A Method of Determining Bridge Tolls

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The toll charge on publicly-owned bridges should equal the sum of (a) costs directly occasioned by a vehicle's passage (for pavement wear and toll collections), plus (b) a proportionate part of the fixed bridge costs (interest on the investment, insurance, etc.). The costs included in the first group vary with use and may be assigned directly to each user, but are so small a part as to be unimportant. The second group makes up almost all the cost of providing bridge service, but being unaffected by use these costs cannot be attributed directly to individual users.

Each of the types or groups of vehicles constituting the annual traffic volume that was in any way planned for by those responsible for the decision to build a bridge of given traffic capacity and strength should share in the payment of the resulting fixed costs in proportion to the extent that each contributed to the magnitude of these costs. The decision to construct a vehicular bridge capable of carrying some maximum hourly traffic volume is determined by peak-hour traffic. Since the hourly volume capacity necessary for peak-hour use is not required by the off-peak traffic, which could be accomodated by a smaller structure, all the fixed costs of a bridge of given capacity should be charged to the peak-hour traffic. Vehicles crossing during off-peak hours do not add to fixed costs, but only take advantage of capacity which otherwise would be unused. The increase in fixed costs resulting from building greater strength into the structure so as to accommodate heavier vehicles should be paid for by the truck traffic. To determine what part of the fixed cost should be assigned solely to trucks because of their weight, it is necessary to compute the saving in construction cost that could have been realized if the bridge had been designed only for passenger cars.

If trucks use the bridge during peak hours, their presence makes it necessary for the structure to have a greater volume capacity than would be required if all the vehicles were passenger cars. When the traffic volume using any roadway equals the maximum hourly capacity of the roadway, two passenger cars can be substituted for each truck without the capacity of the roadway being exceeded.

The toll charge is found as follows: First compute the user costs for pavement wear, toll collections, etc., which are chargeable to the non-peak-hour users and distribute this cost equally among all vehicles using the bridge during the non-peak hours. Distribute all other user costs, plus all fixed costs except those associated with incremental weight capacity, equally among the traffic units using the bridge during the peak hours, counting each passenger car as a unit and each truck as two units. Add to the charges thus computed for each truck an amount to cover the fixed costs of the incremental weight capacity. The charge for the incremental weight capacity is assigned equally to all trucks whether they use the bridge during peak or non-peak hours.

Toll charges computed using this procedure were determined for the Chesapeake Bay Bridge with the following results (peak hours are 6 AM to midnight daily): Passenger cars, $1.25 during peak hours and $.25 during non-peak hours; trucks and buses, $3.20 during peak hours and $1.00 during non-peak hours.

● A METHOD of determining charges on publicly-owned bridges which will result in tolls that have an appropriate relationship with bridge costs and traffic is presented herein. At present there is a wide diversity in the tolls charged on publicly-owned bridges in the United States, the rate for a passenger car being as low as $0.05 on some bridges and over $1.50 on others.

This diversity might be explained by differences in costs and traffic volumes, except that these two factors do not explain the variation adequately. This is evident when the ratio of original cost to the product of the average daily traffic and the passenger car toll charge is computed for each of the publicly-owned bridges and these ratios are compared. If the toll rates for each bridge had been established by giving reasonable weight to costs and traffic volumes, the ratio, which is the relationship of original cost to the daily revenue from passenger cars, should be about the same for each. Far from being the same these ratios actually fluctuate over a range of values between 80 and 99,200.

Present toll rates vary also for different types of vehicles, being generally greater for the larger and heavier vehicles than for passenger cars, although there is little agreement among toll bridges as to how much more a truck should be required to pay. For example, where the identical toll is charged on several bridges for a passenger car plus driver, the same bridges charge different amounts for single-unit two-axle trucks, some charging about the same as for passenger cars and others charging several times the passenger car rate. It is apparent that there is no fixed rule or guide to determine whether all types of vehicles should pay the same toll or different tolls, or how much more one type of vehicle should pay than another.

This report presents formulas for toll determination which are based on modern economic theories of pricing for publicly-owned facilities. A preliminary discussion of basic price theories serves to clarify all the factors involved and leads to the formulas and procedures most appropriate for pricing on toll bridges. Toll rates for the Chesapeake Bay Bridge are worked out using these formulas in order to demonstrate their application and explain how the necessary data may be obtained.

PRICE THEORY

Costs, both fixed and variable, are important factors in determining price. Although this is not always evident, it is true, at least implicitly, in every case. Fixed costs in the short run are not changed by volume of traffic or use, whereas variable costs change as traffic volumes change. Almost all the cost of ownership and operation of a bridge (such as interest on the investment, costs of insurance, painting, maintenance, and administration) are fixed.

Even toll collection costs, which could vary with the magnitude of total daily traffic volumes, are practically fixed because daily peak-hour traffic usually requires all toll booths to be in operation and once the booths are opened and toll collectors put on duty, they remain open and the collectors remain on duty for a certain period of time (usually 8 hr) regardless of traffic volumes at other hours. The number of toll collectors on duty may vary from season to season, being greater in summer than in winter; but on a yearly basis toll collection costs re-

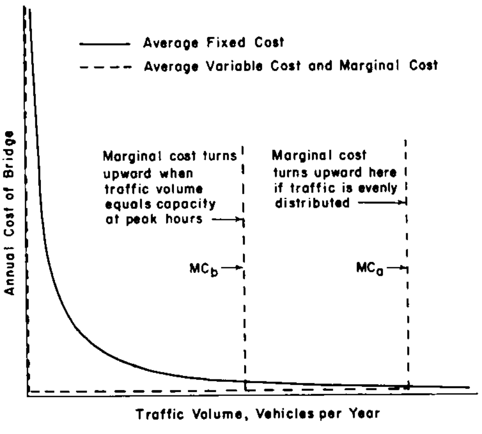

Figure 1. Economic model of bridge costs in the short run.

main roughly the same even though yearly use of the bridge changes.

Some additional costs are incurred when traffic increases (such as the cost of extra bridge guards, some increase in toll collection costs, and greater maintenance costs because of increased wear of pavement), but these are very small.

An economic model of bridge costs in the short run is shown in Figure 1. The average fixed-cost curve represents the yearly fixed cost divided by the volume of traffic at various traffic volumes. The average variable-cost curve is horizontal and almost coincident with the X-axis.

A concept important in the study of prices is marginal cost, which in the case of a bridge is the additional cost incurred by the passage of one more vehicle at any given volume of traffic. It is a cost directly occasioned by the vehicle, such as the cost of the actual amount of pavement surface worn away by the movement of the vehicle (short-run marginal cost, as no additional investment is necessary) or the entire cost of a new bridge if greater capacity is needed to pass one more vehicle (long-run marginal cost).

The value of marginal cost at different volumes of traffic may be presented as a curve, such as the long-run marginal-cost curve in Figure 1, which branches into curves MC_a and MC_b. The marginal-cost curve may slope upwards, downwards, or be horizontal, but it will always be above the average variable-cost curve if the average variable-cost curve is rising and below if the average variable-cost curve is dropping (*1*). Because the average variable-cost curve is assumed to be horizontal, the marginal-cost curve will be coincident with it.

At that yearly volume of traffic which is the maximum volume which the bridge can carry, the marginal-cost curve (and average variable-cost curve) will rise vertically because in order to pass one more vehicle at that volume a large sum has to be spent to provide additional capacity. This is usually done by building another bridge.

MC_a represents how the long-run marginal-cost curve would appear if use of the bridge is spread out uniformly over time so that at every hour of every day the same number of vehicles use the bridge. Under this condition of operation, when bridge capacity is reached and MC_a rises vertically, the bridge will be carrying an absolute maximum number of vehicles per year.

This, however, is unrealistic because traffic is always greater at certain peak hours than at other hours of the day. This irregularity of use means that the bridge volume will reach capacity at a sufficient number of peak hours per year to warrant the cost of constructing additional bridge capacity at a total yearly volume much less than the absolute maximum.

Branch curve MC_b represents marginal cost under actual conditions and shows that, because of the effect of peak-hour traffic volumes, long-run marginal cost rises vertically at a much smaller total yearly volume of traffic than would be the case if traffic used the bridge uniformly all the time. The point at which branch curve MC_b will rise vertically will be determined by the number of peak hours per year that traffic will tolerate congested conditions. The volume of traffic at this point is the yearly volume of traffic at the time that additional capacity is constructed by building a larger bridge in place of the first bridge or by building an additional bridge. The long-run marginal-cost curve has no significance to the right of the point where branch MC_b turns upward, because as soon as traffic volume increases beyond this point, the bridge capacity will be increased.

Economists generally agree that price should equal the amount spent for production which would not have been spent if a particular unit had not been produced (*2, 3*). In a perfectly competitive market where the individual sellers in an industry are so numerous that none are able to affect price by their output, the summation of outputs will be such that the price will automatically equal the marginal cost for the industry (*2, 4*).

