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Optimal Peak-Load Pricing, Investment, and Service Levels on Urban Expressways

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Optimal tolls, capacities, and service levels for highways can be determined jointly by way of an integrated peak-load pricing model. In this paper, such a model is developed and estimated with data for roads in the San Francisco Bay Area. The results suggest optimal peak user tolls of 2–7 cents per automobile mile on rural highways, 2–9 cents on suburban highways, and 6–35 cents on central city highways. Although our results are to some degree dependent on the interest rate, time value, and peak demand configuration assumed, one basic conclusion holds up under all alternative assumptions: current user charges are well below optimal peak tolls. However, our results also suggest considerably higher rush-hour speeds than currently prevail on Bay Area roads, and the lower travel time costs suggested by our analysis (relative to the current situation) should to some degree offset the corresponding higher user charges.

Given the crowded condition of most metropolitan freeways during rush hours in this country, the question of optimal pricing and investment policies for urban roads is a topic of some interest and controversy. It is the aim of this paper to derive a long-run model of highway pricing and investment to shed light on these issues. The model is developed and estimated, using data from a sample of freeways in the San Francisco Bay Area.

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In brief, the model is concerned with trading off the cost of providing urban expressway capacity against the value of travel time to minimize total system costs. Out of the model comes a set of long-run peak-load tolls (equal to optimal short-run tolls when investment is made correctly), as well as an optimal service level (as a function of time values and capacity costs). These results give some indication as to whether auto transportation in a given corridor is priced efficiently and whether capacity provided is appropriate.

In Section I the model is set forth, consistent with the previously established theory of peak-load pricing, but particularly suited to highways. Sections II–V are concerned with empirical estimation of the parameters of this model. More specifically, Section II is concerned with the estimation of capital and maintenance costs and with determining returns to scale in the provision of freeway services. Section III is concerned with estimating the technological trade-off between travel time and capacity utilization. Section IV discusses briefly the issues involved in valuing travel time and presents the assumptions made in this study, as well as some evidence to support them. In Section V attention is directed to the peaking characteristics of demand for Bay Area freeway services.

Section VI pulls together the theoretical and empirical work of the previous sections, discusses the optimization procedure used, and presents the results. Section VII presents a comparison of optimal and existing prices on service qualities on the relevant freeways, and Section VIII discusses the policy implications of our results.

I. The Theory of Optimal Highway Pricing and Investment

As was first shown by Mohring and Harwitz (1962), the optimal pricing and investment decision for highways can be dealt with analytically in a single model. This model was extended to include peak-load pricing by Vickrey (in Fitch 1964), Strotz (1964), and Mohring (1970). The present model draws from all these previous ones, although it is not identical with any of them in every detail.¹

To start, we make two simplifying assumptions. First, we assume that highway construction can be done without problems of plant indivisibility. Although this is not strictly realistic, it is not an unreasonable assumption for large urban highways, for the wider the roads in the system, the less relevant indivisibilities become to the analysis. Second, we assume that demand in each period is independent of prices in other periods. The

¹ Strotz's analysis, couched completely in terms of utility functions, is quite rigorous, but empirically unworkable. Mohring (1970) works out the solution starting with utility functions, then translates the results into intertemporally dependent demand functions. The reader seeking a more complete derivation of the basic results shown here is directed to his work.

implications of dropping these assumptions will be considered in detail later.

We assume, then, that over an annual period there are T subperiods over which demand varies: let $P_t = P_t(Q_t)$ be the demand function for period t , where Q_t is the flow of vehicle trips over a given urban route per unit of time and P_t is the total user cost of a trip on the route, including cost of travel time.

The rental cost of the road used for these trips includes interest and amortization on the investment, plus those maintenance costs which are variable with road size (as opposed to traffic volume using the road). It is thus

$$\rho(w) = \left(\frac{r}{1 - e^{-rL}} \right) K(w) + M(w) + rA(w), \quad (1)$$

where r is the interest rate, L is the effective lifetime of the road, $K(w)$ is the construction cost (as a function of width, w), $M(w)$ is the maintenance cost varying with width, and $A(w)$ is the land acquisition cost.

We now define an average variable cost function, which includes all expenses of user-supplied inputs—variable ownership maintenance, and operating costs of the autos, plus the value of in-vehicle travel time for the average number of passengers in each vehicle. In addition, it includes the cost of publicly supplied inputs whose costs vary with vehicle-miles and not lane capacity (police costs, for example). Let this variable cost function be

$$C_t = C_t(Q_t, w), \quad (2)$$

where $\partial C_t / \partial Q_t > 0$, and $\partial C_t / \partial w < 0$. That is, additional traffic, holding land capacity constant, will slow everyone down, thereby raising costs; additional lane capacity, on the other hand, will allow everyone to speed up, holding traffic constant (when the road is uncrowded, however, these effects may be very small).

We also assume that $C_t(Q_t, w)$ is homogeneous of degree zero in Q_t and w ; this is equivalent to assuming that the speed of traffic on the road is dependent only on the volume-capacity ratio of the road and not the absolute size. There is considerable evidence to support this assumption, at least for roads with widths of two or more lanes in each direction (since our analysis is strictly for expressways, this is reasonable; see Highway Research Board [1965, p. 76]).

We wish to maximize net benefits of all trips on the route over the life of the road:

$$NB = \sum_{t=1}^T \left[\int_0^{Q_t} P_t(Q_t) dQ_t - Q_t C_t(Q_t, w) \right] - \rho(w). \quad (3)$$

Necessary conditions for the maximum may be found by differentiating (3) with respect to each Q_t , and with respect to w , and setting each derivative equal to zero.

Differentiating with respect to each Q_t , setting the result equal to zero, and rearranging, we have

$$P_t = C_t + Q_t \frac{\partial C_t}{\partial Q_t}, \quad (t = 1, \dots, T). \quad (4)$$

This condition is simply that total price paid in each period should be equal to short-run marginal cost. The second term after the equal sign is the optimal congestion toll, the difference between optimal price and average variable cost.

Optimizing (3) with respect to w yields the following condition:

$$- \sum_{t=1}^T Q_t \frac{\partial C_t}{\partial w} - \rho'(w) = 0. \quad (5)$$

This states that the lane capacity should be expanded to the point where the marginal cost of an extra unit of capacity is equal to the marginal value of user cost savings brought about by that investment.

It is now worth considering the relationship between the revenues from optimal tolls charged on the road and the costs of owning and maintaining it. To do so, we multiply equation (4) by Q_t and sum over all time periods. By use of condition (5), and of Euler's theorem on homogeneous functions C_t , we obtain the following equation for toll revenues:

$$\sum_{t=1}^T [P_t(Q_t) - C_t] Q_t = w\rho'(w). \quad (6)$$

If there are constant returns to scale in highway construction, then $\rho(w) = aw$, where a is a constant, so $w\rho'(w) = \rho(w)$, and total tolls from the road will just cover its rental costs. With increasing returns, the road will have to be subsidized for efficient operation, and similarly, with decreasing returns the road will earn a surplus.

