

Research Report
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**TRUCK DESIGN AND USAGE
AND
HIGHWAY PAVEMENT PERFORMANCE**

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INTRODUCTION

When the term highway pavement is used, most people think of the moderate to thick systems on which their vehicles travel on intermediate- or high-type roadways. These pavement systems are typically constructed of bituminous concrete or portland cement concrete. This is not to say that low-volume roads do not have a pavement system; however, in case of low-volume roads, the pavement system usually consists of unbound aggregates, sod, soil materials, or at the most very thin or moderate applications of a binding material. It is the high-type pavement systems to which the comments in this paper will be addressed specifically.

These high-type pavements serve two primary functions. On the one hand, these pavements are the wearing surface upon which the tires of the vehicles travel. Because of high stresses at the tire-pavement interface, the surfacing materials must be extremely stable. The hard, bound surface provides a dust-free and smooth-riding surface. Secondly, the pavement system provides a means of transferring the total load of the vehicle to the supporting subgrade or earth foundation. The design of such a pavement system is thus a structural problem very similar to the design of bridges or office buildings.

The load which the pavement system must support is applied at the tire-pavement contact. The magnitude and nature of this loading is very much dependent upon the design and usage of the vehicles expected to travel the roadway. The design of a pavement involves the selection of thicknesses of various components of the layered pavement system which will be sufficient to support the vehicular loadings applied at the surface.

No one would deny the need to transport people and goods from one point to another. One mode of such transportation has historically been the highway networks of this country. The American people have decided, whether by default or by deliberate decision, that this mode of transportation will be provided by governmental agencies. Thus, the highway systems of this country are a public service which are not subject to the normal "controls" of the commercial marketplace for the purpose of pricing the benefits to be derived from and the cost of providing such a network. Public officials have an interest in providing adequate highways at an optimum cost. Since there are limited funds available, public officials are not only attempting to balance the need for various public services, but transportation officials are attempting to balance the needs among various modes and elements of the transportation network so that the maximum benefit is obtained from the

funds available.

Many relationships are involved -- some are engineering in nature, others are social and economic. Some of these relationships are reasonably well defined, others may be unknown. In other instances, data are not readily retrievable so that they may be analyzed and the necessary and appropriate relationships developed.

TRUCK DESIGN AND USAGE

Inasmuch as the load which must be supported by the pavement is transmitted to it at the tire-pavement contact, it is the nature of the vehicle above this interface that is of significance with regard to pavement performance. The more significant contributors to the loads on the pavement system are trucks; thus, it is these types of vehicles which receive most of the attention. It should also be noted that the design and usage of trucks 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 are also key elements in the performance of highway pavements as reflected by the way in which they load and use their vehicles.

Since the vehicular load is transmitted to the pavement system by means of the tire-pavement contact, it is not surprising that the tires of the vehicle are a major factor in the loading of the pavement structure. The width of the tire, of course, controls the contact area between the tire and the pavement and thus is a factor limiting the stresses which are applied to the pavement. 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.

The design of tire treads and the tire pressures which are used are important in other than the structural performance of the pavement. The tread, for example, is relevant from the safety aspect in that it influences the degree to which skid resistance can be developed between the tire and the pavement in braking and emergency situations as well as under normal tractive conditions. The tire pressure may also have significance with regard to operating costs of vehicles and the wear and tear on the tires themselves. Higher tire pressures decrease the contact area, resulting in reduced tire friction or skid resistance and increased potential for pavement rutting under the high stresses.

As with tires, the number and spacing of axles is important. Here again, an increased

number of axles provide additional contact points to transmit a given load to the pavement. If axles are spaced close together, there may be an overlapping of stress fields and an additive effect within the pavement system.

An increased number of axles may provide a false sense of safety with regard to the loading of the pavement structure. The distribution of the vehicular load among the axles may be more prevailing than the number of axles or number of tires. If it is assumed that the load is distributed uniformly to the axles, when in fact it is not, the highway pavement designer may grossly underestimate the effects of that particular vehicle. The placement of the load within the vehicle and the design of the suspension system may be very important in this respect. As an example, it has been found that only about 10 percent of the tandem axle groups observed in Kentucky have loads uniformly distributed between the two axles. Analyses indicate that the non-uniform distribution between the axles in a tandem group can account for as much as a 40-percent increase in the damage to a pavement. The use of "floating" axles may also be undesirable unless means are provided by which the floating axle carries its proper share of the load. It has been observed that the load carried by the 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. Both conditions increase the damage significantly over the situation when the load is distributed uniformly among all axles.

The kingpin location, the connection between a trailer and the tractor, can be varied by the trucker from zero up to as much as 24 or 30 inches from its desirable location. Displacements of the kingpin by as much as 18 inches is not uncommon. 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 proportionately more damaging to the pavement as well as creating a safety problem by increasing the difficulty of steering.

PRINCIPLES OF PAVEMENT DESIGN

A CONCEPT OF LOAD DISTRIBUTION

For purposes of discussion, it is convenient to assume that a load applied at the surface of a pavement is distributed downward through the pavement over a triangular pattern (see Figure 1). At the tire-pavement interface, the unit load or stress is very high. Thus, high-strength materials must be used in the upper portions of a pavement to resist these very high stresses. The load from the tire is distributed over larger and larger areas as greater and

greater depths within the pavement are reached. The unit forces or stresses are accordingly reduced. The objective of the design of pavement thickness is to select the combination of thicknesses of various component layers to reduce the stress at any given level within the pavement to a value which can be resisted by the material at that level without failure. Ultimately, the stresses at the subgrade or foundation level must be sufficiently low so that the relatively low-quality subgrade material will not be overstressed.

The inter-reactions between the various materials of a pavement system and the environment are extremely complex. Even though satisfactory engineering theories have been available for long periods of time, it was not until the coming of the computer that it was possible to make necessary calculations to develop reasonably accurate design procedures. The Kentucky Department of Transportation (Division of Research) has developed a computerized mathematical model based on the elastic theory which can be used to obtain a first approximation of the stresses and strains within a pavement system under various loading configurations. By extending the elastic theory and making use of energy (or work) concepts, the Department of Transportation has accounted for some phenomena which heretofore have not been subject to explanation.

