Use of Traffic Volume Data in Evaluation of Highway User Costs for Economic Analysis

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A method for computing annual user costs for economic analysis of highway improvements is described which takes into consideration the effect of traffic conditions over the entire year. The distribution of traffic volumes over time is used to establish a traffic speed for determining unit costs of vehicle operation and travel time. The method can be applied to proposed route locations where projected traffic volumes are known.

•THE EVALUATION of highway user costs is an important step in the economic analysis of highway improvements. These costs are compared with initial capital and continuing maintenance costs to determine the economic feasibility of a proposed investment. This paper presents a technique for computing annual user costs which takes into account the changes in vehicle operating and time costs resulting from variable traffic flow rates. The technique can be applied to highways in urban and rural areas where large variations in traffic flow rates occur during the year.

Highway user costs are defined in this paper to include the costs of vehicle operation and travel time. Total annual user costs on a highway section may be computed with the equation:

$$TAUC = 365 \cdot (AADT) \cdot L \cdot (uc) \qquad (1)$$

where TAUC is the total annual user cost, AADT is the average annual daily traffic, L is the length of the section in miles and uc is the average unit cost of travel in dollars per vehicle-mile.

The average unit cost represents the operating and time costs incurred by an average vehicle operator and his passengers in traveling 1 mi along the highway under conditions averaged over the entire year. The conditions influencing unit costs, according to AASHO (1), include the types of vehicles, number of lanes, road surface, gradients, highway geometric design, type of operation and the average speed of the traffic. The type of operation and the average speed of traffic are a function of the number of vehicles on the highway. Changes in these variables affect both the operating and time cost components of the average unit cost. However, it is difficult to estimate a single average unit cost which adequately accounts for the wide range of traffic conditions occurring on a highway during a year.

The accuracy with which user costs can be evaluated depends a great deal on the techniques employed to compute them. A computation technique is often formulated with the objective of limiting the number of calculations performed by hand. However, the electronic computer removes this limitation and permits a thorough examination of highway user costs with refined techniques. A method has been proposed by Martin and Manheim (2) for computing an average unit cost which accounts for the changes in traffic conditions over the year. The unit costs are defined for the range of possible

Paper sponsored by Committee on Highway Engineering Economy.

traffic conditions on the highway. Each unit cost is then weighted by the number of vehicles using the highway under the corresponding traffic condition. These conditions are measured by the volume of vehicles traveling over the highway in 1 hr or the traffic flow rate. The number of vehicles at each flow rate is the product of the flow rate and its frequency of occurrence during the year. In mathematical terms, the total annual user cost for a highway section is

$$TAUC = \frac{L \cdot N}{100} \cdot \sum_{i=1}^{n} \left[(uc_i) \cdot (V_i) \cdot (P_i) \right] \quad (2)$$

where

TAUC = total annual user cost in dollars per year;
L = length of highway section in miles;
N = number of hours in the year;
n = number of flow rate intervals;
uc_i = unit cost in dollars per vehicle-mile at ith flow rate;
V_i = ith flow rate in vehicles per hour; and
P_i = percent of hours in the year that ith flow rate occurs.

The total annual operating costs or the total annual time cost could be evaluated with this equation by substituting the unit costs of operation or of time for the total unit cost term (uc_i). The user costs for a time period less than 1 yr can be computed by defining P_i as the percent of hours in the year that flow rate V_i occurs during the relevant time period. For example, the time period of interest might consist of all the hours in one month or the peak hours of each day of the year.

The technique requires a definition of the frequency of occurrence of volumes per hour and a description of unit user costs as a function of volume per hour. These data are discussed in the next two sections. Finally, an example application is presented to illustrate the technique.

TRAFFIC FLOW FREQUENCY DISTRIBUTIONS

Traffic counts at many locations throughout the country have established that repetitive patterns exist in the flow rates as a function of the hour of the day, the day of the week, and the month of the year. These patterns exist because of the repetitive nature of traffic-generating activities. For this reason, they remain as stable as the activities of the people who use the highway.