We are now in a position to consider qualitatively the implications of relaxing our assumptions regarding demand interdependencies and plant indivisibilities.

As Mohring (1970) has shown, the existence of intertemporal demand dependencies does not alter the short-run pricing rule (6), but it will affect the magnitude of the toll in long-run equilibrium. By taking the current demand distribution over time as given and fixed, we should obtain reasonable first-round approximations to optimal tolls for each period. To get an idea of what the effect would be of "demand spreading" on equilibrium tolls, we also recalculate our results with a much flatter peak than the existing one. While this procedure is not a precise one, it should tell something about the likely effects of potential demand interdependencies.

The main impact of indivisibilities is to force construction of roads either too large or too small for the amount of traffic using them. This means, as Neutze (1966) has shown, that if there are constant returns to scale in constructing and maintaining the road some roads will make

money and others will lose, but with a large group of roads they should tend to break even overall. Similarly, with increasing returns to scale the system will lose money, and with decreasing returns it will make money. In ignoring indivisibilities, our work may thus give misleading results for any one road, but for a system as a whole, the results are likely to be suggestive of what would happen under a regime of optimal pricing and investment.

II. Estimation of the Highway Capacity Cost Function

This section is concerned with estimation of the function $\rho(w)$, mentioned above. This is done by way of three statistical cost models, one for construction, one for land acquisition, and another for maintenance.

A. Construction Costs

In estimating construction costs for urban highways, it is necessary to disentangle several effects which cause the cost per lane-mile to differ for different stretches of road.

First, scale economies or diseconomies may exist, making wider roads cheaper or more expensive per lane-mile than narrower roads. Evidence from previous studies of this question leaves the answer in dispute.

On the basis of prior engineering considerations, Meyer, Kain, and Wohl (1965, pp. 200–204) find considerable economies of width. But this result would seem to stem more from their initial engineering assumptions than from empirical evidence. They also do not take account of the fact that when wide roads meet they require a more elaborate and expensive interchange system than smaller roads. Thus, they state that, especially for autos (as opposed to buses), their method could considerably overstate costs for a four- or six-lane freeway relative to an eight-lane freeway.

And it is difficult to separate the effects of urbanization and scale in determining highway costs. Walters (1968, p. 184), looking at a data sample of construction costs compiled by Meyer, Kain, and Wohl, finds considerable evidence of decreasing returns to scale in the figures, which seem to imply higher cost per lane for a wider road. Meyer, Kain, and Wohl, on the other hand, attribute all these cost differences to the effects of urbanization (1965, p. 204).

In another study, Fitch and Associates (1964, p. 131) find evidence of decreasing returns to scale for urban freeways. They examine the costs of two highway plans for Washington, one with far more freeway capacity than the other. They find that the freeway-intensive plan is considerably costlier on a lane-mile basis than the non-freeway-intensive plan. The evidence on scale economies in freeway construction then, is inconclusive.

Urbanization, the second important variable determining freeway

capital costs, is difficult to measure. Joseph (1960) uses net residential density, which is likely to be the most reliable available measure of urbanization, but data on that are difficult to get for the Bay Area roads in our sample. In our model, the impact of urbanization is estimated by allowing construction costs per lane-mile to vary discretely between central city areas (i.e., Oakland–San Francisco,) urban but outside the central cities areas, and rural-suburban (unincorporated) areas.

The data sample over which the model was estimated includes all state-maintained roads in the nine Bay Area counties, including arterials, expressways, and rural roads.² Each observation consists of a single stretch of road in a given county. Thus, costs per lane-mile for State Highway 24 in Contra Costa County represent one observation (average lane widths of each road were calculated from state records). Data on 57 such observations were collected.³

The construction cost data used were historical in nature. The following procedure was used to convert them into 1972 dollars. Annual investments made in each of these roads over the period 1947–72 were converted to 1972 prices using the California Highway Construction Cost Index. The costs were then added up, under the assumption of a “one-horse-shay” depreciation policy, with an estimated lifetime of 25 years.

In order to separate the effects of urbanization and scale on freeway costs, two alternative specifications were used: a nonlinear one and a log-linear one. The nonlinear specification took the following form:

$$KLM = (a_1CRS + a_2CUC + a_3FR + a_4FSU + a_5FC)w^{a_6}, \quad (7)$$

where KLM is 1972 construction cost per lane-mile, CRS is the fraction of the length of the road in the sample accounted for by conventional (non-freeway) roads outside of city limits, CUC is the fraction of the observed road made up of conventional arterial streets or roads within city limits; FR is the fraction of the observed road made up by rural freeways; FSU is the fraction of the road made up of urban or suburban freeways, as defined by the California division of highways; FC is the fraction of the observed road made up of freeways within the city limits of Oakland or San Francisco (freeways in Oakland and San Francisco are counted in both FSU and FC . Thus, to get the total cost of a freeway in these cities, FSU should be added to FC); finally, w is the average width of the observed stretch of road in lanes.

This nonlinear regression can be used to determine the cost of a lane-mile of freeway for different degrees of urbanization and with different widths. For example, the cost per lane-mile of a six-lane freeway in Berkeley is $a_46^{a_6}$.

² The nine Bay Area counties are Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma.

³ Data come from California Department of Public Works (1947–72), sec. D.

Estimation of this model requires use of a nonlinear estimator. Non-linear least squares was used (see Malinvaud 1970, chap. 9).

An alternative specification used is a log-linear form, described by the following equation:

$$\ln(KLM) = a_1CRS + a_2CUC + a_3FR + a_4FSU + a_5FC + a_6 \ln(w), \quad (8)$$

where all notation is the same as before, save that \ln stands for natural logarithms. Exponentiation of this equation yields the following:

$$KLM = \exp(a_1CR + a_2CUC + a_3FR + a_4FSU + a_5FC)w^{a_6}. \quad (9)$$

Again using the example of a six-lane Berkeley freeway, construction cost per lane-mile would be $\exp(a_4FSU) \cdot 6^{a_6}$.

This form has the advantage that it can be estimated linearly, while still allowing costs per lane-mile to vary depending on the degree of urbanization. But like (7) above, it still allows estimation of a degree of homogeneity a_6 .

In the case of both equations, if $a_6 = 0$, that is evidence of constant returns to width; if $a_6 < 0$, that is evidence of increasing returns; and if $a_6 > 0$, that implies decreasing returns.