FATIGUE CONCEPTS

When designing structures such as bridges or buildings, the maximum load to which the structure is to be subjected is selected. By application of various factors of safety, either directly or indirectly using such procedures as working stress theories, members of the structure are sized so that stress levels within any given member are below some specified tolerable level. The luxury of a factor of safety is not allowed in the design of highway pavement systems. When such factors of safety are applied (often as high as six to ten in the case of structures), the stresses induced in the structural members are very often reduced to levels below that at which fatigue must be considered. In the case of highway pavement design, fatigue failure of the structure becomes of primary significance.

The concept of fatigue is best understood by reference to an idealized stress-repetitions (S-N) curve. Every material has an S-N curve wherein the fatigue performance of a material can be exhibited by plotting stress level on the vertical axis versus the number of applications of that stress level to reach failure on the horizontal axis (see Figure 2). Assume, for example, 200 applications of a given stress level are applied to a structural member. It can be determined from the S-N curve that 1,000 of these stress applications would be necessary to fail the member. Thus, 20 percent of the fatigue life of that member has been

"consumed" by those 200 applications. It will also be noted from the S-N curve that there is some stress level below which the structural member can withstand an infinite number of applications of those stresses. This is often referred to as the endurance limit and is usually approximately 50 percent of the ultimate strength of many materials used in structural construction.

A highway pavement is subjected to a highly variable vehicular stream of traffic over a long period of time. There are a number of different types of vehicles, each carrying different gross loads, affecting the highway pavement to differing degrees. It is necessary then, to develop a procedure for expressing this variable traffic stream in terms of a single number which can be used for design purposes and which can be related to the S-N or fatigue concept.

The equivalent axleload (or EAL) approach was selected in Kentucky as a means to accomplish this task. This procedure involves the expression of all axleload weights that pass over a pavement during its design life in terms of some reference or base axleload. The reference axleload weight selected was 18,000 pounds. Any axleload could have been selected, and the change from one axleload reference to another will not change the results of a design process. The 18,000-pound axleload was probably selected because it represented, at the time the concept was developed, the typical legal axleload limit recognized in many states. The 18,000-pound axleload was also the reference used at the AASHO road test in the early 1960's. The passage of one 18,000-pound axleload would result in the application of one EAL (or equivalent axleload). If a 20,000-pound axleload were to traverse the pavement, it would result in the application of 1.7 EAL's. That is to say, the 20,000-pound axleload would cause 1.7 times the damage to the pavement as would one 18,000-pound axleload. The EAL for a given axle configuration, thus, represents the damage factor for that particular configuration. Figure 3 illustrates how the damage factor for selected axle configurations varies with increasing loads on those configurations.

Experience has indicated that the elastic theory and work concept used by the Kentucky Department of Transportation predicts very reliably the number of EAL's a given pavement system can support in its life time. Conversely, it is possible to design a pavement which will adequately resist the damage of a specified number of EAL's. However, the problem of predicting the rate at which EAL's will accumulate remains. This involves estimates of the numbers and types of vehicles which will be using a section of highway as much as 30 years in advance. Consider how difficult it is for an individual to predict his own

usage and driving habits 30 years in advance. The highway planner, then, has a much more complex problem in predicting the driving patterns and habits of other people 30 years into the future. He must also predict the locations of future high-traffic generators so he may design specific sections of highways. To illustrate the problem, a section of Ky 15 was designed to carry a given number of EAL's. The pavement, however, failed after only 12 months. Analyses showed that the pavement did in fact carry the EAL's for which it was designed. Unfortunately, the opening of a high- and heavy-traffic generator (a coal producing operation) was not foreseen and the rate of accumulating EAL's was underestimated.

SELECTED ILLUSTRATIONS

Figure 3 illustrates how the damage to a pavement increases as the total loads on various axle groups are increased. A single axle with four tires (two on either end of the axle) carrying 18,000 pounds will cause one unit of damage to the pavement. This was the legal axleload in Kentucky prior to 1974. The current legal axleload of 20,000 pounds on this same axle results in a 70-percent increase in damage (damage factor is 1.7) for only an 11-percent increase in total load. A tandem axle group can support a load of 37,000 pounds with a resultant damage factor of 1.0; three-axle groups can carry 56,000 pounds at a damage factor 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 can be increased by slightly more than 18,000 pounds with no increase in damage to the pavement.

In Figure 4, the damage factors for three commonly used vehicle types are shown to increase as the gross load on the vehicle is increased. The single-unit three-axle vehicle loaded to approximately 80,000 pounds (an additional payload of 40,000 pounds on Figure 4) is extremely damaging compared to the other two vehicle types. An 80,000-pound, single-unit three-axle vehicle is not uncommon on Kentucky highways. Assuming an empty weight of the vehicles of approximately 30,000 pounds (obtained from manufacturers' data), the single-unit vehicle will carry a payload of about 50,000 pounds at a damage factor of approximately 20. If that same payload is transported by the combination vehicles, the damage factor is less than 2 (in the case of the five-axle vehicles) or a tenfold decrease and less than 1 in the case of a six-axle vehicle or a twentyfold decrease in damage. The importance of the proper selection of vehicle type is vividly illustrated.

As the allowable gross weight limits are increased, the payloads that can be transported also increase. Figures 5, 6, and 7 show that the percentage increase in payload is

very much less than the corresponding percentage increase in damage. It is at this point that economic considerations become very significant. It is obvious, intuitively and from Figures 5, 6, and 7, that there are economic benefits to increasing gross vehicular weights. It is also intuitively recognized and illustrated in Figures 5, 6, and 7 that the damage and thus the resulting maintenance costs also increase as vehicular weights are raised; but this damage and attendant maintenance costs may be mollified by use of the appropriate vehicles. What may not be so obvious to many is the fact that the costs of increased maintenance increases at a much faster rate than the economic benefits from increased payloads.