In the case of firms in perfect competition (such as wheat farms), plant divisibility is high so that to change from one range of output to a higher range of output does not generally involve a great change in plant investment. Consequently, short-run and long-run marginal costs are similar for such firms. When marginal cost (short-run or long-run) is less than price, many inefficient producers will be attracted to the industry and the summation of the outputs of the individual firms will rise, causing a drop in price; but if marginal cost is greater than the price, inefficient high-cost producers will be forced to leave the market and this will lower the summation of the outputs of the firms until price equals marginal cost (*1*).

Figure 1 shows that at any volume of traffic less than capacity the marginal cost will be less than the average fixed cost in the short run. It will also be less than the average total cost, which is the sum of fixed costs and variable costs. Consequently, in the case of a toll bridge, if the charges were to equal the short-run marginal cost, the full costs of the bridge would not be covered by revenues.

This will always be the situation for industries such as the railroads and public utilities, all of which have high fixed costs and low variable costs. The long-run marginal-cost curves of these industries would be very jagged, with sharp upturns (Figure 1), very different from their short-run marginal-cost curves. This is explained by the high indivisibilities of the plants of such industries.

Expressed more precisely, a toll bridge is a decreasing-average-cost firm in the short run. The average total cost could rise slightly because of higher variable costs if traffic volumes increased to such an extent that large numbers of patrolmen or bridge guards were necessary to keep congested traffic moving. This, however, does not occur because a new bridge would have to be built to relieve congestion long before the traffic volume became that great. The short-run marginal-cost curve is always below a decreasing average-cost curve (*1*).

In the case of a toll bridge, in the short run the facility reaches capacity use, or congestion requires additional bridge capacity at a volume of use less than the volume at which average total cost changes from a downward-sloping decreasing-cost curve to an upward-sloping increasing-cost curve.

In the short run the marginal cost will always be less than the average total cost for the bridge, unless there is a high demand for the use of a low-cost bridge which can be spread out evenly throughout the 24 hours of every day. In practice, heavy density of traffic at peak hours and low density at other times makes it impossible for absolute capacity of a bridge to be approached and average total cost always exceeds short-run marginal cost. Consequently, in the short run all costs of the bridge cannot be paid from bridge revenue if price is equaled to marginal cost.

The problem is to determine what the price should be in an industry with decreasing costs in the short run. If price is set equal to the short-run marginal cost, how will fixed costs be paid? On the other hand, if price is to be greater than short-run marginal cost, how much greater should it be? Before attempting to solve this problem, the market situation of toll bridges should be reviewed briefly, because the type of market establishes the manner in which price will be selected.

The market of a toll bridge is made up of all those who wish to make a crossing at a toll bridge, and the position of the bridge in this market is highly monopolistic. Rational entrepreneurs would never attempt to operate toll bridges in a competitive situation, such as where two or more bridges are at the same location and competing for the same traffic. The reason for this, as seen in Figure 1, is the low short-run marginal cost of bridges for all traffic volumes less than capacity volume. To attract traffic the competing bridge owners would undercut prices until the rate on each bridge was equal to the short-run marginal cost, at which point none of the bridges would be earning enough to pay total costs (*5*). The competitiors, to stay in business, would probably combine, forming a monopoly that would charge the same price on each bridge.

A toll bridge enterprise as a monopoly may charge any one of a wide range of prices. The actual price charged will depend on the objective of the bridge owner, who is in a position to charge the price that appears to serve his purposes best. Basically, there are only three motives or objectives which a bridge owner, whether a private company or a government body, may have. These are as follows:

1. Maximization of profits.
2. Equivalence of price and short-run marginal cost.
3. Equivalence of price and long-run marginal cost.

These motivations and the kind of price structure that will result in each case will now be considered relative to applicability in the case of publicly-owned toll bridges.

Maximization of Profits As a Pricing Objective

A bridge owner, if his objective is to maximize profits, must be able to estimate how much the traffic volume will be at various prices. This estimate may be expressed as a demand curve, plotting traffic volume as the abscissa and price as the ordinate. The demand curve, which may be straight or curved, almost always slopes downward to the right, indicating that the smaller the price, the greater will be the volume of traffic using the bridge. The ratio of the percent change in traffic volume to the corresponding percent change in price at any point on the curve is called elasticity of demand.

A concept important in monopolistic pricing is marginal revenue, which may be defined as the total change in revenue that will be realized if the price is lowered just enough to induce one more unit of traffic to use the bridge. Marginal revenue is generally different at different prices, and may be positive or negative. A marginal-revenue curve showing marginal revenue at various prices can be derived from an average-revenue curve by geometrical construction (*1*). In fact, any marginal curve may be derived from an average curve in the same manner. The demand curve is the same as the average-revenue curve in the case of the single price monopolist.

Assuming that the bridge owner is able to predict accurately the demand curve for the use of his bridge for any one kind of traffic, he is in a position to select the price which will produce greater profits than any other single price. The price he will charge will correspond to that volume of traffic at which marginal cost equals marginal revenue. At any traffic volume less than this, where marginal revenue is greater than marginal cost, it will add more to total revenue than to total cost to reduce price to attract more users. Conversely, at any traffic volume greater than this, where marginal cost is greater than marginal revenue, total revenue will be reduced less than total cost if price is increased.

A toll bridge owner, however, is not only in a monopoly position, but his products (bridge crossings) can not be resold. In most cases the tolls are paid at toll booths without the use of tickets. Where tickets are sold at some other point for use on a given bridge, their resale not only is prohibited, but is easily detected through license numbers. A firm in this position is able to increase its profits over those of a single price monopolist by charging different prices to different groups through some form of price discrimination.

Figure 2 demonstrates how profit may be increased by discriminatory pricing, assuming a straight-line demand curve. If a single price *cb*, is charged to all passenger cars, the revenue received from automobile tolls will be represented by area *oabc* (product of price and volume of passenger cars). However, if all of the traffic which is willing to pay a price of *cb* or more is divided into two groups — those who are willing to pay a price greater than *fe* and those who will not pay a price greater than *fe* — then total revenue will be shown by area *odeibc*

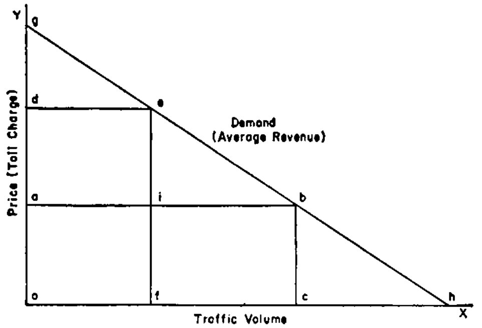

Figure 2. How profits may be increased by discriminatory pricing.

when the first group pays a toll of *fe* and the second group pays only *cb*. Because area *odeibc* is larger than area *oabc*, charging the two prices has increased total revenue without changing output. As the number of different prices between *og* and *cb* is increased, the amount of total revenue will increase until an infinite number of different prices are charged and the total revenue for output *oc* equals its maximum, represented by area *ogbc*. Practical difficulties of dividing the traffic into an infinite number of price groups make this maximum unattainable, but bridge traffic usually may be divided into groups each of which is composed of vehicle users of somewhat similar demand elasticity.

The bridge owner who wishes to maximize his profits through discriminatory pricing must somehow divide traffic into as many groups of different demand elasticity as possible and charge a different price to each group. Those groups with the more elastic demand will be charged a lower rate, as those with an inelastic demand will more readily pay more rather than forego the use of the bridge than will those with the more elastic demand.

Several devices may be used to group traffic roughly according to demand elasticity. One method is to charge according to the value of the vehicle or, in the case of a truck, the value of its cargo. The assumption in this case is that users of expensive automobiles and truckers carrying a very expensive type of cargo would be less likely to forego use of a bridge if prices were to be increased than would be the case with those who are using inexpensive vehicles or carrying low-priced cargo. Although this, of course, is frequently not true, since a wealthy man with a very inelastic demand may, out of preference, use an inexpensive automobile or a trucker carrying a valuable cargo may be operating on such a low margin of profit that he is very sensitive to variation in bridge tolls, it serves as a rough indicator of demand elasticity.

A second method is to charge according to the driver's purpose in making the trip. If the purpose of the trip were to get to or from work, reach a destination a considerable distance away, receive needed medical attention, or carry on a business, the demand will probably be more inelastic than if the purpose were to visit friends or enjoy a casual pleasure trip. This method would be very difficult, if not impossible, to apply in practice.

A third device would be to group traffic according to the location of the origin and destination points of a trip in relation to alternate routes. Traffic whose origin and destination points are close to the bridge would be expected to have a more inelastic demand curve than traffic from or to points located at a considerable distance, which would probably be in a position to select a route using another bridge or a ferry if the toll charges on the bridge were raised.

A workable means of grouping automobile traffic roughly is to charge according to the number of adult passengers in each automobile, the reason being that the greater the number of passengers in the vehicle, the greater will be the money available to pay toll charges and there will be less chance that a trip will be called off or the route changed because of an increase in toll charge.

