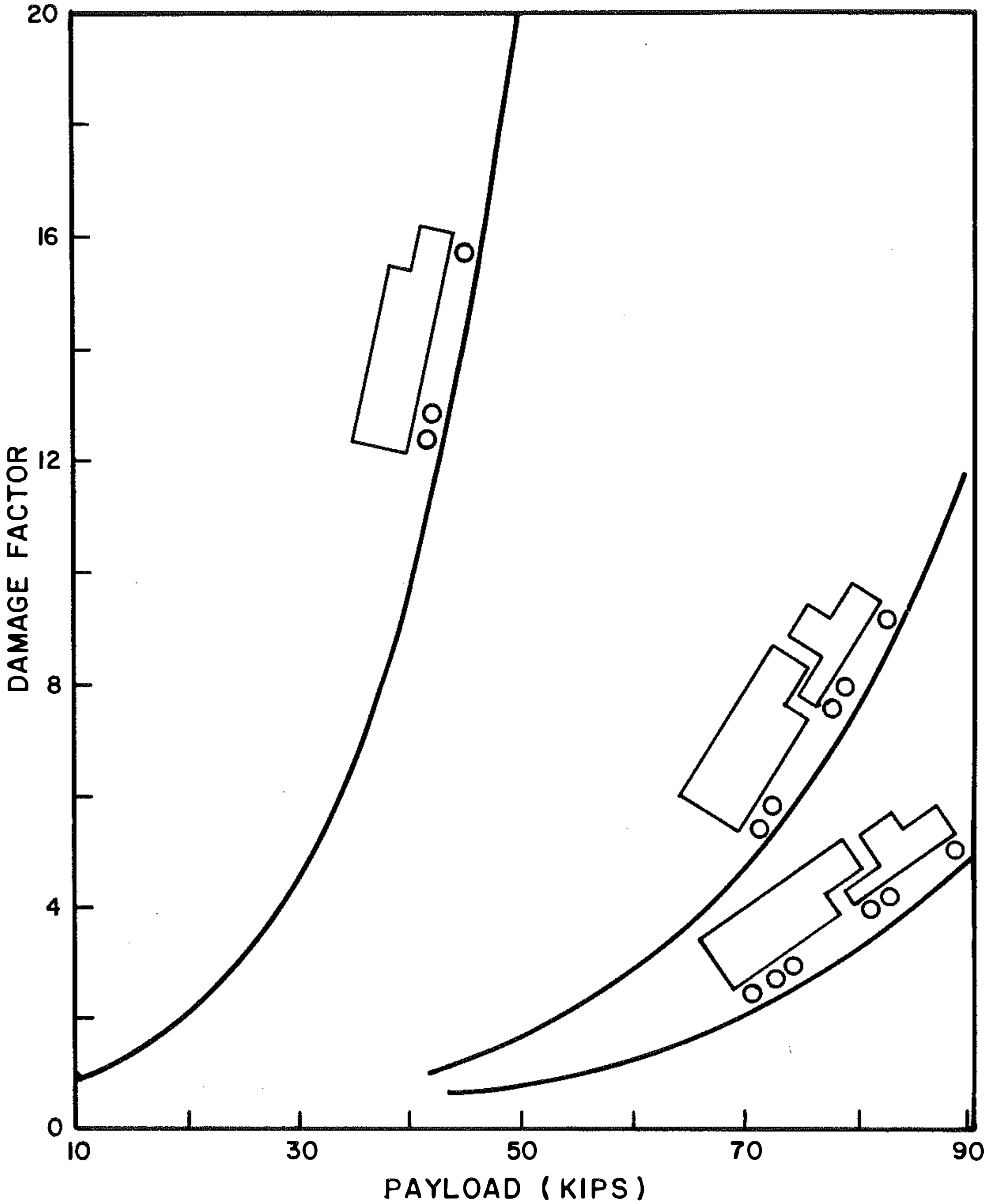

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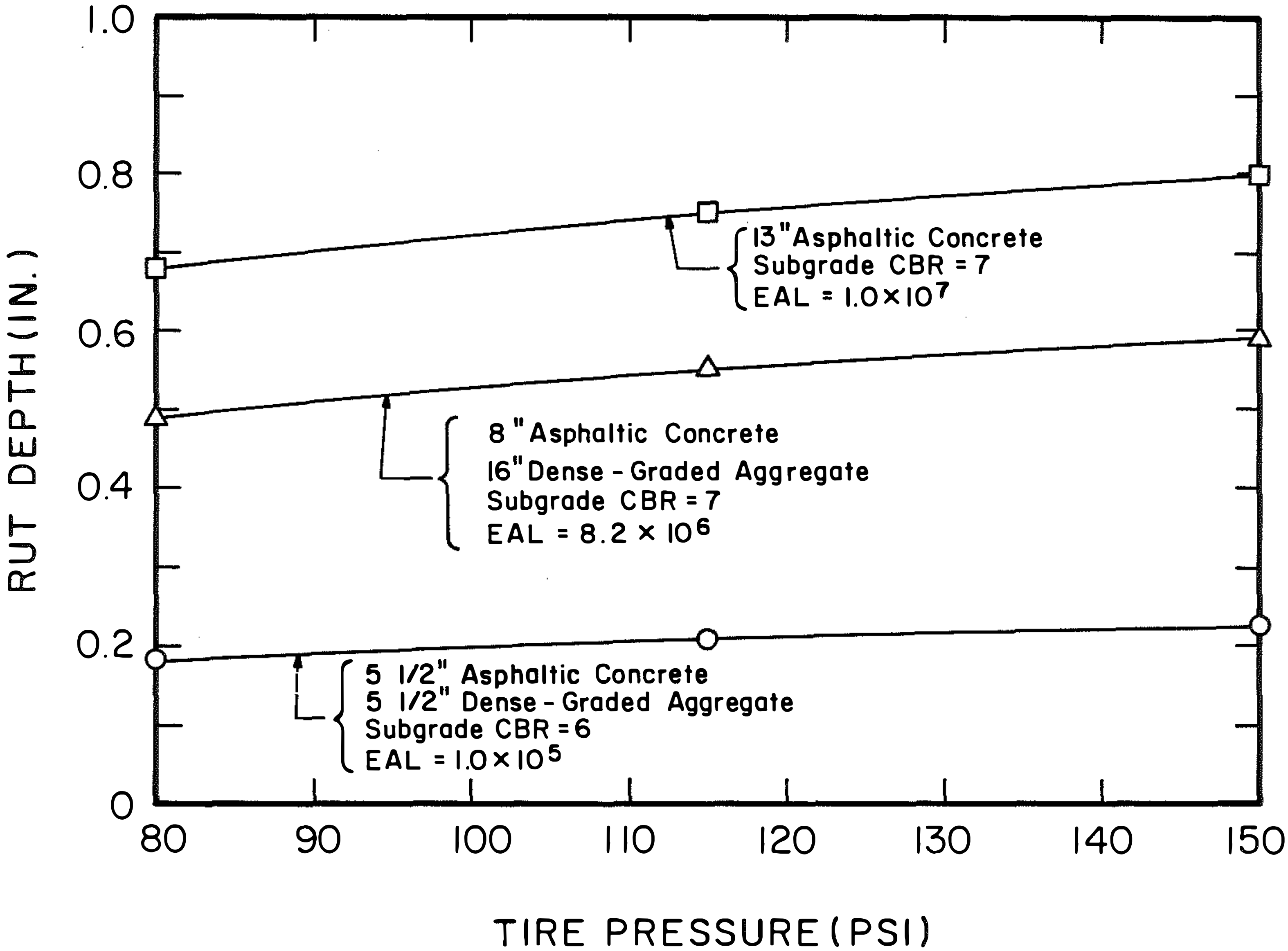
1.0
0.8
0.6
0.4
0.2
0
RUT DEPTH (IN.)
13" Asphaltic Concrete
Subgrade CBR = 7
EAL = 1.0×10^7
8" Asphaltic Concrete
16" Dense - Graded Aggregate
Subgrade CBR = 7
EAL = 8.2 × 10^6
5 1/2" Asphaltic Concrete
5 1/2" Dense - Graded Aggregate
Subgrade CBR = 6
EAL = 1.0×10^5
80
90
100
110
120
130
140
150
TIRE PRESSURE (PSI)