Figure 8 displays the same information in a slightly different form. The very rapid increase in damage factor as the payload increases is again illustrated. The large differences in payloads between the single unit vehicles and the combination vehicles is obvious. This again illustrates the advantages accompanying the proper choice of vehicle type.

OTHER ISSUES AND FACTORS

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. The longer the span, the greater is the likelihood of two or more heavy vehicles being on the same span at the same time. For a given gross load, the longer the vehicle, the less the maximum bending moments at mid span. There is, of course, some load which will cause catastrophic failure. Other loads may induce stresses greater than a safe level and be permanently but insidiously damaging. The safe or endurance level is the stress below which no fatigue damage accumulates regardless of the number of applications of the stress. Any consideration of increased vehicular loads on highways must take into account the effects of these increased loads on the bridges on the highway system. Generalized statements cannot be made, and each bridge must be investigated to determine whether increased vehicle loading will induce stresses above the safe level where fatigue damage may accumulate.

Operating Costs -- Energy (gasoline and diesel fuel) savings might be realized if fewer truck trips result from larger payloads. However, increased fuel consumption per truck trip would be expected in order to move those increased payloads.

Greater weights will result in increased wear and tear on the tires, the brakes, and the basic vehicle itself. Equipment operating costs will be greater per vehicle per year.

Safety -- Accident severity and fatalities involving large trucks might increase. On the

other hand, increased payloads might lead to a reduced number of truck trips which would, in turn, result in less exposure to accidents.

Increased vehicular weights, requiring more efficient braking systems, might result in an increase in potential for brake fade and an increase in effective stopping distance of existing vehicles. The energy upon collision would thus be increased and might lead to an increase in the severity of accidents involving trucks.

Increased truck weights will cause greater differentials in vehicle speeds. Many truck drivers will increase speeds prior to reaching upgrades. This results in speed differences (between trucks and automobiles) which are potential causes of highway accidents.

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 as suggested by proponents of increased truck weights, will these savings in fact be transferred 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.

Enforcement -- Enforcement of present truck weight laws are difficult. Changing the law to make enforcement less difficult is not in itself good reasoning; however, the cost of enforcement might decrease if fewer violations would result. An aspect of enforcement, whatever level of effort is expended, 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 the truckers might be decreased if a system of issuing citations by sight (based on the presence of sideboards or on the length of the tire-pavement pavement contact, for example) could be developed. That might minimize the need to stop, weigh, and inspect vehicles. In the event of a weight violation, who should be fined: the trucker, the shipper, or the receiver?

Enforcement of truck weight laws is a necessary attempt to minimize the potential for premature failure of pavements and bridges. Alternatively, the use of truck-axle configurations which minimize fatigue damage eases the necessity for weight law enforcement. The choice and use of advantageous axle configurations may permit movement of increased payloads and at the same time reduce fatigue damage.

States now are required to certify the adequacy of enforcement of truck size and weight limits. Otherwise, a state may suffer the potential loss of a portion of the federal

funds coming to that state for highway purposes.

CONCLUDING REMARKS

It should again be noted that the mechanics of pavement performance in response to vehicular loadings is reasonably well understood. A reliable mathematical model has been programmed for high-speed computers so that analyses and designs can be made with much confidence. However, a comprehensive modeling of the economic factors has not been satisfactorily accomplished. General trends of many of the component economic relationships may be known, but precise relationships have not yet been defined, nor have these 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. Hopefully, recently initiated studies of the assignment of highway costs to various classes of users may help to extend our state of knowledge and capabilities.

Statutes dealing with limitations on trucks weights might be reviewed for consistency with the mechanics of pavement performance. Efforts should be made, by statute, to encourage the use of those vehicles which are less damaging to highway pavements. Legal limitations, and their enforcement for vehicles which are extremely damaging (for example, a single-unit three-axle truck) should be very stringent. Incentives, in the form of tax credits or increased allowable gross weights, for example, need to be coupled with any modifications of the statutes to further encourage the trucking industry to use those vehicles which are less damaging to highway pavements.

Factors and comments concerning truck design and usage and the mechanics of pavement performance contained in this paper might be used to prepare non-technical leaflets to be used as a part of an educational effort to impress upon various groups the importance of this problem. Such leaflets might be distributed to major trucking companies as well as independent and union truckers. The leaflet could be distributed, for example, at the time licenses are issued to truck drivers or at the time a vehicle is registered. This educational material could also go to vehicle designers and manufacturers as well as legislators on the state and national levels. It is important to convince these people that the types of vehicles used to carry heavy loads and the manner in which loads are distributed on the individual vehicle are relevant. Until users of heavy vehicles understand the significance of these matters, progress will be very difficult and long in coming.

