# Fundamental Problems in Relating Vehicle Size to Highway Costs

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Research on the problem of determining the relationship between highway costs and vehicle size has been in progress at The Ohio State University for more than four years under the sponsorship of four trucking firms and the Ohio Trucking Association. Most recently, a final report covered the entire cost assignment for the conditions and expenditures of the Ohio Department of Highways. The present paper discusses the problems associated with the development of cost responsibility for the studies to date.

Specifically, the paper covers the following philosophies that can be utilized in cost assignment problems:

1. Use of theoretical vs empirical relations between vehicle parameters and cost items.
2. Theoretical vs engineering solutions wherein single-valued results are obtained.
3. Direct or indirect sources of cost responsibility.
4. Distribution of indirect costs, classically designated as engineering or administration.

Several practical difficulties that must be overcome in assessing cost responsibility also are discussed, such as: (a) combining capital improvement costs with annual costs for maintenance and operations, (b) combining of cost factors controlled by weight requirements with those controlled by factors other than weight, (c) influences of traffic data on the assignment of costs to various highway user groups, and (d) extrapolation of empirical data to include vehicle sizes greater than currently authorized.

The paper concludes that the general shape of the curve for cost vs vehicle-size is available. Furthermore, based on a given annual expenditure by a highway department, reasonable estimates of differential cost can be obtained. However, theoretical answers to the cost-size problem will not be available until the establishment of more rational methods for design, particularly for highway geometrics and the related cost factors.

● THERE is no completely rational method for developing the relationship between vehicle size and the highway costs which are required to provide a facility for a specific vehicle. Therefore, current solutions which provide such relationships are empirical and require many assumptions and arbitrary techniques. While fundamental concepts can be studied and used where applicable, large portions of highway expenditures are currently processed without direct reference to the size of the vehicle.

Two types of considerations lead to the need for vehicle size and highway cost relations; namely, (a) the establishment of cost responsibility, and (b) the obtaining of the characteristics of the optimum-sized vehicle for the transportation system. The fact that these two problems require the same data as to vehicle size and highway costs does not necessarily mean that the approaches to solution are comparable. As a result, the philosophies and techniques which are utilized will vary and will be dependent upon the principal reason for the development of the relation. Highway costs as used herein will refer to those expenditures by an industry or governmental agency which are required for the construction, maintenance, and operation of a highway system. Specifically excluded are the operating costs expended by the owner or operator of a motor vehicle.

The research which has been conducted at The Ohio State University has included efforts to delineate the difficulties associated with both cost responsibility and optimum vehicle size. The work has been in progress for more than four years and has resulted in a number of publications (1, 2, 3, 4, 5, 6). Sponsorship for the investigation has come from four individual Ohio trucking firms, which initiated the studies four years ago, and, subsequently, from the Ohio Trucking Association.

The purpose of the following paper is to delineate the various basic philosophies which can be utilized in the highway cost relationships. Furthermore, possible points of departure and orientation for those interested in pursuing such research have also been discussed. The scope is restricted to the problems concerned with the highway cost and vehicle size relationships. Specifically excluded are taxation theories and the operating costs paid directly by the highway user. Rather than to attempt to discuss all of the individual cost items, the following report restricts itself to the broader questions which are in the realm of fundamental philosophy or basic engineering methodology.

## DEFINITIONS

For the sake of brevity, several expressions and concepts requiring definition will be utilized in the following report. Frequent references will be made to weight factors and non-weight factors. These two terms are used to designate vehicle parameters which affect highway costs, or portions of cost items, which are influenced by weight, and by variables other than weight, respectively. The only highway costs which are largely influenced by the weight of the vehicle are structures and pavements. As a matter of fact, since these two cost items are affected by factors other than weight, such as the width and height of the structure, only a part of the costs is completely defined by weight requirements. Weight effects, then, would include those portions of the structural and pavement costs which are influenced by the vehicle weight. The costs may also be referred to as structural effects, because of the influence of structural capacity. Specifically, the non-weight factors include the geometry of the vehicle, the performance characteristics of the vehicle, and the capability of the driver. Since the non-weight variables influence costs which are related to highway geometry, the costs are also referred to as geometric effects. Pedestrians can also be considered weight and non-weight factors insofar as sidewalks and pedestrian underpasses or overpasses are concerned. However, direct pedestrian responsibility is a negligible consideration in most problems.

The following definitions have been found quite useful for the cost assignment problem but are not necessarily valid for more general usage:

1. Construction Costs—direct expenditures related to capital improvement.
2. Maintenance Costs—direct expenditures related to preserving and maintaining facilities which are provided by capital improvement.
3. Operation Costs—direct expenditures required to expedite the flow of traffic.
4. Administration Costs—indirect expenditures incurred for construction, maintenance, or operations in the form of over-all direction and supervision of the sytem.
5. Enginering Costs—indirect expenditures incurred in the construction, maintenance, and operation of the highway required for technical direction, planning, supervision and execution of the work performed.

In the preceding definitions, the term direct expenditure implies that the costs are readily traced to the cost item, whereas indirect expenditure suggests that the normal accounting system would not provide data as to the proper assignment to a specific cost item.

The preceding cost delineation does not eliminate practical problems in assigning highway expenditures. For example, there is certain to be some question as to whether a cost should be classed as construction or maintenance, particularly when the maintenance expenditures are quite large. Also, certain costs could logically be classed as either maintenance or operations, and a good example is the replacement of a guardrail. A precise delineation between groups may or may not be critical. In most instances, the method of allocating cost to vehicles is independent of the group to which a cost is assigned. The decisive consideration as to cost grouping is usually the availability of records.

Cost responsibility as used herein refers to users only and to the direct variables used to obtain the final design. This differs from the more general definition used in the highway economics field (13).

The use of benefits to allocate costs is a recognized procedure, but the benefits are not in themselves variables that affect the magnitude of highway cost items.

## VARIATIONS IN BASIC PHILOSOPHY

In initiating a study of highway cost relationship with vehicle size there will be several choices as to the basic philosophies which will be applied to the research. Some of these constitute true alternatives, while others are related to the purposes for which the investigation is established. In the following paragraphs several of these questions are discussed.

### Theoretical Methods vs Design Techniques

There are two theories under which cost-size relationships can be developed. The first approach might be designated as the "theoretical" in that all expressions relating cost with vehicle size would be rational. The second approach involves the establishment of the relations between cost and size on an empirical basis, namely one that is in current use as a design technique. Complete use of a theoretical approach is not a practical possibility because of the many functions which have not been established on a rational base. Even if one could assume that the weight affects can be evaluated rationally, the non-weight factors represent the complete reversal. The methods for determining roadway width, grade, curvature, structure openings, and other similar geometric factors are completely empirical and direct relations with vehicle size are normally differentiated only by extreme size variations. Even the weight effects are questioned as reflected in the AASHO tests at Ottawa, Illinois. In fact, if a theoretical answer is to be obtained, then all highway research problems are involved.

While certain adjustments between theory and practice could be tolerated in an effort to obtain as theoretical an approach as possible, there is a more fundamental distinction and philosophy involved with the choice between the two. The importance of the concept of using empirical practices goes beyond the fact that the data are based upon the best experience available. If empiricism is used, actual methods employed in the design procedures could be incorporated. Thus, the results would reflect the methods under which the funds are being expended. The fundamental question becomes, then, whether the cost relationships to be developed are intended to reflect a theoretically true condition or the actual manner in which monies are expended.

Where the problem is one of establishing the optimum vehicle size with reference to costs for all types of transportation, then the theoretical approach might be the more desirable. Where the relationships are being developed for the purpose of providing data for assigning cost responsibility, the most equitable method appears to be relationships based upon current design techniques; that is, methods under which funds are being expended.

### Degree of Accuracy

As stated in the preceding paragraph, the absence of specific and implicit functions prevents a completely rational solution to a cost-size investigation and one must assume that any solution achieved during the next few years will require empirical techniques or some modification to a purely theoretical approach. Associated with the empiricism will be a question as to the degree of accuracy of the results. The question will be raised because of (a) the absence of a rational expression, and (b) the evaluation of many variables which require statistical considerations. Assuming that the level of accuracy will be a function, in part, of the dollars available for the study, there is still a part of the accuracy which is controlled by the adequacy of the empiricism.

The question to be considered is whether one relationship will be obtained and referred to as the solution, or whether multiple sets of data are to be developed. Multiple relations could take the form of maximum and minimum solutions (Fig. 2) or could be statistical deviations from a single curve. The advantage of a multiple set of values over a single solution is that less argument will exist as to the competency of the extreme values. Furthermore, the influences of the questionable factors will have been estimated.

Some problems, such as one upon which cost responsibility and, ultimately, taxation is based, may require that a unique result be obtained. After obtaining multiple values, judgment may be needed in order to reduce the data to a single set.

A very difficult problem is encountered in attempting to estimate the total cost requirements, for various sized vehicles, which will be needed for a major road network. For a limited size and type of road system, such as a turnpike, the total costs for various sized vehicles can be reasonably precisely determined. The total cost of a major road system is complicated by the absence of rational methods for design, and by the wide variation in the unit costs which exist on a large geographical unit. Under the existing state of knowledge, estimates varying by 200 to 300 percent should not be surprising (Fig. 2). Furthermore, many different answers can be completely justified when conducted under the design principles of current practice. Unfortunately, a precise type of estimate should not even be considered within the realm of practicality. Total cost relationships should be developed with a firm understanding of the limits of accuracy.

Where differential cost is the principal objective of the study, the results of the investigation can be more precisely obtained than for total cost. Past studies (2, 6) have indicated that while the actual total cost to be anticipated can vary over a wide range the differential costs are predictable within much more narrow dollar values (Fig. 2).

In solving the problem of cost and size relationships, then, it is important to study the reasons for which the research is conducted. Since single-value data may be difficult to justify, the double-set of data is recommended, at least within the framework of the methodology. Of paramount importance, however, is the fact that the limitations of existing knowledge must not be overlooked, and should be evaluated if possible.

## Indirect vs Direct Sources of Cost Responsibility

Consideration must be given at the start of the study as to whether direct or indirect sources of cost responsibility are to be treated as major variables. For the purposes of this report, the assumption is made that highways are solely for the purpose of the highway user and therefore direct sources must be related to the highway user. Direct sources of costs then, refer to the factors used in the design for controlling the magnitude of the structure or geometric conditions. Specifically, the sources of direct costs are the numbers, weights, and types of vehicles. Driver ability, vehicle performance, and pedestrians are direct sources, theoretically, but are rarely utilized as such in current design criteria. Indirect sources of responsibility include such things as railroads, abutting property owners, and physical and natural obstacles. The railroads produce a part of the requirements for a special crossing but the magnitude of the members of the structure are controlled by the vehicles which will be utilizing the crossing.

