User Benefits in Economic Analysis of Metropolitan Freeway Construction

JEROME W. HALL, ROY B. SAWHILL, and JAMES H. MATTESON,
University of Washington

An extensive two-phase study of highway user benefits resulting from the operation of the Seattle Freeway is analyzed for the purpose of simplifying the data requirements and methods of calculation. Results of the detailed study of benefits indicate that travel time savings and accident reduction benefits are the principal components of urban highway user benefits. The basic form of the travel time savings calculation is analyzed. Use is made of the minimum travel time ratio (mttr) to evaluate travel time savings. It is hypothesized that the relationships between the mttr and highway and traffic characteristics will facilitate its estimation. Calculations using these ratios in conjunction with coarse time-of-day subgroupings and a truck factor, to account for the disproportionate travel time benefits enjoyed by commercial vehicles, produce benefits in substantial agreement with the results of multivehicle analysis. An analogous method of accident reduction benefit calculation is proposed. A reliable method of freeway and arterial accident cost estimation is used. A simplified procedure of benefit calculation is presented and tested against the results of previous analysis. Agreement within 2 percent is achieved. The sensitivity of the calculated travel time and accident reduction benefit to errors in the component factors is examined. With one exception, the results are not overly dependent on individual estimates. The results indicate that a simplified method can be used to estimate freeway user benefits in urban areas. A minimization of the data requirements for analysis purposes should facilitate future benefit calculation. Supplementary research of a limited nature may be necessary in the extension of these methods.

•AN EXTENSIVE before-and-after study of three components of highway user benefits was conducted in the Seattle area. The first phase of the study was carried out on four principal components of the 1962 arterial street system. The second phase of the investigation was implemented in 1968 when the entire 16.6-mile length of the Seattle Freeway was open to traffic and local traffic patterns had been allowed to readjust and stabilize (1).

The travel time benefit was definitely the easiest to measure and the hardest to evaluate. Using standard techniques of travel time and delay measurements (2), data were gathered on over 2,000 test runs on the arterial and freeway routes. Because of the significant reductions in arterial traffic volumes, peak period travel times on the arterial routes have decreased by up to 25 percent. The freeway provides a larger benefit by reducing travel times up to 60 percent in comparison to the arterials. Somewhat smaller travel time benefit levels are observed during the off-peak periods (1).

The difficulties normally associated with accurate fuel-consumption measurements for benefit analysis purposes are offset in part by the ease with which the results are

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evaluated monetarily. Fuel consumption was measured concurrently with travel time, using a specially designed fuel meter (3). Although the five types of test vehicles demonstrated different fuel consumption characteristics, analysis indicated that the primary recipients of this benefit component were the standard sedan and the large diesel tractor-trailer (3S2). Arterial fuel-consumption characteristics are dominated by the results for the van-type truck, which consumed more fuel while operating at the lower volume conditions in 1968. The resultant negative fuel benefit for this type of vehicle perhaps reflects a benefit trade-off involving increased vehicular service capabilities (1). The monetary value of the net fuel benefit is equivalent to 1 percent of the travel time benefit.

A third benefit element, resulting from the differential accident rates and costs for arterials and freeways, was evaluated and found to be significant in comparison to the other user benefits (1). Using actual property damage costs for a systematic sample of accidents, a mathematical model was developed relating reported and actual costs. Based on work by others, adjustments were made for injury and fatality costs. Although freeway accidents were found to cost 25 percent more than arterial accidents, the large differential in accident rates results in a net freeway user benefit.

The methodology and results of the exacting fuel and travel time surveys involving five test vehicles operating on five test routes are reported elsewhere (4). The scope and results of the unique accident reduction benefit analysis are reported by Matteson (5). This paper concerns itself with the utilization of the basic procedures and results of these studies to develop a simplified methodology of urban highway user benefit analysis.