The results of estimation are shown in table 1. Both sets of results are consistent with the hypothesis of constant returns; in neither case is it possible to reject that hypothesis at any reasonable level of significance. Although the nonlinear equation provides some very weak evidence of increasing returns, the log-linear equation is in some ways preferable on prior grounds, given that linear regression estimators are generally more efficient than nonlinear ones and, consistent with this, that the actual lane-mile cost estimates coming from the log-linear equation are more plausible than those from the nonlinear one. For these reasons, we base our analysis and conclusions on the results of the log-linear equations.⁴

In calculating costs per lane-mile, constant returns to scale were assumed throughout on the basis of the log-linear results shown in table 1. However, in order to get an unbiased estimate of lane-mile costs using the estimation equation (11), we assumed w to have a mean of 6. As a result, all costs on the basis of coefficients a_1 – a_5 were multiplied by $6^{-.0305} = .9468$. Because a_6 is so small, the estimated cost per lane-mile is highly insensitive to the value of w assumed.

One further refinement is needed to make the log-linear results useful for our purposes. All our calculations involve automobiles only. Hence, it would be inappropriate to include in them any construction costs necessary only for heavy commercial vehicles. Therefore, the costs per

⁴ It is worth noting that when the w^{a_6} term was excluded from the nonlinear equation (so it could be estimated additively and linearly) the resulting estimates of the cost of lane capacity were virtually identical with those of the log-linear equation, for each degree of urbanization.

TABLE 1
CONSTRUCTION COST REGRESSION RESULTS

Parameter Estimated	Nonlinear Equation	Log-linear Equation
a_1	116,983 (97,193)	11.609 (0.359)
a_2	945,214 (585,588)	12.767 (0.597)
a_3	563,649 (388,066)	12.993 (0.729)
a_4	911,784 (426,089)	13.255 (0.771)
a_5	2,017,817 (1,583,633)	1.1151 (0.5389)
a_6	0.3178 (0.3399)	0.0305 (0.3931)
R^25262	.5183

NOTE.—SEs shown in parentheses.
SOURCE.—See text.

TABLE 2
FREEWAY CAPITAL COSTS (\$)

Capital Cost Category (per Lane-Mile)	Urban-Central City Freeway	Urban-Suburban (Outside Central City) Freeway	Rural Freeway
Construction cost	1,648,427	540,545	415,955
Portion of construction costs allocable to an autos-only highway	1,269,289	416,219	320,285
Annualized capital costs of an autos- only highway:			
at 6%	86,767	28,456	21,898
at 12% (35-year life)	154,599	50,695	39,010
Total land acquisition cost	465,829	134,439	124,787
Annualized land acquisition cost:			
at 6%	27,950	8,066	7,487
at 12%	55,899	16,133	14,974
Annual capacity-related maintenance costs	2,917	2,917	2,917
Total annual rental per unit of capacity:			
at 6%	117,634	34,439	32,302
at 12%	213,415	69,745	56,901

SOURCE.—See text.

lane-mile derived from equation (8) should be scaled down to reflect the costs of an autos-only road. For a typical urban expressway, the United States Bureau of Public Roads estimates that costs for an autos-only road should be about 77 percent of costs for a general-purpose highway.⁵ Therefore, all construction costs estimated above are multiplied by a factor of .77 to get the cost attributable to autos. The results are shown in table 2.

⁵ These calculations are especially for an urban freeway, and they are taken from data presented by Meyer, Kain, and Wohl (1965), pp. 204-6.

B. Land Acquisition Costs

Conversion of land acquisition costs to 1972 values poses problems. It is clearly inappropriate to count only historical costs, given that land costs have risen over the years. Furthermore, no satisfactory land acquisition cost index is available. However, some new roads have been built in very recent years in each county, and the land acquisition costs of these roads are probably the most reliable available guidelines for what it would cost to acquire the land anew for other roads in those locations.

Therefore, we have assumed that each observation in our cross section would have the same ratio of land acquisition costs to construction costs as the roads built in its county during the 1968–72 period. “Typical” costs for each road type (rural, urban-suburban, and central city) were calculated on this basis using the following procedure. First, for each of the nine Bay Area counties, the countywide ratio of land acquisition to construction costs was calculated for all construction undertaken during the 1968–72 period.⁶ Then, a cross-section regression was estimated, using as the independent variable the fraction of the stretch of road accounted for by each road type (the same independent variables as in equation [7], save for width). The dependent variable was the countywide ratio of land acquisition to construction costs for the stretch of road involved. The results are as follows:

$$\begin{aligned}
 ROW/K = & .267 CRS + .342 CUC + .300 FR \\
 & (.007) \quad (.011) \quad (.021) \\
 & + .323 FSU + .367 FC \\
 & (.101) \quad (.024)
 \end{aligned} \tag{10}$$

where ROW/K is right-of-way costs as a fraction of construction costs, and the fractional variables, CRS , CUC , FR , FSU , and FC are as defined below equation (7). Standard errors are in parentheses below the estimates, but they are downward biased because, given our method of calculating ROW/K for each observation, we really have nine rather than 57 observations on the dependent variable.

Given estimates of lifetimes and interest rate, the construction and land acquisition costs we have estimated can be converted to annual rental rates, based on equation (1). The lifetimes assumed are 25 years for construction investments and infinity for land. The choice of interest rate is difficult, for there is little agreement among economists as to the discount rate appropriate to public investments. We therefore base all our calculations on two alternative interest rates, 6 percent and 12 percent. The resulting rental costs, so calculated, are shown in table 2.

⁶ Land acquisition cost data come from California Department of Public Works (1968–72).

C. Maintenance Costs

To estimate these costs, basically the same sample was used as for construction costs (it was possible to include a few more stretches of road, however, making the total number of stretches in the sample 66). Maintenance costs were estimated for the year 1972, and the data were tabulated from state work-order records.⁷ The following equation yielded the best results:

$$MC/LM = \$2,917 + \$0.00045 (V/L), \quad R^2 = .20, \quad (11)$$

(456) (.00011)

where MC/LM is annual maintenance cost per lane-mile, and V/L is average annual vehicles per lane on the relevant stretch of road (it was impossible to discern different marginal maintenance costs for heavy commercial vehicles relative to autos).

Total capacity costs per lane-mile are tabulated in table 2. These provide the estimates of $\rho(w)$ needed to implement empirically the model developed in Section I.

III. Road Capacity Utilization and Travel Time: The Technological Relationship

The relationship between traffic speed and capacity utilization has been estimated under varying circumstances by traffic engineers; it is commonly called a speed-flow curve, graphing the average speed of traffic on the road against the flow of traffic on the road per unit of time (usually measured as a fraction of the ideal capacity of the road and called its volume-capacity ratio). These curves are a function of such things as maximum design speed of the road, weather, terrain, vehicle types, driving habits, and the number of interchanges which the road encounters over the observed stretch.

Since our concern is with passenger commutation, we are interested mainly in speed-flow curves for radial expressways representing typical driving conditions in this area. To estimate such a curve, it is necessary to take observations of actual speeds and volume-capacity ratios at different times for such roads. The Institute of Transportation and Traffic Engineering (ITTE) has recently completed a large-scale study doing just that for a sample of Bay Area freeways.⁸ The curves estimated by the ITTE are not, however, perfectly suited to our needs as they stand. They

⁷ These data are unpublished and come from state computer-tape records.