The geology, topography, and climate of an area are typical of indirect sources of cost responsibility. They are a source of cost in that the dollars expended are affected by their characteristics, but are indirect in the sense that ultimately vehicle parameters control the design. The principal influence of indirect sources is to increase or decrease the magnitude of the cost differential. In conducting a cost-size study, a statistical evaluation of the effect of geology, topography, and climate will be required. Thus, if one part of an area is particularly mountainous and another part is essentially flat then the cost differential assignable for earthwork for the combined areas will be some value between those produced in the two extreme conditions.

Direct cost responsibility, therefore, associates all highway expenditures with the highway user. Indirect costs on the other hand, affect the magnitude of expenditures and of cost differentials, and contribute to, but do not "control," the ultimate design.

There is no inference intended that indirect sources of cost responsibility are not important to highway economic studies. For such items as geology, topography, and climate the indirect sources will become a factor in statistical evaluations for a given area of application. For other indirect sources, such as railroads, abutting property owners, and the general public the question is concerned with economics of the total society and whether the highway user should be relieved of any part of the total cost responsibility. In questions of taxation this last decision is critical and associated with broad economic questions. In attempting to determine the optimum size of vehicle the importance of the indirect sources may or may not be pertinent. In any event, in

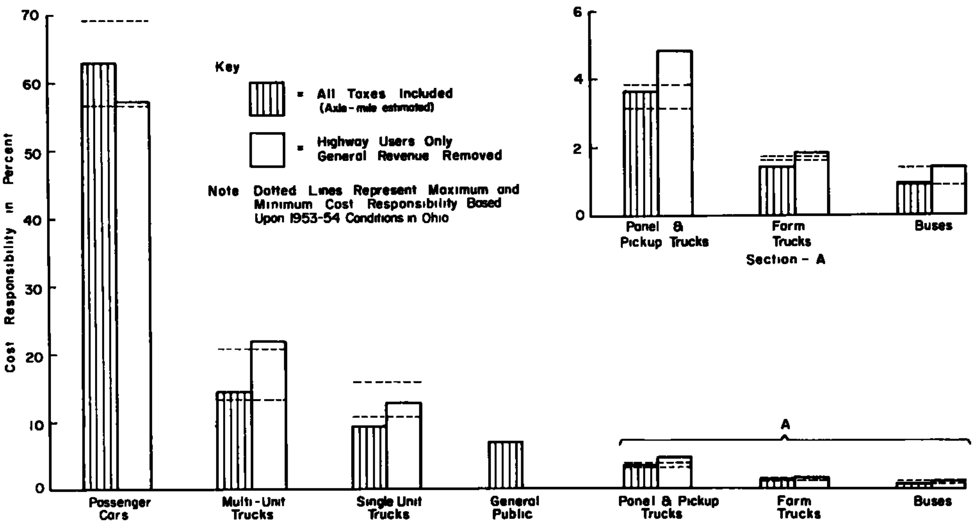


Figure 1. Relationship between cost responsibility and taxes paid.

order to develop rational expressions of the relation between highway cost and vehicle size, indirect sources should not be confused with the direct sources which control the design of the various elements.

## Types of Cost to Include

To a certain extent, the types of costs which should be included in the research are a function of the particular problem. In most cases, the problem will be addressed to the total expenditure required to construct, maintain, and operate a system. Attempting to include all possible costs leads to some interesting questions. For example, the officials of the state government who deal with the highway system, such as the governor, state treasurer, legislators, etc., undoubtedly should have part of the expenditures of their offices attributed to highways. For major systems these costs will be a very small part of the highway budget, and can be safetly neglected. For a toll turnpike the question is a little more confused, since the relationship between the toll facility and the governmental offices may be less clearly defined. If no charges are made, then no actual costs arise, and, therefore, none need be considered.

An interesting cost is that required for conducting the business of agencies such as the public utilities commissions. In some states, the operating funds, insofar as highways are concerned, are collected directly from trucking companies in the form of taxes. The purposes of such commissions are for the regulation, and thereby, to a degree, the protection of the individual trucking companies and are not for the assistance of highway users in general. Therefore, such expenditures would appear to be more logically "operating costs" of the user than highway costs as defined herein.

Included in many highway department lists of expenditures are certain interest charges on bonds sold for some phase of highway construction or maintenance. There is little question but that these interest costs are charges accumulated because of the highway system. Sometimes forgotten, however, is the fact that the dollars collected on a pay-as-you-go basis theoretically deprive the citizens of opportunities to invest or to reduce their own obligations. Therefore, highway programs which are based upon a pay-as-you-go program should include consideration of when money is collected with reference to when the improvements are obtained or expended. If one is to consider the total transportation picture, including railroad, airports, waterways, and pipelines, then the interest costs, both on dollars collected and on bonded indebtedness, should be included as cost. The inclusion or exclusion of interest costs will ultimately be decided by the demands of the problem. Consistency as to treatment of interest should be encouraged, particularly where interest on bonded indebtedness is obviously present, but the loss of income to the taxpayer on a pay-as-you-go plan is not so obvious.

### Types of Taxes to Be Included

Cost responsibility studies will frequently lead to a comparison between costs and taxation for various highway user groups. Many such studies have led to conflicting results, particularly as efforts are made to express taxes paid on a unity basis. One of the reasons for the apparent discrepancies lies in the types of taxes which are included. For example, in a preceding paragraph the taxes collected by the public utilities commissions were suggested as logical "operating costs" and as such could not be termed taxes paid to compare with cost responsibility. Thus, a principle is suggested; namely, that the taxes to be compared with cost responsibility should be "highway user taxes" if highway users are considered as the direct source of all highway costs. As used here, "highway user taxes" are intended to designate those taxes paid by the user and which are utilized for highway purposes.

If the preceding principle is valid, then taxes paid by the highway user which are not used for highway purposes would not be included. Examples of such taxes would be Federal and State income taxes and some excise taxes. In certain states and local governments portions of the general fund are used to supplement the highway user taxes in order to have sufficient operating funds. Thus, certain portions of general taxes may be logically presumed as "highway use" taxes. In such cases, the non-highway-user sources of highway use tax should be credited as the source of part of the monies collected. Results from the Ohio State studies(6) are included in Fig. 1 and the influence of the taxes included in the investigation is shown.

Since the inclusion or exclusion of taxes paid is argumentative, data under several assumptions may be required. However, the validity of comparing cost responsibility with taxes paid, when the tax included monies which are not utilized on highways, is to be questioned. There does appear to be greater consistency if only highway use taxes are included.

## PROBLEMS OF APPLICATION

In the actual development of the relationship between highway costs and vehicle size many practical problems are encountered. Some of the more critical of these questions of methodology are covered in the following paragraphs. In order to facilitate the discussion, the methods used at The Ohio State University have been used by way of illustration. There is no inference intended that the solutions constitute the only way nor the best way for general conditions.

### Selecting a Single Vehicle Parameter

Most cost-size problems must ultimately be expressed as a relation between a single vehicle-parameter and a highway cost. The selection of units for cost and size is a troublesome problem, particularly for the vehicle parameter. Perhaps the situation is best exemplified by considering pavement and earthwork costs. Pavement expenditures are obviously more related to axle load than to any other vehicle parameter, and dimensions of the vehicle are not of much importance in differential pavement cost analysis. On the other hand, earthwork expenditures are hard to relate to axle load and cannot be done on a direct, rational basis, for they are more logically associated with vehicle dimensions, performance, and the driver. While there is no established requirement that a single parameter be utilized, many problems, and particularly the taxation question, must be expressed as a single parameter or else the solution will be confused with two vehicle parameters for expressing relationships. While it is reasonable and necessary in the early stages to develop independent functions in terms of more than one vehicle parameter, one should not be surprised to find pressures or reasons to reduce the relationship so as to express the highway cost in terms of one vehicle variable.

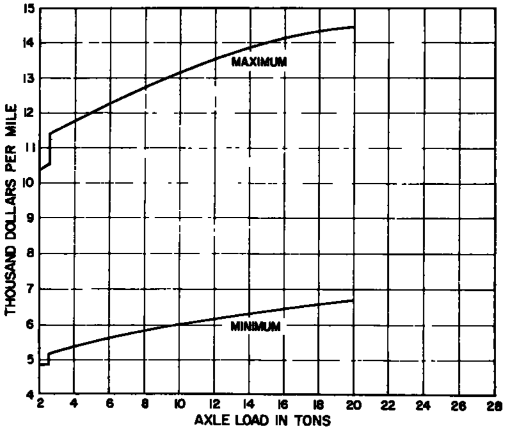


Figure 2. Relationship between annual costs and the design axle load.

To develop a single vehicle parameter one must return to the basic factors which influence expenditures. Assuming that only direct sources of cost responsibility are to be considered, then cost responsibility can be traced reasonably, to either (a) a vehicle weight factor, or (b) to a vehicle dimension or performance characteristic. This assumes that the very minor effect of pedestrians can be neglected. The vehicle weight factors can conveniently be reduced to axle load, if certain considerations are treated in terms of axle spacing. Similarly, the effects of vehicle dimensions and performance can be traced to the way they affect various phases of highway geometry. All items of cost which are not affected by weight will then by necessity be affected by the vehicle geometric factors. To reduce the geometric factors to a single vehicle parameter does cause some difficulties. The best solution is achieved by a statistical evaluation of the traffic using the highways. Another possible technique would be to use a common design methodology, wherein vehicle characteristics are handled solely on the basis of trucks

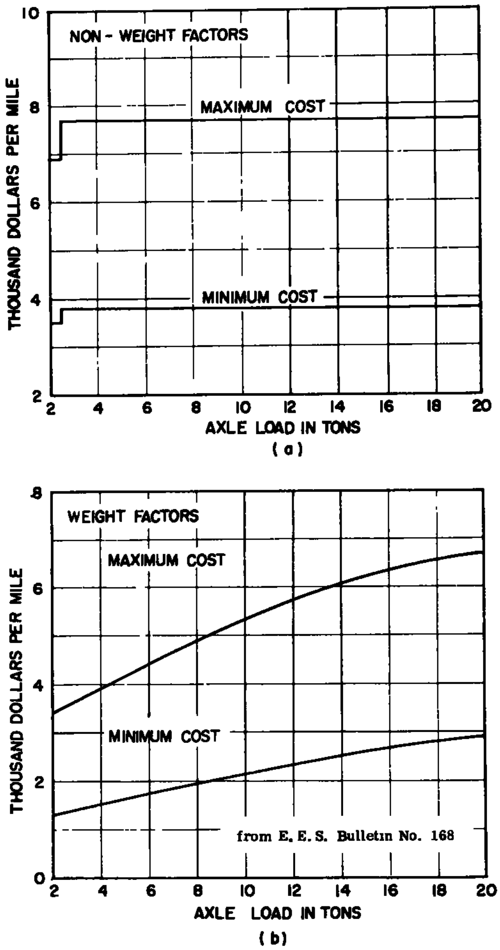


Figure 3. Annual costs versus design axle load for weight and non-weight factors.

and passenger cars. Utilizing the last-mentioned approach, one can set the maximum axle load for passenger cars and pick-up trucks and produce a cost differential for heavier trucks due to geometric factors.