THE 1968 BENEFITS

The 1968 user benefits, based on the previously mentioned analysis, total $35.6 million and are definitely in excess of the user benefits projected prior to freeway construction. The higher level of benefits is due principally to the large volume of induced traffic using the freeway. Analysis indicated that the total freeway traffic, which exceeds even the most liberal preconstruction estimates, is composed of nearly equal elements of diverted and generated traffic.

The component user benefits, calculated on the basis of finely stratified subgroupings of the data with recognition given to the differential level of benefits for diverted and generated traffic, are summarized in Table 1. The relative monetary importance of the benefits indicates that the accident reduction benefit may be more important than previously thought. The comparatively small value of savings in fuel consumption is in accordance with the results of other studies (6). Time savings provide the largest benefit component, although the monetary value of this benefit is directly related to the assigned unit value of time. Under an assumption of uniform annual benefits, it is seen that the benefit exceeds the net annual highway cost, thus providing a favorable benefit ratio. Giving consideration to the different lifetimes of the highway cost elements, the rate of return is approximately 9 percent.

The benefit summary appears in such a simple form that the costs involved in the economic analysis are not readily appreciated. In actuality, the cost of this investigation exceeded $75,000, with data collection and analysis costs being nearly equal. Recognizing that staff and financial limitations preclude frequent studies of this nature, it is logical to reexamine the structure of the investigation to determine if approximation techniques might be used to simplify the analysis while retaining the integrity of the study.

TABLE 1

SUMMARY OF 1968 BENEFITS IN THOUSANDS OF DOLLARS

Category	Freeway	Arterial
Travel time		
Passenger vehicles	24,785	2,841
Commercial vehicles	3,222	-111[a]
Fuel consumption		
Passenger vehicles	390	0
Commercial vehicles	46	-69[a]
Total accident reduction	4,570	_[b]
Total benefit	35,674	
Net annual highway cost	24,800	

[a] The negative benefits for commercial vehicles operating on the arterials are explained in detail in another report (4).

[b] No arterial accident benefit was observed in this study.

A TRAVEL TIME BENEFIT MODEL

The travel time savings benefit, being monetarily the largest of the highway user benefits resulting from this improvement, is easily examined on a theoretical basis. In essence, the basic form of a travel time savings calculation can be expressed as follows:

$$B = (T)\,(\Delta t)\,(C) \qquad (1)$$

where

B = user travel time benefit, dollars per year;
T = annual route travel, person-trips per year;
Δt = unit travel time savings, hours per trip; and
C = cost of time, dollars per person-hour.

The factor T is, of course, composed of several variables, normally assumed to be independent. Vehicle occupancy, average traffic volumes (ADT), and a factor converting from daily to annual volumes (in general, not equal to 365 in an urban area) are used to determine T. In the typical case, where traffic volumes are not uniform over the route length, volumes must be weighted over several sections of roadway. Thus, T is evaluated using the following equation:

$$T = (O)\,(D)\,(L)^{-1} \sum_{i=1}^{n} L_i V_i \qquad (2)$$

where

O = vehicle occupancy, person-trips per vehicle;
D = volume conversion factor, days per year;
L = total route length, miles;
L_i = length of section i, miles; and
V_i = traffic volume on section i, vehicles per day.

Based on existing or easily obtained information, this value is readily determined. Projections of future travel can normally be made using existing techniques and localized assumptions. In most cases, future travel estimates have been based on historical traffic growth, projected population and vehicle registration trends, and anticipated land use development.

The unit travel time savings represents the difference in vehicular operating times between the existing and the proposed conditions. Because travel time in urban areas is definitely a function of traffic volumes, T and Δt are not independent. Peak period congestion mirrors this dependency. The fact that peak and off-peak period travel times differ has been well established. However, the extent of time-of-day subgroupings necessary to evaluate this difference and to provide reliable analysis has not been researched in detail. Directional time-of-day subgroupings have been used by several investigators to stratify the data.