These devices are only imperfect means of attempting to divide traffic according to demand elasticity. They would be used by bridge owners who wish to try to make their profits as large as possible through discriminatory pricing, but it must be emphasized that they are not precise or accurate, but only rough indicators of groupings of those whose demand elasticity is similar.

Once a bridge owner has divided his traffic into some kind of groups he must estimate what price to charge in each group. To set the price which will return the most profit, he must be able to predict the demand curve for users in each group. This he can not do with any precision. He can only make an estimate and charge the price which he believes will bring the greatest profits. By charging different prices at different times and comparing the profits in each case he may, by successive approximations, approach the maximum, although he will never know with assurance if he has struck that combination of traffic groupings and prices which maximize profits. Monopoly pricing with the objective of maximizing profits is largely a matter of conjecture and judgment.

Privately-owned toll bridges, railroads, electric power companies, and other organizations which are usually monopolies and in position to charge discriminatory prices, will wish to charge a price or system of prices which they hope will maximize profits. In this they will be restrained to some extent by fear of public disapproval, government interference, and even philanthropical impulses. However, unless there are definite governmental restrictions, these companies will probably charge prices which produce very large profits — profits which are much greater than necessary to keep them in business. Consequently, the federal, state, and local governments have passed laws and set up government organizations (such as public service commissions) to restrain such companies from pursuing the profit maximization motive as much as they would wish.

Profit maximization as a motive in price setting should be eliminated in the case of publicly-owned toll bridges for two reasons. The first is the impossibility of determining demand curves accurately and, in the case of discriminatory pricing, of dividing the traffic accurately according to demand elasticities, so that the objective can not be attained with assurance in any case. It could easily happen that lower prices, which would make the bridge useful to more people, would actually bring in more revenue. The second is that a government-owned facility should be operated for the benefit of the people and not to gain profits. Toll charges on a government-operated bridge should not be so great as to prevent many citizens from benefiting from its use for the sole purpose of gaining greater profits. Further, because both federal and state governments have legislated to prevent abuses arising from the use of the profit maximization motive in the case of permitted monopolies, such as public utilities and railroads, it is not right for the government itself to use this motive in setting prices.

Equivalence of Price and Short-Run Marginal Cost as a Pricing Objective

An economic theory of pricing pertinent to publicly-owned toll bridges is the theory that optimum allocation of resources results if prices (revenues) in all industries are made equal to short-run marginal cost (*5*). The theory may be explained as follows. Short-run marginal cost is the specific cost occasioned by the production of one more unit of output, which, in the case of a bridge, would be one more vehicle crossing and is, therefore, the cost of the use of all the factors used for the production of the given unit of output that could have been used as factors of production of some other commodity. Short-run marginal cost does not include the cost of fixed factors, because these are not affected by the volume of output in the short run and are not readily transferable to other uses.

Fixed factors include plant, structures, and machinery necessary for production but which, once established in a particular use in the past, can not be quickly changed from that use to another use, even though people may now be willing to pay more for their use in the production of some other commodity on which the changing desires of the people now place greater value. Also, technological advances may have made it possible for a given factor to have greater usefulness to the people in a different occupation than that to which it has been assigned in the past. Variable factors, however, may usually be applied directly in whatever use provides the greatest satisfaction to the people.

The amount of satisfaction people derive from the use of goods and services is measured by the amount they will pay for their use (within the limitations of the individual's income). The factors that are used to produce consumer goods and services are paid for by entrepreneurs, who in turn receive payment directly from the consumers who buy the products for the satisfaction they expect to receive. Factors such as raw materials and labor, which have mobility, will be bid for by entrepreneurs and will be used in the production process which pays the most for production factors. If, for all entrepreneurs, the amount that any entrepreneur pays for a factor used to provide a good is equal to the amount received by him in the sale of the good, then the factor is being used to give the greatest satisfaction.

Should an entrepreneur charge a price for a good higher than what he pays the factors, he would receive an excessive profit (excessive because normal cost of necessary entrepreneurship is included in the sum of factors). Then factors will be enticed into some other productive process where greater prices are paid factors, although, if the divergence between short-run marginal cost and price in the other plant were less than in the given plant, people may pay less for, and receive less satisfaction than if the factors stayed in the given plant. On the other hand, if the price were less than the short-run marginal cost, the price will be insufficient to hold the factors and, even though people may be willing to pay more in order to receive the satisfactions derived from the product, the good will not be produced. Consequently, it is only when all producers charge a price equal to short-run marginal cost that factors (resources) will be allotted to those productive processes that provide the greatest satisfactions.

Fixed costs contracted in the past for equipment, plant, or structures which, once having been provided, can not be used for other purposes should not affect the price of a product if all factors are to be used to provide the greatest satisfactions continually in the future. According to this theory, only the short-run marginal cost, or the cost of factors which might be used in some other productive process if a given product were not produced, should be covered by the price of the product.

There are many firms which can profitably operate at an output volume where average total cost is rising and short-run marginal cost is above the average total cost. Such firms may charge a price equal to the short-run marginal cost and it will be sufficient to pay the average total cost. In fact, in most cases these companies will operate in a competitive market where price will automatically be equated to the short-run marginal cost.

However, in the case of firms which sell a product under conditions where fixed costs are high relative to variable costs, the short-run marginal cost will be less than the average total cost so that a price equal to the short-run marginal cost will not pay the total costs. Some economists advocate that in the case of such companies as toll bridges, railroads, and public utilities, where there are decreasing average total costs, the price charged to the users should equal short-run marginal cost and the difference between this price and the average total cost should be paid for by the government (*5*).

In practice, in the case of a toll bridge, this would mean that the government would finance construction and pay all fixed costs, charging the users only the actual cost occasioned by the passage of a vehicle, which for a bridge would be almost nothing. The result would be that fixed costs would be paid for by general taxation rather than by toll levies on users.

Although paying for a bridge with

such taxes would give greater benefits to many people, it is questionable whether the public in the aggregate would benefit, as there would be many individuals who would suffer a loss. These would be those land owners and earners of taxable income who would not wish to use the bridge, but who would have to pay a tax for its construction.

An alternate method of taxation to obtain funds necessary to cover the annual fixed costs of the bridges in a given state without reducing the use of the bridges would be to tax all vehicle owners at the time of the annual registration of vehicles. This tax would secure the necessary funds, without limiting the use of the bridge, unless the tax induced some owners not to own or register a given vehicle at all which would be unlikely if the tax were low.

Although this tax would not be perfect, it would relieve taxpayers who do not own or operate vehicles from paying for bridges built for vehicular use and is, in fact, the kind of tax used to defray much of the fixed cost of the so-called free roads. This tax is the sizeable registration fee required of motorists in all states. Revenues from such fees reimburse the states to a large extent for expenditures for constructing and maintaining their free roads.

There are basic objections to the theory that optimum allocation of resources will result if prices are equated to short-run marginal cost in the case of decreasing cost industries. Coase (*6*) points out that, because prices set according to this theory do not cover fixed costs, there is no direct means by which the usefulness of a particular railway, public utility, or bridge can be demonstrated.

It is only when price covers total cost that use proves the value of a facility. With no yardstick to gage the usefulness or value of facilities constructed in the past, there is every likelihood that many structures (bridges, for example) may be built in the future for which there is no real need and others for which there is a great need may fail to be built.

Aside from this basic objection, there are two reasons why, in the case of a government-owned toll bridge, it would not be satisfactory to set toll charges equal only to short-run marginal cost with the fixed costs paid for by the government body with money collected by some kind of general taxation. One reason is that, because of the high cost of bridge construction, those who would be taxed to pay for construction would object and resist government expenditures for this purpose. These objections would prevail in many cases, so that some needed bridges would never be built. It is better for a bridge to be built and tolls charged which produce any amount of social good, even if it is not the maximum, than not to have the bridge at all with total lack of the social usefulness which the bridge could have provided.

The second reason is the delay in construction of the bridge which would take place if the government expenditure were not to be repaid out of toll revenues. At least in the case of the more expensive structures, political resistance of those whose taxes would pay for construction would cause long delays, even though potential users would be willing to pay high tolls in order to get the bridge because of its usefulness. A method of charging tolls which results in something less than optimum social usefulness is better than total lack of bridge utilization for many years.

That governments are slow to act and often do not act at all to provide facilities for which there is a great demand, but for which the government does not expect to be reimbursed through user charge, is evident in the case of toll roads. Since the end of World War II, there has been a demand for more and better highways, especially in certain congested areas. State and local governments have failed to provide suitable free roads; but whenever good toll roads have been built, large volumes of vehicles have used them, demonstrating that users are willing to pay high tolls for the social benefits of such roads. If it had been necessary to finance these roads by general taxation rather than by tolls, the benefits would have been reduced greatly by delay, and possibly lost altogether.

It is seriously doubtful if this objective of toll bridge pricing is sound in theory. In any event it should be eliminated from consideration as failing in practicality.