⁸ Speed-flow data come from the following reports: Ybarra and May (1968, pp. 5-6, 22-23): Nimitz Freeway northbound, Hayward to S. Oakland, October 1 and November 1, 1967; Jacobs (January 1969, pp. 23-24, 34-35): Bayshore Freeway northbound, San Mateo to Daly City, November 14-16, 1967; and Jacobs (April 1969, pp. 25, 26-27): Eastshore Freeway southbound, San Pablo to Emeryville, April 25-28, 1968.

measure instantaneous speeds on each freeway, intentionally using "straight-pipe" segments and avoiding bottlenecks. This may be useful from an engineering viewpoint, where separate calculations can account for queuing behind bottlenecks, but we are concerned here with the effects of differing levels of capacity utilization over an entire trip.

Therefore, for each of three freeways in the Bay Area we reworked the ITTE data, calculating average speeds over trips of 5–15 miles and regressing them against average volume-capacity ratios over the same stretches. ("Capacity" here refers to an engineering standard carefully defined by the Highway Research Board [1965] and calculated for each freeway segment by the ITTE staff.) The observations on speeds and volume-capacity ratios were calculated for each of the following stretches of road: the Eastshore Freeway, San Pablo to Emeryville; the Bayshore Freeway, San Mateo to Daly City; and the Nimitz Freeway, Hayward to South Oakland (calculations were also done for the Bay Bridge, but it has certain unusual characteristics which gave us reason to exclude it here). For each of the three freeways, a quadratic equation of volume-capacity-ratio (V/C) as a function of speed (S) fit the data well (see fig. 1). Note specifically that both stems of the parabola fit the data well. The backward-bending portion is a result of stop-and-start driving at bottlenecks during congested periods, and its existence has been well documented theoretically and empirically in the literature (see, for example, Walters 1961).

The two roads which could most reasonably be called typical radial commutation expressways are the Bayshore and the Eastshore. It is worth noting that the estimated speed-flow curves for each road are virtually identical, and it is most appropriate to use them in our calculations (the Nimitz would appear atypical in having more interchanges than the typical radial and also in having a disproportionate amount of trucks; these factors tend to congest it at traffic levels lower than the other two). For the two radials one might regard as typical, the ITTE studies on the Eastshore contain more observations. We therefore use it in subsequent calculations. The details of the regression results for it are as follows:

$$V/C = -3.153 + 0.1757 S - 0.001923 S^2, \quad R^2 = .76. \quad (12)$$

(0.791) (0.0311) (0.000303)

Although the results based on this curve are not universally applicable, they should be suggestive for most radial expressways dealing mainly in automobile traffic and built with design speeds somewhere between 60 and 70 miles per hour.⁹ In order to apply the curve to our model, we

⁹ It would be desirable to do alternative calculations for highways with design speeds other than 65 miles per hour, both because some downtown roads have lower design speeds and because of the 55-mile per hour speed limit which has been imposed more recently to save fuel. However, we do not have data for slower-moving roads save for the

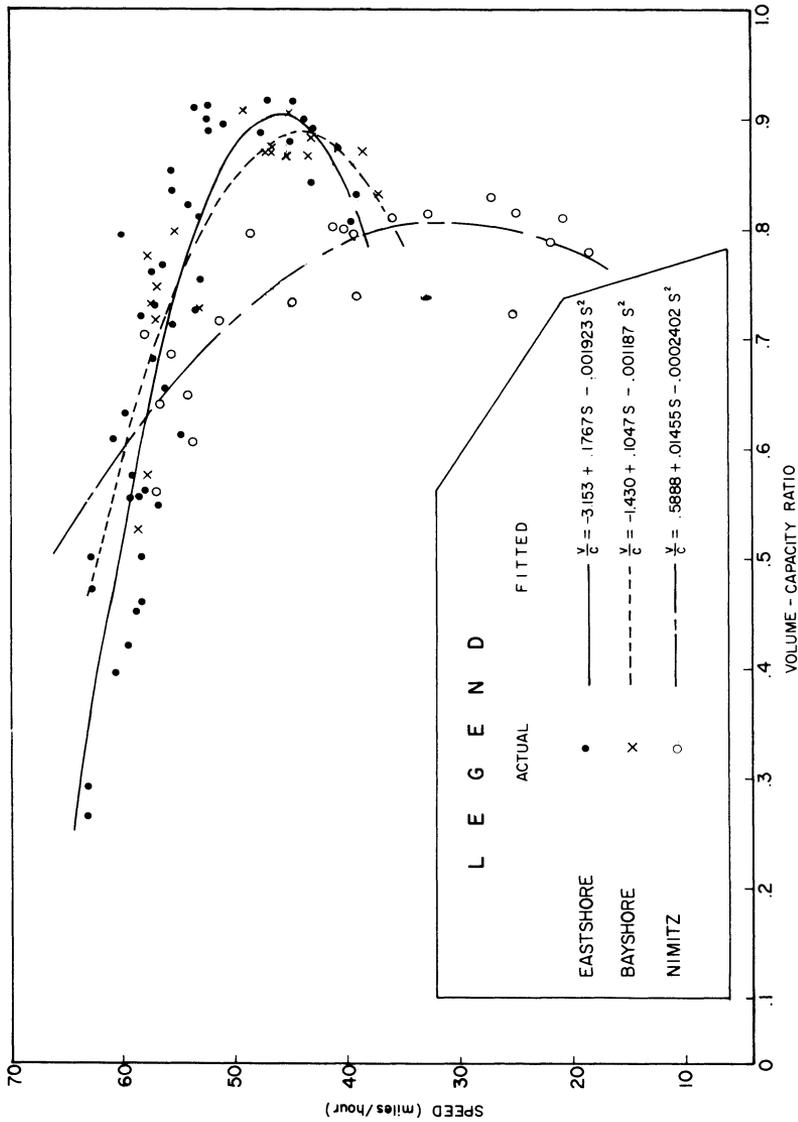


Fig. 1.—Speed-flow curves

Bay Bridge, which is atypical for reasons given in the text, and the imposition of the 55-mile per hour speed limit is still so recent as to make extensive speed-flow data based on it unavailable. It would appear that the denominator of eq. (13) could be used for lower design speeds simply by reducing the intercept (46) by the reduction in the design speed minus 65 miles per hour. But the evidence on this is tentative, and other engineering evidence on the effects of differing design speeds is ambiguous, so we are not attempting to analyze the impact of differing design speeds on our analysis.

must choose a per lane capacity consistent with the definition used in deriving that curve and then adjust for autos-only traffic. The capacities calculated by the ITTE for the segments comprising the Eastshore Freeway vary according to curves, grades, lane widths, and other factors; they averaged approximately 1,915 vehicles per hour per lane, including 4 percent trucks. Since one truck is equivalent to about two autos on level freeways (Highway Research Board 1965, p. 257), this converts to approximately 2,000 autos per lane per hour.