Considering for a moment the actual influence on a given study, one can consider the three elements or groups of cost; namely, capital improvement, maintenance, and operation. For the first two, the weight and the geometric factors can be related to the actual capital improvement costs. Operations, however, are restricted to geometric considerations. For a given problem, then, cost is divided into weight and geometric requirements within the capital improvement and maintenance groupings. Having the total costs which are affected by the weight variable and the total expenditures which are influenced by geometric considerations, two cost differentials can be established. Combining the two on a basis of a single vehicle parameter is accomplished from the Ohio State studies (6) in Fig. 2. The basis for the combined cost is given in Fig. 3. It can be seen that there is a cost differential between axles smaller and larger than 2.5 tons for the geometric factors but an exponential type of curve reflects the weight influence. The curves of Fig. 2 require a statistical evaluation of the point at which the geometric differential occurs. For some problems, the single differential at 2.5 tons (or similar-type value) is all that might be required. However, for the case of establishing the optimum size of the vehicles or for predicting the effect of increasing the size of the axle load, the relationship suggested by the cost versus axle load would be useful. There is no way, based upon design practice, for estimating the effect of lengthening or widening the vehicle. Figure 3 suggests that geometric effects are independent of the vehicle geometry, but such an answer is a reflection of design methods rather than sound analysis of cost differential.

To summarize, then, attempts to relate all highway unit costs to a single vehicle parameter may produce misleading concepts. It will be desirable to indicate for highway unit costs separate relationships for geometric factors and for a weight parameter. One additional reason for developing two parameters is related to assigning cost responsibility because use must be made of axle-mile and vehicle-mile for allocating costs to various user groups.

## Reducing Highway Costs to a Unit Basis

Insofar as the highway cost variable is concerned, several methods could be used for reducing all expenditures to a common highway unit cost parameter. Two commonly used factors are total cost and annual cost per mile. For certain kinds of problems, the total cost expended by a highway department or by an agency could be plotted versus vehicle size. Total cost is particularly useful for a taxation problem or for a condition where a known amount of funds is to be available. However, where the intent is to establish the optimum vehicle size it will be necessary to reduce the highway costs to a unit basis.

The handling of maintenance and operation costs is not particularly difficult. Since the expenditures are made on an annual basis and presumably can be spread over the entire mileage in the system, total maintenance and total operations costs can be divided by the number of miles. For capital improvement some reduction is necessary to obtain an annual figure to combine with maintenance and operations. The reduction of capital investment to an annual cost poses the normal question as to the proper interest rate to be utilized with a capital recovery factor. The selection of the interest rate will undoubtedly parallel the practice of a particular agency in its normal economic studies.

Reduction of expenditures for major improvements to annual cost also involves predictions or establishment of design life. There is quite a range of values commonly assigned to various items of capital improvement; for example, the design life of right-of-way may extend for 50 to 75 years whereas for pavements the period is rarely more than 20 years. Fundamental principles of engineering economics, as used in industrial practice, suggest that the life period to be utilized for a study should be based upon the longest period of some component of the cost, provided that the period is consistent with the planned use of the facility. Components with shorter lives must have replacement values computed. Based on experiences of the past in the United States, it is somewhat difficult to envision the current right-of-way and earthwork designs being sufficiently advanced to permit a design life of 75 years. Furthermore, the problems of obtaining costs of several successive pavements 20 to 40 years in the future are obviously in the realm of conjecture. As a result, in the studies conducted at The Ohio State University, a design life of 20 years was utilized for all elements of new construction costs. This in effect assumes that within 20 years the roads being constructed at this time will have outlived their current right-of-way and earthwork design. For the average state highways, this is probably true, whereas for the interstate system it is quite likely that a longer design life would be permissible.

In order to combine annual costs of capital improvement with those for annual-type expenditures, the total mileage in the system must be considered. The rate of new construction on an existing system will rarely be great enough to rebuild the system completely within the design life. Therefore, some adjustment must be made for new construction costs to obtain costs for capital improvement per mile. If a completely new system is under study, the cost of new construction or capital improvement can be readily reduced to an annual basis and combined with anticipated maintenance and operations to obtain total cost. Such a condition exists for a toll turnpike.

One adjustment which can be made for an existing system is accomplished by assuming that the capital improvement for a specified period of time will consist of four types of activity; namely, new construction, reconstruction, resurfacing, and surface treatment. One may also have to assume that certain mileages will receive no capital improvement. By statistically evaluating and weighting the costs for the four types of capital improvement, one can get the average cost of capital improvement per mile per year. Such a procedure, in effect, reduces the cost of capital improvement from the typical value for new construction to an expenditure commensurate with the type of improvement received by the system as a whole. Including resurfacing and surface treatment as capital improvement rather than maintenance is not particularly critical. If it were included as maintenance there would merely be a higher number of miles with "no capital improvement," and the weighted average annual cost of capital improvement would be reduced.

Reducing the cost of structures to an annual expenditure per mile obviously requires special procedures. Variations in structure costs are frequently obtained for lineal feet of bridge or for square feet of bridge roadway. The conversion of such data to annual cost per mile requires a reduction of the capital investment to an annual basis as well as the determination of how many lineal feet or square feet of bridge are present on a mile of highway. The fact that the type of bridge structure will vary, thus changing the relationship between cost and size, must be handled on a statistical, weighted basis. Assuming that one can get a realistic relationship between a vehicle parameter and the average cost per lineal foot of structure, the problem is to convert to a structure cost per mile for the system.

One reasonable approach would be to obtain the total number of bridge feet in the system and by dividing this value by the number of miles, the average number of bridge-feet per mile could be obtained. By employing a factor to account for the rate of replacement, annual costs would be available.

A less complex procedure was utilized in the studies at The Ohio State University (6). The total dollars expended per year each of a six-year history were averaged in order to obtain the average dollars for structures per year. The total number of miles of new construction were also computed on an average annual basis and the total structural dollars per mile of new construction was obtained. It was then assumed that the same ratio of structure cost to new construction mileage would be followed throughout the period studied. Such an approach produces the structural dollars per mile of new highway construction and no conversion to lineal feet is involved. Since maximum and minimum solutions were obtained the accuracy of the estimate was considered to be reasonable in light of other assumptions required in the study.

## Considerations of Highway Systems

In many studies involving incremental or differential costs, the highway expenditures are separated on a basis of highway systems. Sometimes this is done on the basis of political subdivisions, such as federal, state, county, municipal, etc., and in others it is on the basis of types of highways required. For example, in Pancoast's studies in Ohio (7) a division was made on the basis of Type A, B, C, and D roads where each of the four types had typical cross sections for pavement and other cost items. The need for such a breakdown can be traced in part to auditing and accounting procedures. There are also requirements for such a delineation because of differences in design, construction, maintenance, and operation procedures. In many problems, there is no need to consider the type of roads. In fact, for theoretical considerations, the solution should be achieved using only the fundamental direct cost parameters. However, when costs are being assigned on the basis of the method utilized in design, then road-type becomes a consideration insofar as the method of design varies for the several systems.

Responsibility for certain types of highway costs should not vary appreciably with the road system, even utilizing the applied approach. For example, structure capacity is normally established for a constant type of maximum load and the frequency of loading produces minor variations. With the exception of low-traffic secondary highways, even pavements are currently designed for the heaviest axle load to be expected, but with variable numbers of applications. Unfortunately, the quantitative effect of repetitions is not well understood. The cost factors controlled by geometric considerations do not normally require a delineation into highway systems since there is some indication that the traffic volume itself indicates the cost differential (6). Thus, the basic variables of vehicle weight and geometry plus the number of repetitions should describe the variation adequately, and the use of road systems would be restricted to those cases where different political subdivisions or design philosophies produce different design standards.

One of the more difficult, fundamental decisions which is required is in the realm of the low-travelled secondary systems, particularly for the allocation of cost responsibility for the minor traveled highways with only a nominal pavement thickness. Such roads are capable of carrying some heavy axle loads, particularly during certain seasons of the year. The loads originate from private, industrial, and commercial sources. The question is, should all vehicles which use the road be responsible for the costs on a differential basis, or should the largest vehicles be treated on an equivalent basis with the largest vehicle for which the design is completely adequate? Two answers appear reasonable. One is to assume that the theories and cost assignments which are applicable to the heavy pavements can be applied proportionally to the thin ones. A second theory would be to arbitrarily assign the costs of the low-cost pavement to the axle load group which most frequently uses the highway and for whom the pavement is completely adequate. This, in effect, would give the heavier vehicles a "differential-free" ride. More precisely, they would be paying essentially the same amount per repetition as would the smaller vehicles. In effect, the second theory suggests that such roads are designed for the smaller vehicles, and a few larger loads can be tolerated in a quasi-restricted manner.

There are sound reasons for applying either of the two concepts. In the studies at The Ohio State University, such problems were handled by obtaining a minimum and a maximum relationship between pavement costs and axle load. In the cost assignment part of the studies, the pavement costs for the thinner pavements were distributed in the same manner as for the heavier pavements. In all fairness, since requirements for the heavier vehicles are not built into the road, there is some question as to whether the use of differential costs is a proper assumption.

## Vehicle-Mile and Axle-Mile Allocations

The data of Figs. 2 and 3 refer to the increase in cost which is required for an increase in axle load. A second problem involves the allocation of the cost of a system to a various size vehicles or to user groups. For example, in Fig. 2 the cost to provide a highway capable of carrying 9-ton axles is suggested. However, all vehicles share a part of the responsibility for that cost, and the problem is to determine what portion of a given expenditure can be attributed to the various-sized axles.

As stated in the definitions, highway costs are a direct function of axle load, vehicle dimensions and performance (including driver ability), and the number of vehicles. Furthermore, the repetitions of these factors consistently affect all phases of design. In fact, there are practically no costs which are independent of load or vehicle repetition. Thus, there are relatively few dollars which can be allocated solely on the basis of the number of vehicles in the system insofar as direct cost responsibility is concerned. One notable exception is the collection of part of the revenue (motor vehicle registration). In states where a third-structure tax such as axle-mile or a ton-mile is used, even a part of the revenue collection costs are affected by the mileage traveled. In the studies at The Ohio State University it was assumed that the amount of cost which was strictly related to the number of vehicles was negligible and all costs were distributed on the basis of either axle-mile or vehicle-mile.