Equivalence of Price and Long-Run Marginal Cost

The third possible objective of pricing is to make the revenue received from each user balance the long-run marginal cost or total cost of service. For bridges, this means that the toll charge for each vehicle crossing must cover (a) the short-run marginal cost (for pavement wear, etc.) plus (b) a proportionate part of the long-run marginal cost at zero traffic volume. For convenience, costs may be treated on an annual basis, with the second part of the toll covering that amount of the annual fixed cost apportioned to each vehicle.

This objective of pricing leads neither to excessive profits (as does the profit maximization motive) nor to inadequate revenues (as does the equivalence of price and short-run marginal-cost motive). Rather, it tends to provide sufficient funds to repay the government for the cost of the structure without seriously restricting the use of the bridge by high tolls. This motive will result in toll charges which will neither reduce the social value of the bridge unduly nor fail because of impracticality.

If the toll charge were properly established so that it equals, as far as possible, the cost of service for each user, the greatest practical social usefulness will result. Economists such as Pigou (*7*) and Davidson (*8*) have advocated this objective in pricing for railroads and electric power companies, which have decreasing costs in the short-run similar to toll bridges. It follows that this motive will lead to the best system of tolls practicable for a publicly-owned toll bridge.

ALLOCATION OF FIXED COSTS TO USERS

To determine a toll which is equal to long-run marginal cost (or total cost of service), all costs, including fixed costs, must be allocated to the bridge users. The short-run marginal cost, of course, must be paid by each user; but this cost is very small, consisting mainly of the cost of pavement worn away and the cost of collecting tolls. The long-run marginal cost is essentially the fixed cost, which may be expressed as a fixed annual cost to cover the cost of construction, interest, insurance, painting, repairs, and most of maintenance.

The annual fixed cost cannot be allocated on the basis of use, because fixed cost is not affected by use. Neither should it be allocated to users merely by dividing it by the average number of users per year, because some users are more responsible than others for the annual bridge costs. Also, the traffic capacity and strength and, consequently, the fixed cost of the structure, could be less if it did not have to be built to accommodate certain users whose requirements for capacity and strength are higher than others. To make the amount of toll accurately reflect the cost of providing bridge service or the long-run marginal cost, the effect of each user on the amount of the annual fixed cost should be known.

The effect that each user could have had on the amount of the annual fixed cost depends on the following considerations:

1. Did any user or group of users have greater effect than others on the decision that the bridge be built in the first place? Obviously, if the bridge were built to accommodate one group of users and would not have been built if it had not been for them, this group should pay the most if not all of the fixed costs.
2. Once the decision was made that the bridge be built, did any user or group of users influence the location of the bridge more than others? Subject to foundation requirements, any bridge could be built in a number of locations. The actual location selected may be such as to give better service to some group of users and, if so, this group is responsible for

incremental fixed costs incident to location at a given point.

3. If any user or group of users requires the bridge to be of greater size (more lanes, higher portals, wider approach roads, etc.) than required by others, these users are responsible for a greater incremental amount of fixed cost.

4. Any user or group of users which requires the bridge to have greater strength than would otherwise be necessary is responsible for any increase in annual fixed cost caused by this requirement.

General traffic is essentially responsible for the decision to construct, the location, and the volume capacity of the bridge. In some cases a bridge may be built primarily for military purposes and would not be built otherwise. If this is the case, these fixed costs should be paid for by the military. But this is seldom true for major bridges in this country. It is possible, also, that some bridges may be built mainly to provide places, otherwise inaccessible, with police and fire protection and emergency ambulance service. Where this is the case, these fixed costs should be paid for by those who benefit from these services. However, in general all major bridges are built because they are demanded by general traffic. Their location and volume capacity are dependent upon the requirements of the traffic volume which is to use the bridge.

Annual fixed cost can be considered as a cost of providing capacity in a bridge. The capacity is divisible into two categories: volume capacity and weight capacity.

Volume capacity is the ability of the structure to carry all vehicles which wish to cross at a given location without congestion or delay. Because, in order to pass any vehicle at all, the bridge must be able to support some weight, volume capacity includes the ability to carry the weight of the lightest type of vehicles for which the bridge would be designed, the passenger car. Weight capacity is the ability to support the weight of all vehicles which are heavier than the passenger car.

The fixed cost of providing volume capacity includes the cost of site, approach roads, insurance, repairs, and all other fixed costs incurred to provide volume capacity as well as basic structure costs. The incremental fixed cost for weight capacity is the cost of additional depth of pavement slab and additional area in the cross-sections of the steel members supporting the load.

Two terms which will be used extensively in this paper are marginal volume capacity cost and marginal weight capacity cost. The marginal volume capacity cost is the annual cost of producing volume capacity for a segment of traffic which would not be incurred if the particular traffic were not to use the bridge. The marginal weight capacity cost is the amount of annual cost to provide weight capacity for a segment of traffic which would not be incurred if that particular traffic were not to use the bridge.

Marginal Volume Capacity Cost

If the volume of bridge traffic were distributed uniformly so that hourly traffic volume was constant, and if each vehicle were to occupy the same space on the bridge, all of the vehicles would be equally responsible for the fixed cost of volume capacity. This, however, is seldom if ever the case. There are hourly, daily, weekly, and seasonal fluctuations in traffic volumes. During each day there will be peak hours when the traffic volume is higher than at other hours. There may be one peak period per day or there may be several, depending on the hourly distribution of traffic.

As far as responsibility for annual fixed cost of volume capacity is concerned, traffic can be divided into two segments, peak-hour traffic and non-peak-hour traffic. In each of these segments there will be large vehicles which occupy more space and are slower on grades than the basic vehicles (passenger cars). The presence of these vehicles in the traffic stream reduces the total number of vehicles per hour which can use a bridge of given capacity. These vehicles are, therefore, responsible for the cost of volume capacity in proportion to the effect which they have on traffic capacity.

The volume capacity of a bridge is determined by the magnitude of peak-hour traffic. If the daily traffic were distributed uniformly throughout the day, it could be handled by a bridge with a capacity less than that which is necessary to provide for large volumes for short periods during peak hours. Further, the original decision to build the bridge and the selection of the site is determined in general by the traffic during the peak hours, because it is this traffic that provides sufficient demand for the bridge.

If there were only the non-peak-hour traffic, there would seldom be sufficient warrant for a bridge to be built at all. Therefore, the marginal volume capacity cost of a bridge for peak-hour traffic is the entire fixed cost of providing volume capacity, because if it were not for the peak-hour traffic, this cost would not be incurred. The marginal volume capacity cost for off-peak users is zero, since, if there were no off-peak users, volume capacity cost would not have been any less; that is, use by the off-peak users does not affect the volume capacity cost.

The concept that those users who require the maximum capacity of fixed plant are responsible for the total fixed cost of this capacity has been ably presented and defended by Davidson (*8*). His study concerned gas and electric utilities, which have a cost picture similar to that of the toll bridge in that most of the cost is the fixed cost of plant.

He has shown that it is the peak hour use which determines the size of the generating plant. If all the non-peak-hour users were eliminated. the size and type of plant would be the same. However, if the peak-hour users were eliminated from consideration, the generating plant would be entirely different. It not only would be smaller, but it also would be constructed to be efficient for the smaller capacity. It would not be merely a portion of the larger plant, or a smaller replica, but would be of a different design, probably at a different location, and possibly make use of a different source of energy.

The non-peak-hour users are not responsible for the capacity, location, or source of energy of the generating plant and, consequently, are not responsible for the fixed cost of the plant. The marginal capacity cost of peak-hour users is the total fixed cost of the plant, whereas for the non-peak users it is zero. The non-peak-hour users make use of capacity which would otherwise be idle.

The arguments advanced by Davidson are valid also for a toll bridge. The plant in this case is the bridge itself. The location and capacity of the structure is determined by the traffic during peak hours. If there were no peak-hour users, the bridge would not have been designed any differently; but if the peak-hour users were not considered, the bridge might have been built with fewer traffic lanes (probably no less than two), possibly at a different location, and of a design in keeping with the smaller capacity. It is possible, in fact, that no bridge would have been built at all if only non-peak-hour users were considered.

Application of this concept requires knowledge of which hours of the day are peak hours of traffic. The peak hours can be selected only by studying traffic and determining traffic volumes during each hour of the average day. A traffic counter may be used to count and record the number of vehicles crossing the bridge each hour. When a toll bridge is already in operation, this information can be obtained from records of toll collections if collections are recorded as of the time of passage.

When tolls must be established before the bridge is in operation, the number of vehicles expected to use the bridge each hour must be estimated as closely as possible by studying hourly traffic volumes at crossings carrying the traffic before the new bridge is opened. This is very inaccurate, because the amount of diversion of traffic to a new bridge and the volume of induced traffic is uncertain. It is better for a short time after the bridge is opened to charge a toll rate based on the best possible estimate of traffic volume and hourly traffic distribution obtainable, until sufficient hourly traffic volumes have been measured to establish the traffic pattern, before selecting peak hours and setting regular toll rates.