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ABSTRACT

The function of a pavement is to serve traffic safely, comfortably, and efficiently at reasonable costs. Automobile traffic typically accounts for the major volume of traffic using high-type facilities. However, heavy truck traffic accounts for the major portion of accumulated fatigue and therefore requires greater structural designs. Truck design and usage has tended toward larger vehicles and greater payloads. The impact of elements of truck design and usage (such as suspension systems, floating axles, axle configurations, uniformity of loading, payloads, etc.) on fatigue "damage" are illustrated. The effects of increasing vehicle loadings and increased tire pressures are related to potential for rutting of asphaltic concrete pavements. Mechanisms for implementation of vehicle damage factors and accumulated pavement fatigue in the assessment and allocation of costs to highway users also are presented.

1. INTRODUCTION

High-type pavements, typically constructed of bituminous concrete or portland cement concrete, serve two primary functions: a wearing surface upon which the tires of the vehicles travel and a means of transferring the total load of the vehicle to the supporting subgrade or earth foundation.

Loads the pavement system must support are applied at tire-pavement contacts. The magnitude and nature of that loading is very much dependent upon the design and usage of the vehicles traveling the roadway. The design of a pavement [1, 2] involves the selection of thicknesses of various components of the layered system sufficient to support the vehicular loadings applied at the surface.

The highways of the United States are a public service not subject to normal "controls" of the commercial marketplace for pricing benefits to be derived from and the costs of providing such a network. Public officials attempt to balance the needs among various elements of the transportation network so the maximum benefit is obtained from the funds available. Many relationships, are involved -- some are engineering in nature, others are social and economic. Some relationships are reasonably well defined, others may be unknown. In other instances, data are not readily retrievable so they may be analyzed and necessary and appropriate relationships developed.

2. TRUCK DESIGN AND USAGE

The more significant vehicular contributors to the loads on the pavement system are trucks, the design and usage of which are not within the direct control of the highway engineer. Vehicle designers and manufacturers can play a significant role in this respect. Shippers as well as the truckers also are key elements in the performance of highway pavements as reflected by the way in which they load and use their vehicles.

Since vehicular loads are transmitted to the pavement at tire-pavement contacts, the tires of the vehicle are a major factor in the loading of the pavement structure. The width, wall stiffness, and pressure of the tire control the contact area and thus is a factor limiting stresses applied to the pavement [3]. The number of tires supporting a given load also influences the contact pressure and the stresses induced in the pavement structure. Spacing between tires is important in that stress fields from adjacent tires may overlap and result in additive stresses at certain points within the pavement system.

An increased number of axles provide additional contact points to transmit a given load to the pavement. If axles are closely spaced, there may be an overlapping of stress fields. The distribution of the vehicular load among the axles may be more prevailing than the number of axles or number of tires [4]. If it is assumed the load is distributed uniformly among the axles, when it is not, the effects of that particular vehicle may be underestimated [5, 6]. Placement of the load within the vehicle and the design of the suspension system may be important. As an example, only about 10 percent of the tandem axle groups observed in Kentucky have loads uniformily distributed between the two axles. Such a nonuniform distribution may account for as much as a 40-percent increase in the fatigue damage to a pavement. The use of "floating" axles also may be undesirable unless means are provided by which the floating axle carries its proper share of the load [6]. It has been observed that the load carried by third floating axles may vary from a very low portion of the total load, providing very little benefit from the additional axle and shifting the additional load to the two remaining axles in the group, to a very large percentage of the load (up to 240 percent).

The kingpin location may be varied up to 24 or 30 inches (610 or 760 mm) from its desirable location (midpoint between tandem axles). Displacements of the kingpin by as much as 18 inches (460 mm) are not uncommon [3]. Such a displacement tends to shift a portion of the trailer load to the front steering axle of the vehicle where small increases in load are disproportionately more damaging to the

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pavement; i.e., a 10-percent increase in load produces a 35-percent increase in fatigue.