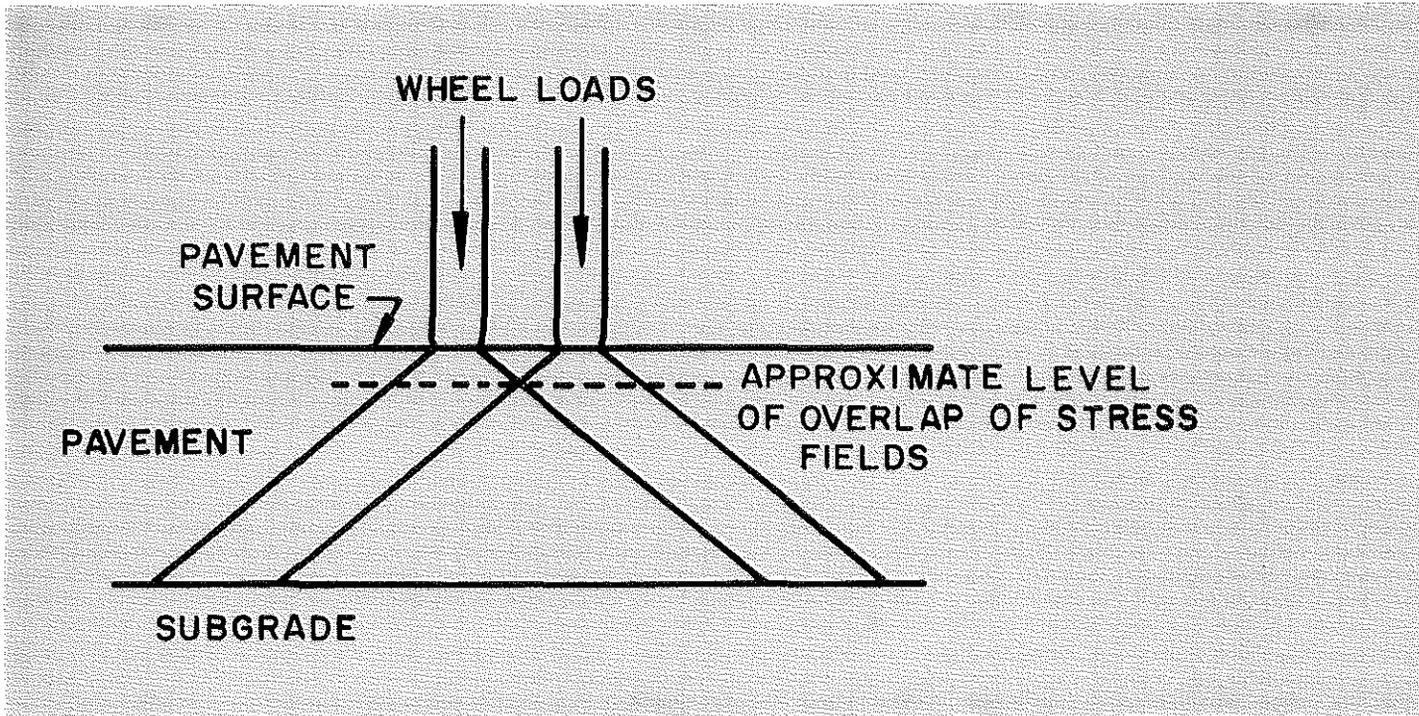


Figure 1. Distribution of Wheel Loads.

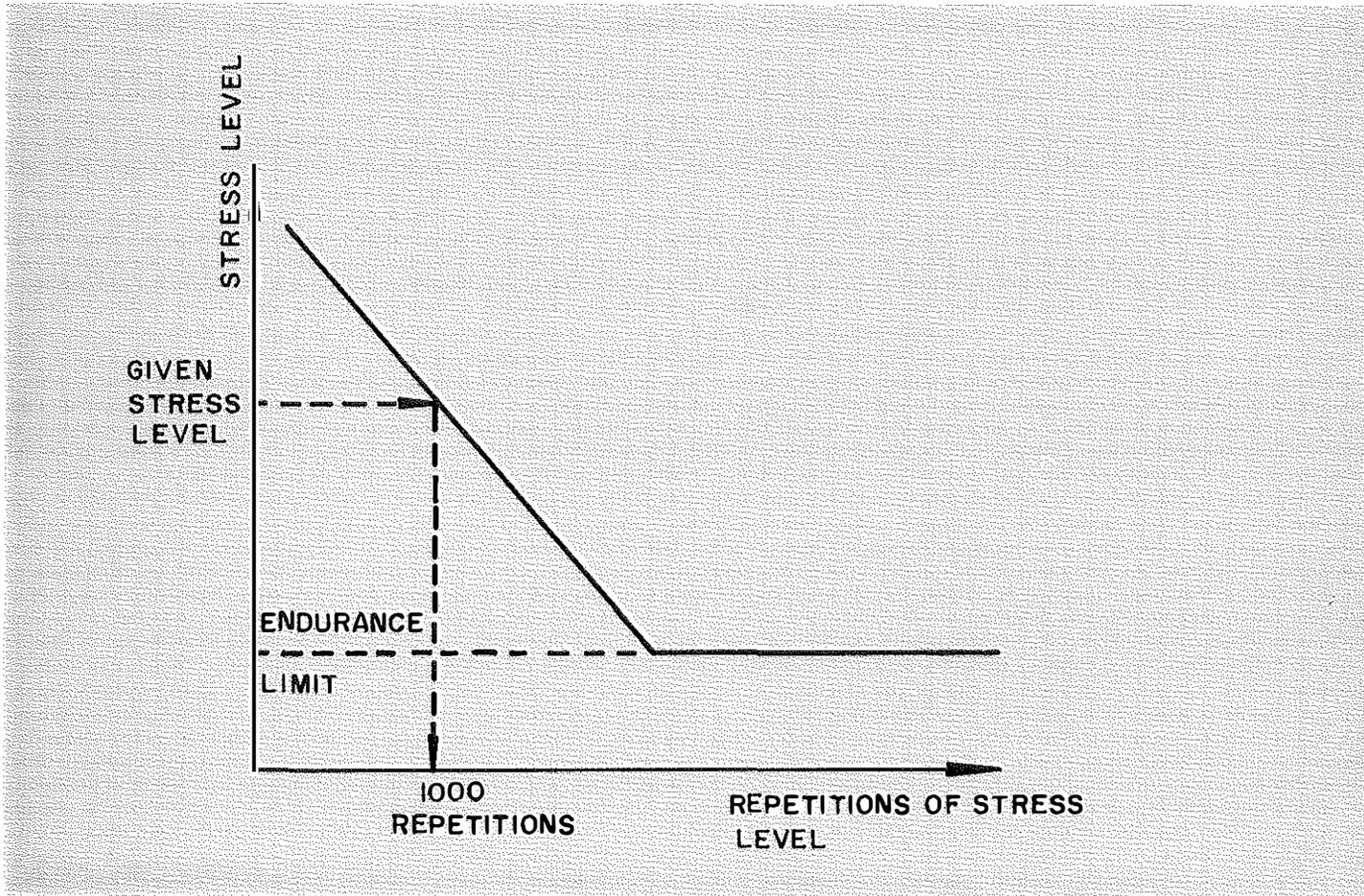


Figure 2. Idealized Stress-Repetitions (S-N) Curve.