There are significant differences in the observed patterns at different highway locations. For example, Figure 1 is a plot of the average annual traffic volumes in each hour of the day at three different locations in Massachusetts. The urban-recreation station is located on US 6 in Fairhaven where it serves summer recreation traffic in addition to local traffic. The recreation station is also on US 6 but is located near Barnstable on Cape Cod. (Volumes for only one direction, eastbound, are plotted.) The third location is at Sterling on Rt. 12 in the central corridor of Massachusetts. There are significant differences in the average volumes per hour in each case. The daily traffic volumes vary in magnitude throughout the year. The ratios plotted in Figure 2 relate the average daily traffic in each month to the average annual daily traffic for each station. The considerable increase in daily volumes during the summer months on the recreation routes is quite evident. At these stations, the highest volume hours occur only during the short summer season.

The differences in the distribution of traffic flow rates at the three stations are summarized in Figure 3 as histograms of the frequency of occurrence of volume intervals. The distribution for the rural route is spread over only a few intervals and has a relatively short tail at the high volume end. This shape follows from the low annual average hourly volumes and the small seasonal fluctuation. The distribution for the urban-recreation route is spread over a wider range of volume intervals because of the larger average annual volumes per hour and a longer seasonal cycle. The frequency distribution for the recreation route (one way, eastbound) is distributed

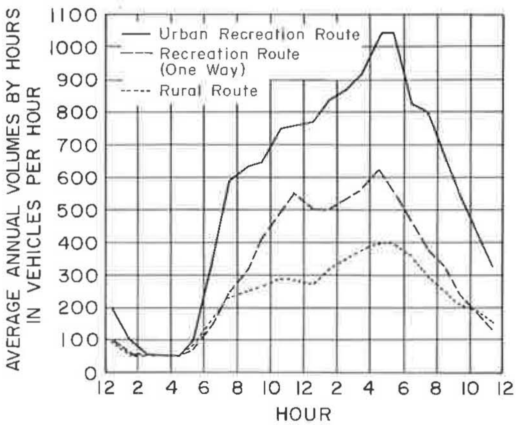

Figure 1. Average annual volumes by hour of day.

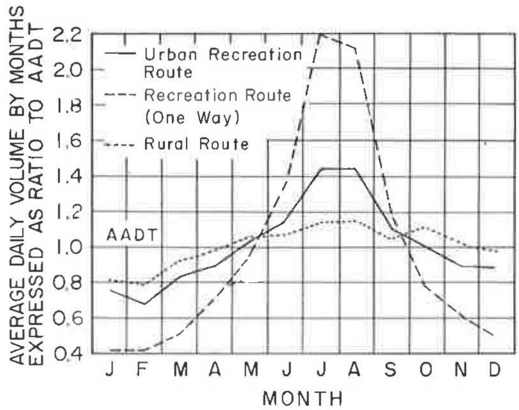

Figure 2. Traffic volume trends by months.

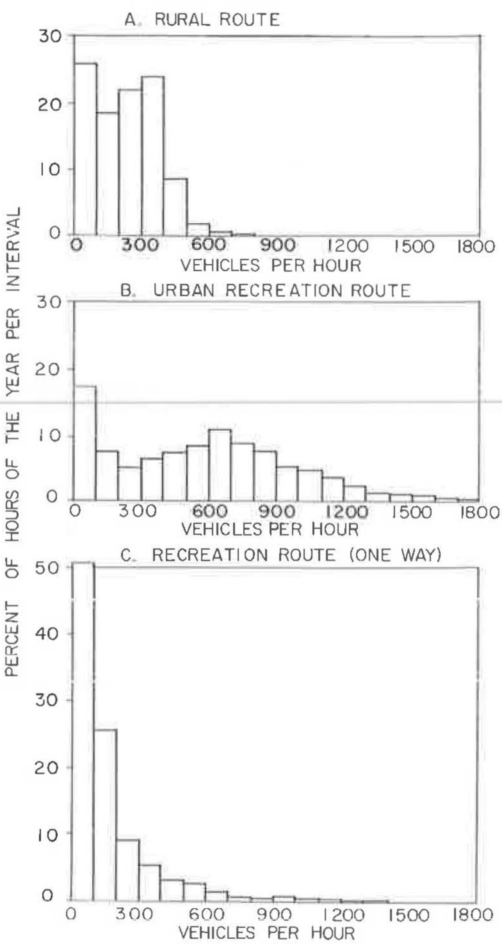

Figure 3. Frequency distributions of traffic counts.