3. PRINCIPLES OF PAVEMENT DESIGN

A load applied at the surface of a pavement is distributed downward through the pavement to underlying materials. The objective of the design of pavement thickness is to select the combination of thicknesses of various component layers to reduce the stresses and strains at any given level to a value that can be resisted by the material at that level without failure.

Interactions between various materials of a pavement system and the loading are extremely complex. Computerized mathematical models [1, 2] based on elastic layer theory may be used to obtain a first approximation of stresses and strains within a pavement under various loading configurations. By extending the elastic theory and making use of energy (work) concepts [3], it has been possible to further refine evaluations and interpretations of observed phenomena.

The equivalent axleload (EAL) approach was selected in Kentucky as a means to express a variable traffic stream in terms of a single number that can be used for design purposes and that can be related to a stress (or strain)-repetitions of load curve or the fatigue concept. All axleloads are expressed in terms of a reference or base axleload (18,000 pounds (80 kN)). The EAL for a given axle configuration represents the damage equivalency for that particular configuration. Figure 1 illustrates the variation of damage or load equivalency for selected axle configurations as a function of loads on those configurations [3].

4. PAVEMENT RESPONSES TO LOADS

4.1 SELECTED ILLUSTRATIONS

A single four-tired axle carrying 18,000 pounds (80.0 kN) will cause one "unit" of damage (1 EAL) to the pavement. This was the legal axleload in Kentucky prior to 1974. The current legal axleload of 20,000 pounds (88.9 kN) on this same axle results in an equivalent damage of 1.7 units (Figure 1). A tandem axle group can support a load of 37,400 pounds (166.4 kN) with a resultant damage equivalency of 1.0; three-axle groups carry 56,300 pounds (250.4 kN) at an equivalent damage of 1.0. There is a significant increase in total load on the axle group as additional axles are added. For the fourth and each additional axle, the load on the axle group may be increased by slightly more than 18,000 pounds (80.0 kN) with no increase in damage to the pavement.

In Figure 2, damage equivalencies for three commonly used vehicle types increase as the gross load on the vehicle is increased. The importance of the proper selection of vehicle type is vividly illustrated when, for the same payload, the style of vehicle utilized may result in damage equivalencies from 1 to 20. Figure 3 shows that the percentage increase in payload is very much less than the corresponding percentage increase in damage equivalency.

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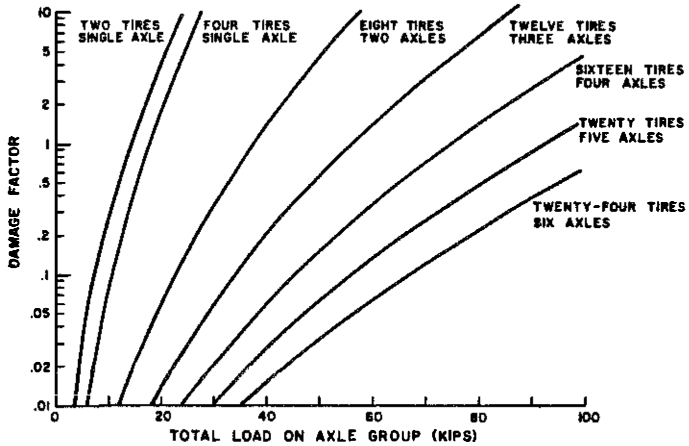

Figure 1. Damage (or Load Equivalency) Factor for Selected Axle Groups as a Function of Load on the Axle Group.