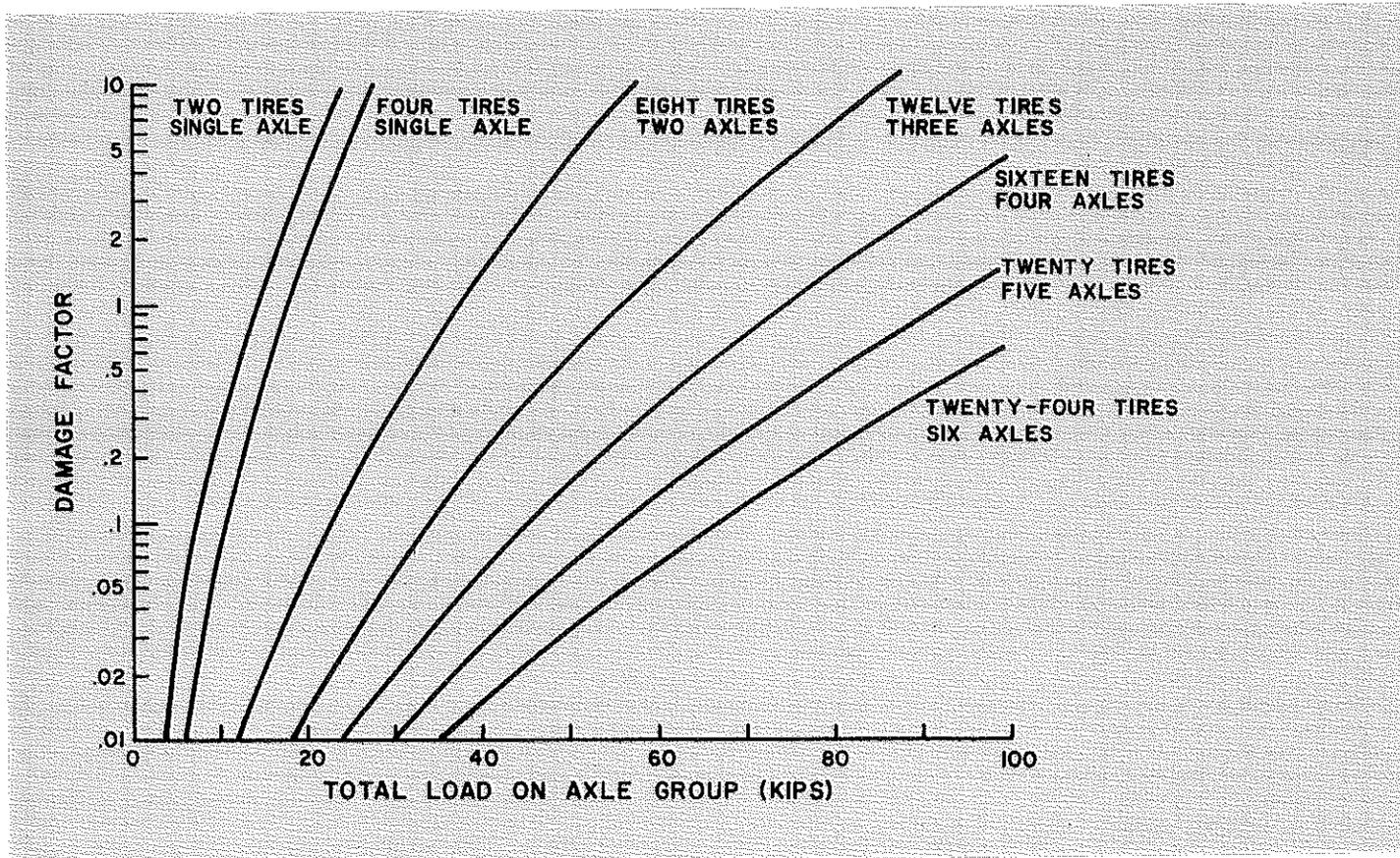


Figure 3. Variation of Damage Factor for Selected Axle Groups as Load on Axle Group Is Changed.