Care must normally be exercised in this subdivision, because in urban areas of moderate size neither the peak hour nor the peak period volumes (generally 2 hours) adequately describe the amount of travel occurring under higher volume and lower speed conditions. The impact of heavily directional peak period traffic volumes, which in some cases requires the use of reversible lanes or roadways, further complicates the problem.

In the Seattle area, approximately 20 percent of the travel occurs under peak volume conditions. This relationship holds true for all test routes, despite the fact that the time of the peak hour is not uniform among the several test routes, or even at different points along the same test route. It was theorized that this percentage might form the basis for a simplified time subdivision structure, recognizing the two elements of peak and off-peak travel. Adjusting Eq. 1 under the localized assumption that 20 percent of the travel occurs during the peak period, we have

$$B = (T)\ (C)\ (0.2\ \Delta t_1 + 0.8\ \Delta t_2) \tag{3}$$

where

Δt_1 = peak period unit time savings, and
Δt_2 = off-peak period unit time savings.

Of itself Eq. 3 is not a radical departure from current practice. However, it does isolate in a simple format the specific data requirements. Normally, the difficulty in evaluating the travel time benefit results from an inability to evaluate the unit time savings. In the truly comprehensive studies (4, 6), a fleet of test vehicles is operated for several days on specific test routes to gather the needed data. If care is exercised to determine exactly what was measured, this method can be considered valid.

In the course of evaluating the merits of alternative estimators, the concept of a minimum travel time ratio (mttr) was investigated. As hypothesized, this ratio relates the minimum route travel time (t), defined as the time required to negotiate the route at the posted speed limit, to the average route travel time for a typical passenger vehicle. Assuming that the speed limits have been established in accordance with accepted traffic engineering standards (7), the upper limit of the ratio is unity.

Recognizing that there are inherent differences among arterials with respect to speed limits, access control, and the like, the congruity of the values for the mttr for the two arterial test routes enjoying significant time savings was investigated. Only slight interroute differences were observed, and a set of mean values was calculated. These values are as follows:

Route	Year	Peak Hour	Off-Peak Hour
Freeway	1968	0.80	0.94
Arterial	1968	0.78	0.86
Arterial	1962	0.67	0.80

Recalling that the mttr has a maximum value of one, improvements between 1962 and 1968 of 33 and 30 percent are observed for the arterial peak and off-peak hours respectively. The value of 0.80 for the freeway during the peak hour represents a condition of moderate congestion, whereas the off-peak value of 0.94 is associated with a freeway level of service B, i.e., stable flow with operation, speeds beginning to be restricted somewhat by traffic conditions (8).

The actual travel time is easily estimated when the mttr has been established. The quotient of the minimum route travel time and the mttr provides the actual travel time. The value of this method is that the mttr is related (in a manner not yet defined) to several observable variables, such as design speed, volume/capacity ratios, access control, and signal progression. Basing the mttr on data from a typical passenger vehicle, which is an acceptable procedure because no significant difference in travel times could be found among the compact sedan, the standard sedan, and the pickup truck (1), the number of required test vehicles is reduced.

The value of C, the cost of time, has been the subject of numerous studies. In a companion analysis (4), a value of $2.50 per person-hour is used. In arriving at this cost, recognition was given to the generally higher value of commuter (9, 10) and business time and the normally lower values of time associated with other trip purposes. It must be noted that commercial vehicle unit time costs are typically in the range of $4.00 to $8.00 per vehicle hour (11, Table 35), reflecting the values of driver wages and other associated costs. In the Seattle study, it was found that commercial vehicles enjoyed 12 percent of the annual time savings benefit, although they constitute only 5.6 percent of the traffic (4). To account for this fact, a truck factor Z was defined as

$$Z = \frac{\text{(percent passenger vehicles) (total time benefit, dollars)}}{\text{(passenger vehicle time benefit, dollars)}} \tag{4}$$