over almost as large a range of volume intervals as the suburban recreation route but the frequency of occurrence of the higher volumes is much lower. The highest hourly volumes occur during the summer season which is only three months of the year. During the remaining months, the traffic volumes are significantly lower.

The preceding discussion has described characteristics of the variation of traffic volumes per hour with reference to three specific cases. The frequency distributions can be prepared directly from traffic count data which have been recorded separately for each direction or recorded as total two-way volumes with directional splits for each time period. The percent of truck traffic and an estimate of future growth in traffic volumes are needed. If it is assumed that the same pattern of flow rates over time will occur in future years, an annual growth rate is sufficient. A more sophisticated analysis of future traffic growth would consider changes in the patterns of traffic-generating activities.

USER COST FUNCTION

The purpose of a user cost function as referred to here is to relate unit user costs in dollars per vehicle mile to the traffic flow rate in vehicles per hour. This section outlines the development of a user cost function with reference to a particular highway but user cost functions for other highways can be developed using similar techniques.

There are two major consequences of increasing traffic flow rates. First, the

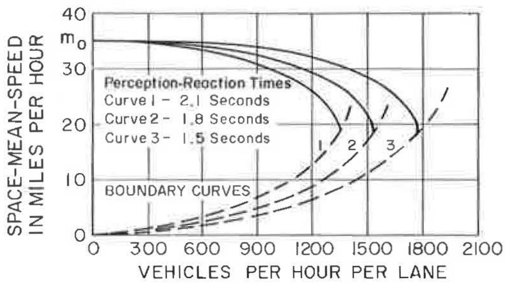

Figure 4. Speed vs volume per hour.

average speed of the traffic stream decreases and changes unit operating and travel time costs. The relationship between speed and volume per hour is developed from theoretical considerations and empirical evidence. The second consequence is an increasing interference between individual vehicles leading to more frequent speed changes, higher fuel consumption, and greater tire wear. It is assumed that these costs are a function of the ratio of the volume to the practical capacity of the highway.

A mathematical expression to relate average speed and volume per hour must satisfy two boundary conditions. First, at very low flow rates, the average speed of all vehicles approaches the mean free speed or average desired speed of traffic on the highway. The second boundary condition is the locus of maximum uninterrupted flow rates which can be maintained on the highway.

The maximum flow rates can be developed by considering the limiting capacity of a single lane of traffic with vehicles moving so that passing is not permitted. As the density increases, all vehicles approach the same speed and the time gaps between vehicles decrease. The limiting gap which each operator would maintain between his vehicle and the one in front of him would be determined by his intuitive evaluation of the time necessary to perceive and react to a change in speed of the preceding vehicle. Studies of minimum vehicle separations (4) have reported that the gaps between moving vehicles are statistically distributed about a mean which is a characteristic of the vehicle operators and the design of the road.

An observer stationed at the side of the road could measure the total time elapsed between the passage of successive vehicles at capacity flow. This total headway is composed of the time gap between the vehicles and the time for the length of the vehicle to pass. The average headway between vehicles is expressed in the following equation:

$$H = t + d/m \tag{3}$$

where H is the average headway in seconds per vehicle, t is the average perception-reaction time of vehicle operators in seconds per vehicle, d is the average vehicle length in feet per vehicle and m is the average speed of the traffic in feet per second.