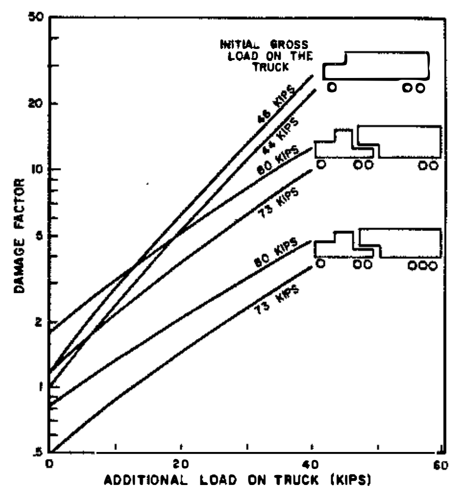

Figure 2. Damage (or Load Equivalency) Factor for Selected Vehicles as a Function of Load on the Truck.

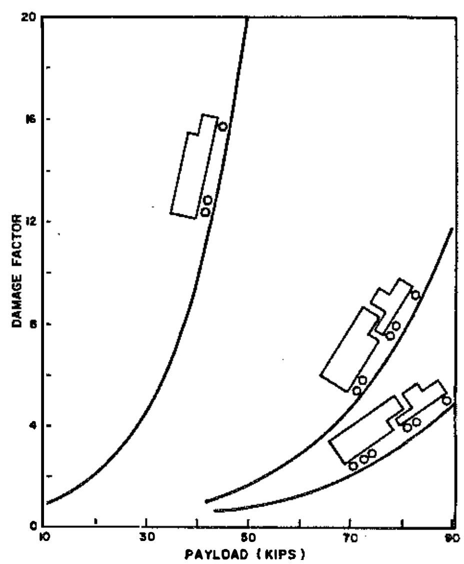

Figure 3. Damage (or Load Equivalency) Factor for Selected Vehicle Types as a Function of Payload.

4.2 TIRE PRESSURES AND RUTTING

It is expected that increased tire pressures would decrease the area of the tire footprint and increase the potential for rutting or a punching shear failure. Allen and Deen [7] reported on an extensive laboratory investigation into the rutting potential of flexible pavement components (asphaltic concrete, dense-graded aggregate, and subgrade soils). Rut prediction models were formulated for each pavement component. In addition, traffic and environmental models were developed, and all models were combined into a single computer program (PAVRUT) capable of providing estimates of rutting for any flexible pavement structure.

The rutting models take the following form for all three pavement components tested:

$$\epsilon_p = A (\log N) + B (\log N)^2 + C (\log N)^3 + D, \qquad (1)$$

in which ϵ_p is the permanent strain, N is the number of load repetitions, and A, B, C, and D are experimentally determined variables dependent on stress, temperature, moisture content, and subgrade CBR. The environmental (temperature) model was developed from data reported by Southgate and Deen [8] to predict temperatures of asphaltic concrete layers at any depth and for any hour of the year.

The effect of tire pressures on rutting was investigated using PAVRUT. Three typical pavement structures were analyzed for tire pressures of 80, 115, and 150 psi (552, 793, and 1,030 kPa). Figure 4 describes the three structures and illustrates the influence of tire pressures. Increased tire pressures have a greater effect on estimated rut depths at higher EAL values. However, when considering the percentage increase in rut depth, increased tire pressures are more damaging at lower values of EAL.

At the AASHO Road Test, tires were inflated to 67.5 psi (465 kPa). Tire pressures, recently (1984), have been measured at 125 psi (862 kPa) and indications

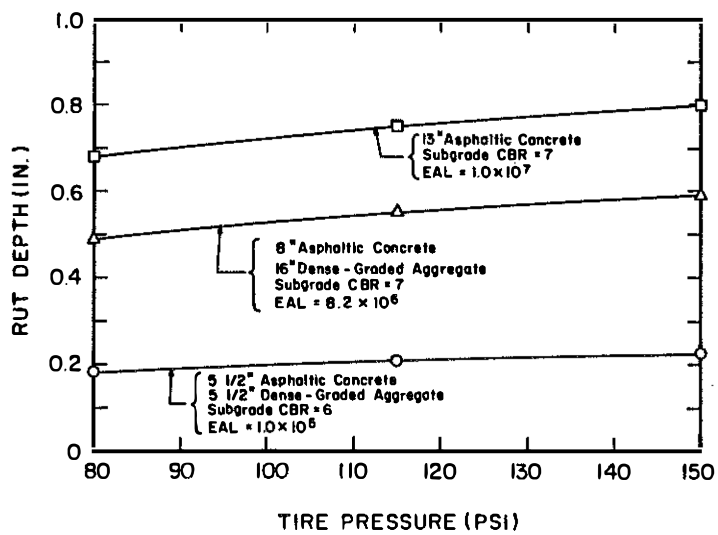

Figure 4. Estimated Rut Depths as a Function of Tire Pressure.

