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16. Abstract <p>A critical examination is made of the conventional method for highway sizing, that is, determination of lane requirements. Ranked hourly traffic volume distributions, obtained from 1977 Kentucky volume stations are examined to test certain assumptions common to the conventional approach. Several of these distributions have no distinct "knee" and, for those which do, the knee is most frequently found outside the normally anticipated range. Of equal importance, the knee location can be arbitrarily altered simply by changing the number of highest volume hours that are examined.</p> <p>The fundamental fallacy of the conventional procedure is its focus on a single design hour and its orientation toward conditions experienced by the highway rather than the user. This can readily be overcome by basing size decisions on an alternate criterion such as the percentage of vehicles that suffer congestion during the design life. An example demonstrating this concept is presented.</p> <p>More significant improvement can be achieved by directly computing the economic efficiency of investment in additional lanes. An example is presented to demonstrate current capabilities for such computations. The example also demonstrates that current procedures do not always yield the most economical designs and that the most economical highway size is affected by the specific shape of the traffic volume distribution. Use of economic efficiency analysis as a standard tool in evaluating critical sizing decisions is highly recommended.</p>					
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HIGHWAY SIZING

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INTRODUCTION

In many highway construction or reconstruction projects, an important decision regards the number of lanes to be provided. Procedures used to determine lane requirements (herein termed highway sizing) are normally based on identification of a single design hour within which the anticipated demand volume (commonly the 30th highest hourly volume, 30th HHV, in the design year) is balanced against supply volumes (capacities or service volumes) for alternate highway sizes under consideration.

During the past three decades, conventional highway sizing procedures have remained virtually unchanged. During this same period, other highway decision-making processes have changed markedly as emphasis has highlighted broad social concerns and environmental impacts and as competition for the public dollar has intensified. In view of this situation, it is appropriate to reexamine conventional sizing procedures. The project reported herein was initiated to determine if wise and defensible investment decisions are being made regarding lane requirements and to identify, if necessary, possible techniques for improvement.

CURRENT METHODOLOGY

Development of the current sizing methodology must be credited to Peabody and Normann. In 1941, using the single design hour volume versus capacity approach, they recommended use of a design hour volume within the range of the 30th to 50th HHV (1). Endorsements for use of the 30th HHV soon came from the American Association of State Highway Officials (AASHO) and the Committee on Highway Capacity of the Highway Research Board. In 1945, AASHO adopted the 30th HHV for a year 20 years from the date of construction as the design hour volume for the National System of Interstate Highways, an adoption that, with only slight modifications, has remained in subsequent design standards (2). In 1950, the Committee on Highway Capacity recommended use of the 30th HHV as the normal design hour volume (3). However, the Committee cautioned, as had Peabody and Normann, that the 30th HHV was not necessarily applicable in every instance and that it would "... not always result in the best engineering practice" (3).

To understand the rationale for those recommendations, it is necessary to examine the characteristic shape of a ranked hourly volume distribution plot. Figure 1a, constructed from hourly volume data obtained from one automatic traffic recorder (ATR) in Kentucky during 1977, is one such plot. The resulting curve seems to show a "knee," a small region with a

rapid change in slope, at or about the 30th HHV. After observing the regularity with which such a knee occurred in the region between the 30th and 50th HHV for a large number of highway locations; Peabody and Normann concluded that it was "impractical" to design for volumes greater than the 30th HHV, and that designs for volumes less than the 50th HHV would likely result in only small savings in construction costs, but at great loss to the expedition of traffic movement (1). Over the years, use of the 30th HHV appears to have been based to a large degree on the assumption that it yielded the most economic design or, as stated by the Committee on Highway Capacity, it is at this point that the "... ratio of benefit to expenditure is near the maximum" (3). Matson, Smith, and Hurd more subjectively argued that "The most equitable ratio between the service provided by the road and its costs will be achieved when the design volume is selected near the knee of the curve" (4).

While endorsement of the 30th HHV design concept by these respected authorities contributed to its rapid and widespread adoption, at least one other factor was also of importance. The Committee on Highway Capacity had concluded that the 30th HHV, when expressed as a percentage of the annual average daily traffic (AADT) volume, changed very little from year to year (3). A future-year AADT prediction could be easily and accurately converted to the design hour volume through application of what has come to be called the "K" factor, the frequently measurable ratio of the 30th HHV to the AADT. Confidence in the design-hour volume prediction was thus greatly enhanced.