For those costs which are related to structure capacity (structures and pavements), the distribution was on the basis of axle-miles (Fig. 3b). For those expenditures which were related to geometry or vehicle dimensions (earthwork, right-of-way, drainage, etc.) the allocation was made on the basis of vehicle-miles (Fig. 3a). While there may be justification for assigning costs on a "per vehicle" basis in some highway economic studies, there appears to be no such justification for such an assignment where the question is one of cost responsibility.

A fairly substantial portion of all highway expenditures can be classed as "uniform" costs. These values represent the expenditures which are independent of vehicle dimensions.

Pavement and structure costs required for the basic vehicle are typical, as are all costs for axle loads of approximately two tons or less (Fig. 2). The compilation of uniform costs can be separated so as to indicate whether the expenditures are for structural or geometric requirements. While it might be argued that these uniform costs could be allocated on a unit vehicle basis, a fair presumption is that ownership of a vehicle does not constitute reasons for providing extensive mileages of highways; rather, usage of that vehicle. Therefore, axle-miles or vehicle-miles are considered a more reasonable bases for allocation of the uniform costs.

## Influences of Traffic Data

The type of traffic data which are available affects the accuracy of cost allocation problems. Since highway costs are associated with axle-miles or vehicle-miles, the average ADT (including the number of various types of vehicles), and the average number of axles per vehicle are required for the highway system being studied. Most state highway departments have developed traffic volumes for the various roads in the system. Furthermore, periodic checks have established a reasonable basis for assumption as to the numbers and sizes of vehicles. It is probably that the degree of accuracy of the traffic data is commensurate with the accuracy of the other phases of a cost-size investigation.

The contribution of foreign vehicles travelling in the state and the amount of travel of domestic vehicles out of the state is a source of question. Such a problem arises in the application of average miles travelled per year to the numbers of vehicles in order to get axle-miles or vehicle-miles. While a state bureau of motor vehicles can normally give the number and types of registered vehicles, the amount of travel per year which is driven in or out of the state is quite a different matter. It is also difficult to determine the number and average mileage of foreign vehicles. Studies designed to obtain such data are in progress in some states but no reliable data are yet available. For the studies at The Ohio State University a simplifying assumption was made; namely, that the amount of out of state travel by domestic vehicles was equal and identical in terms of types of vehicle to the amount of in the state travel by foreign vehicles.

While traffic data has a pronounced influence on the allocation of cost responsibility, there is also a significant effect on the crediting of taxes paid to various highway user groups. In attempting to determine how much tax was paid by a given type of user, the total revenue obtained is frequently utilized. Thereafter, average miles per vehicle, average gasoline consumption per mile, and average number of vehicles are used to account for the taxes paid. In the case of third-structure taxes, gross weight, axle-load, or number of axles may also be needed. Having achieved the allocation of taxes to various groups, one may wish to compare the cost responsibility for the same groups. To do so, the same assumptions must be utilized for numbers of vehicle-miles and axle-miles.

In reviewing cost-tax studies, a point of discussion frequently arises with reference to the assumptions that lead to the vehicle-mile and axle-mile values. Smaller or larger mileages are debated in order to improve relationships. A greater number of vehicle-miles assigned to a group will indicate a higher percent of the total taxes paid. On the other hand, a greater number of vehicle-miles increases the percent of cost responsibility. Special studies were conducted at Ohio State in June, 1958, by Robert Chieruzzi, research associate, to learn more of the rate of change of taxes and cost responsibility with changes in the ratio of vehicle-mile and axle-mile data between the severl highway-user groups. Contained in the following paragraphs is a summary of the results of that study.

The vehicle miles used in obtaining cost allocation (6) were obtained for the year 1953 in an earlier investigation (1) by multiplying the number of registered units in each vehicle category by the average annual mileage for the particular vehicle group. The six user-groups selected were passenger cars, panel and pickup trucks, other single-unit trucks, multi-unit trucks, farm trucks, and buses. The registered numbers of units for the passenger car, farm truck, and bus groups were initially obtained directly from the registration records of the Ohio Bureau of Motor Vehicles. Panel and pickup trucks were considered as all registered single-unit trucks with empty weights of 4,000 lb or less. As estimating procedure was necessary to obtain the numbers of

TABLE I

VEHICLE AND AXLE-MILE DATA FOR OHIO IN 1953

| Vehicle Group | Registered Units (Adjusted) | Average Annual Mileage* | Vehicle-Miles | Per Cent of Total | Number of Axles | Axle-Miles | Per Cent of Total |
|---|---|---|---|---|---|---|---|
| 1. Passenger Cars | 2,772,063 | 9,235 | 25,600,001,805 | 81.1 | 2 | 51,200,003,610 | 76.2 |
| 2. Panel and Pickup Truck | 140,721 | 10,127 | 1,425,081,567 | 4.5 | 2 | 2,850,163,134 | 4.2 |
| 3. Other Single Unit Trucks | 121,644 | 17,582 | 2,138,744,808 | 6.8 | 2.064 | 4,414,000,000 | 6.6 |
| 4. Multi-Unit Truck | 38,354 | 42,188 | 1,618,078,552 | 5.1 | 4.46 | 7,220,000,000 | 10.8 |
| 5. Farm | 72,691 | 8,044 | 584,726,404 | 1.8 | 2 | 1,169,452,800 | 1.7 |
| 6. Bus | 3,475 | 47,750 | 165,931,250 | 0.7 | 2 | 331,862,500 | 0.5 |
| Total | 3,148,948 | | 31,532,564,386 | 100.0 | | 67,185,482,044 | |

* Assumes that the travel out-of-state by local vehicles is equal and similar to travel in-the-state by foreign vehicles.

units for the "other single-unit" and the multi-unit groups, since such a breakdown was not available. The total truck and tractor registered units with empty weights greater than 4,000 lb was given. The division of these totals into the two groups was based on an estimate reported by Pancoast (7) which involves the fractions of trailer-miles pulled by trucks and by tractor-semi-trailer combinations obtained from studies made in Ohio in 1950 and assumed to be valid for 1953. The average mileages per vehicle for each category were equal to those estimated for 1962 by Pancoast (7) and assumed to be adequate for accelerated conditions existing in 1953. Table 1 summarizes the data for each of the vehicle groups and the vehicle miles are taken verbatim from the tax study (1).

A direct method for obtaining the axle-miles was employed. Essentially, it consisted of multiplying the assigned vehicle-miles by the average number of axles per vehicle for each group. A total of two axles each was arbitrarily assigned to the passenger car, panel and pickup truck, farm truck, and bus groups. Considerably greater difficulty was encountered in computing the number of axles per vehicle for the other two groups. An estimate was obtained for the single-unit trucks with empty weight greater than 4,000 lb from the data on the study by Pancoast (7). From the estimated vehicle-miles for two and three axle units, a weighted average number of axles of 2.064 was obtained. The calculations are shown below.

| | Two Axles | Three Axles | Total |
|---|---|---|---|
| Vehicle-miles | 1,816,501 | 123,690 | 1,940,191 |
| Axle-miles | 3,633,102 | 371,070 | 4,004,172 |

$$\text{Average number of axles} = \frac{4,004,172}{1,940,191} = 2.064$$

The steps which were required to obtain the axle-estimate for the multi-unit groups were as follows:

1. The average number of axles for semi-trailers was obtained from data in the study by Pancoast (7) as follows:

| | One Axle | Two Axles | Total |
|---|---|---|---|
| Vehicle miles | 25,479 | 171,916 | 197,395 |
| Axle miles | 25,479 | 343,832 | 369,311 |

$$\text{Average number of axles} = \frac{369,311}{197,395} = 1.871$$

2. Average number of axles for trailers with empty weights greater than 4,000 lb was assumed as equal to two.

3. The bases for combining power units with trailers were the following statements of Pancoast (7) who traced the data to results obtained from a study in 1950: (a) 45 ⅓ percent of trailer-miles was pulled by a commercial truck (single-unit greater than 4,000 lb); (b) 54⅔ percent of trailer-miles was pulled by a tractor-semi-trailer combination.

Accordingly, the following calculations were made with the use of data from the tax study (1):

| | Vehicle-Miles | Number of Axles | Axle-Miles |
|---|---|---|---|
| 1. Trailers greater than 3,000 lb | 498,287,600 | | |
| 2. Trailers pulled by commercial trucks (45 ⅓ percent of Step 1) | 225,800,000 | 4.00 | 903,200,000 |
| 3. Trailers pulled by tractor-semi-trailer (Step 1 - Step 2) | 272,500,000 | 5.87 | 1,600,000,000 |
| 4. Semi-trailers, total (from tax study) | 746,444,160 | | |
| 5. Semi-trailer combination only (Step 4 - Step 3) | 473,944,160 | 3.87 | 1,834,163,000 |
| 6. Total | 972,244,160 | | 4,337,363,000 |

$$\text{Average number of axles} = \frac{4,337,363,000}{972,244,160} = 4.46$$

The axle-mile data are summarized in Table 1.