Equation 3 can be modified, using the theory of the mttr to evaluate the unit time savings and the truck factor, to account for the disproportionate benefit to commercial vehicles. The following equation is obtained for individual arterial travel time benefits:

$$B = (T)\ (C)\ (Z) \left[0.2 \left(\frac{t}{m_{11}} - \frac{t}{m_{12}}\right) + 0.8 \left(\frac{t}{m_{21}} - \frac{t}{m_{22}}\right)\right] \tag{5}$$

where

m_{11} = peak hour mttr for existing arterial,
m_{12} = peak hour mttr for relieved arterial,
m_{21} = off-peak hour mttr for existing arterial, and
m_{22} = off-peak hour mttr for relieved arterial.

Although this equation is appropriate for arterial analysis, the form must be altered to permit evaluation of freeway user benefits. Because freeway volume is composed of both diverted and generated traffic, which are normally assumed to enjoy different levels of benefits, it is necessary to assign portions of the freeway travel to the available arterial routes, and to establish the unit benefits for the diverted and generated traffic. This may be accomplished by using a set of predicted diversion factors, $A_1, \ldots, A_i, \ldots, A_n$, where A_i is the percent of diverted freeway traffic having arterial route i as the alternate route of travel. A complementary set of factors, A_i^*, can be used to characterize the generated traffic using the freeway. These factors will be established on the basis that

$$\sum_{i=1}^{n} A_i + \sum_{i=1}^{n} A_i^* = 1 \tag{6}$$

The calculation of the freeway travel time benefit for diverted traffic requires the use of the factors A_i in conjunction with total freeway volumes. The travel time savings for diverted traffic is based on the mttr's for the projected alternatives of freeway travel and arterial travel without the existence of a freeway. The associated benefit is expressed as follows:

$$BF = (T)\ (C)\ (Z_F) \left[0.2 \sum_{i=1}^{n} A_i \left(\frac{t}{m_{1i}} - \frac{t'}{m_{1F}}\right) + 0.8 \sum_{i=1}^{n} A_i \left(\frac{t}{m_{2i}} - \frac{t'}{m_{2F}}\right)\right] \tag{7}$$

where

t' = minimum freeway travel time,
m_{1i}, m_{2i} = peak and off-peak hour mttr for arterial i,
m_{1F}, m_{2F} = peak and off-peak hour mttr for freeway, and
Z_F = freeway truck factor (not necessarily equal to Z).

Using the set of diversion factors A_i^* and the appropriate values for the mttr, the benefit for generated traffic is calculated in an analogous manner. The actual benefit calculations for both the arterial and freeway users are straightforward once the parameters have been estimated. The truck factor, which in theory is based on the final results of a multivehicle study, is the only exception to the basic data requirements of this method. Based on the results of an analysis, the truck factor was found to be unity for the arterials and 1.07 for the freeway. Even though these values are probably unique to this study, they should provide a guide for localized estimations.

The reliability of Eqs. 5 and 7 for estimating user time savings benefits was tested by utilizing only the basic data (i.e., traffic volumes, passenger vehicle travel time) from the detailed study, and comparing the results with the established travel time benefits summarized in Table 1. Using Eq. 5, the arterial travel time benefit was found to differ from the results of the previous multivehicle analysis by less than 1 percent. The freeway user benefit, based on equations for generated and diverted traffic characterized by Eq. 7, was virtually identical with the sum of the freeway travel time benefits for passenger and commercial vehicles given in Table 1.

The degree of reproducibility of this component of user benefits is unexpected. Interpreted within their area of relevance, Eqs. 5 and 7 indicate that refinements in traditional methods of analysis can be made to account for the nonuniform distribution of benefits among the several types of vehicles. In addition, it appears that extensive analysis of directional peak and off-peak hour travel for the purpose of maintaining accurate estimation levels may not always be necessary.