The most authoritative, current recommendations for highway sizing are those of the American Association of State Highway and Transportation Officials (AASHTO). AASHTO recommends use of an hourly volume representative of flows at the end of the design life, that is, 10 to 20 years following completion of construction. For rural highways with normal flow variations, the 30th HHV should be used. For rural highways with unusual or highly seasonal traffic fluctuations, the design hourly volume should be:

"... About 50 percent of the volumes expected to occur during a very few maximum hours of the design year... A check should be made to insure the expected maximum hourly traffic does not exceed possible capacity." (5)

For urban streets and highways, the design hourly volume should be the average of the 52 highest afternoon peak-hour volumes for each of the weeks in the design year. After observing that this average is not significantly different from the 30th HHV, AASHTO concluded:

"Therefore, for use in urban design the 30th highest hourly volume can be accepted since it is a

reasonable representation of daily peak hours during the year. Exception may be necessary in those areas or locations where concentrated recreational or other travel during some seasons of the year results in a distribution of traffic volume of such nature that a sufficient number of the hourly volumes are so much greater than the 30 HV that they cannot be tolerated and a higher value must be considered in design." (6)

KENTUCKY DEPARTMENT OF TRANSPORTATION PROCEDURE

Determination of number of lanes for a new or reconstructed facility involves comparison of the design hour volume (DHV) to an appropriate service volume. The DHV is defined to be the arithmetic average of the 50 highest hourly volumes in the design year. The service volume is determined by the procedure outlined in the 1965 Highway Capacity Manual. The design year is considered to be 20 years after the completion of plans, specifications, and estimates. This usually places the design year 23 to 27 years after the initiation of the planning phase.

The initial step in determining the DHV is the estimation of the design-year AADT. For rural facilities, this estimate is usually based on a projection of historic AADT data. Depending on the judgement of the analyst, traffic growth may be considered to be simple or compound. Historic AADT data usually consist of estimates based on short-term volume counts and/or comparisons with data from automatic traffic recorders at similar sites. Developmental, generated, and diverted traffic are frequently ignored in forecasting traffic growth. For urban facilities, the design-year AADT is determined from conventional urban transportation planning procedures.

The DHV is determined by multiplying the design-year AADT by a K-factor, defined as the ratio of the average of the 50 highest hourly volumes to the AADT. The K-factor is usually based on data from the current year and is assumed to remain constant over time. In the process of determining a K-factor, a comparison is first made between characteristics of the highway in question and characteristics of available automatic traffic recording sites, for which actual K-factors may be determined annually. If a similar site can be found, the design K-factor may be taken directly from the relevant automatic traffic recording data. If a similar site cannot be found, judgement may be used to select a design K-factor (a method particularly common in urban areas). A short-term traffic count (usually one to seven days) may also be taken. If this is done, the K-factor is approximated by first determining for each day the ratio of the highest hourly

volume of the day to the adjusted daily volume, which is an estimate of the AADT derived from the measured 24-hour volumes. The K-factor is then approximated as the average of these ratios. Short-term counts and the K-factors estimated from them usually reflect only average weekday traffic. If used to estimate the K-factor, such counts are normally conducted over a two- or three-year period.

To determine the number of lanes required, two additional items may be needed: the directional distribution factor (D), and the percentage of trucks (T) in the design hour. The D-factor is necessary to convert DHV to a one-directional flow for the analysis of multilane facilities. It is not a measured quantity, but it is usually selected by the analyst from within a range of 56 to 60 percent. The T-factor is usually an estimate based on classification counts at appropriate locations. The D-factor, T-factor, and K-factor are assumed to be constant over the period between the current year and the design year.

If the current-year AADT for a proposed facility is less than 750 vehicles per day, the facility will be two-lane and will be assigned a class within the range of three to six. For higher-volume facilities (Class 1 or 2), the number of lanes is determined by comparing the DHV with the service volumes for the appropriate levels of service. Rural highways are usually designed to provide Level of Service B in the design hour, but Level of Service C is accepted if the differential cost is excessive or if other pertinent constraints exist. Urban facilities are usually designed to provide Level of Service C in the design hour, with Level of Service D being accepted if necessary.

Before making a final decision regarding number of lanes, subjective consideration is given to other factors such as route continuity. Major structures also receive special attention and may have extra lanes due to their high construction cost and long service life.