The reciprocal of H is the limiting volume flow rate in vehicles per second. This can be expressed in vehicles per hour by multiplying by 3,600 sec/hr:

$$V_c = \frac{m \cdot 3,600}{(m \cdot t) + d} \tag{4}$$

where V_c is the maximum volume in vehicles per hour for a given speed and the other symbols are as defined in Eq. 3. Since the values of both t and d are assumed to be independently distributed, there is no unique relationship between the flow rate V_c and the speed m. However, boundary curves can be plotted for appropriate values of these parameters for the highway under study. In Figure 4, the three boundary curves are based on an average vehicle length of 16 ft and average minimum perception-reaction times of 2.1, 1.8 and 1.5 sec (curves 1, 2 and 3, respectively).

The shape of a curve to represent the state of flow between the two boundary conditions will depend on the effect of the geometric design of the highway on vehicle operators and the interaction between vehicles. The particular curve chosen should reflect the conditions on the highway under study.

One possible relation suggested for uncontrolled-access facilities has been used in the example problem of this paper. The equation was originally formulated by Guerin (3) on the basis of empirical studies he performed. This form of the equation is due to Haight (5):

$$m = \left[\frac{m_o \cdot (D' - D)^{1/2}}{A \cdot m_o \cdot D^2 + (D' - D)^{1/2}} \right] \tag{5}$$

where

m = average speed in feet per second;
m_o = mean free speed in feet per second;
D' = maximum density of traffic in vehicles per foot, equal to reciprocal of average vehicle length;
D = density of traffic in vehicles per foot; and
A = constant dependent on parameters of the system.

The constant A can be evaluated using two conditions: (a) the slope of the curve is infinite at maximum capacity, and (b) the headway at maximum capacity derived from Eq. 3. The following expressions can be developed (6):

$$A = \left[\frac{2 \cdot (D' - D_c)^{3/2}}{m_o \cdot D_c{}^2 \cdot (2 \cdot D' - D_c)} \right] \tag{6}$$

where symbols not previously defined are

D_c = density of traffic at maximum capacity in vehicles per foot;

$$D_c = D' \cdot \left[\frac{X - \sqrt{X^2 - 4Y}}{Y} \right];$$

$X = 3.5 + m_o \cdot t \cdot D'$; and
$Y = 3.0 + m_o \cdot t \cdot D'$.

The speed vs volume per hour curves in Figure 4 illustrate the shape of curves derived from Eq. 5. Each curve begins at the same mean free speed but intersects a different boundary curve at capacity flow. The slopes of these curves vary between zero at zero flow and infinite at capacity flow.

A unit operating cost and a unit travel time cost are associated with each point on the speed vs volume per hour curves. An example user cost function is plotted in Figure 5 based on the first speed-volume curve in Figure 4. The operating cost curve was developed using cost data published by AASHO (1) for 0 to 3 percent grades and no commercial vehicles. These cost data are divided into three categories, free, normal and restricted, based on the ratio of the traffic volume in the 30th highest hour of the year to the practical capacity of the highway. Each category is a weighted average for the entire distribution of volumes over the year. For this reason, the unit costs in each category are not necessarily equal to the unit cost in the corresponding 30th highest hour. However, to adapt the data, the volume per hour axis was divided into the same categories, defined by the ratio of the volume to the practical capacity, and the appropriate tabulated data were then used for each category. The free traffic range in this example extends from zero to three-quarters of the practical capacity (720 veh/hr/lane), the normal traffic range extends to 1¼ times practical capacity (1,200 veh/hr/lane), and the restricted range extends to higher volumes.

The unit time cost curve assumes a value of time of $0.86/person/hr and an average of 1.8 persons/veh. These values are suggested by AASHO as typical but other values could be substituted when more specific data are available. The total unit cost curve is the sum of the unit operating and time cost curves.

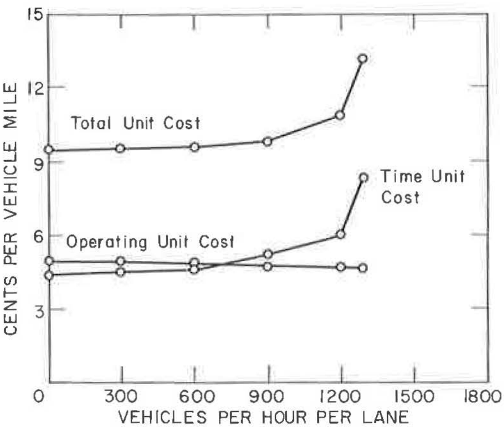

Figure 5. Example user cost function.