In the general case, knowledge of the relationship between the value of mttr and the several associated driver and highway characteristics will limit the applicability of these equations. A small but continuing localized study and analysis of the mttr should provide the best guide in predicting its value.

AN ACCIDENT REDUCTION MODEL

Very low freeway accident rates (2.0-3.0 per million vehicle-miles) (12) compared to the universally higher rates on arterials will generally provide a net freeway user benefit. Although some researchers have noted a direct relationship between traffic volumes and accident rates, a statistically significant reduction of arterial accident rates resulting from the diversion of arterial traffic to the freeway was not observed in the Seattle area. Based on the research reported by Matteson (5), it is possible to discuss this benefit only as it occurs to freeway users.

The calculation of an accident reduction benefit must consider the amount of travel, the probability of an accident, and the cost of an accident. In a basic form, the calculation is expressed as follows:

$$AB = (V)\,(L)\,(AC) \tag{8}$$

where

AB = user accident reduction benefit, dollars per year;
V = annual route traffic volume, vehicles per year;
L = route length, miles; and
AC = unit savings in accident cost, dollars per vehicle-mile.

The route length, L, is easily determined, while the annual volume, V, is calculated in a manner similar to Eq. 2, (i.e., V = T/O). However, many analyses cannot complete this calculation for lack of a unit value of accident costs.

Matteson describes a reliable method of adjusting property damage costs as estimated by the driver or the enforcement officer to predict actual accident costs (5). Based on a detailed study of a 10 percent sample of Seattle freeway accidents, these adjustment equations are

$$C' = (1.15802)D^{0.997898} \tag{9}$$

$$r_D = 0.946$$

$$C' = (0.77464)E^{1.062966} \tag{10}$$

$$r_E = 0.892$$

where

C' = actual property damage cost per vehicle,
D = drivers' property damage estimate,
E = enforcement officers' property damage estimate, and
r_D, r_E = correlation coefficients.

Although these equations provide good estimates of accident cost, they must be used prudently because of the limitations of the basic research. Because they evaluate only property damage cost per vehicle, the number of vehicles involved per accident must be considered. For both the freeway and the arterials, it was found that there were 1.93 vehicles per accident (1). A separate factor must be used to account for injury and fatality costs. Based on the results of accident cost studies by Drake and Kraft (13) and Matteson (5), and adjusting downward for the economic importance of loss of future earnings, it was found that injury and fatality costs constitute 61 percent of total accident costs. Incorporating these two factors, the average Seattle freeway accident cost is $1,467, whereas the arterial accident cost is $1,172.

The unit savings in accident cost resulting from a comparison of the Seattle Freeway with arterial i is

$$AC = 10^{-6}\left(\$1{,}172\ R_i\ -\ \$1{,}467\ R_F\right) \tag{11}$$

where

R_i = arterial accident rate, accidents per million vehicle-miles; and
R_F = freeway accident rate, accidents per million vehicle-miles.

In the most general case, the diverted and generated traffic will enjoy different unit savings, equal at the time of their generation or diversion to the value of AC given by Eq. 11. When past arterial accident rates vary slightly from year to year, an average accident rate can be used. For projection purposes, a freeway accident rate can be established by comparison with local freeways having similar design and operational characteristics.

Incorporating the previously defined diversion factors, A_i and A_i^*, to account for the percent of generated and diverted freeway traffic that has arterial i as the alternate route of travel, Eq. 8 for diverted traffic can be expressed as

$$AB = (V)\ (L)\ (10^{-6}) \sum A_i \left(\$1{,}172\ R_i\ -\ \$1{,}467\ R_F\right) \tag{12}$$

A similar equation can be established for generated traffic. In deriving these equations, uniformity of average accident costs among the arterials was assumed. If there is reason to believe that this may not be the case, the equation is easily modified, although the analysis is consequently lengthened.