It is not necessary when measuring hourly traffic volumes to obtain data for an entire year. A sampling procedure may be followed to give good average values of hourly traffic for each hour of the day. The average hourly traffic volumes were computed for the Chesapeake Bay Bridge based on data taken from toll collection machines for twelve days during 1953. To obtain a good representative sample, three days were selected in winter, three in spring, three in summer, and three in fall. Each day of the week is represented, with twice as much data for days of the weekend (Fridays, Saturdays, and Sundays) and a typical working day, Tuesday. The average hourly volumes for a year were computed from these data.

To show the accuracy of the data, known yearly traffic totals were compared with the total yearly traffic found by multiplying the average hourly traffic for each hour of the weekend and work days by the number of these days per year and summing the products. The discrepancy between the year's traffic found by expanding the hourly values and the known total yearly value was found to be only 7.9 percent. This is sufficiently accurate, as the variation of traffic volume between the year of measurement and the years that the tolls based on these volumes are in effect will undoubtedly be greater than this. If the values agree within 10 percent, they would be satisfactory.

When average hourly traffic volumes are known, the hours of peak traffic may be selected. The hourly traffic volumes should be plotted as ordinates with the hours of the day as abscissa. From such a graph, the peak hours may be selected by noting the hour at which the curve turns upward for the peak period and the hour at which the downward-sloping portion of the curve levels off. The time between these two points on the curve is the daily period of peak-hour traffic.

As already noted, vehicles which reduce the traffic capacity of a bridge in terms of numbers of vehicles should pay a toll in proportion to their effect on capacity. Trucks (other than light panel trucks) and buses are such vehicles. Their presence in the traffic stream, whether on a bridge or elsewhere, reduces the capacity of a roadway lane, because a greater length of lane is influenced or affected by a bus or truck at any instant than is true in the case of passenger cars. The ratio between lane length occupied by a truck and that occupied by an automobile is approximately two for level terrain and four for hilly country (*9*).

Two pasenger cars, consequently, can be substituted for one truck on level roadways during hours of peak traffic. Four passenger cars can be substituted for one truck on a roadway during peak hours in rolling terrain where the numerous grades and restricted sight distances reduce the speeds of trucks and limit the number of passing opportunities. Because most bridges constitute only a short length of roadway and have relatively flat approach grades, they should be considered as having level roadways. On the longer bridges and on those with appreciable grades, trucks and buses would have the same effect on traffic as three or four passenger cars.

On the bridges where spacing studies have been made it has been found that four passenger cars could be substituted for each truck. However, until further data on the effect of trucks on bridge capacity have been gathered and studied, it appears reasonable to consider the bridge as having the same effect on traffic capacity as two passenger cars.

During the non-peak hours traffic is less than the capacity of the bridge and less than the peak-hour traffic, and has no effect on volume capacity cost. Trucks as well as passenger cars using the bridge during these hours are not responsible for the volume capacity of the bridge and should not pay, as part of their toll charge, for any part of the volume capacity cost.

It is necessary to know the number of trucks which will use the bridge during the peak hours in order to determine the truck tolls. A visual count of trucks is necessary, because automatic counting devices cannot differentiate between passenger cars and trucks. At toll bridges already in operation the hourly count of trucks can be taken from the toll collection records. The average total number of trucks to use the bridge per year during both the peak and non-peak hours can be computed from the average of the observed hourly truck volumes.

Marginal Weight Capacity Cost

A bridge must have not only sufficient volume capacity to handle the peak hour traffic but also sufficient weight capacity to support safely the weight of all vehicles which will be permitted on it. Construction of a bridge at the proper location and of sufficient size to accommodate peak-hour traffic volume presumes sufficient strength to carry passenger cars and other lightweight vehicles, because no vehicular bridge would be constructed with a capacity less than that sufficient to carry vehicles which have gross weights of 10,000 lb. Consequently, there is no separate weight capacity cost if only the basic traffic units (passenger cars and light panel trucks) are to use the bridge. The weight capacity cost of these vehicles is included in the volume capacity cost.

All vehicles which have gross weights exceeding 10,000 lb, or which would weigh this amount if fully loaded, require that greater strength be built into a bridge. The marginal weight capacity cost of these vehicles is that portion of the fixed costs of the actual bridge which would not be incurred if the bridge were constructed for passenger cars and light panel trucks only.

The marginal weight capacity cost can be determined by computing the saving in annual fixed cost which could be realized if the bridge were designed for lightweight vehicles only, rather than for the heavier vehicles. This capacity cost should be apportioned among the heavy vehicles using the bridge, whether use is during the peak hours or non-peak hours. The toll charge for such heavy vehicles should be increased by an amount equal to that portion of the weight cost assigned to each.

The marginal weight capacity cost should be divided equally among all vehicles which share in requiring the greater strength. The reason for this is as follows. Because the greater strength is built into the bridge to enable it to carry safely all heavy vehicles, trucks and buses, which are to use it, the design engineer must design for the maximum weight which will be allowed on the bridge, even though it is possible that no vehicles of this weight will ever use the bridge. It is the decision of the planners to permit trucks or other heavy vehicles to use the bridge at all that makes it necessary to construct extra strength into the structure. The relatively few very heavy trucks which may make use of the maximum weight capacity are not alone responsible for the weight capacity cost, because if the planners had expected these to be the only heavy vehicles to use the bridge, the added strength over and above that necessary for a vehicle weight of 10,000 lb probably would not have been justified.

Further, if the planners knew that the maximum weight vehicles would never use the bridge, they would not construct the bridge with smaller members inasmuch as the fatigue stresses induced by the many repeated load applications of the large volume of less than maximum weight vehicles make the larger sections necessary in any event.

The marginal weight capacity cost can be determined by summing the differences between the cost of part of the bridge structure as designed and the cost of these same parts if designed for a 10,000-lb gross vehicle weight only. The saving in cost will be due entirely to the fact that smaller beam and girder sections and thinner floor slabs can be used for the lighter loads, resulting in a lower cost for material. The saving in

TABLE 1

WEIGHT OF MATERIAL IN FLOOR SYSTEMS OF SELECTED SPANS OF THE CHESAPEAKE BAY BRIDGE FOR H20-S16 AND H5 LOADINGS

Type of Span	Length of Spans, ft	Weight of Pavement per Foot of Bridge, lb			Weight of Floor Beam per Foot of Bridge, lb			Weight of Stringers per Foot of Bridge, lb			Total Saving in Steel,
		H20-S16	H5	Saving, %	H20-S16	H5	Saving, %	H20-S16	H5	Saving, %	%
Beam spans	60	2,705	2,521	6.8	None	None	None	950	572	39.8	39.8
Deck girders	100	2,130	1,995	6.3	None	None	None	1,187	913	23.1	23.1
Deck girders	200	2,670	2,122	20.5	None	None	None	2,961	2,038	31.2	31.2
Deck trusses	250	2,130	1,995	6.3	149	71	52.3	352	225	36.1	40.9
Deck trusses	300	2,130	1,995	6.3	135	70	48.1	452	250	44.7	45.5
Cantilevers	450-600	2,130	1,995	6.3	174	90	48.3	452	250	44.7	45.7
Cantilevers	470-780	2,180	1,995	8.5	211	143	32.2	540	350	35.2	34.3

costs of engineering, labor, erection, etc., will be negligible or nonexistent, because the type of bridge and its over-all dimensions will be unchanged by increasing or decreasing its weight capacity.

The amount of material necessary for the roadway and floor system is greatly affected by the design weight capacity or design live loading, because a relatively large percentage of the stress in the members of the floor system is due directly to the live load and only a small percentage is due to the dead load of the roadway and floor system. In the case of the main supporting members the effect of live load is less important, whereas the effect of the dead load is greater. For the piers and abutments the effect of the dead load of the superstructure is most important and the effect of the live load on design requirements of the piers becomes relatively small.

An example of the effect of a change in the design live loading on the weight of material in the floor system of typical spans is given in Table 1. The weight of material necessary for the design live loadings of H20-S16 and H5 (gross weight 10,000 lb) are presented in this table for selected spans of the Chesapeake Bay Bridge, together with the saving in material which could be realized if the lighter design live loading were used.

The variation in the amount of material used in bridges due to different design loadings is most important in the floor system. Not only is the floor system affected greatly by the weight of the live loading, but the amount of material in the floor system also represents an appreciable percentage of the total material in the bridge. In beam and deck girder bridges the floor system is also the main support, so that the floor constitutes almost the entire superstructure. For through girder bridges and truss bridges of moderate length, the percentage of steel in the floor system is from 25 to 50 percent of the total steel in the bridge (Table 2). The weight of steel in the floor system of very long spans (cantilever and suspension spans)

TABLE 2

WEIGHT OF STEEL IN THE FLOOR SYSTEM AND TRUSSES OF VARIOUS SPANS OF THE CHESAPEAKE BAY BRIDGE FOR H20-S16 LOADING

Type of Span	Length of Span, ft	Weight of Steel in Floor System, lb/ft	Weight of Steel in Laterals and Trusses, lb/ft	Total Steel, lb/ft	Percent of Total Steel in Floor System
Beam Spans	60	950	150	1,103	86.3
Deck Girders	100	1.187	200	1,390	85.5
Deck Girders	200	2,961	250	3,211	92.3
Deck Trusses	250	501	1,466	1,967	25.5
Deck Trusses	300	587	1,539	2,126	27.6
Cantilevers	450-600	626	1,834	2,460	25.4
Cantilevers	470-780	751	2,976	3,727	20.2

is a small percentage of the total superstructure steel, but in this case the only appreciable variation in material due to design loading will be in the floor system, because the heavy dead load of the trusses and suspension cables determines the design of the bridge members other than those members that make up the floor system.