The results of traffic variations can be expressed as percentages of either vehicle-miles or axle-miles, so that the variation can be in any one of the independent variables of (a) registered units, (b) average annual mileage, and (c) number of axles. For instance, axle-miles ($A_m$) are obtained by the following equation:

$$A_m = R \cdot M_a \cdot a \qquad (1)$$

TABLE 2

CHANGES IN COST RESPONSIBILITY
WITH TRAFFIC VARIATIONS

| Vehicle Group * | Variation (%) | Vehicle-Mile Distribution (%) | Axle-Mile Distribution (%) | Vehicle-Mile Cost Responsibility (%) | | Axle-Mile Cost Responsibility (%) | | Total Cost Responsibility (%) | | Change (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Max. | Min. | Max. | Min. | Max. | Min. | Max. | Min. |
| P | | 81.1 | 76.2 | 43.6 | 46.5 | 13.0 | 22.7 | 56.6 | 69.2 | (0) | (0) |
| C | 0 | 6.8 | 6.6 | 5.1 | 6.8 | 5.8 | 9.6 | 10.9 | 16.4 | (0) | (0) |
| B | | 5.1 | 10.8 | 3.8 | 5.1 | 9.5 | 15.8 | 13.4 | 20.8 | (0) | (0) |
| P | | 82.6 | 77.9 | 44.4 | 47.4 | 13.3 | 23.2 | 57.7 | 70.6 | (+1.1) | (+1.4) |
| C | +10P | 6.3 | 6.1 | 4.9 | 6.7 | 5.8 | 9.9 | 10.7 | 16.6 | (-0.2) | (+0.2) |
| B | | 4.7 | 10.0 | 3.7 | 5.1 | 9.5 | 16.2 | 13.2 | 21.3 | (-0.2) | (+0.5) |
| P | | 79.5 | 74.2 | 42.8 | 45.6 | 12.7 | 22.1 | 55.4 | 67.7 | (-1.2) | (-1.5) |
| C | -10P | 7.4 | 7.1 | 5.5 | 7.3 | 6.1 | 10.1 | 11.7 | 17.4 | (+0.8) | (+1.0) |
| B | | 5.6 | 11.6 | 4.2 | 5.5 | 10.0 | 16.4 | 14.2 | 22.0 | (+0.8) | (+1.2) |
| P | | 83.8 | 79.4 | 45.1 | 48.1 | 13.5 | 23.7 | 58.6 | 71.7 | (+2.0) | (+2.5) |
| C | +20P | 5.8 | 5.7 | 4.7 | 6.5 | 5.7 | 9.8 | 10.4 | 16.3 | (-0.5) | (-0.1) |
| B | | 4.4 | 9.3 | 3.5 | 4.9 | 9.3 | 16.0 | 12.8 | 21.0 | (-0.6) | (+0.2) |
| P | | 77.5 | 71.9 | 41.7 | 44.5 | 12.3 | 21.5 | 54.0 | 65.9 | (-2.6) | (-3.3) |
| C | -20P | 8.1 | 7.8 | 6.0 | 7.7 | 6.3 | 10.2 | 12.3 | 17.9 | (+1.4) | (+1.5) |
| B | | 6.1 | 12.7 | 4.5 | 5.8 | 10.3 | 16.2 | 14.8 | 22.4 | (+1.4) | (+1.1) |
| P | | 80.6 | 75.7 | 43.4 | 46.2 | 12.9 | 22.6 | 56.3 | 63.8 | (-0.3) | (-0.4) |
| C | +10C | 7.4 | 7.2 | 5.6 | 7.5 | 6.4 | 10.6 | 12.0 | 18.1 | (+1.1) | (+1.7) |
| B | | 5.1 | 10.7 | 3.9 | 5.1 | 9.5 | 15.7 | 13.3 | 20.9 | (-0.1) | (+0.1) |
| P | | 81.8 | 76.7 | 44.0 | 46.9 | 13.1 | 22.9 | 57.1 | 69.8 | (+0.5) | (+0.6) |
| C | -10C | 6.1 | 5.9 | 4.8 | 6.5 | 5.5 | 9.3 | 10.3 | 15.7 | (-0.6) | (-0.7) |
| B | | 5.2 | 10.8 | 4.0 | 5.5 | 10.0 | 16.9 | 14.1 | 22.4 | (+0.7) | (+1.6) |
| P | | 80.1 | 75.2 | 43.1 | 45.9 | 12.8 | 22.4 | 55.9 | 68.3 | (-0.7) | (-0.9) |
| C | +20C | 8.1 | 7.8 | 6.1 | 8.0 | 6.8 | 11.2 | 12.9 | 19.2 | (+2.0) | (+2.8) |
| B | | 5.0 | 10.6 | 3.8 | 5.0 | 9.2 | 15.2 | 13.0 | 20.2 | (-0.4) | (-0.6) |
| P | | 82.3 | 77.3 | 44.3 | 47.2 | 13.2 | 23.0 | 57.5 | 70.3 | (+0.9) | (+1.1) |
| C | -20C | 5.5 | 5.3 | 4.3 | 5.9 | 5.0 | 8.5 | 9.3 | 14.4 | (-1.6) | (-2.0) |
| B | | 5.2 | 10.9 | 4.1 | 5.7 | 10.3 | 17.5 | 14.4 | 23.2 | (+1.0) | (+2.4) |
| P | | 80.8 | 75.4 | 43.4 | 46.3 | 12.9 | 22.5 | 56.3 | 68.8 | (-0.3) | (-0.4) |
| C | +10B | 6.7 | 6.5 | 5.1 | 6.8 | 5.7 | 9.4 | 10.8 | 16.3 | (-0.1) | (-0.1) |
| B | | 5.6 | 11.7 | 4.3 | 5.7 | 10.3 | 17.0 | 14.5 | 22.7 | (+1.1) | (+1.9) |
| P | | 81.6 | 77.0 | 43.9 | 46.8 | 13.1 | 23.0 | 57.0 | 69.8 | (+0.4) | (+0.6) |
| C | -10B | 6.8 | 6.6 | 5.3 | 7.2 | 6.2 | 10.6 | 11.5 | 17.7 | (+0.6) | (+1.3) |
| B | | 4.7 | 9.8 | 3.6 | 4.9 | 9.2 | 15.5 | 12.8 | 20.4 | (-0.6) | (-0.4) |
| P | | 80.4 | 74.6 | 43.2 | 46.1 | 12.7 | 22.3 | 55.9 | 68.3 | (-0.7) | (-0.9) |
| C | +20B | 6.7 | 6.4 | 5.1 | 6.7 | 5.5 | 9.0 | 10.5 | 15.6 | (-0.4) | (-0.8) |
| B | | 6.1 | 12.6 | 4.6 | 6.1 | 10.7 | 17.6 | 15.3 | 23.7 | (+1.9) | (+2.9) |
| P | | 82.0 | 77.9 | 44.1 | 47.0 | 13.3 | 23.2 | 57.4 | 70.3 | (+0.8) | (+1.1) |
| C | -20B | 6.9 | 6.7 | 5.4 | 7.3 | 6.6 | 11.2 | 11.9 | 18.6 | (+1.0) | (+2.2) |
| B | | 4.1 | 8.8 | 3.3 | 4.4 | 8.6 | 14.7 | 11.8 | 19.2 | (-1.6) | (-1.6) |

* P - Passenger Cars
C - Single Unit Trucks ( Type C )
B - Multi-Unit Trucks ( Type B )

where:

$R$ = number of registered units
$M_a$ = average annual mileage per unit
$a$ = number of axles per unit

A ten percent change in axle-miles can be obtained by a ten percent change in any one of the three independent variables or as the aggregate of individual changes in all three variables.

For the special study, variations in traffic data were expressed as percentage changes in the vehicle-mile and axle-mile quantities of three vehicle groups, (a) passenger cars, (b) other single-unit trucks, and (c) multi-unit trucks, and were limited to plus and minus ten and twenty percent. Interpolation and extrapolation are possible for other values. The scheme produced a total of twelve separate variations. The panels and pickups, bus and farm truck groups have a total influence of less than ten percent of total taxes and cost responsibility, and therefore were conbined into a single group.

For each of the twelve variations considered, there are corresponding changes in both the vehicle-mile and axle-mile distributions, which produce proportionate changes

TABLE 3

OHIO TAX DATA FOR 1953*

1. Registration Fees

| Vehicle Group | Registered Units | Registration Fees | Fees per Unit |
|---|---|---|---|
| Passenger Cars | 2,772,063 | 26,576,913 | 9.58741 |
| Single Unit Trucks | 121,644 | 13,511,092 | 111.07076 |
| Multi-Unit Trucks | 79,592 | 11,991,923 | 150.66744 |

2. Gas Tax

| Vehicle Group | Vehicle Miles | Amount Collected (dollars) | Unit Tax (dollars per vehicle mile) |
|---|---|---|---|
| Passenger Cars | 25,600,001,805 | 79,258,191 | 0.003096 |
| Single Unit Trucks | 2,138,744,808 | 12,514,276 | 0.005851 |
| Multi-Unit Trucks | 1,618,078,552 | 18,330,204 | 0.011328 |

3. Highway Use Tax

| Vehicle Group | Axle-Miles | Amount Collected (dollars) | Unit Tax (dollars per axle mile) |
|---|---|---|---|
| Single Unit Trucks | 4,414,000,000 | 229,000 | 0.00005188 |
| Multi-Unit Trucks | 7,220,000,000 | 14,501,000 | 0.0020084 |

* From tax studies (1)

in the assignment of cost responsibility. Shown in Table 2 are the results thus obtained.

For each of the twelve variations in the vehicle-mile and axle-mile quantities, the changes produced in the distribution of tax credit were also computed. Of the various sources of taxes, only the three major sources were considered in the special study—(a) registration, (b) gas, and (c) highway use. Pertinent tax data, shown in Table 3 were obtained from the tax study (1). The changes in the three taxes which are associated with the traffic variations are summarized in Table 4.

TABLE 4

SUMMARY OF DATA FOR TRAFFIC VARIATIONS

| Vehicle Group Involved | Variation (%) | Registration Fee (dollars) | Gas Tax (dollars) | Highway Use Tax (dollars) | Total Taxes (dollars) |
|---|---|---|---|---|---|
| Passenger Car | 10P | 2,657,688 | 7,925,816 | - | 10,583,504 |
| | 20P | 5,315,375 | 15,851,633 | - | 21,167,008 |
| Single Unit Trucks | 10C | 12,164 | 1,297,678 | 24 | 1,309,866 |
| (Type C) | 20C | 24,328 | 2,595,356 | 48 | 2,619,732 |
| Multi-Unit Trucks | 10B | 3,835 | 1,833,022 | 1,443 | 1,838,300 |
| (Type B) | 20B | 7,670 | 3,666,044 | 2,886 | 3,676,599 |