The verification of these equations, using average values of R_i, resulted in an annual user benefit of $4.49 million, approximately 2 percent less than the benefit given in Table 1. The difference is primarily attributed to Matteson's use of more refined techniques regarding the source of freeway traffic (5).

IMPORTANCE OF THE FUEL CONSUMPTION BENEFIT

Table 1 gives an indication that, based on detailed analysis, the savings in fuel consumption resulting from freeway operation is comparatively small. In monetary terms, this benefit is approximately 1 percent of the travel time savings and 8 percent of the accident reduction benefit. Because the fuel savings is the same order of magnitude as the error resulting from the benefit-prediction equations, no attempt is made to develop an equation for estimating these savings. The relative impact of these three types of user benefits should be noted in future analysis of urban facilities.

SENSITIVITY TO INCORRECT COMPONENT ESTIMATION

For evaluation of the simplified benefit equations, it is necessary to determine the values of a limited number of variables. In the general case, the existing conditions (volumes, travel time ratios, and accident rates) can be measured. The future values for these components must be estimated for a specific locale using available techniques. It is important that the economist note the sensitivity of the resultant benefit to errors in such estimates.

In some cases the dependency is quite obvious. For example, the value of B obtained from Eq. 5 will change in direct relationship to changes in T, C, or Z. Thus, if the travel T′ exceeds the estimated travel T by 10 percent, the actual and estimated benefits will also differ by 10 percent.

However, a direct relationship does not exist between B and the travel time ratios. Referring to Eq. 5, the partial derivative of B with respect to m_{12} is determined:

$$\frac{\delta B}{\delta m_{12}} = (T)\,(C)\,(Z)\left[0.2\left(\frac{t}{m_{12}^{2}}\right)\right] \tag{13}$$

From Eq. 13, it is clear that

$$\delta B = B(\delta m_{12})\,(0.2)\left(\frac{t}{m_{12}^{2}}\right)\left[0.2\left(\frac{t}{m_{11}} - \frac{t}{m_{12}}\right) + 0.8\left(\frac{t}{m_{21}} - \frac{t}{m_{22}}\right)\right]^{-1} \tag{14}$$

Equation 14 indicates that the user benefit is quite sensitive to changes in the travel time ratio, and, in general, $\delta B > (B)\,(\delta m_{12})$. For the specific case studied, a 2.5 percent reduction in m_{12} (changing 0.78 to 0.76) results in a 6.5 percent reduction in the user benefit. A similar relationship holds for the freeway user travel time benefit equation. As a result, it is important that the mttr be carefully estimated.

Because the accident benefit is related to the portions of traffic that might have used the available arterial routes, an error in the estimation of a specific value of R_i affects the calculated benefit in relation to the associated value of A_i. An error in estimating R_F is normally of comparatively minor importance because, in general, $R_i > 2R_F$. For the data previously analyzed, a 12.0 percent error in the estimate of R_F (assuming R = 2.5 instead of the correct value, 2.81) results in a benefit that is incorrect by approximately 3.0 percent.

CONCLUSIONS

The economic analysis of urban highway facilities has traditionally been hampered by the apparent need for an extensive program of data collection. This report has shown that it is possible to duplicate the results of an extensive analysis using a simple benefit model in conjunction with several data approximations. In evaluating the travel time and accident reduction benefits, which outweigh the fuel consumption savings in the typical urban situation, a limited data-gathering program is sufficient to permit accurate benefit analysis. This analysis may not be acceptable in areas having unusual topography or a high percentage of commercial vehicles.

With respect to the travel time benefit, additional research in the specific area of the relationship of travel time ratios to the several associated variables would be quite beneficial. For accident reduction analysis, localized accident cost information is required. The magnitude of this latter benefit suggests that it is worthy of consideration in urban freeway analysis.

It is hoped that the simplified benefit evaluation models that have been developed and presented in this paper may, within the domain of their applicability, serve as a guide for future user benefit analysis in urban areas.

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