TABLE 1

HOURS GROUPS FOR ANALYSIS

No.	Date From	Date To	Day of Week	Hours From	Hours To	Direction Split (%)	Trucks (%)
1	1/1	12/31	M-F	0	6	50	6.3
2	1/1	12/31	M-F	6	9	35	5.9
3	1/1	6/15	M-F	9	15	50	6.9
4	6/16	9/15	M-F	9	15	50	6.9
5	9/16	12/31	M-F	9	15	50	6.9
6	1/1	6/15	M-F	15	19	58	5.5
7	6/16	9/15	M-F	15	19	58	5.5
8	9/16	12/31	M-F	15	19	58	5.5
9	1/1	12/31	M-F	19	24	50	6.3
10	1/1	12/31	Sun	0	12	50	2.0
11	1/1	6/15	Sun	12	20	50	2.0
12	6/16	9/15	Sun	12	20	50	2.0
13	9/16	12/31	Sun	12	20	50	2.0
14	1/1	12/31	Sun	20	24	50	2.0
15	1/1	12/31	Sat	0	10	50	6.3
16	1/1	6/15	Sat	10	20	50	6.3
17	6/16	9/15	Sat	10	20	50	6.3
18	9/16	12/31	Sat	10	20	50	6.3
19	1/1	12/31	Sat	20	24	50	6.3

EXAMPLE APPLICATION

The purpose of this example application is to illustrate the technique and some computation results. An existing highway is analyzed to determine the annual user costs in the present year and in future years. An alternative highway design for the same location is also examined and compared to the existing condition. All computations for the example were performed on a computer.

The highway selected for study is a section of US 6 in Massachusetts from Fairhaven east to Mattapoisett. This section serves traffic desires in the urbanized area of New Bedford and also summer recreation traffic between southern New England and Cape Cod. The time distribution of traffic is characteristic of an urban recreation route (Figs. 1, 2, and 3) with morning and evening peak periods on weekdays during the off-season. However, from mid-June to mid-September, there is a large influx of recreation traffic on the highway.

The total two-way traffic volumes for each hour of the year 1959 were used to prepare the frequency distributions. These volumes were recorded by a permanent traffic counting station maintained by the Massachusetts Department of Public Works. The recorder is located in Fairhaven approximately 1.8 mi east of the New Bedford town line. The unit costs of travel on the highway have been computed and compared for a number of different traffic conditions by analyzing the frequency distributions of the hours of the year in groups. The breakdown into hour groups in Table 1 reflects low, moderate and high volume hours, and weekday, weekend and seasonal characteristics. The hours from and to are based on a 24-hr clock. All hours of the year are included in the list.

Vehicle classification and directional distribution data were obtained from short count samples made by the Massachusetts Department of Public Works. The average growth rate of traffic over the previous 6 yr was 4.1 percent. This is used to project future volumes in all hour groups. For the purpose of this example, it is assumed that the basic characteristics of the traffic demand and the growth rate would not change in the future.

The existing highway has two 10-ft wide lanes in each direction with no median strip. There is no control of access to the roadway. The geometric design of the vertical and horizontal curves does not permit safe travel at high speeds and, hence, the highway is posted for 35 and 40 mph. In two test trips made over the facility, a speed of 35 mph was found to be reasonably safe at low volumes.

A user cost function similar to the one developed previously and plotted in Figure 5 is used in the computations. An average minimum perception-reaction time of 2.1 sec, an average vehicle length of 16 ft and a mean free speed of 35 mph define the parameters of the user cost function. The length of the highway is divided into subsections with different gradients. These subsections are listed as separate alignments in Table 2.