TABLE 5

CHANGES IN TAXATION ESTIMATES
WITH TRAFFIC VARIATIONS

| Variation (%) | Vehicle Group | Tax Scheme (1) (%) | Tax Scheme (2) (%) | Tax Scheme (3) (%) | Tax Scheme (4) (%) |
|---|---|---|---|---|---|
| 0 | P | 68.1 | 58.1 | 52.9 | 51.3 |
| | C | 10.0 | 12.6 | 10.8 | 11.1 |
| | B | 15.4 | 21.3 | 18.2 | 18.8 |
| | Gen. Pub. | -- | -- | 13.0 | 11.8 |
| +10P | P | 68.9 | 59.8 | 54.7 | 53.0 |
| | C | 9.8 | 12.1 | 10.4 | 10.7 |
| | B | 15.0 | 20.5 | 17.5 | 18.1 |
| | Gen. Pub. | -- | -- | 10.8 | 11.4 |
| -10P | P | 67.2 | 56.3 | 50.9 | 49.4 |
| | C | 10.3 | 13.1 | 11.3 | 11.5 |
| | B | 15.9 | 22.2 | 18.9 | 19.5 |
| | Gen. Pub. | -- | -- | 11.7 | 12.2 |
| +20P | P | 69.7 | 61.3 | 56.3 | 54.6 |
| | C | 9.5 | 11.6 | 10.0 | 10.3 |
| | B | 14.7 | 19.7 | 16.8 | 17.5 |
| | Gen. Pub. | -- | -- | 10.4 | 11.0 |
| -20P | P | 66.3 | 54.4 | 48.8 | 47.5 |
| | C | 10.6 | 13.7 | 11.8 | 11.9 |
| | B | 16.3 | 23.2 | 19.7 | 20.3 |
| | Gen. Pub. | -- | -- | 12.2 | 12.7 |
| +10C | P | 67.9 | 57.8 | 52.6 | 51.0 |
| | C | 10.3 | 13.0 | 11.3 | 11.5 |
| | B | 15.4 | 21.2 | 18.1 | 18.7 |
| | Gen. Pub. | -- | -- | 11.2 | 11.7 |
| -10C | P | 68.3 | 58.4 | 53.1 | 51.5 |
| | C | 9.7 | 12.1 | 10.4 | 10.7 |
| | B | 15.5 | 21.4 | 18.3 | 18.9 |
| | Gen. Pub. | -- | -- | 11.3 | 11.8 |
| +20C | P | 67.6 | 57.5 | 52.3 | 50.8 |
| | C | 10.6 | 13.4 | 11.7 | 11.9 |
| | B | 15.3 | 21.1 | 18.0 | 18.6 |
| | Gen. Pub. | -- | -- | 11.1 | 11.7 |
| -20C | P | 68.5 | 58.7 | 53.4 | 51.7 |
| | C | 9.4 | 11.7 | 10.0 | 10.3 |
| | B | 15.5 | 21.5 | 18.3 | 19.0 |
| | Gen. Pub. | -- | -- | 11.3 | 11.9 |
| +10B | P | 67.8 | 57.7 | 52.5 | 51.0 |
| | C | 10.0 | 12.4 | 10.8 | 11.0 |
| | B | 15.8 | 21.9 | 18.7 | 19.3 |
| | Gen. Pub. | -- | -- | 11.2 | 11.7 |
| -10B | P | 68.4 | 58.5 | 53.2 | 51.6 |
| | C | 10.1 | 12.6 | 10.9 | 11.1 |
| | B | 15.0 | 20.7 | 17.6 | 18.3 |
| | Gen. Pub. | -- | -- | 11.3 | 11.9 |
| +20B | P | 67.5 | 57.3 | 52.1 | 50.6 |
| | C | 9.9 | 12.4 | 10.7 | 10.9 |
| | B | 16.2 | 22.4 | 19.3 | 19.8 |
| | Gen. Pub. | -- | -- | 11.1 | 11.6 |
| -20B | P | 68.7 | 59.0 | 53.6 | 51.9 |
| | C | 10.1 | 12.7 | 11.0 | 11.2 |
| | B | 14.6 | 20.2 | 17.0 | 17.8 |
| | Gen. Pub. | -- | -- | 11.4 | 11.9 |

By introducing the proper changes in the tax credits for each of the traffic variations, corresponding tax credit distributions were obtained. As stated previously, a significant factor in the comparisons of cost responsibility with taxes paid is the taxes which are included in the analysis. Each of the following four tax schemes was considered in the specidal study:

TABLE 6

EFFECT UPON TAXES PAID-COST RESPONSIBILITY RELATIONSHIPS

| Vehicle Group | More Favorable* | | Negligible Effect |
|---|---|---|---|
| | Increase | Decrease | |
| Passenger | | P1 | |
| Cars (P) | P2 | | |
| | P3 | | |
| | P4 | | |
| | C1 | | |
| | B1 | | |
| | | | C2, C3, C4 |
| | | | B2, B3, B4 |
| Other Single- | | | P1, P2, P3, P4 |
| Unit Trucks | | C1 | |
| (C) | | C2 | |
| | | C3 | |
| | | C4 | |
| | B1 | | |
| | B2 | | |
| | B3 | | |
| | B4 | | |
| Multi-Unit | | | P1 |
| Trucks | | P2 | |
| (B) | | P3 | |
| | | P4 | |
| | C1 | | |
| | C2 | | |
| | C3 | | |
| | C4 | B1 | |
| | | B2 | |
| | | B3 | |
| | | B4 | |

* Numbers used with letters refer to the four tax assumptions. The column indicates the tax assumptions that produce more favorable cost-size relations, and whether the traffic variation for a given vehicle group must be increased or decreased to obtain the better relation.

1. All taxes were included except the general public's portion.
2. All taxes were included except state sales, federal excise and the general public portion.
3. All taxes were included except non-highway use taxes.
4. All taxes were included except state sales and federal excise taxes.

Non-highway use taxes were those obtained from highway users but not expended on Ohio highways, while the general public's portion came from the general funds of the state and local governments; that is, not highway user taxes. The results are somewhat misleading in that the federal tax laws of 1953 and 1954 are considered. Several types of taxes which were not utilized on highways at that time must now be incorporated into the highway budget. The various tax credit distributions are tabulated in Table 5.

The influences of the traffic variations were expressed on the basis of the variations produced more or less favorable taxes paid-cost responsibility relationships for each

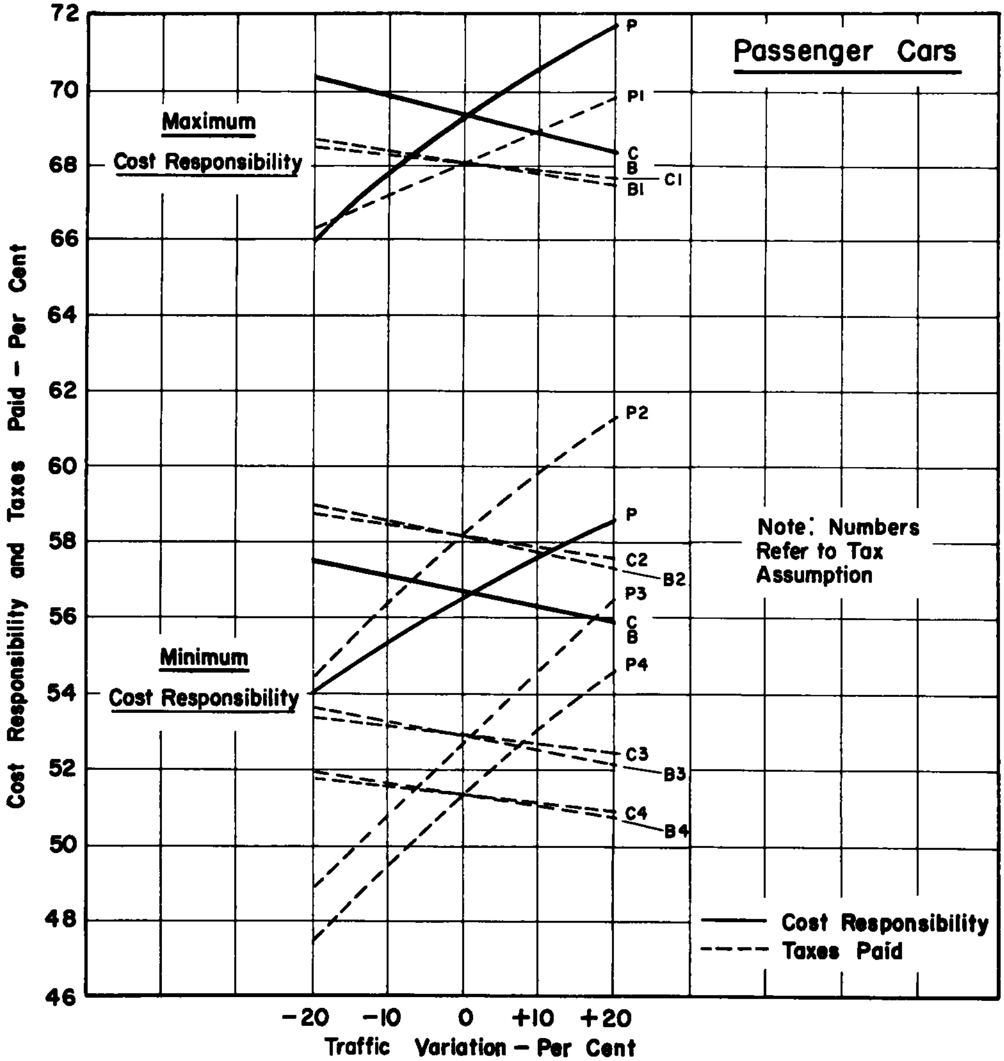


Figure 4. Effect of traffic variation on taxes paid and on cost responsibility passenger cars.

of the vehicle groups considered. Summarized in Table 6 and in the following are the trends indicated in the plots of the data shown in Figs. 4, 5, and 6.

Passenger Cars.—(a) Under the Tax Schemes 2, 3, and 4 the effects of variations in both C and B Type traffic data (Table 3) are negligible. (b) Under Tax Scheme 1 an

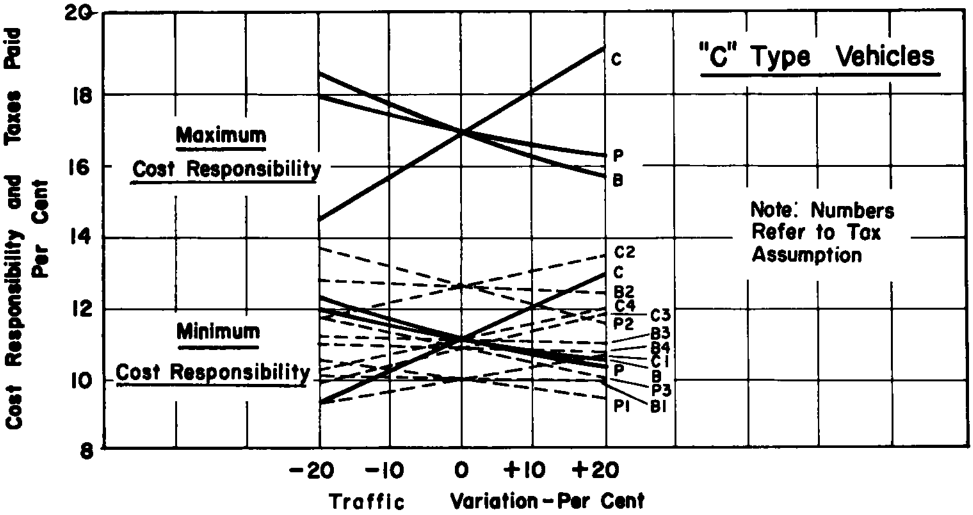


Figure 5. Effect of traffic variation on taxes paid and on cost responsibility type "C" vehicles.