Consequently, to find the marginal weight capacity cost, it is always necessary to compute completely the design requirements of the floor system for an H5 loading and determine the difference between the cost of material for this loading and the cost of material in the floor system of the bridge as designed. The main supporting members, however, do not have to be redesigned for the H5 loading, because if the span is very long (800 ft or more) the effect of the live load on these members is negligible; for the shorter spans, the effect of the live load on the weight of steel necessary can be determined by the use of shortcut formulas for computing dead loads, such as those given by Waddell (*10*). For all bridges the saving in the cost of materials for the piers and abutments which could be realized by designing for smaller live loads is small and can be ignored.

FORMULAS FOR COMPUTING TOLL CHARGES

The toll charges to achieve equivalence between cost of service and revenue may be computed with the following formulas. The factor of two is the number of passenger cars which are considered to have the same effect on the volume capacity of a bridge as one truck.

Toll for passenger cars, peak hours =

$$\frac{A + D}{N + 2M} \tag{1}$$

Toll for trucks, peak hours =

$$\frac{A + D}{N + 2M}\,(2) + \frac{B}{M + P} \tag{2}$$

Toll for passenger cars, off-peak =

$$\frac{E}{O + P} \tag{3}$$

Toll for trucks, off-peak =

$$\frac{E}{O + P} + \frac{B}{M + P} \tag{4}$$

in which

A* = yearly cost for depreciation and interest based on original cost C_3, the amount that the original cost of the bridge would have been if it had been constructed for automobiles only;

B* = yearly cost for depreciation and interest based on incremental cost C_2, the portion of the actual original cost that was necessary to make the bridge

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* A and B may be computed using the sinking fund formulas in which i is the interest rate on borrowed funds, n is the number of years over which the original cost of the bridge will be amortized, and S is the salvage value of the bridge after n years.

$$A = (C_3 - S)\,\frac{i}{(1 + i)^n - 1} + C_3 i \tag{5}$$

$$B = (C_2)\,\frac{i}{(1 + i)^n - 1} + C_2 i \tag{6}$$

strong enough for trucks;

D = the sum of all annual costs for toll collection, taxes, insurance, and maintenance attributable to peak-hour users;

E = the sum of all annual costs of toll collection and maintenance attributable to off-peak-hour users;

M = the number of trucks which are expected to use the bridge during peak hours annually;

N = the number of passenger cars which are expected to use the bridge during peak hours annually;

O = the number of passenger cars which are expected to use the bridge during off-peak hours annually; and

P = the number of trucks which are expected to use the bridge during off-peak hours annually.

Application to Determine Tolls on a Typical Bridge

The computation of the toll charges for the Chesapeake Bay Bridge using these formulas is presented here to serve as a guide for determination of tolls for other publicly-owned toll bridges, as well as a demonstration of this method of determining tolls.

The Chesapeake Bay Bridge, which opened for traffic July 30, 1952, is a multi-span, two-lane structure over a narrow section of Chesapeake Bay near Sandy Point, Md. It is 21,286 ft in length between abutments and has a clearance above mean high water of 186.5 ft at its highest point, which is midway between the towers of the suspension span. The roadway has a clear width between curbs of 28 ft, providing two 14-ft lanes. The bridge is designed to carry a H20-S16 live loading (*11*).

In order to compute the values of annual costs A and B it is first necessary to determine C_2, C_3, n, i, and S as previously defined.

The actual original cost of the bridge is \$44,793,633. C_2, the portion of this cost required to make the structure strong enough to carry trucks, is \$2,113,650 (Table 3). C_3, the actual cost of the bridge less the saving in cost which would have been realized if the bridge had been designed for passenger cars and light panel trucks only (H5 loading), is the difference between these values, or \$42,679,983.

n is the number of years of physical life of the structure, or the number of years, T, between the time of construction and the time when traffic volume during peak hours becomes equal to the capacity of the bridge if this period is less than the physical life. The physical life of a bridge may be taken as 50 years.

TABLE 3

SUMMARY OF COST SAVINGS OF THE CHESAPEAKE BAY BRIDGE WHICH WOULD HAVE BEEN REALIZED IF DESIGN HAD BEEN FOR H5 LOADING ONLY

Group	Type of Spans Represented	Length of Bridge in Each Group, ft	Cost Savings, \$
A	Simple deck trusses	1,017	90,730
B	Steel beam spans	4,120	245,430
C	Deck cantilever trusses	6,130	762,100
D	Simple deck trusses	1,833	244,940
E	Deck girder spans	2,131	97,500
F	Deck girder spans	1,414	156,330
G	Through cantilever spans	1,719	363,220
H	Suspension spans	2,922	153,400
Total		21,286	2,113,650

T is found by using

$$T = \frac{\text{Log } \dfrac{L}{V}}{\text{Log } (1 + r)} \qquad (7)$$

in which r is the average annual percent increase in traffic, V is the mean peak-hour traffic volume during the first year of bridge use (1953), and L is the maximum possible hourly bridge capacity.

The average annual percent increase in traffic, r, is difficult to determine with accuracy. Figure 3 shows that the trend of annual increase in vehicle miles of travel in Maryland is approximately 5 percent accumulative. This yearly rate of increase shows the trend of all general traffic increases in the state and reflects local trends, such as traffic increases due to industrial activities in many areas. The rate of increase in Maryland is approximately the same as that for the United States as a whole. This is important in the case of this particular bridge, because much of the traffic using it consists of north-south movements from and to points outside the state. Consequently, 5 percent was selected as the value of r to be used in computing T.

V, the mean hourly traffic volume during the peak hours in 1953 (first year of bridge use) was computed by averaging the average hourly volumes of all vehicles using the bridge during the peak hours, which were selected as the hours from 6 AM to midnight (Figure 4). The value of V was found to be 330.5 vehicles per hour.

L, the possible traffic capacity of the bridge, was determined by a method described in the "Highway Capacity Manual" (*9*). Briefly, the procedure was to measure average differences in speeds and corresponding traffic volumes at a time when traffic volume was low and again when traffic volume was high. Each of the two sets of measurements was made during periods when the character of the traffic was substantially the same. The data were plotted as two points on a graph with the average difference in speeds as ordinates and the traffic volume plotted as abscissa. The possible traffic capacity is the abscissa value where a straight line through the two points intersects a straight line parallel to the X axis representing points of zero average difference in speeds. L was found to be 1,800 vehicles per hour for the Chesapeake Bay Bridge.

T, the number of years between the time of the opening of the bridge and the time when the average peak-hour traffic volume will equal the bridge capacity, by substitution of the foregoing values in Eq. 7 is found to be 34.7 years. This is less than the physical life of 50 years, so the value of n to be used is 35.

It should be noted that all of the bonds issued October 1, 1948, to obtain construction funds were to be redeemed by October 1, 1972. Inasmuch as the bridge

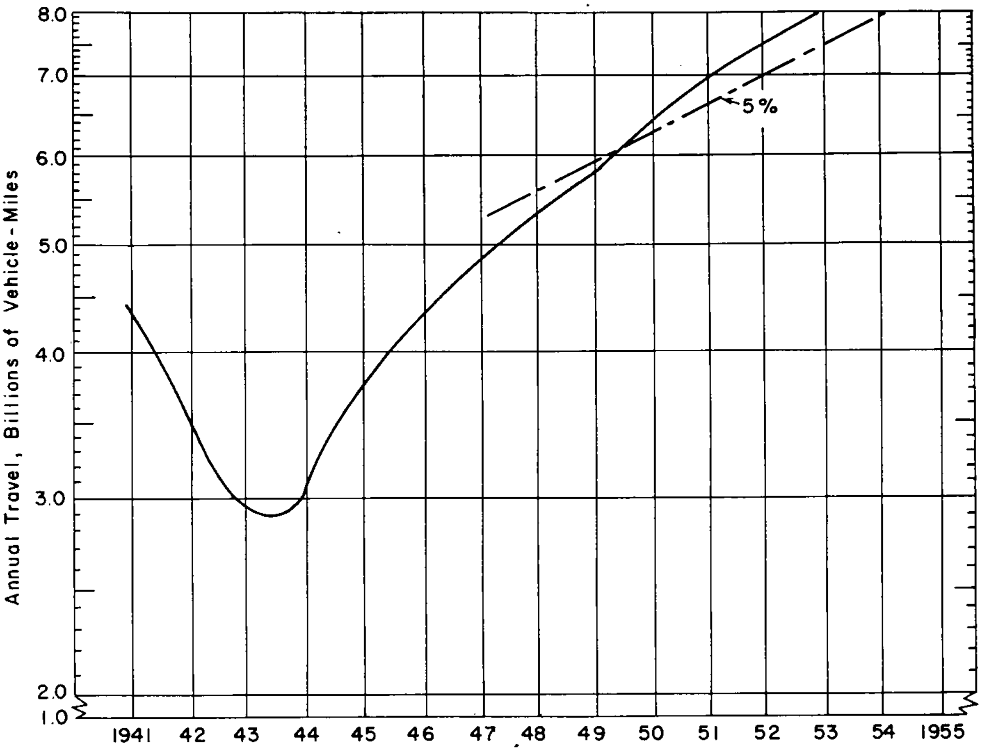

Figure 3. Annual rural and urban highway travel in Maryland, 1941-53.

was opened for traffic in 1952, this means that the money borrowed to build the bridge must be repaid during the first 20 years of bridge life. The economically valid period over which the cost of the bridge should be amortized is the useful life, *n*, which was computed to be 35 years. Consequently, it will be necessary for the state to supply the difference between the yearly amount collected in tolls to cover depreciation and interest based on the 35-year period of amortization and the yearly bond payments during the first 20 years of bridge life. Funds obtained for this purpose should be repaid to the state from tolls collected during the following 15 years.