CRITIQUE

To evaluate the soundness of sizing procedures, one would prefer to examine a large number of past sizing decisions and determine, in retrospect, the fraction that were successful. Unfortunately, such an evaluation is very difficult, if not impossible, both because of the difficulty of acquiring the necessary data and because of the absence of an accepted criterion for defining "success." The approach taken in this critique is, therefore, to focus on the identification of procedural difficulties and on an assessment of the validity of assumptions that undergird the decision-making process.

In the conventional procedure, the designer is continually challenged to determine when the 30th or 50th HHV should be used (for "normal" flows) or when

other "more appropriate" measures should be sought (for "unusual" flows). This choice is one of increasing difficulty: there is simply a continuum of traffic flow patterns reflecting the wide variety of travel desires served by individual facilities and their varying degrees of operational adequacy. Not only does this difficulty raise questions about procedural technique, but also an analysis of flow patterns suggests possible fallacies in underlying assumptions.

The conventional highway sizing procedure draws its strength in part from the following four basic assumptions: (1) the ranked hourly volume distribution exhibits a discernible knee; (2) this knee occurs at or near the 30th HHV; (3) the knee defines the point of most economical sizing; and (4) the 30th HHV, expressed as a percentage of the AADT, remains constant over time.

To examine the first two assumptions, traffic volume data collected in 1977 from 45 Kentucky ATR stations were analyzed. Three ranked hourly volume distribution graphs for each station, similar to those of Figure 1, were constructed for use in the visual component of the analysis. While most prior analyses had examined in detail only the 200 or so highest volume hours, the three different data sets were used herein to identify any possible bias in the more conventional but also more limited examination.

The first portion of the analysis was a subjective one. Four observers were asked to independently examine each ranked hourly volume distribution graph and to determine whether a knee could be discerned. They were told only that a knee was a small region on either side of which the slopes of the curve were markedly different. Figure 1 is typical of the situation where there was general agreement among the observers that knees did exist. In Figure 1, the four observers located knees on the 100-hour, 1000-hour, and 8760-hour graphs within the following ranges in ranks, respectively: 23rd to 25th HHV, 70th to 84th HHV, and 100th to 200th HHV. Figure 2 is representative of graphs for which the observers had more difficulty locating knees. Three of the four observers were unable to locate knees on the 100-hour and 1000-hour graphs, and two did not find a knee on the 8760-hour graph. The difficulty with the graphs of Figure 2 was that the curves, although well-behaved, exhibited slopes that changed quite gradually with increases in rank. Any knee that may have been present was, therefore, very difficult to identify.

The first part of Table 1, which summarizes this portion of the analysis, shows there was a discernible knee in most instances and the likelihood of finding a knee increased as the size of the data set increased. However, in a substantial percentage of cases (approximately 16 percent for the 100-hour graphs), no knee could be found; these cases cannot be dismissed as

mere exceptions. Also noted, although not shown by Table 1, is the fact that there were many cases where individual observers disagreed over the existence of knees. Assuming the observers were reasonably competent, this type of disagreement effectively demonstrates the subjective and somewhat vague nature of the knee-of-curve concept.

Observers were also asked to determine, where possible, the location of each knee. This subjective analysis was augmented by a more objective one employing a nonlinear regression program of the Statistical Analysis System (SAS). SAS was used to fit a segmented model to each set of volume data. This involved the optimal separation of each set of data into two subsets and the fitting of independent models to each of the two subsets. Figure 3 typifies the results. Location of the knee was assumed to occur at the intersection of the two fitted curves, the location labelled "boundary" in Figure 3. The remarkable similarity between the observer-reported knee locations and those determined by SAS gave much credibility to the SAS analysis. While both linear and quadratic models were tested, they were found to yield similar boundary locations and only results from the quadratic models are reported herein.

Results of the analysis of knee-of-curve location are also summarized within Table 1. The first striking observation is that the location of the knee is influenced drastically by the extent of the data set. This fact became readily apparent early in the research when graphs for individual stations were compared (see, for example, Figure 1); it was confirmed by both visual and SAS analyses when the average ranks of Table 1 were determined. Sensitivity of the location of the knee to the amount of data is sufficient to cast serious doubt on the efficacy of knee-of-curve procedures. A knee whose location varies, for a given data set, with the method for graphically portraying those data would seem to be of questionable reliability.