To convert this speed-flow curve to a relationship between volume and travel time per mile, we thus set $C = 2,000 w$, where w is width in lanes in each direction, invert the upper portion of (12),¹⁰ and take the reciprocal. The resulting travel time per mile is

$$T = \frac{1}{S} = \frac{1}{46 + \sqrt{2,111 - 520.1[(V/C) + 3.153]}}. \quad (13)$$

IV. The User Benefits and Costs of Speed

Faster travel confers benefits mainly because it saves time. But there are as well other highway travel costs which may vary with speed. More specifically, fuel consumption per mile (and certain related operation costs) decreases with speed starting with low speeds and then increases with high speeds.

Regarding fuel economy, the only recent field study of the relationship between fuel economy and freeway speed is that of Ybarra and May (1968). They estimated a quadratic relationship between speed and fuel economy, using a full-sized auto on California freeways. However, the curve they estimated was almost perfectly flat over any plausible range of optimal rush-hour speeds.¹¹ This means that in the present study optimization of speed with respect to fuel consumption is quite unlikely to be necessary. Furthermore, as Ybarra and May suggest, total operating costs are likely to be proportional to fuel consumption as a first approximation.

Thus, the only important way in which travel costs and highway speed are likely to be related for freeway travel is through the value of travel time. There is a vast literature on the theory and estimation of the value of travel time, and it is difficult to arrive at a single number for use in a

¹⁰ That is, we take the positive root. The lower part (negative square root) describes the flow in queuing situations, with which we need not be concerned in a long-run optimization model, since this leg of the parabola represents the region of the production function where additional vehicles have a negative marginal product.

¹¹ As is shown later, all the optimal rush-hour speeds found in this study range between levels of 42 and 58 miles per hour. Ybarra and May's equation yields a fuel economy of 22.34 miles per gallon of gasoline at 42 miles per hour and 22.39 miles per gallon at 58 miles per hour.

given study.¹² However, based on traveler characteristics in the Bay Area and on the results of a number of studies (especially McFadden 1974), it is reasonable to assume that the value of in-vehicle auto travel time lies between \$1.50 and \$3.00 per hour per person. With an assumed average of 1.5 persons per vehicle,¹³ this makes for a range of average time values between \$2.25 and \$4.50 per vehicle-hour. We shall do our calculations on the basis of these two alternative assumptions.

V. Demand and Peaking Characteristics

The most reliable data on hourly vehicle flows on California expressways comes from the California Department of Public Works (1970), which takes counts at 17 points in the state. One such point is on U.S. 101, a major commutation route in San Rafael, a northern suburb, and we have used data from this route to calculate peaking characteristics on a representative commutation corridor. The results, shown in table 3, are shown in terms of a peaking ratio. This is simply the traffic per hour for each period and direction as a fraction of total average hourly traffic during the day (this average volume is defined as average daily volume in both directions divided by 48).

Peaking ratios are shown for major and minor directions over four periods: peak (7:00–8:00 A.M. and 5:00–6:00 P.M.); near peak (6:00–7:00 and 8:00–9:00 A.M., 4:00–5:00 and 6:00–7:00 P.M.); daytime (9:00 A.M.–4:00 P.M.); and night (7:00 P.M.–6:00 A.M.). The data collected are representative of a typical weekday; none were collected for weekends. This is not a serious problem, except that the assumption that there is zero traffic volume during the weekend will result in upward-biased estimates of optimal tolls during weekday periods. To compensate for this, it is not an unreasonable guess to assume that overall, daily traffic on weekends is more or less the same as on weekdays.¹⁴ The traffic on weekends, however, is likely to be spread out more evenly than on weekdays, except for a few shorter peaks. To account for such peaks, we assume that each weekend has a single 1-hour peak each way with a peaking ratio of 3.0, the same as for a weekday rush hour. Furthermore, we assume that weekend nights have traffic levels equivalent to those of weekday nights, for a peaking ratio of about 0.4. The peaking ratio for

¹² For surveys of much of the evidence to date on the value of travel time, see Harrison (1974, chap. 6).

¹³ Using data for the San Francisco Bay Area, McFadden (1974) finds a value of in-vehicle time of about \$1.60 per person-hour. Also, using Bay Area data, Chan (1974) finds a value of in-vehicle time of \$3.14 per hour, using a somewhat different specification of the model.

¹⁴ For California roads as a whole, weekend traffic is higher than weekday traffic (see California Department of Public Works [1970], blue section of appendix). However, this probably reflects patterns on intercity roads more than urban ones.

TABLE 3
WEEKDAY PEAKING CHARACTERISTICS ON TYPICAL
BAY AREA EXPRESSWAY, 1967

TIME PERIOD	LENGTH (Hours)	DEFINITION (Actual Time)	PEAKING RATIO	
			Major Direction	Minor Direction
Peak	2	7:00-8:00 A.M. 5:00-6:00 P.M.	3.0	1.15
Near peak	4	6:00-7:00, 8:00-9:00 A.M. 4:00-5:00, 6:00-7:00 P.M.	2.1	1.15
Day	7	9:00 A.M.-4:00 P.M.	1.5	1.15
Night	11	7:00 P.M.-6:00 A.M.	0.4	0.4

SOURCE.—Calculated from California Department of Public Works 1970.

TABLE 4
ASSUMED DISTRIBUTION OF PEAKING RATIOS

Period	Peaking Ratio (X_i/\bar{X})	Peaking Ratio as Fraction of Highest Peaking Ratio (X_i/X_1)	Hours per week Assumed in Each Direction ($n_i/52$)	Hours per week as Multiple of Peak Hours (n_i/n_1)
1	3.0	1.00	6.0	1.00
2	2.1	0.70	10.0	1.67
3	1.50	0.50	42.5	7.08
4	1.15	0.383	32.5	5.41
5	0.40	0.133	77.0	12.83

SOURCE.—Calculated from table 3, plus assumptions discussed in the text.

the rest of the day during weekend periods is found by allocating remaining traffic evenly over the remaining time. This gives a peaking ratio of 1.5 in both directions for weekend daytime periods.

On the basis of the evidence and assumptions presented, it is possible to estimate the total distribution of traffic over a typical 1-week period. In table 4, the total assumed hours per week for each peaking ratio are set forth. Also, peaking ratios for each period are calculated as a fraction of the ratio for the peak period, and the hours per week for each ratio are calculated as a multiple of the hours per week for the peak period. This estimated distribution is used in the following section to calculate optimal tolls and utilization rates.

VI. The Complete Model

We are now ready to pull together the strands of the previous sections, adapting the theoretical model developed in Section I to make it tractable with the empirical evidence assembled. The peak-load pricing and investment model will be optimized with empirical data in two steps. First, an

optimal investment policy is developed, so that, for any given traffic level, total costs (agency plus user costs, peak and off-peak) are minimized according to equation (5). This yields estimates of optimal volume-capacity ratios as a function of lane capacity costs and time values. Second, once these optimal volume-capacity ratios have been calculated, the optimal long-run price for each period is determined.