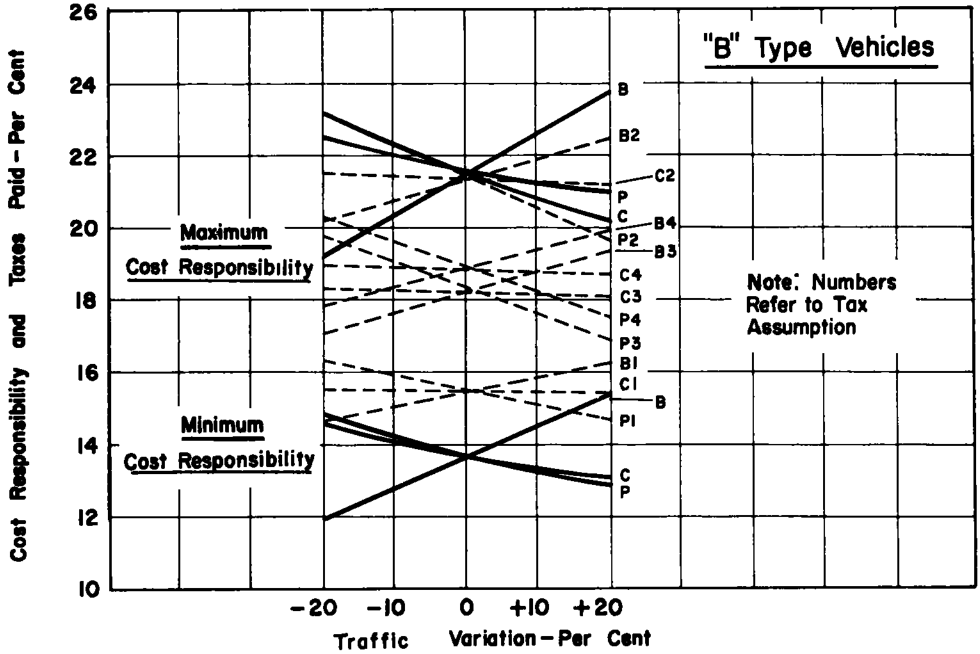


Figure 6. Effect of traffic variation on taxes paid and on cost responsibility type "B" vehicles.

increase in both C and B traffic and a decrease in P vehicle-miles will produce favorable effects.

Type C Trucks.—(a) Variation in the passenger car vehicle miles will have negligible effect, regardless of tax schemes. (b) Favorable effects are produced by a decrease in the C Type vehicle-miles under Tax Schemes 1, 3, and 4 and an increase in B Type vehicle-miles under Tax Schemes 1. (c) Under Tax Scheme 2 an increase in the C Type vehicle-miles will produce non-favorable effects.

B Type Trucks.—(a) Favorable effects will be produced by an increase in C Type vehicle-miles and a decrease in both P and B Type vehicle-miles under all Tax-Schemes except one which has negligible effect, namely a passenger car variation under Tax Scheme 1.

The analyses for the special study were not complete and represent the results produced by the consideration of only three of the tax sources: (a) registration fees, (b) fuel tax, and (c) highway use. Furthermore, the tax and traffic data were obtained from the tax study (1) and highway cost study (6) and variations were made therefrom. However, the following significant statements are considered reasonable interpretations of the results.

There are two major variations which improve the taxes paid-cost responsibility relationship for the B and C Type vehicles. One condition is produced by a decrease in their respective vehicle and axle miles. This infers that although the tax credits increase with increased vehicle and axle mileage, the cost responsibility increases at a faster rate. Conversely, the cost responsibility diminishes at a faster rate than taxes paid. The other favorable variation is an increase in vehicle and axle mileage in the other group; that is, an increase in B Type vehicle and axle mileage will produce improved relationships for the C Type group and vice versa. Again, the reason for this situation stems from different rates at which the taxes paid and cost responsibility are affected.

An increase in passenger car vehicle-miles produces favorable effects for all tax schemes except the one which includes most of the taxes which are paid by highway users but are not used on Ohio highways. This indicates that the taxes paid increase at a greater rate than cost responsibility except for the one instance.

## Considerations in Establishing a Basic Vehicle

The basic vehicle can be defined as that vehicle which can satisfactorily operate on highways without adding to the minimum highway costs required for the safety and convenience of the smallest vehicle. The establishment of the basic size of vehicles is critically necessary for problems where differential costs between vehicles is the basis or where allocation of cost responsibility is concerned. On the other hand, if one is attempting to establish the optimal design, considerations of the basic vehicle may not be pertinent. The last statement assumes that the size of the basic vehicles is at least as great as a passenger car. In developing a relationship between highway costs and vehicle size, one can originate with, or extrapolate to, the lowest sized vehicles. At some point near the lowest limit of vehicle size, climatic and non-highway user requirements start controlling. It is at this point that the size of the basic vehicle is defined. Figure 2 illustrates the point by use of the Ohio studies. As can be seen, if the optimum-sized vehicle has an axle load larger than 2.5 tons, the size of the basic vehicle is not a factor.

On the other hand, assignment of cost responsibility requires an estimate of the size of the basic vehicle, since all vehicles share, on some equivalent basis, the costs required for the basic vehicle. The indirect source of cost which affects the size of the basic vehicles more than any other is climate. Another contribution however, is the minimum construction cost which is feasible. To a certain extent, the topography is also a factor in the geometrics due to the performance characteristics of the vehicle. Since climate, topography, and construction costs are factors, the size of the basic vehicles will vary from one locale to another; that is, the basic vehicle for the State of Maine will be different than that for New Mexico. For area-wide studies, then, the basic vehicle is based upon a statistical evaluation of the conditions in the area.

In starting an investigation of the relationship between highway costs and vehicle size it will be important to know whether the establishment of a basic vehicle is required in the problem. Secondly, it should be understood that the size of the basic vehicle is a function of the region and the area under study must be utilized as a basis rather than the adoption of a value derived for different conditions.

## Reconstruction, Resurfacing, and Surface Treatment

Allocating cost responsibility for reconstruction, resurfacing, and surface treatment includes certain unique considerations. While the following discussion is limited to pavement costs, the principles would be applicable to other costs which are normally included in reconstruction.

An interesting question, pertaining primarily to reconstruction and resurfacing, can be stated as follows: to what size vehicle should costs be assigned for those pavement expenditures which attempt to extend the design life? In the strictest sense, there is no problem because the heaviest axle loads which are utilizing the pavement undoubtedly produce the greatest stress per repetition. The confusing element is the fact that climate has contributed to the reduction in structural capacity of the pavement. Unfortunately, the effect the smaller vehicles would have on the pavement cannot be rationally determined. Furthermore, climate alone may start producing damage which will require maintenance. It has been argued that since the pavement has gone beyond the design life, all vehicles should share on an equivalent basis for its rehabilitation. For the studies at The Ohio State University, however, the direct responsibility for the pavement disintegration was considered as resting with the heavy trucks. It was also recognized that this assumption produced extreme relationships since the climatic deterioration of the structure and the activity of the lighter-weight vehicles undoubtedly contribute. Therefore, the method finally adopted was to compute maximum cost differential by assigning the entire reconstruction and resurfacing pavement costs to the heavy vehicle. For the minimum cost differential it was assumed that vehicles shared responsibility on the same basis as they would for new construction.

The uncertainties associated with surface treatment are somewhat different. The definitions for surface treatment vary with organizations, but for the following discussion it will be assumed that surface treatments are those additions to the pavement which add no structural capacity. It is also assumed that no serious surface irregularities could be levelled by surface treatment, and one can conclude, therefore, that the surface treatment is principally placed for control of climatic influences.

On newly-constructed secondary highways the inclusion of surface treatment may furnish the completion of a long-range, new-construction project. In such cases, surface treatment should be considered as new construction and prorated in accordance with the accepted pavement design techniques. The procedure followed for The Ohio State studies consisted of applying the principles of pavement cost allocations for new construction in order to obtain the maximum cost differential. Whereas for a minimum cost differential, the costs were distributed uniformly on a usage basis. In no case were the costs of surface treatment assigned directly to the truck as was done for reconstruction and resurfacing.

From the foregoing it will be noted that an engineering decision was made with reference to the assignment of the costs. By more rigorous study of the cost data, it might be possible to assign the expenditure on a more rational basis. However, it will be quite an unusual situation where the available cost and design records are sufficient to permit a detailed analysis of the type and extent of reconstruction, resurfacing, and surface treatment.

## Engineering and Administration

The cost responsibility for engineering and administration has been generally allocated on one of two basic concepts. One philosophy states that engineering and administration is a function of the dollar size of the program and should, therefore, be divided proportionally among the various cost items for which the engineering and administration has been required. Under this theory the dollars for engineering and administration would be allocated on the same basis as the individual cost items to which they are assigned; that is, dollars of engineering and administration added to the cost of pavements would be allocated on the same basis as the actual pavement costs.

A second theory for considering engineering and administration deals with the assumption that such costs are a function of the numbers of vehicles and miles of highways in the system and not a function of the size of the vehicle; that is, engineering and administration would be approximately the same even if passenger cars were the largest vehicles using the highway. From a viewpoint of plan preparation or design engineering, one is inclined to accept the second theory. For actual construction, however, the increased quantities required for the heavier vehicles undoubtedly add to the cost for field engineering and administration. The fact that engineering fees are based upon a percentage of the contract costs is used as an argument in favor of the first theory. However, actual costs of plan preparation and construction supervision would not vary significantly with the sizes of the vehicle for which the design is accomplished without varying the level of effort to achieve the design.

From a practical point of view, it seems certain that the actual relationship lies somewhere between the two extremes suggested in the two aforementioned theories. In application, the first theory leads to the allocation of costs on the same basis as other highway costs which would place a higher cost differential on the larger vehicles. Under the second theory, the engineering and administration would be considered a function of the number of vehicle-miles or of axle-miles, but on a uniform basis, rather than an added increment assigned to the larger vehicles.

## Estimating Differential Costs

The extensive work required for developing cost-size relations, and the dependency upon design methods for current results discourages many agencies from undertaking detailed analyses. Most of the research at Ohio State was devoted to the basic methodology of obtaining cost-size relationships for the individual cost items. Since the studies were for Ohio highway conditions only, the results are not directly applicable to other areas or agencies. However, in lieu of other information, the data are considered to be approximately equivalent, at least qualitatively. Where comparable design criteria are utilized, the shape of the cost-size curve shown in Fig. 2 is considered as representative of results using comparable assumptions. Further enlightenment may be provided by Table 7 which summarizes the equations which lead to the combined data.