Originally, there was considerable interest in whether the knee occurred at or near the 30th HHV; interest waned when it was conclusively established that the knee location was influenced by the number of hours within the data subset. A quick glance at the average ranks in Table 1 suggests that, by selecting some subset of data between the 100 and 1000 highest volume hours, the location of the knee would average at or near to the 30th HHV. At the same time, Table 1 shows that most of the knees were located outside the accepted range of the 30th to 50th HHV for the data groupings employed herein.

There was also much variability in the location of the knee from station to station. Visual observations of the 1000-hour graphs indicated that about 14 percent of the stations had no knees, 16 percent had knees between the 1st and 20th HHV, 20 percent had knees between the

21st and 40th HHV, 15 percent had knees between the 41st and 60th HHV, 20 percent had knees between the 61st and 120th HHV, 10 percent had knees between the 121st and 300th HHV, and 5 percent had knees at locations in excess of the 300th HHV. Certainly those using knee-of-curve sizing procedures would be well-advised to determine the location of the knee of curve for each individual situation rather than assuming it lies within the 30th to 50th HHV range. This recommendation supports earlier work of Werner and Willis (7) who showed that the knee was not necessarily located at the 30th HHV and that it tended to lie within the 200th to 600th HHV range for the larger AADT's.

A third assumption implicit in the conventional sizing procedure is that the knee defines the point of most economical sizing. Unfortunately, it has been impossible to conclusively prove or disprove this assumption. There is certainly an intuitive appeal to the argument that as one considers volumes to the left of the knee, construction costs would increase greatly while only a very few more hours or users would be accommodated; as one considers volumes to the right of the knee, very little is likely to be saved in construction costs but much would be sacrificed by the users as many additional hours would become congested. At the same time, it seems obvious that such a conclusion might be seriously distorted by focusing, as has been common in the past, on the few heaviest volume hours (perhaps 200) in some year 10 to 25 years in the future. In effect, a design to accommodate the future year 30th HHV is very similar to a design to accommodate the maximum hourly volume in the design life, a design that most designers would consider to be inappropriate and uneconomical. Further to the point of economy in highway sizing, no study has been discovered in which any tests have been made or other objective evidence presented supporting the assumption that the knee defines the point of most economical sizing. At the same time, it is possible to demonstrate, as is done later herein, specific examples for which the knee does not define the most economical size.

The fourth assumption important to widespread adoption of the conventional sizing procedure is that the 30th HHV, expressed as a percentage of the AADT, remains constant over time. Following such an assertion by the Committee on Highway Capacity in 1950 (3), a number of significant studies have shown that the K-factor is not invariant and typically decreases with the increasing volumes that often accompany the passing of time. Among these studies are those of Walker (8), Bellis and Jones (9), Reilly and Radics (10), Chu (11), and Cameron (12). With these rather conclusive analyses, it was not imperative to examine the matter fully during this investigation. A superficial examination was made, however, of data from Kentucky ATR stations for the

years of 1973 and 1977. Between 1973 and 1977, the K-factor decreased for 28 of the 40 common ATR stations, increased for eight, and remained the same for four. The average K-factor decreased during this period from 11.5 to 11.2 percent. It is obvious that the K-factor for a specific highway location is a time-varient quantity.

Conventional sizing procedures have been used with much success for many years, they are viewed quite favorably by design agencies, and their widespread use is likely to continue for many years. Those continuing to use the procedures, however, should consider implementation of changes suggested by the above analysis. The design hour volume should be selected at the knee of the ranked hourly volume distribution graph rather than at some arbitrarily chosen point such as the 30th HHV. Additionally, the graph should contain all hourly volume data collected throughout the year rather than some arbitrarily chosen subset such as the 200 highest volume hours. Finally, as the pattern of traffic flow is likely to be different from location to location, each site must be individually analyzed to ascertain what volume corresponds to the knee and how the K-factor is likely to vary with time. Other improvements, as identified and addressed in the following section, should also be considered for adoption.

EXTENSIONS

In examining highway sizing literature, two promising extensions to the conventional procedure were discovered. Because of their relative ease of implementation and because they overcome certain valid objections to the conventional procedure, they are described herein and their use is illustrated by means of examples. Hourly traffic volume distributions used in these and subsequent examples are shown in Figure 4; other traffic characteristics are described in Table 2. The standard traffic distribution of Figure 4 is representative of the 1977 median for Kentucky ATR stations, while the alternate represents 1977 data for one particular station chosen because the hourly flows were less variable than those for the standard. Both distributions have K-factors of 11.2 percent, the 1977 median for Kentucky ATR stations.