The interest rate used to compute the annual cost of depreciation and interest should be the interest rate which would be charged if the funds were borrowed for the full useful life of the bridge, or 35 years. The interest rate for a 35-year bond life should be somewhat greater than for 20-year bond life because the lender has to wait longer for repayment and may suffer a greater risk. However, the difference in interest rate for 20- and 35-year bond periods is so small that it will be neglected in the computation of the toll charges. The decision to use the economically valid period of 35 years for amortizing the original cost will result in toll charges not greatly different from what they would be if the original cost were to be amortized in 20 years.

The interest rate, *i*, to use in computing the tolls is taken as the average interest rate on the serial and term bonds issued October 1, 1948, for the construction of the Chesapeake Bay Bridge. It is recognized that the interest rate may be changed by refunding procedures during the life of the bridge, but this cannot be foreseen when the tolls are established and, in any event, any change in the interest rate would be small. The average interest rate, *i*, of the bonds issued for this construction is 3 percent.

The salvage value, *S*, is impossible to estimate, because it depends on the use which will be made of the bridge after traffic volume becomes greater than bridge capacity. The only assured salvage value is the amount of money set aside during the life of the bridge to pay the deductible portion of the insured value of the structure. This is 2 percent

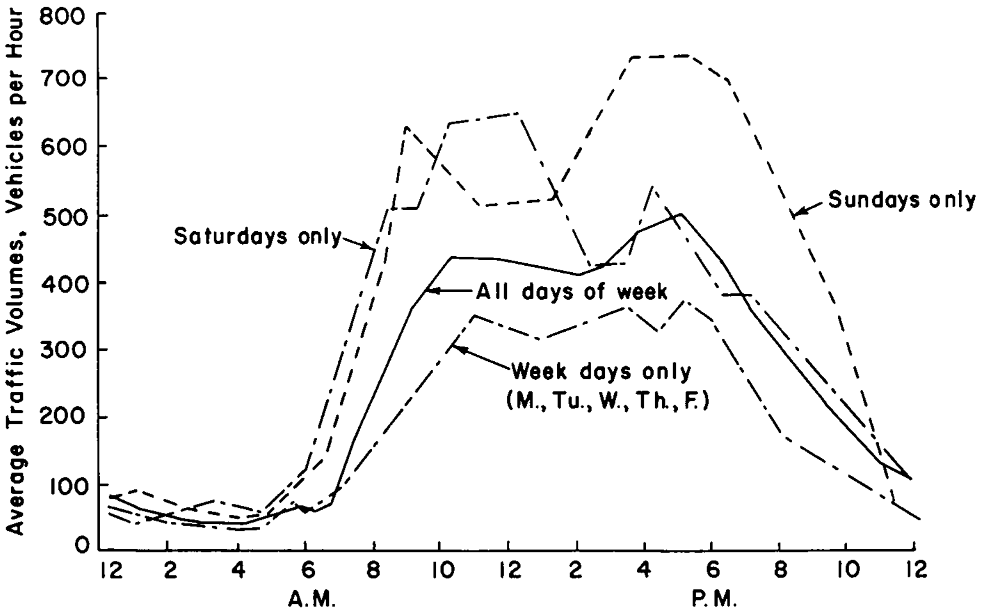

Figure 4. Daily variation of traffic volumes on Chesapeake Bay Bridge, 1953.

of the insured value in the case of the Chesapeake Bay Bridge. Because the insured value is \$32,000,000, the deductible portion is \$640,000, so $S = \$640{,}000$. Therefore, by Eqs. 5 and 6, $A = \$1{,}975{,}711.90$ and $B = \$98{,}367.80$.

D is the sum of the annual costs of toll collection, maintenance, insurance, and administration attributable to the traffic during the peak hours. It includes all of the costs of these items except those costs which would not be incurred if the bridge were closed and unused during the non-peak hours.

The annual cost of toll collection during peak hours is the sum of wages paid to toll collectors and toll sergeants for service occasioned by peak-hour traffic for a year. It is necessary to assign the entire 8-hour day to peak-hour service, even if the actual peak-hour period is less than 8 hr, because the peak-hour traffic required the men to be on duty and once on duty they must be paid for a minimum of 8 hr.

Annual maintenance cost for peak-hour traffic is the sum of the annual cost of the regular maintenance crew, the annual cost of periodic maintenance, and the annual cost of such patrols or bridge guards as may be necessary during the peak hours.

The annual cost of the regular maintenance crew includes the annual cost of owning and operating the necessary equipment, as well as labor costs. This cost depends on the size and type of bridge and the standards of maintenance. It can be taken from the records of a bridge already in operation, or estimated on the basis of proposed maintenance procedures in the case of a bridge not yet in use. All of this cost is attributable to the peak-hour traffic.

Periodic maintenance cost is the amount set aside yearly in a sinking fund for such major repair work as repainting, resurfacing, etc. Repainting is done every five or six years for steel bridges and resurfacing of pavement every 20 to 30 years. The cost of painting is approximately \$16 per ton of steel; surfacing costs vary greatly, depending on the type of surface and the kind of traffic.

Bridge guards are employed to protect the bridge and keep traffic moving. They are usually equipped to refuel and do light repairs on stalled automobiles and to remove disabled vehicles. The cost of bridge guards during peak hours should be assigned to peak-hour traffic in the same manner as the cost of toll collection.

Insurance costs should be paid for by the peak-hour traffic inasmuch as this cost is necessary because of the existence of the bridge. Because the peak-hour traffic necessitated the bridge, it is responsible for all insurance costs. The types of insurance carried vary from bridge to bridge, but in general include multi-risk, use and occupancy, and liability policies. The sum of all yearly premiums constitutes the annual cost of insurance.

The annual cost of administration, like insurance costs, should be paid for by the peak-hour traffic. It includes the salary of the administrative officer and the salaries of the office staff, as well as the cost of telephone service, fuel, and supplies. Table 4 presents a breakdown of annual costs for the Chesapeake Bay Bridge. These make up the value of D for this bridge, \$370,105.40.

E is the yearly cost incurred to allow traffic to use the bridge during the off-peak periods and should be paid for by this traffic. Since the non-peak hours are usually during the late evening and night, almost all yearly costs of electricity for lighting purposes is attributable to this traffic. The yearly wages of such toll collectors and bridge guards as

TABLE 4

SUMMARY OF ANNUAL COSTS ATTRIBUTABLE TO PEAK-HOUR TRAFFIC FOR THE CHESAPEAKE BAY BRIDGE

Toll collection	\$48,230.60
Toll sergeants	12,255.10
Bridge guards	13,368.30
Maintenance crew	59,726.40
Periodic maintenance	90,408.00
Insurance	68,306.00
Administrative:	
Baltimore office	51,984.00
Office at bridge site	25,827.00
Total annual cost (= D)	\$370,105.40

are necessary because the bridge is used during non-peak hours should also be paid for by the non-peak-hour traffic.

The costs of electric power, toll collection, and guard service can be evaluated, but other small costs which should be paid for by the non-peak-hour traffic cannot be accurately determined. These include some small portion of administrative costs and part of the costs of snow removal and sanding of icy pavements. On the other hand, part of the cost of electricity should be paid for by the peak-hour traffic. Assignment of the entire cost of electricity to the non-peak-hour traffic will tend to balance not assigning any cost of administration or maintenance to this traffic. *E*, therefore, is the total annual cost of electricity plus the annual wages of such toll collectors and guards as are necessary because of the non-peak-hour traffic.

Table 5 presents a breakdown of annual costs of the Chesapeake Bay Bridge constituting the value of E for this bridge ($= \$22{,}552$).