Assuming that the relations expressed in Fig. 2 are acceptable, particularly as to the shape of the curves, differential costs can be estimated directly from total annual cost (or total cost per mile) and the legal load (or design load). The following is the mathematical expression for total costs:

$$C_{max} = 9.7W_1^{\ 0.1412} \tag{2}$$

in which:

$C_{max}$ = Maximum total annual cost per mile in thousands of dollars.

$W_1$ = Weight of axle load in tons.

$$C_{min} = 4.5\,W_1^{\ 0.1302} \tag{3}$$

in which:

$C_{min}$ = Minimum total annual cost per mile in thousands of dollars.

The equations hold for a range of W of 5 to 20 tons, and for the single value of 2 tons. However, there is an implication that the axle load weights of 10 to 20 tons will (a) not involve a change in vehicle dimensions, or (b) not affect the geometric requirements.

For the general solution:

$$C = C_a W^s \tag{4}$$

in which:

$C$ = annual cost per mile for the axle load, W.
$C_a$ = annual cost per mile for the unit axle load.
$s$ = constant (equal to the slope of the logarithmic relation).

The unit axle load is defined as the axle load for which $C_a$ is known. If no data are available as to cost for a specific axle load, Equation 4 will not be helpful. However, for an existing system, the legal (or design) load can be used in conjunction with the actual expenditures and a solution achieved. Values of s are a function of the design techniques, which for Ohio were defined by:

$$s = 0.00163C_{9.5} + 0.1210 \qquad (5)$$

in which:

$C_{9.5}$ = Total annual cost per mile in thousands of dollars for a design axle load of 9.5 tons.

The equation is considered applicable for $C_{9.5}$ values between $6,000 and $13,200. Where the differential costs between two axles is desired:

$$D = C_1 - C_2 = C_a W_1^{s} \qquad (6)$$

in which:

$D$ = Differential costs between requirements for axle loads of $W_1$ and $W_2$.

TABLE 7

EQUATIONS USED IN DEVELOPING COST-SIZE RELATIONS

| Cost Item | Equation | Remarks |
|---|---|---|
| Pavements (P) | $C_P = C_{9.5} W^s$ | New construction, two-lane full depth |
| Structures (S) | $C_S$ max = 410 log W + 90<br>$C_S$ min = 115 log W + 155 | Weighted combination for six structural types and seven vehicle types |
| Earthwork (E) | $C_{EN}$ = 32.8 log T -63.6<br>$C_{ER}$ = 0.001 log T +12.1 | Rural new construction<br>Rural reconstruction |
| Right-of-Way (A) | $C_{AN}$ = 4.0 T +6.4<br>$C_{AR}$ = 0.003 T +3.8 | Rural new construction<br>Rural reconstruction |
| Roadside Development (Q) | $C_{QN}$ = 0.000005 T +5.5<br>$C_{QR}$ = 0.0001 T +3.7 | Rural new construction<br>Rural reconstruction |
| Drainage (U) | $C_{UN}$ = 0.007 T +2.8 | Rural new construction no relation found for reconstruction |
| Maintenance (M) | $C_M$ = 4.91.19 + 0.206 $T_H$ | Roadbed and surface maintenance and repair - excludes resurfacing, surface treatment, etc. |
| Total | $C_{max} = 9.7\ W^{0.1412}$<br>$C_{min} = 4.5\ W^{0.1302}$ | Discontinuous over the range 2 to 5 ton axle loads. Assumes no increase in geometric dimensions of vehicles for 10 to 20 tons. Unit axle load is one ton. |

C - Annual cost per mile in thousands of dollars.

N - New construction

R - Reconstruction

S - Constant

W - Axle load in tons.

T - Adjusted ADT - number of heavy vehicles increased by topographic factor.

H - Heavy vehicle - (Type B & C trucks).

If costs are to be compared to the legal axle load or to the unit axle load, then:

$$D_u = C_u \left( W^s - 1 \right) \quad (7)$$

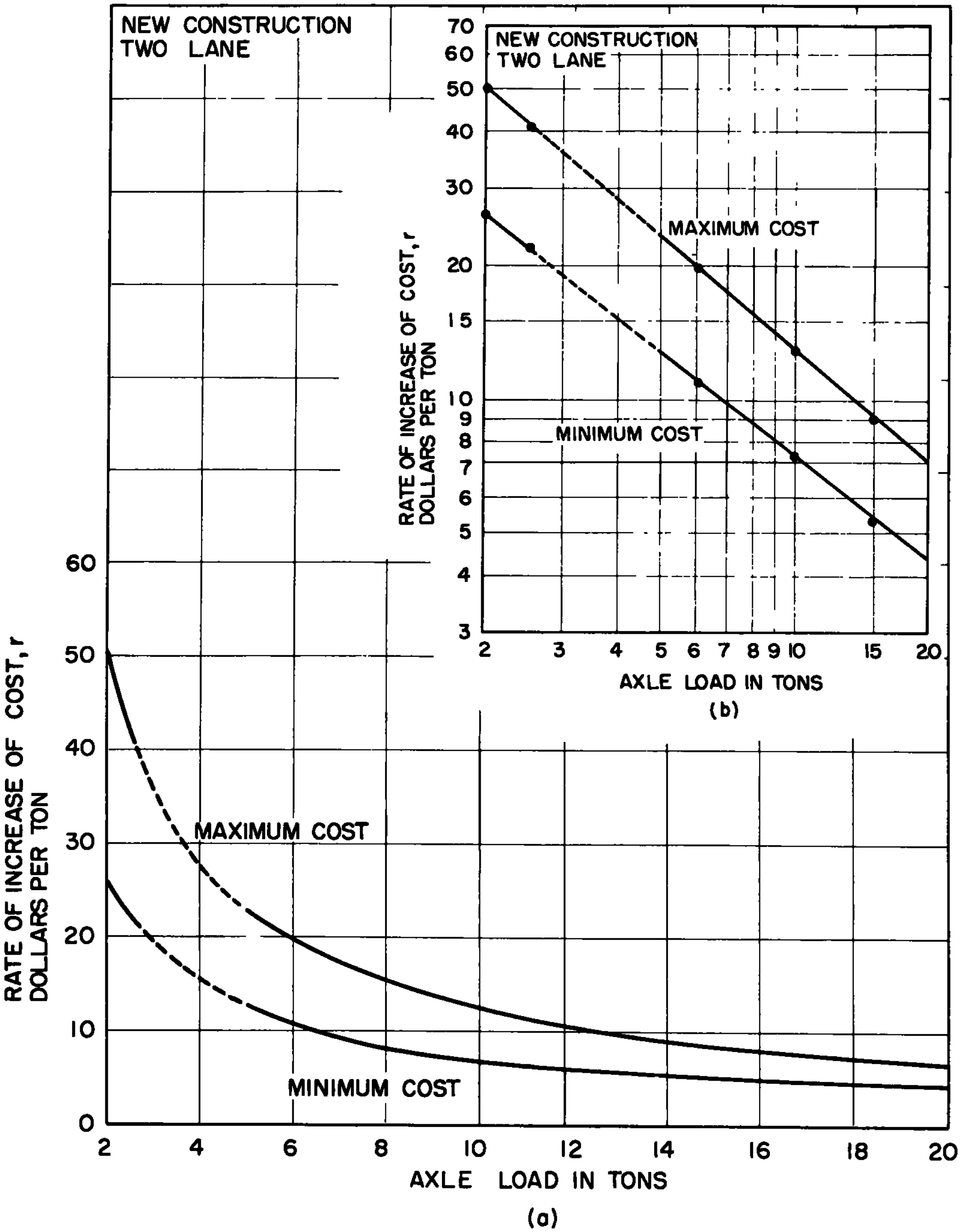


Figure 7. Rate of increase of annual cost with increase in axle load.

in which:

$D_u$ = Differential annual cost per mile in thousands of dollars between the unit axle load and W.
$C_u$ = Annual cost per mile in thousands of dollars for the unit axle load.
W = Axle load in tons for which differential costs are desired.

Values for s are determined as discussed in the preceding and in Equation 5.

Another interesting consideration is the rate of increase of highway costs with axle load. Based upon Equation 4:

$$dC = C_a s W^{s-1} dW \tag{8}$$

and:

$$r = C_a s W^{s-1} \tag{9}$$

in which:

r = rate of increase of total annual cost responsibility in thousands of dollars per mile per ton (axle load).

A typical plot of Equation 9 is shown in Fig. 7 for Ohio conditions. The implication of Fig. 7 is that for higher axle loads, the rate of cost increase is reduced, particularly for weights in excess of 6-8 tons.

## SUMMARY

In considering the differential cost studies to date, the problems of developing the relationship between highway-cost and vehicle-size leads to certain conclusions. The complexities of rationally expressing the relations which are needed prevent too many general statements.

For a truly rational and theoretically sound development of the relation of highway costs to vehicle size a great deal of research is still required. Since so many phases of highway engineering are still empirical and since the elements of highway costs which are rational represent such a small part of the total cost, the values derived from the cost-size investigations are certain to be questioned. On the other hand, studies based upon the methods currently used for design will at least reflect present practice and expenditures. Insofar as this type of an answer is suitable, reasonably reliable estimates can be made.

From a research viewpoint, the studies which are most needed for cost-size investigations are related to the geometric factors. While it is true that a rational solution to structural elements such as pavements is not available, the empiricism utilized in pavement design is more effectively related to vehicle size than is the design for geometric factors.

The shape of the curve of highway costs versus vehicle size appears to be reasonably well established at this time, at least for current design procedures. There is little question but that the curve is basically of the exponential form Fig. 2 rather than the reverse curve frequently used as a qualitative description of the relationship. There is greater question as to the validity of the geometric capacities than for the structural elements.

Considering the complexities of achieving values for cost-size relations, a suggested procedure for estimating differential costs may be quite adequate for many problems. The method proposed involves knowing the dollars per mile which are available for a given highway system. Using the legal load as the axle load for which the system is designed, one point on the cost-size curve is available. Equations for projecting the curve above and below this given point have been suggested (6).

One of the major problems for which little direct research is currently under-way is involved with the problem of solving for the optimum sized vehicle to be used on an existing road network. There are a great many miles of highways in this country, and until it is possible to evaluate the load-carrying characteristics of these pavements, it will be illogical to extrapolate current expenses for reconstruction and resurfacing.

The same is true for maintenance costs which are associated with vehicle weight (structural capacity). There is also some question as to the validity of extrapolating the geometric capacity requirements beyond the current values. According to the standard design practice today, the vehicle dimensions make no difference other than on the broad basis of passenger cars and trucks. Thus, changing vehicle dimensions would not appear to change highway costs. It is quite obvious that such a statement is not theoretically sound. As an example, a substantially wider vehicle would unquestionably increase the geometric capacity requirements. Drastic changes of vehicle height, length, and performance could also affect highway geometrics.

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