TABLE 2

ALTERNATIVES AND ALIGNMENTS FOR EVALUATION OF USER COSTS

Alter-native	Align-ment	Mean Free Speed (mph)	No. of Lanes	Length (mi)	Avg. Gradient (%)
1	1	35	4	1.6	1.0
	2			0.8	0.73
	3			1.6	0.75
	4			1.3	0.57
2	1	45	4	1.6	1.0
	2			0.8	0.73
	3			1.6	0.75
	4			1.3	0.57

TABLE 3

SUMMARY OF ANNUAL USER COSTS

Alter-native	Yr from Present	Total Annual User Cost ($ millions)	Avg. Annual Unit Costs (cents/veh-mi)		
			Operating	Time	Total
1	1	2.92	4.94	4.49	9.43
	5	3.43	4.94	4.51	9.45
	10	4.21	4.94	4.53	9.47
	15	5.17	4.93	4.57	9.50
	20	6.34	4.92	4.63	9.55
2	1	2.75	5.41	3.49	8.90
	5	3.24	5.40	3.50	8.90
	10	3.96	5.38	3.52	8.90
	15	4.84	5.35	3.57	8.92
	20	5.93	5.32	3.61	8.93

TABLE 4

SUMMARY OF EQUIVALENT ANNUAL USER COSTS

Alter-native	Millions of Dollars		
	0% Int.	5% Int.	10% Int.
1	4.44	4.14	3.90
2	4.15	3.89	3.67
	(0.29)[a]	(0.25)[a]	(0.23)[a]

[a]Equivalent annual user cost savings on second alternative existing highway.

An alternative design (No. 2 in Table 2) is assumed to replace the existing highway on the same right-of-way. This design is basically the same as the existing condition but would incorporate necessary improvements to increase the free running speed to 45 mph. In this analysis, it is desired to know what savings to road users would result from the higher travel speeds. If the improvements are to be justified, the present value of these savings must exceed the initial investment. These improvements might include straightening curves, imposing a partial control on access, and widening the pavement. For this alternative, an average minimum perception-reaction time of 1.8 sec is used in the user cost function.

The total annual user costs for each year in the future were computed in accordance with Eq. 2. These total annual user costs have been converted to an equivalent annual user cost at interest rates of 0, 5 and 10 percent. To examine the effect of increasing traffic on user costs, the average unit costs for each year have been computed and serve as output in the analysis.

The total annual user costs are summarized in Table 3 by alternatives for selected years. The existing condition has the higher user cost in all years. The average annual unit operating and time costs are also summarized for the same selected years. For both alternatives, the unit time costs increase as future volumes increase. On the other hand, the unit operating costs decrease slightly with time.

The equivalent annual user costs are summarized in Table 4 at selected interest rates. These costs correspond to the total annual user costs in all years expressed as an equal annual sum. The figures in parentheses represent the equivalent annual user cost savings on the second alternative over continued use of the existing highway.

The trends over time of the computed average annual unit costs per vehicle-mile for each alternative are plotted in Figure 6 as dashed lines. These unit costs were obtained as a weighted average of the unit costs in each hour group. In the first year, the unit cost of the second alternative is 6 percent below those of the existing highway. After 20 yr, the annual unit costs have increased 1.3 percent for the existing condition and 0.3 percent for the second alternative.

The average annual unit costs for the separate hour groups are also plotted in Figure 6. The highest unit costs are associated with the highest volume hours. On the existing highway over a period of 20 yr, the total unit travel costs increase 5.5 percent in the peak hours of the summer season. The rate of increase of travel costs