A. Optimization of Capacity

As previously stated, we are including for optimization only those costs which vary with capacity utilization. These costs fall into two categories: time costs and fixed lane capacity costs. Costs of each are normalized to represent 1 mile's worth of travel over a given road type. Therefore, total time costs in a given period will be total traffic volume per unit of time, \times the value of time, \div by the speed (which is in turn a function of traffic flow, as estimated earlier). Capacity costs are the costs per mile shown in table 1. Therefore, the equation to be minimized, the sum of costs over all periods in the year, will be

$$TC = \sum_{t=1}^5 \frac{Vn_tX_t}{46 + \sqrt{471 - 0.260(X_t/w)}} + Aw, \quad (14)$$

where TC is total annual costs to be minimized, X_t is the one-directional hourly volume of traffic during each of the five periods indexed by t (described in the previous section), n_t is the total number of hours of the year during which flow X_t prevails, w is the width of the road in lanes in each direction, V is the value of time per vehicle-hour, and A is the estimated annual rental of a unit of lane capacity, as calculated in table 1.

In table 4, each X_t was shown as a fraction of X_1 and each n_t as a fraction of n_1 . Since each of the fractions is assumed to be constant, we can then write the entire expression as a function of X_1 . From table 4, we find that $n_1 = 6$ hours per week, or 312 hours per year; also, to simplify, let $x = X_1/w$. Then, using the fractions in table 4, (14) can be rewritten:

$$\frac{TC}{312X_1} = V \sum_{t=1}^5 \frac{(n_t/n_1)(X_t/X_1)}{46 + \sqrt{471 - 0.26(X_t/X_1)x}} + \frac{A}{312x}. \quad (15)$$

It will be noted now that total cost (for all periods) per rush-hour vehicle-mile is a function of one variable and two parameters. The variable (x) is peak-hour traffic per lane-hour, and the parameters are the value of time (V), and the cost of a unit of lane capacity (A). Given available estimates of the parameters, it is possible to minimize system costs by minimizing (15). The minimization process was done numerically,¹⁵ with the alternative parameter values previously discussed.

¹⁵ The optimization work was done with the FCDPAK program, on the University of California, Berkeley, CDC 6400 computer.

The results, shown in table 5, are generally consistent with what the economic theory of production says they should be: for example, an increase in the value of time reduces the optimal capacity utilization. The optimal speeds for each period implicit in the results are also shown in table 5. Not surprisingly, optimal speed rises with the value of time and falls with higher interest costs. It is also lower during rush hour than at other times.

B. Calculation of Optimal Long-Run Tolls

As was shown in Section I, the optimal congestion toll in each period is the difference between short-run marginal cost and short-run average cost. In the case of the present model, it will be recalled that the short-run average variable cost (exclusive of variable costs unrelated to capacity utilization) is

$$C_i = \frac{V}{46 + \sqrt{471 - 0.26(X_i/w)}}. \quad (16)$$

Therefore, the optimal capacity-related toll is

$$T_i = \frac{\partial C_i}{\partial X_i} X_i = 0.13V \left(\frac{X_i}{w} \right) \left[471 - 0.26 \left(\frac{X_i}{w} \right) \right]^{-1/2} \\ \times \left\{ 46 + \left[471 - 0.26 \left(\frac{X_i}{w} \right) \right]^{1/2} \right\}^{-2}. \quad (17)$$

Estimates of the optimal tolls, based on this equation, are shown in table 5. The most striking thing about these results is the high level of the optimal peak tolls. With a 6 percent interest rate, they range from about 3 cents per vehicle-mile in the least-populated areas, to about 15 cents per vehicle-mile in Oakland and San Francisco. At a 12 percent interest rate, they range from 5 to 6 cents in rural areas up to 27–34 cents per mile in the more densely populated central city areas.

The other striking thing about the peak tolls is their relationship to the assumed value of time. One would expect that a lower value of time would lead to lower toll. That is true for all the off-peak periods. But for the peak periods we get the paradoxical result (except for one case) that a lower time value *increases* the optimal peak toll. This is not so surprising as it might first seem. A lower time value means it is preferable to build fewer lanes and allow them to be more congested during each period. Given the shape of the speed-flow curve, if we allow the road to get more congested during all periods it is possible that the lower time value could cause congestion during the peak period to rise so much as to increase the optimal long-run peak toll, despite the lower time value.

TABLE 5
RESULTS OF MODEL: OPTIMAL SPEEDS, UTILIZATION RATES, AND CAPACITY-RELATED TOLLS

ROAD TYPE AND LINE CONSUMPTION	PERIOD 1		PERIOD 2		PERIOD 3		PERIOD 4		PERIOD 5		
	Flow*	Speed	Toll†	Speed	Toll†	Speed	Toll†	Speed	Toll†	Speed	Toll†
Rural-suburban	1,427	56.0	2.7	60.5	1.1	62.9	0.6	64.1	0.4	66.5	0.1
6% interest:											
V = 4.50†	1,427	56.0	2.7	60.5	1.1	62.9	0.6	64.1	0.4	66.5	0.1
V = 2.25‡	1,681	51.8	3.1	58.9	0.8	61.9	0.4	63.4	0.3	66.3	0.1
12% interest:											
V = 4.50	1,645	52.6	5.3	59.1	1.5	62.0	0.8	63.5	0.5	66.4	0.1
V = 2.25	1,775	49.1	6.9	58.2	0.9	61.5	0.4	63.2	0.3	66.2	0.1
Urban-suburban:											
6% interest:											
V = 4.50	1,512	54.8	3.3	60.0	1.2	62.6	0.7	63.9	0.5	66.5	0.1
V = 2.25	1,726	50.7	4.2	58.5	0.8	61.7	0.4	63.3	0.3	66.3	0.1
12% interest:											
V = 4.50	1,700	51.4	7.0	58.7	1.6	61.8	0.8	63.4	0.5	66.3	0.1
V = 2.25	1,789	48.5	9.1	58.1	0.9	61.4	0.5	63.1	0.3	66.2	0.1
Central city:											
6% interest:											
V = 4.50	1,777	49.0	14.5	58.2	1.8	61.5	0.9	63.1	0.6	66.2	0.2
V = 2.25	1,805	47.4	17.4	57.9	0.9	61.4	0.5	63.1	0.3	66.2	0.1
12% interest:											
V = 4.50	1,803	47.5	31.0	58.0	1.8	61.4	0.9	63.1	0.6	66.2	0.2
V = 2.25	1,810	46.7	34.3	57.9	0.9	61.4	0.5	63.1	0.3	66.2	0.1

SOURCE.—See text.
* Vehicle-miles per peak-period lane-hour.
† Capacity-related toll in cents per vehicle-mile.
‡ Value of time in dollars per vehicle-hour.