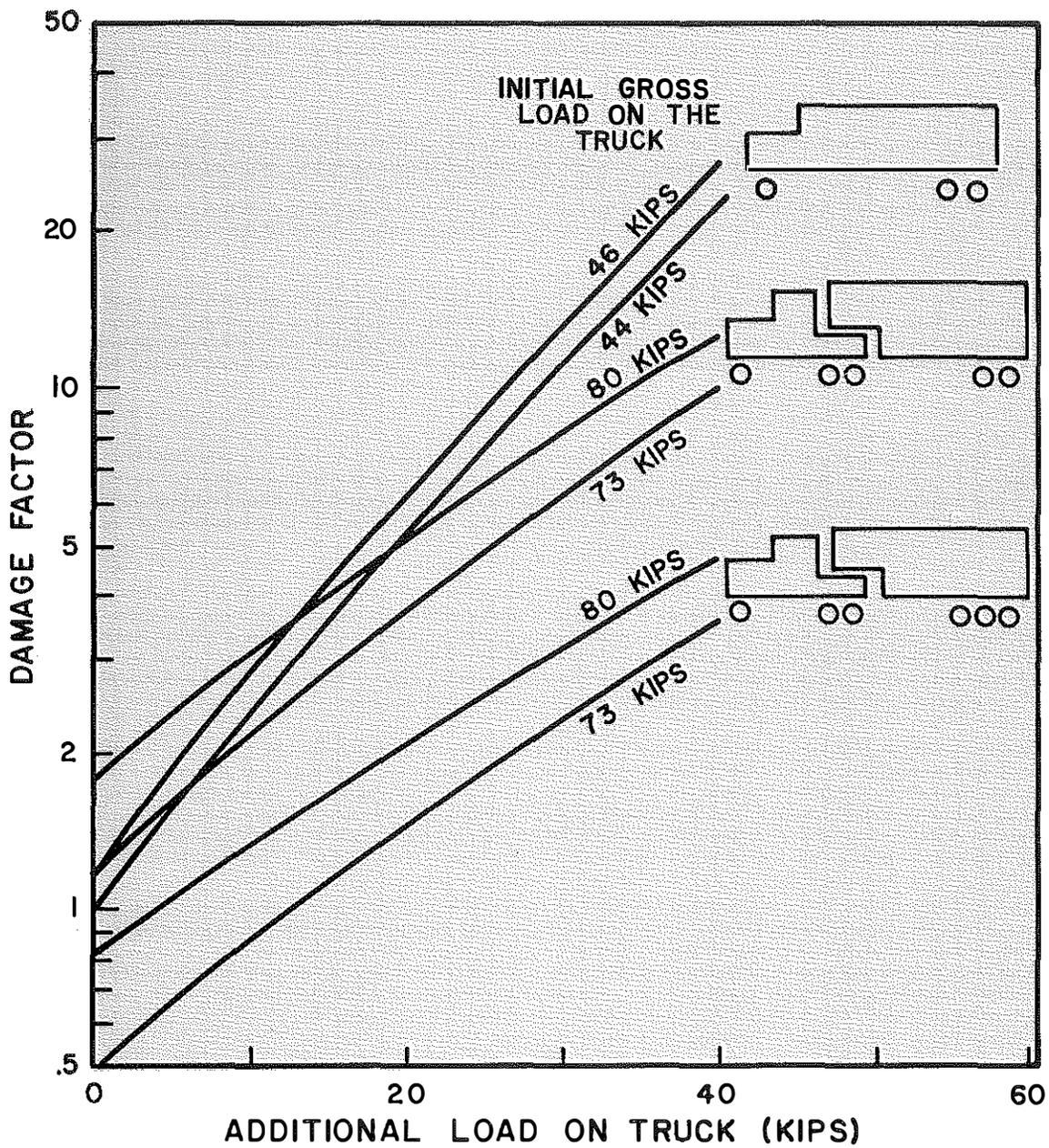


Figure 4. Increase in Damage Factor for Selected Vehicles as Load on Truck Is Increased.

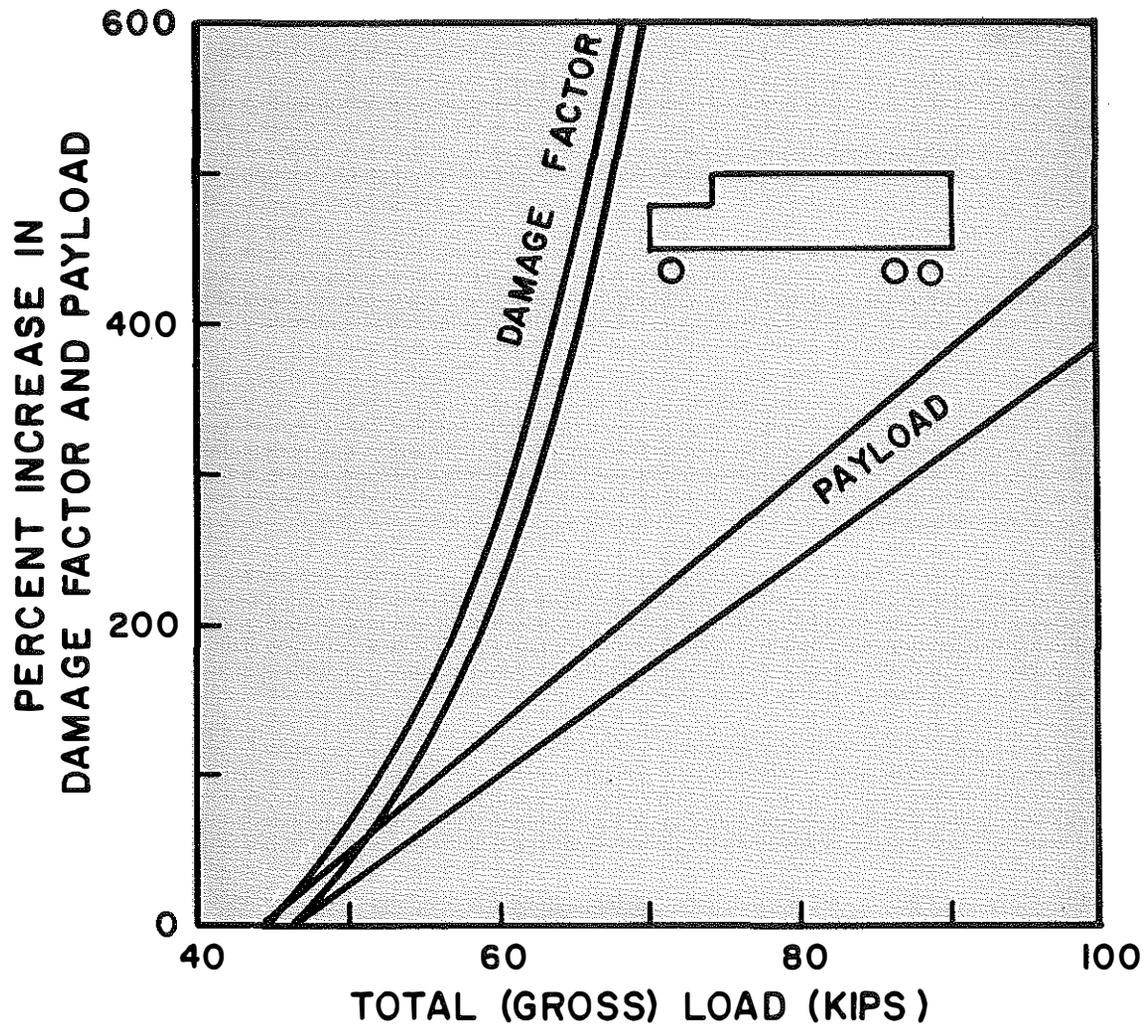


Figure 5. Increases in Damage Factor and Payload as Gross Vehicle Weight Increases for a Single-Unit Three-Axle Truck.