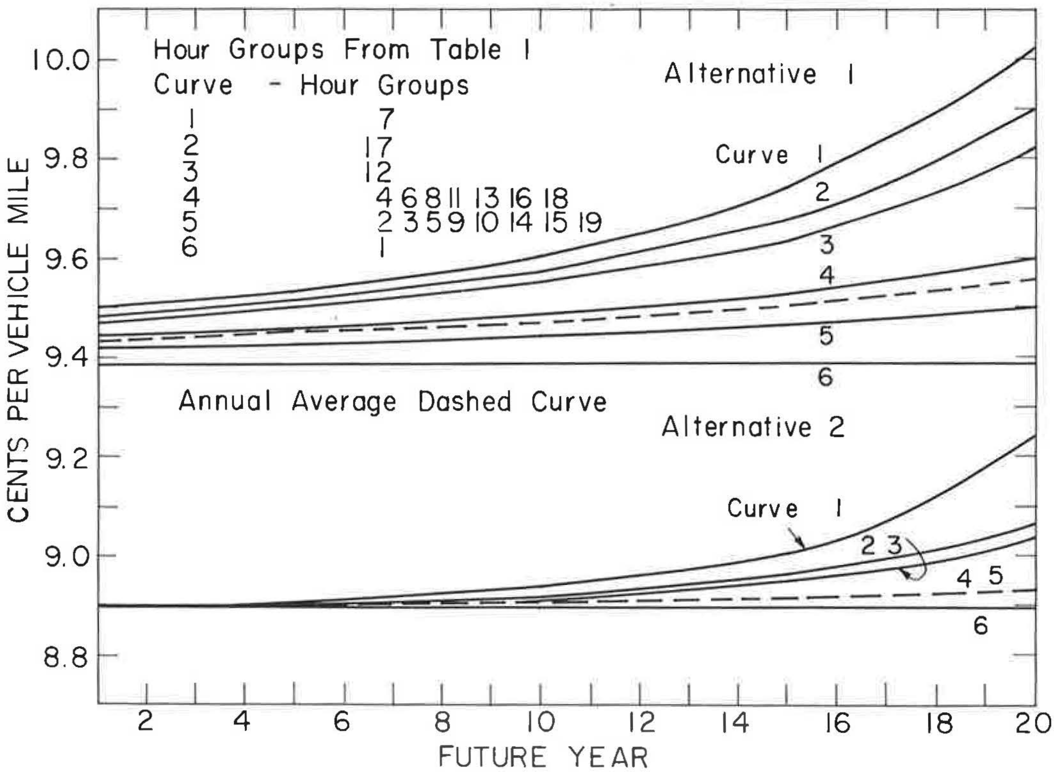

Figure 6. Total unit costs in future years.

during the same peak hours is lower for the assumed alternative and amounts to only 3.8 percent after 20 yr.

CONCLUSIONS

A method for computing user costs which takes into account the variation of traffic volumes over time has been outlined in this paper. Examples of traffic volume distributions over time at three dissimilar stations have been examined and techniques for obtaining unit costs as a function of volume per hour have been developed.

The annual user cost of the example application increased in future years for two reasons: the traffic volume increases each year and the total unit cost of travel increases each year. The rate of increase of total unit costs is a function of the traffic volume per hour and is highest in the peak volume hours. This particular example was selected because the proposed alternative would not appreciably affect the demand characteristics and the same volumes could reasonably be used for both alternatives. The change in unit costs in this example is not large because the range of operating speeds on this highway is near the optimum speed for lowest total unit cost. Near this point, the variation in unit costs is small for relatively large changes in travel speed.

The advantage of this method is that it provides a rational procedure for selecting a unit cost under conditions of varying traffic flow. The traffic volumes in all hours of the year, not merely the highest hours, are taken into consideration. Use of the method in an economic analysis of a highway improvement should result in a more precise estimate of the costs incurred by road users.

ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to Brian V. Martin, Assistant Director of Research, Transport Research Program, Harvard University, and to

Marvin L. Manheim, Assistant Professor of Civil Engineering at MIT, who contributed to the formulation of the ideas in this paper and to Alexander J. Bone, Associate Professor of Civil Engineering at MIT, who reviewed the text and encouraged the author throughout the research.

The research for this paper was supported by the Highway Transportation Demand Research Project at MIT which is jointly sponsored by the U. S. Bureau of Public Roads and the Massachusetts Department of Public Works. The traffic data used in this paper were supplied through the courtesy of the Massachusetts Department of Public Works.

The computations involved in the example application were performed on the Project MAC time-shared computer at MIT.

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