C. The Effects of "Demand Spreading" Induced by Peak-Load Pricing

The results presented so far are based on the (unrealistic) assumption that the cross-elasticity between peak and off-peak demand travel is zero. Because no estimates of intertemporal cross-elasticities of demand exist, it is not possible to determine with any degree of rigor the equilibrium solution, given intertemporal demand spreading. Nevertheless, it is possible to make some intelligent guesses as to the likely effects of demand spreading on prices. For purposes of sensitivity testing, the calculations of the preceding two sections were redone based on the alternative assumption that peak-load pricing will, in equilibrium, cause rush-hour demand to spread itself evenly over the entire "peak" and "near-peak" periods, as described in table 4. Thus, in periods 1 and 2 in table 4 traffic is assumed to be of equal amount during each hour, with the same total amount of traffic over the entire period as assumed before. For all other periods, peaking patterns are assumed to be the same as before.

The results, shown in table 6, are consistent with what one would expect: tolls during the near-peak period rise, and tolls during what was previously the peak hour decline. But they still remain high, relative to any user charges paid by most U.S. commuters; they range from 2 to 3 cents per vehicle-mile on rural-suburban roads up to 6–13 cents on central city roads. Furthermore, it is worth noting that the paradoxical relationship noted before between the value of time and the optimal rush-hour toll persists: for all but two combinations of interest rate, road type, and time value, a lower value of time leads to a higher peak (and near-peak) toll. This suggests that this result is not a fluke.

D. Other Public Costs of Auto Transportation

Optimal user tolls for auto transport should include not only the capacity-related congestion costs mentioned in the previous sections but also the marginal costs of other government-provided services to highway users which vary not with capacity, but directly with use. Also, some measure of net externality cost should be included. Estimation of appropriate marginal cost figures for these variables is imprecise, and the figures which we suggest here have a higher variance than the ones just presented for capacity-related tolls.

As regards local government services whose costs should be expected to vary with auto use, there are many categories in addition to the two obvious ones, police and highway administration. In addition, these costs could include portions of the budgets for city planning, electricity, public health, coroner, city attorney, district attorney, municipal court, superior court, juvenile court, and fire department. It is not possible to determine what portions of these costs are variable with auto use, but in a previous

TABLE 6
RESULTS WITH "SPREAD-OUT" PEAK

ROAD TYPE, COST ASSUMPTION	PERIODS 1-2			PERIOD 3		PERIOD 4		PERIOD 5	
	Flow*	Speed	Toll†	Speed	Toll†	Speed	Toll†	Speed	Toll†
Rural-suburban:									
6% interest:									
$V = 4.50\ddagger$	1,214	58.5	1.7	62.8	0.6	64.1	0.4	66.5	0.1
$V = 2.00\ddagger$	1,489	55.2	1.6	61.5	0.5	63.1	0.3	66.2	0.1
12% interest:									
$V = 4.50$	1,442	55.8	2.8	61.7	0.8	63.3	0.6	66.3	0.2
$V = 2.00$	1,662	52.2	2.9	60.6	0.5	62.5	0.4	66.0	0.1
Urban-suburban:									
6% interest:									
$V = 4.50$	1,296	57.6	2.0	62.4	0.7	63.8	0.5	66.4	0.1
$V = 2.25$	1,558	54.1	1.9	61.1	0.5	62.3	0.3	66.1	0.1
12% interest:									
$V = 4.50$	1,516	54.8	3.4	61.3	0.9	63.0	0.6	66.2	0.2
$V = 2.25$	1,705	51.3	3.6	60.4	0.6	62.4	0.4	66.0	0.1
Central city:									
6% Interest									
$V = 4.50$	1,670	52.1	5.9	60.5	1.1	62.5	0.7	66.0	0.2
$V = 2.25$	1,771	49.3	6.6	60.0	0.6	62.1	0.4	65.9	0.1
12% interest:									
$V = 4.50$	1,763	49.6	11.7	60.0	1.2	62.2	0.8	65.9	0.2
$V = 2.25$	1,799	47.8	12.8	59.8	0.6	62.0	0.4	65.9	0.1

SOURCE.—See text.

* Vehicle-miles per peak-period lane-hour.

† Capacity-related toll is in cents per vehicle-mile.

‡ Value of time in dollars per vehicle-hour.

paper (Keeler, Cluff, and Small 1974) we have estimated the average cost for these services relating to autos at \$0.0045 per vehicle-mile in the Bay Area.¹⁶ To the extent that there are no economies or diseconomies of scale in the production of these services, this figure would be a reasonable estimate of the marginal cost of an auto-mile for such services. But it must be emphasized that the estimates are rough.

Externality costs are even more difficult to measure than public service costs; nevertheless, it is worth making a guess as to their size. Valuing illness and death from pollution at foregone wages and hospital bills, Small (1975) has calculated the cost of auto emissions in California urban areas at about 0.8 cents per vehicle-mile for an average-aged auto in 1974. Because of lower auto use and different meteorological conditions in other U.S. cities, the cost outside California should be lower—about 0.15 cents per auto-mile in a typical urban area. Furthermore, as older, uncontrolled autos are retired, total pollution costs should decline. Thus, a 1974 model auto in California had emissions costs of only 0.06 cents per vehicle-mile in that year, and a post-1977 auto should have costs well

¹⁶ The 1974 paper in turn draws on Lee (1972) for some of its figures, although our estimates are generally more conservative than his.

below 0.2 cents per vehicle-mile in California and no more than 0.03 cents outside California. The optimal toll for pollution costs is therefore likely to vary considerably depending on the situation. Suffice it to say that for now in California, autos 2 or more years old should be paying considerable tolls (0.5–1.0 cent per mile) to cover the costs of their effluents. But this problem should diminish in importance over time, assuming that emissions control devices perform as expected, and assuming future standards are not further delayed.

Overall, then, the total public costs which should be included in auto tolls would seem to range somewhere between 0.5 and 1.5 cents per vehicle-mile, depending on the considerations mentioned above.

However, the externality costs connected with highways could conceivably be offset, at least to some extent, by externality benefits. Strotz (1964) has shown that under not-too-implausible assumptions the spatial externality benefits of a transportation network can justify subsidization of it, even with constant returns to scale. The fact that such externality benefits could offset the externality costs mentioned makes the estimates given in this subsection all the more tentative. Nevertheless, the cost figures presented here are worth knowing, rough as they may be, and it must be remembered that the pollution costs are on the conservative side, valuing human life and health at no more than hospital bills plus foregone wages. It would thus require considerable externality benefits to offset these costs.

VII. Actual versus Optimal User Charges

The results of the previous three sections would imply that optimal tolls charged to expressway users in the Bay Area, assuming optimal expansion of the system, should range somewhere from below 1 cent per vehicle-mile for off-peak periods up to rush-hour tolls of 2–7 cents on rural roads, 2–9 cents on suburban roads, and 6–35 cents on downtown roads. Do these results imply that roads are subsidized and/or overused?