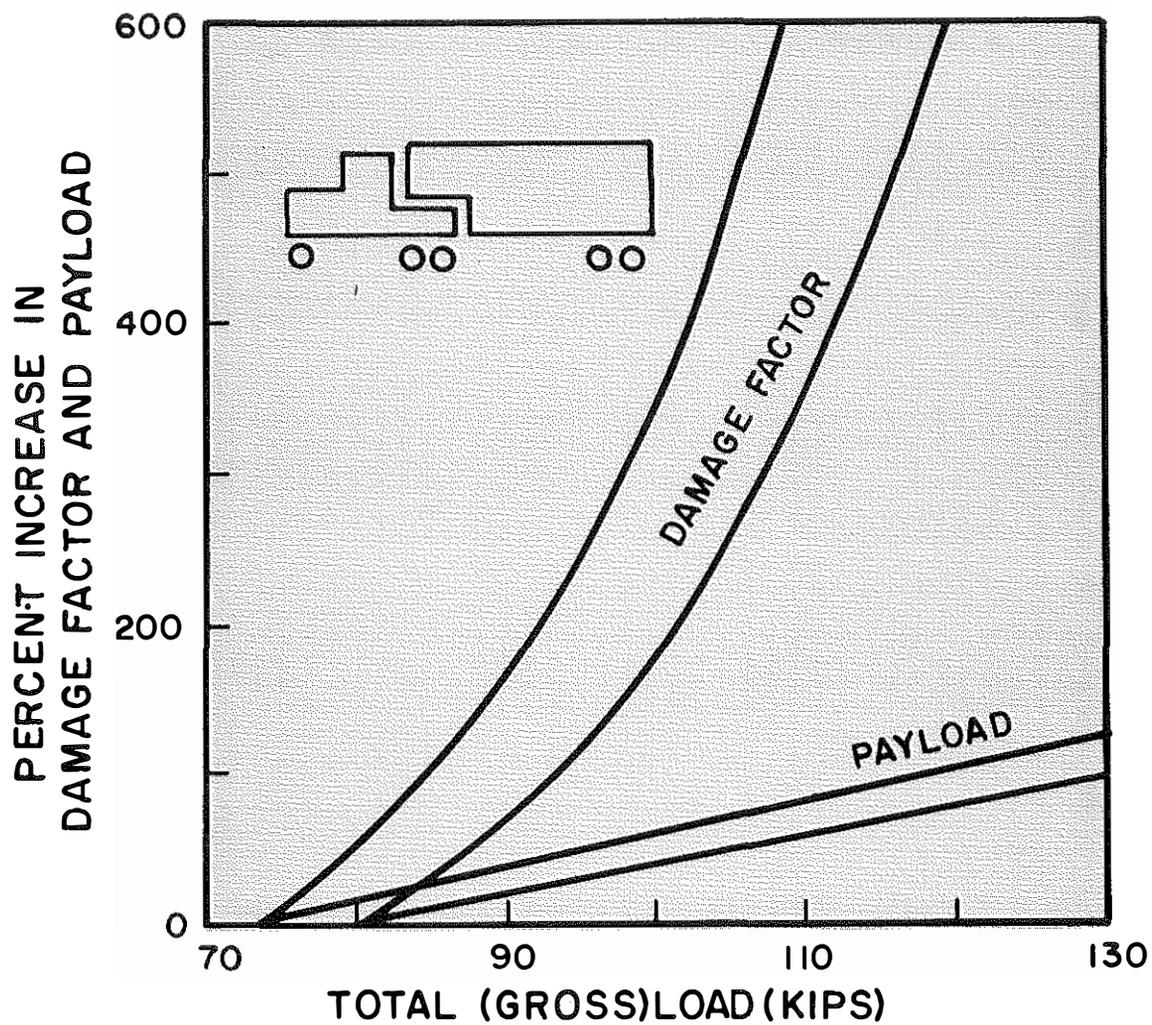


Figure 6. Increases in Damage Factor and Payload as Gross Vehicle Weight Increases for a Five-Axle Combination Tractor-Trailer Truck.