are that pressures will increase in the next few years. Recent research indicates increased tire pressures cause substantial increased fatigue for the same axleload. Thinner pavements are affected more than thicker pavements, as indicated by a multiplying factor of 3.40, 1.95, and 1.43 for 3 inches (76 mm), 5 inches (127 mm), and 8 inches (203 mm) of asphaltic concrete, respectively.

4.3 OTHER ISSUES AND FACTORS

4.3.1 Bridges

Bridge loadings are considered in two ways: the wheel loading on the floor or deck system and the loading on the span. Capacity may be limited by either or both. There is some load that will cause catastrophic failure. Other loads may induce stresses greater than a safe level and be permanently but insidiously damaging (in fatigue).

4.3.2 Operating Costs

Energy savings might be realized if fewer truck trips result from larger payloads. However, increased fuel consumption per truck trip would be required to move those increased payloads. Greater weights will result in increased wear and tear on the tires, the brakes, and the basic vehicle.

4.3.3 Safety

Accident severity and fatalities involving large trucks may increase. On the other hand, increased payloads may lead to a reduced number of truck trips that would, in turn, result in less exposure to accidents. Increased vehicular weights, requiring more efficient braking systems, may result in an increased potential for brake fade and may lead to an increase in the number and severity of accidents involving trucks. Increased truck weights will cause greater differentials in vehicle speeds that are potential causes of highway accidents.

4.3.4 Other Economic Considerations

Increased truck weights will require heavier and more durable equipment. Thus, capital costs will increase. If savings do accrue as a result of increased productivity, will those savings be passed to the consumer? Productivity in the trucking industry may or may not increase. Other modes of transportation, such as rail and water, may experience a decrease in goods movement.

4.3.5 Enforcement

Enforcement of truck weight laws is a necessary attempt to minimize the potential for premature failure of pavements and bridges. Enforcement of present truck weight laws are difficult. Changing the laws to make enforcement less difficult is not in itself good reasoning; however, the cost of enforcement may decrease if fewer violations would result. An aspect of enforcement is the comparison of the issuance of citations for oversized and overloaded vehicles to the rate of convictions and the severity of fines. The costs of enforcement and the delays to truckers may be decreased if a system of issuing citations by sight (based on the presence of sideboards or on the length of the tire-pavement contact and tire pressure, for example) could be developed to minimize the need to stop, weigh, and inspect vehicles. The use of available technology to weigh vehicles in motion also may be used to screen potential violators, allowing those trucks obviously not in violation to proceed without delay.

5. USER COSTS ALLOCATIONS [9]

The first step in determining costs and revenues attributable to the highway system involves the establishment of the degree of stratification necessary to adequately represent the variability of costs and revenues generated. Characteristics of the highway considered significant are federal-aid classification, rural or urban character, number of lanes, total mileage, vehicle-miles traveled, and annual average daily traffic.

To determine total annual costs for the highway system in Kentucky, it was necessary to develop construction, replacement, or current value costs representing capital investment components. Components of roadway costs considered of interest were limited to pavements and shoulders.

The method of allocation of capital investments for pavements and shoulders differed significantly from the traditional incremental approach. Typical pavement designs and their accompanying thicknesses are an integral part of the traditional approach. For this study, pavement and shoulder cost allocation was based on the concept of proportional distribution of equivalent axleloads (EAL). Percent cost responsibility was related directly to accumulated EAL´s for a 20-year design period for each highway classification. Damage factors and repetitions of vehicle types were used to calculate accumulated EAL´s for the design period for each highway classification. Percentage of cost responsibility for various vehicle classes and/or weight registrations for each highway classification are presented in Table 1.