Let us consider first the issue of subsidies. The typical auto in the Bay Area in 1972 paid user charges of 1.15 cents per vehicle-mile (Keeler et al. 1974, p. 31). This would imply that while night users are paying at least as much as they should, rush hour (and even near-peak) users are not paying tolls nearly so high as they ought to pay. Furthermore, it is worth noting from table 6 that even with considerable spreading of the peak rush-hour tolls would still be considerably higher than they now are on most roads. In this sense, it can be said that commuter auto traffic is being subsidized.

But it does not follow from this that peak-hour auto service is being overused and should be contracted. It is true that the higher user tolls suggested here could raise toll costs considerably for commuters. However,

the higher tolls would be accompanied by a much higher service quality than now exists on many routes, and it is quite conceivable that raising tolls to the levels suggested here *and* adjusting capacity to achieve the prescribed service levels could actually reduce trip costs and increase demand.¹⁷

Whether this actually will occur depends on how congested Bay Area freeways are during rush-hour periods. If they are so congested as to be at or near the backward-bending segment in figure 1, it is possible that higher user tolls will result in lower trip costs. Resources are not available to investigate this issue for all roads studied, but some relevant figures are available for the year 1972 for the Eastshore Freeway, whose speed-flow curve was used for our earlier calculations on the grounds that it is likely to be fairly typical. (Details of these calculations are not shown here for lack of space, but may be found in Keeler 1975, p. 53.) The results for this road indicate an ambiguous answer which depends on the interest rate and time value assumed: for a 12 percent interest rate, at either time value, full trip costs would rise on the Eastshore Freeway under a regime of optimal pricing and investment relative to what they are now. In the case of a 6 percent interest rate, however, the result is dependent on the time value assumed. With \$4.50 per hour time value, full costs would decline. With \$2.25 value, they would rise. For three of the four combinations, full trip costs would rise, then, and for one, they would fall. But in every case, the costs of higher tolls would be to some degree offset by the benefits of a much better service quality.

VIII. Policy Implications and the Feasibility of Change

The results of this work have important implications for public policy. The most important result is that, unless Bay Area roads are grossly overbuilt, peak tolls of considerable amounts (ranging from 2 to 35 cents per vehicle-mile) should be imposed on Bay Area freeway commuters.

Previous studies of optimal short-run congestion tolls (as opposed to the long-run ones estimated here) for urban highways have generally arrived at similar conclusions—that urban freeways are underpriced during peak periods.¹⁸

Such conclusions have, however, incurred some significant objections, and it is worth considering these objections here to examine the extent to which our results are subject to the same criticisms.

The first objection is that, while optimal short-run tolls may be very high, that is strictly a sign of underbuilding of the freeway network; if

¹⁷ Unlike the case of a short-run congestion toll model, the present model does not achieve higher service qualities by “tolling off” some travelers from the road. It can do so by expanding road capacity, as well.

¹⁸ See, for example, Vickrey (1963) and Walters (1961).

long-run expansion policies were pursued, there would be no need for such high peak tolls. Our results show that these objections are not valid, at least for the San Francisco Bay Area.

Another objection to high peak tolls is that they discriminate against those with low time values.¹⁹ Our results, however, show that with optimal long-run investment, the appropriate peak toll is not very sensitive to the assumed value of time; in fact, a reduction in time value actually *increases* the optimal peak toll. (Those who argue that higher time values necessitate higher peak tolls are thinking of a short-run model, where capacity is fixed; it remains true, however, that total toll revenues, over both peak and off-peak periods, will rise with an increase in the value of time.) In any event, inefficient road user charges represent a peculiar method of redistributing income.

Third, objections have been raised to short-run peak tolls because they will result in excessive profits for road authorities; even some proponents of such optimal tolls have suggested that they be returned to motorists through a lump-sum redistribution of some sort. But, on the basis of the evidence presented here, it would seem that the sum of tolls collected over all periods will just cover the cost of the road system and supporting services. To return such revenues to motorists would conflict with the reasonable principle of equity that people should pay for what they use.

A final objection to high peak user tolls on expressways regards technical feasibility. One feasible way of charging such tolls is by way of booths at interchanges, though it may be that more sophisticated metering devices are cheaper. It has been objected, however, that higher expressway tolls will induce more motorists to take parallel arterial streets, congesting them badly, and it is much harder to collect optimal tolls on these roads. Our results indicate that this problem is not likely to be an important one in the long run. The reason, simply, is that the service qualities accompanying the tolls proposed here are so much higher than those offered by rush-hour arterials that even motorists with low time values are likely to choose the tollway.

To see this, consider a numerical example: for the sake of argument, we analyze this issue with the lower-bound time value of \$2.25 per hour. Let us suppose that, at existing levels of congestion, it is possible to travel during rush hour at an average speed of 15 miles per hour using arterials for the entire distance. Time cost will then be \$0.15 per vehicle-mile. Adding on existing user charges would make total user-perceived costs (exclusive of auto ownership and operation) greater than \$0.16 per mile.²⁰ However, for an urban-suburban freeway, the optimal long-run user cost (including time and tolls) is \$0.086–\$0.138 per mile, plus external and

¹⁹ See, for example, Nichols, Smolensky, and Tideman (1971)

²⁰ To get this, we simply add the 1.15 cents per mile user charge (mentioned above) to the time cost figure of 15 cents per mile.

maintenance costs, depending on the interest rates.²¹ With a higher time value, the tollway has an even greater advantage.²² Admittedly, freeway travel usually necessitates some circuitry not accounted for here; furthermore, on the most expensive of downtown expressways, optimal tolls could certainly be considerably higher than the ones shown here (although in these rare instances, average rush-hour street speeds are likely to be considerably slower than 15 miles per hour even now). The point is that the optimal tolls suggested here, combined with optimal service levels, are unlikely to result in a significant increase in congestion on parallel arterials, even assuming that pricing these arterials optimally is impossible.

In short, most objections raised to high peak tolls on urban expressways would seem to have questionable content when made to a long-run optimal toll scheme as proposed here.

The upshot of all the discussion and evidence presented in the paper is that higher peak charges (combined with higher service levels) are both feasible and desirable for Bay Area roads. Admittedly, there may be political obstacles to such tolls, but the more general understanding there is of the benefits of such tolls, the more feasible they will be. It is hoped that this paper has contributed to such an understanding.

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²¹ These time costs, plus user charges, are calculated from the optimal speeds and tolls in table 1, for an urban-suburban freeway, with a time value of \$2.25.

²² This raises the interesting question as to why more urban expressways are not tollways, especially given that such tollways have been successful in large cities when no freeways were competing with them (consider, for example, the Massachusetts Turnpike in Boston). The answer to this question is outside the scope of this paper, but it is an interesting one and one worthy of further research.

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