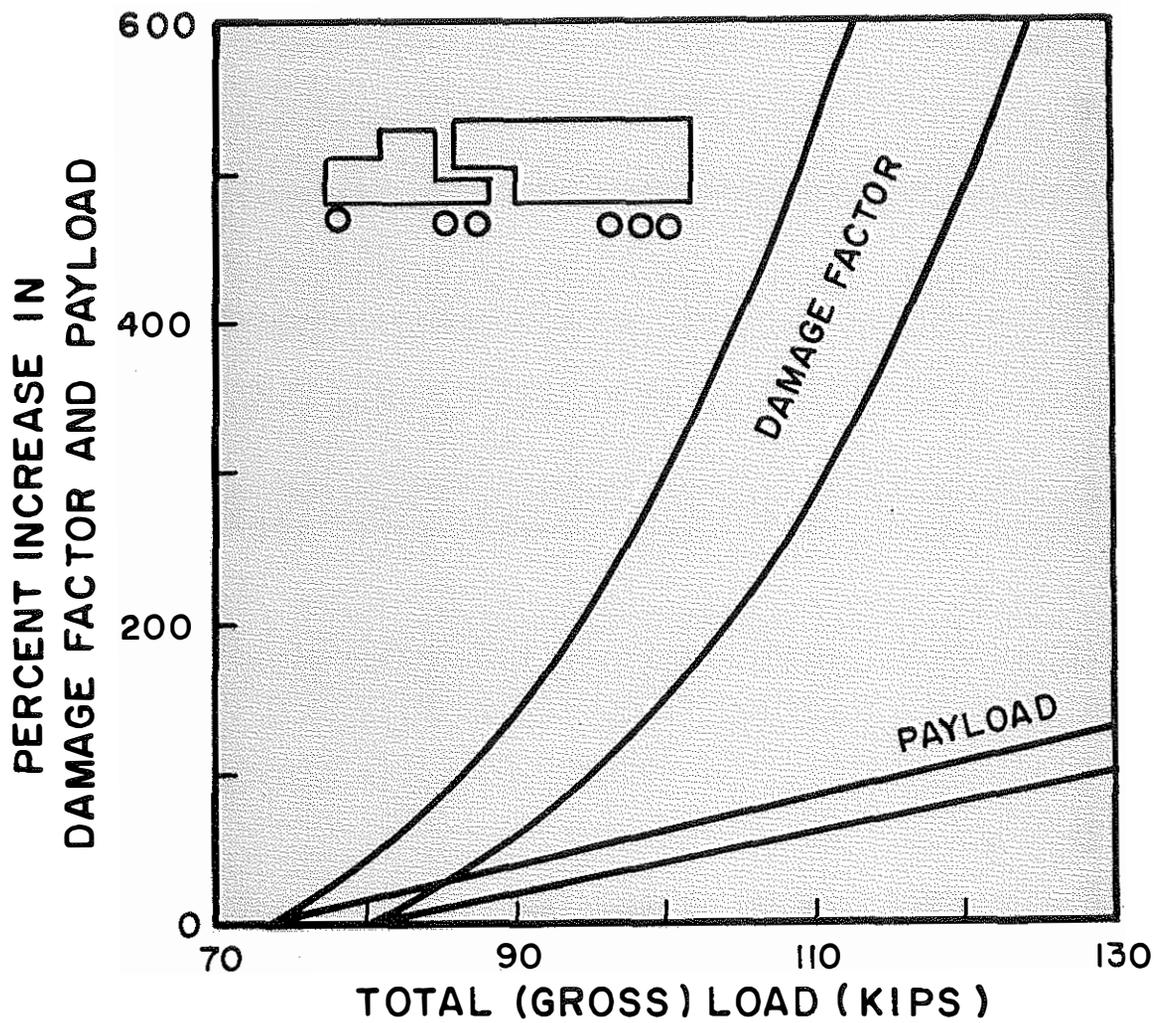


Figure 7. Increases in Damage Factor and Payload as Gross Vehicle Weight Increases for a Six-Axle Combination Tractor-Trailer Truck.

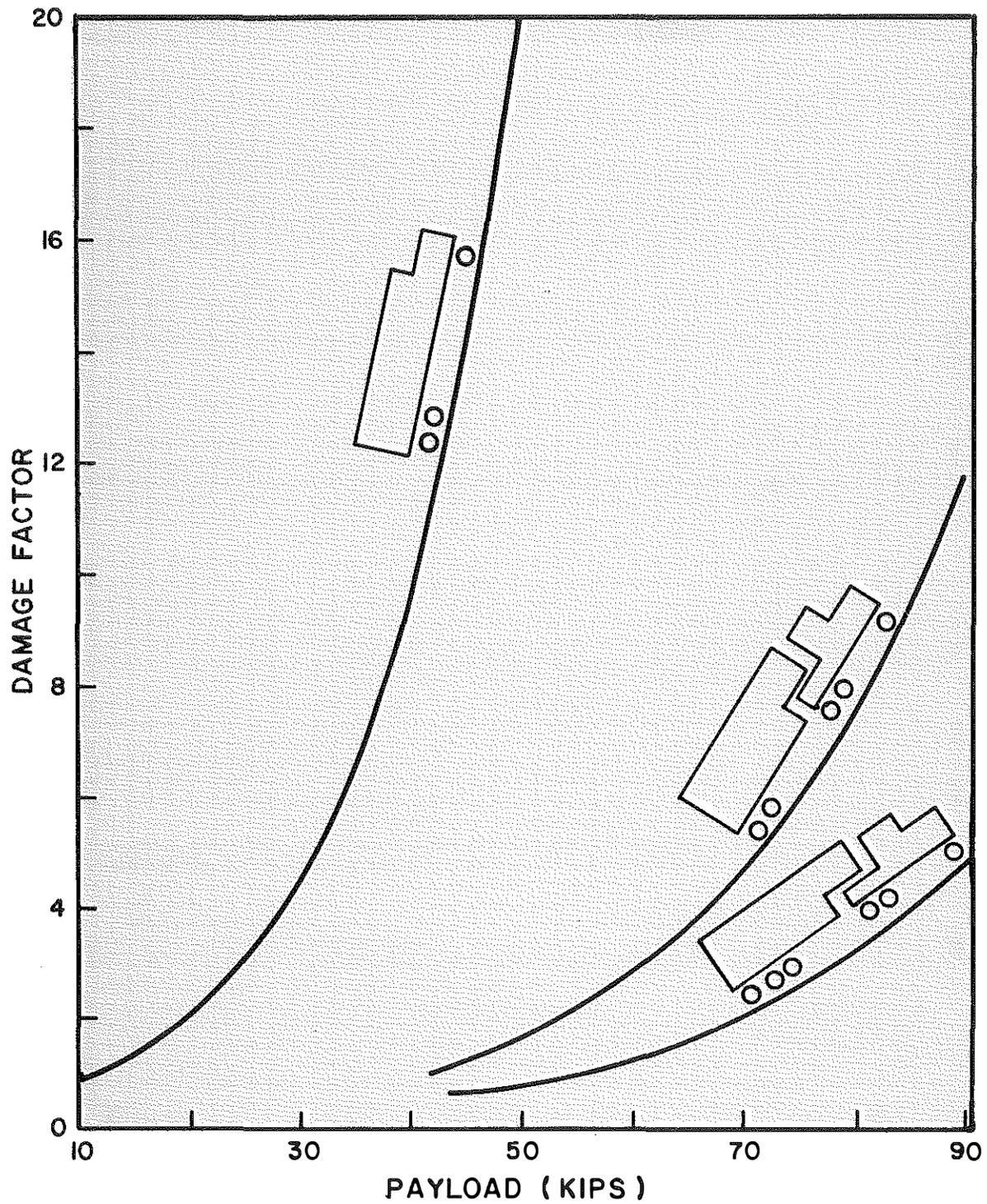


Figure 8. Variation of Damage Factor for Selected Vehicle Types as Payload Is Changed.