Pavement and shoulder maintenance expenditures were allocated on the basis of axle-miles of travel. All vehicles shared 80 percent of the expenditures and the remaining 20 percent was shared by trucks only. For the primary road system, Iowa [10] assigned 80 percent of the expenditures for pavement maintenance to all vehicles based on axle-miles traveled and 20 percent to trucks only. All vehicles were charged with 85 percent of the total costs for shoulder maintenance and 15 percent was assigned to trucks. The percentage assigned to all vehicles rose to 90 percent for secondary and municipal road systems. Similar results were noted in a Federal Highway Administration study [11], but the percentage assigned to all vehicles was nearly constant for each highway system listed.

6. CONCLUDING REMARKS

The mechanics of pavement behavior in response to vehicular loadings are reasonably well understood. Reliable mathematical models have been programmed for high-speed computers so that analyses and designs may be made with confidence. Comprehensive modeling of the economic factors has not yet been satisfactorily accomplished. General trends of many of the component economic relationships may

TABLE 1. PERCENTAGE OF COST RESPONSIBILITY FOR PAVEMENTS AND SHOULDERS BY VEHICLE TYPE

HIGHWAY CLASSIFICATION		LANES	AUTOS[1]	REGISTERED MAXIMUM GROSS WEIGHT CLASS FOR TRUCKS (1,000 POUNDS) 6-10	14-26[2]	32-44	55-62	73.28	82
Interstate	Rural	4	1.09	4.09	5.96	10.96	16.51	33.87	27.52
		6	1.81	5.09	18.98	11.49	14.70	26.88	21.05
	Urban	4	2.46	11.32	16.85	12.44	14.63	23.68	18.62
		6	3.51	8.52	13.84	12.19	14.89	26.05	21.00
Federal-aid Primary	Rural	2	3.52	12.83	18.23	15.04	15.48	19.63	15.27
		4	1.92	7.91	13.56	13.79	15.97	26.14	20.71
	Urban	2	2.68	9.54	15.32	16.10	17.25	21.80	17.31
		4	6.80	13.60	29.04	12.96	11.92	14.48	11.20
Federal-aid Urban	Urban	2	10.21	19.27	36.11	12.19	8.47	8.00	5.75
		4	10.02	18.13	31.73	15.16	11.59	7.75	5.62
Federal-aid Secondary	Rural	2	4.16	14.92	24.46	16.57	14.85	14.18	10.86
		4	4.25	16.77	23.24	15.22	13.99	14.70	11.83
Nonfederal-aid State Maintained	Rural	2	3.87	12.70	24.39	22.35	19.04	10.24	7.41
		4	4.25	16.77	23.24	15.22	13.99	14.70	11.83
	Urban	2	9.89	19.44	35.93	12.49	8.56	7.96	5.73
		4	10.02	18.13	31.73	15.16	11.59	7.75	5.62
Total, All Systems			2.83	8.45	16.21	12.40	14.92	25.18	20.01

[1] Includes pickup trucks
[2] Includes buses

be known, but precise interrelationships have not yet been defined, nor have those various components been brought together into a comprehensive model. Even in those cases where economic relationships are known, input data for analyzing specific situations are sometimes very difficult to obtain.

Statutes dealing with weight limitations on trucks should be reviewed for consistency with the mechanics of pavement performance. Efforts should be made, by statute, to encourage the use of those vehicle styles that are less damaging to highway pavements. Legal limitations, and their enforcement for vehicle styles that are extremely damaging, should be very stringent. Incentives, in the form of tax credits or increased allowable gross weights, for example, may be coupled with modifications of the statutes to encourage and assist the trucking industry to use those vehicles that are less damaging to highway pavements.

An educational effort is needed to impress upon all affected groups (the trucking industry, users of trucking, vehicle designers, state and national legislators, and the public) the gravity of this problem. Until users of heavy vehicles understand and appreciate the significance of the interrelationships of the types of vehicles used to carry heavy loads and the manner in which loads are distributed on individual vehicles, progress will be very difficult and long in coming.

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