TABLE 5
SUMMARY OF ANNUAL COSTS ATTRIBUTABLE TO TRAFFIC DURING THE NON-PEAK-HOUR PERIODS FOR THE CHESAPEAKE BAY BRIDGE

Electricity for lighting purposes	$3,229
One bridge guard, midnight to 8 AM	4,726
Two toll collectors, midnight to 8 AM	9,027
One toll sergeant, midnight to 8 AM	5,570
Total annual cost ($= E$)	$22,552

The annual costs of the Chesapeake Bay Bridge may be recapitulated as follows:

$A = \$1{,}975{,}711.90$
$B = \$\quad 98{,}367.80$
$D = \$\quad 370{,}105.40$
$E = \$\quad 22{,}552.00$

The traffic volumes, *M*, *N*, *O*, and *P*, were determined from data taken from the toll collection records of the Chesapeake Bay Bridge for the year 1953. The peak hours for this bridge were found to be between 6 AM and midnight (Figure 4). The traffic volumes used in computing the tolls are as follows:

$M = 125{,}627.4$ veh. per year.
$N = 1{,}852{,}974.0$ veh. per year.
$O = 85{,}099.8$ veh. per year.
$P = 22.221.0$ veh. per year.

Using the foregoing values the toll charges for this bridge may now be computed, as follows:

1. The unadjusted toll charge for passenger cars and light panel trucks during peak hours (from Eq. 1) $= \$1.12$.
2. The unadjusted toll charge for trucks and buses during peak hours (from Eq. 2) $= \$2.91$.
3. The unadjusted toll charge for passenger cars and light panel trucks during non-peak hours (from Eq. 3) $=$ $0.21.
4. The unadjusted toll charge for trucks and buses during non-peak hours (from Eq. 4) $= \$0.88$.

These unadjusted toll rates above should be increased by 10 percent to allow for error in the prediction of traffic volumes. The adjusted rates rounded off to the next higher value divisible by five are as follows:

1. The adjusted toll charge for passenger cars and light panel trucks during peak hours = $1.25.
2. The adjusted toll charge for trucks and buses during peak hours = $3.20.
3. The adjusted toll charge for passenger cars and light panel trucks during non peak hours = $0.25.
4. The adjusted toll charge for trucks and buses during non peak hours = $1.00.

Comparison with Present Toll Rates in Effect

The total annual cost of the bridge is the sum of *A*, *B*, *D*, and *E*, and is equal to $2,466,737.10. The total revenue which would have been received during 1953 if the above rates had been in effect, assuming that the traffic volumes would have been unchanged, is equal to $\$1.25N + \$0.25O + \$3.20M + \$1.00P$, or a total of $2,761,621.13. The actual gross revenue collected during 1953, when the rate schedule shown in Table 6 was in effect, was $4,015,381.03. This exceeded the annual cost by more than 60 percent ($1,548,643.93).

TABLE 6
TOLL RATES IN EFFECT ON THE CHESAPEAKE BAY BRIDGE DURING 1953

Class Number	Description	Rate
1	Passenger cars, light panel trucks, station wagons, and light pick-up trucks	$1.40
1-a	Extra passenger (in addition to driver)	$0.25
2	Two-axle vehicles, including trucks, tractors, and buses	$2.25
3	Three-axle vehicles, including tractor and semi-trailer, trucks, and buses	$3.50
4	Four-axle vehicles, including tractor and semi-trailer, trucks, and buses	$4.50
5	Five-axle vehicles, including trucks and tractors, and trailers	$5.00
6	Buses in scheduled run	$1.50
7	Passenger car with one-axle trailer	$2.10
8	Motorcycles and miscellaneous heavy vehicles	
	Motorcycles	$1.00
	Heavy vehicles	$5.00

A comparison of the proposed rates and the actual toll rates shows that passenger vehicles with driver only would be charged $0.15 less during peak hours using the proposed rates than is charged at present. Large numbers of passenger vehicles have at least one passenger in addition to the driver. These passengers are charged an extra $0.25 at present, so that passenger vehicles with one or more passengers would be charged much less using the proposed rates than they are charged now.

During the off-peak periods the present toll structure requires the same payment for passenger vehicles as during the peak hours, but with the proposed rates in effect the charge for off-peak use would drop to $0.25, a great saving to the user.

In the case of trucks other than light panel trucks, the present schedule gives four separate rates, depending on the number of axles per truck. The proposed rates specify a charge of $3.20 for all trucks during peak hours. This is greater than the present charge for vehicles with two axles, but is less than the charge for three-, four-, and five-axle vehicles. Because approximately 35 percent of the truck traffic consists of vehicles with three axles, 19 percent with four axles, and less than 1 percent with five axles, the truck rate would be lower for about 54 percent of the truck traffic during the peak hours if the proposed rates rather than the present rates were in effect. During the non-peak-hour periods the truck rate drops to $1.00, which is much less than any of the present rates.

The proposed rates, therefore, would be lower for passenger cars and light panel trucks during both peak and non-peak periods than they are at present. The truck rate would average out about the same as now for peak hours, but would be much less for non-peak-hour use.

The foregoing comparison between the revenues received in 1953 and the revenues which would have been received if the proposed rates had been in effect is a valid comparison only if the hourly traffic volumes were the same in each case. This is not necessarily true, but depends on the effect which the proposed rates would have had on the use of the bridge. This effect can only be estimated, as there is little factual information on the vehicle user's reaction to rates which are higher during certain hours of the day than at other hours, and the elasticity of the demand curve for passenger cars and trucks is unknown.

However, a general picture of the reaction of vehicle users to the application of the proposed rates can be deduced. First, there will be no reduction in the use of the bridge by passenger cars and light panel trucks, because the proposed rates for both peak and non-peak hours are less than those charged at present for all hours. There may be a change in the hourly distribution of passenger car traffic, because some users may adjust their trips so as to cross the bridge at other than peak hours; that is, before six in the morning and after midnight, as this will save them $1. A committee of the American Association of State Highway Officials has reported that the average value to the vehicle user of one hour of time is approximately $1.35 per vehicle-hour (*12*). Thus, a passenger car user presumably will cross during peak hours if he expects to be delayed more than $\frac{\$1.00}{\$1.35}$ hours, or 45 minutes, by changing his schedule so as to avoid crossing during these hours.

A great many users of the Chesapeake Bay Bridge are long-distance travelers who would be seriously inconvenienced if they were to plan their entire trip so as to cross during the non-peak hours. Therefore, they will probably use the bridge during the peak hours as much if the proposed rates were in effect as they do at present.

The resultant effect of the proposed rates on the use of the bridge will probably be a flattening of the traffic peaks during the peak hours and a general increase of traffic volume during the non-peak-hour periods. There will be a greater utilization of the bridge, because many potential users who do not cross at present because of the high rates will be induced to cross during off-peak periods when the rate is only $0.25.

Truck traffic would probably be similarly affected. There is a drop in the truck rate of $2.20 between the peak-hour period and the non-peak-hour period, which will induce some trucking companies to re-arrange their schedules so as to have their trucks cross during the non-peak periods. However, for most trucking concerns, a saving of $2.20 in the bridge fare will probably be offset by losses occasioned by a schedule change, so that it is likely that use of the bridge by trucks will be affected much less by having the rates different during peak hours and non-peak hours than will be the case with the passenger cars.

It is evident, therefore, that over-all use of the bridge would increase if the proposed rates were put into effect. Some users who cross during the peak hours under the present rate schedule would change and use the bridge during non-peak hours when rates would be lower, but this shift in use probably would not have sufficient effect on income to offset the extra revenue that would be received from new traffic induced to use the bridge because of the lower rates.

REFERENCES

1. BOULDING, KENNETH E., "Economic Analysis," pp. 467-545. Harper, New York (1948).
2. LERNER, ABBA P., "The Economics of Control," pp. 62-77. MacMillan, New York (1944).
3. VICKREY, WILLIAM, "Some Objections to Marginal Cost Pricing." *Jour. Polit. Econ.*, 56:216 (June 1948).
4. ROBINSON, JOAN, "The Economics of Imperfect Competition," pp. 95-182. MacMillan, London (1948).
5. HOTELLING, HAROLD, "The General Welfare in Relation to Problems of Taxation and of Railway and Utility Rates." *Econometrica*, 6:260 (Jan. 1938).
6. COASE, R. H., "The Marginal Cost Controversy." *Economica*, 13:169 (Aug. 1946).
7. PIGOU, A. C., "The Economics of Welfare," pp. 290-317. MacMillan, London (1948).
8. DAVIDSON, R. K., "Price Discrimination in Selling Gas and Electricity," pp. 97-147. Johns Hopkins Press, Baltimore (1955).
9. "Highway Capacity Manual," pp. 38-61. U. S. Gov. Printing Off., Washington, D. C. (1950).
10. WADDELL, J. A. L., "Weights of Metals in Trusses." *Trans. Amer. Soc. Civil Eng.*, 101:1-11 (1936).
11. "Standard Specifications for Highway Bridges — 1949." Amer. Assn. State Highway Officials, Washington, D. C. (1949).
12. "A Committee Report on Road User Benefit Analysis for Highway Improvements." Amer. Assn. State Highway Officials, Washington, D. C. (1951).