The first extension, attributed to Glauz and St. John (13) and reported by ITE Technical Council Committee 6F-2 (14), suggests a user orientation for design rather than the traditional facility orientation. The focus here becomes the percentage of time the typical user experiences high-volume conditions rather than the percentage of time the facility experiences such conditions. In the traditional approach, the highway is sized so it will be "congested" no more than 30 hours during the year or about 0.34 percent of the time. In the

user-oriented approach, the highway would be sized so the user would experience congestion no more than some other acceptable percentage of time. The difference between these approaches derives from the fact that a proportionately greater number of users travel during high-volume hours as compared with low-volume hours.

Figure 5 shows the first 200 hours of the traffic volume data of Figure 4 replotted to convert from number of hours to percentage of time and extended to show the difference between the user and facility orientations. To modify the conventional sizing procedure to the user approach requires use of ranked volume distributions for users rather than for facilities. Reference 14 describes the procedure in some detail. An individual plot, similar to Figure 5a, could be used to select a "knee" to support a specific design decision, or a large number of such plots could be examined to locate the "characteristic" position of a knee or to otherwise derive an acceptable decision criterion.

The user approach is conceptually superior to the traditional one in that it more nearly recognizes the primary purpose of many highway developments, to provide an improved level of service to the user. Practically, as suggested by Glauz and St. John (13), it offers a superior method to recognize and emphasize peculiar characteristics of recreational and other routes having peaked flow characteristics.

A second useful extension to the conventional sizing procedure derives from work of DeVries (15), also reported by ITE (14). To demonstrate the significance of DeVries' contribution, it is necessary to emphasize that the conventional procedure is based on the concept of a single design hour. Lane requirements are determined by comparing the demand volume (design hour volume) with the supply volume (service volume or capacity) for one particular hour during the design life of the highway. Is it not presumptuous to ignore conditions occurring during that overwhelming portion of the design life in which flow is more or less congested than during the design hour? Is it not also presumptuous to base such a design on demand and supply volumes that have been rather arbitrarily selected on the basis of the designer's intuition as to what conditions are acceptable to the traveler and what conditions result in the most "economical" design? Questions such as these lend credence to attempts such as DeVries' to expand the focus from a single hour to a range of hours within the design life.

DeVries suggested that more prudent investment decisions for independent project analysis might result from investigations of the range of top hours (perhaps the highest 500 hourly volumes) encompassed within the desired level of service. This concept might be implemented in any of several ways, including specification of a minimum number of the top 500 hours

that must be included within the desired level of service.

As a variation of the DeVries proposal, which includes the user emphasis of Glauz and St. John, sizing decisions might be based on the percentage of vehicles during the design life that suffer "congestion". A simple but reasonable way to define congestion is in terms of operating conditions representative of "D," "E," or "F" levels of service. The objective would be to make size decisions based on a congestion level acceptable to the design agency. Figure 6 illustrates the output of such an analysis.

This figure shows the traffic volume subject to congestion on two-lane roadways for a range of future-year AADT's and the two different traffic distributions described earlier. Similar analysis showed that no congestion would be anticipated on four-lane facilities with volumes no greater than a future-year AADT of 14,000. The specific criterion for highway sizing in this example would have to be selected by the designer. Alternatives might be no congestion, some fixed level of congestion such as 2 percent, or even the knee of the curve. The knee is reasonably well defined in this example, and, should that prove to be true in other circumstances as well, the knee might furnish an acceptable heuristic decision point.

In summary, design to accommodate a single hour in the design life of a facility masks the reality of variable operational flow conditions through time. This difficulty can and should be overcome by broadening the analysis to include a much larger time frame. Use of the percentage of vehicles during the design life that suffer congestion as the decision criterion accomplishes this objective as well as that of properly focusing on the user rather than the facility. Further testing and use of such a criterion seems warranted.

Brief descriptions of alternative approaches to highway sizing decisions discovered during the literature review have been excerpted from an earlier paper (16) and are included as an appendix to this report.

RECOMMENDED PROCEDURE

Highway sizing decisions rank among the more important decisions confronting the designer or planner. Differential construction costs are measured in hundreds of thousands of dollars per kilometer, and the cost of an additional pair of lanes will, in some circumstances, almost double construction outlays. Because of their importance, sizing decisions merit critical analysis and should not be based on hunch and intuition. While the conventional procedure can certainly be improved as indicated above, to accomplish what is really necessary requires a completely different perspective on the sizing task.

The authors contend that sizing decisions should be approached in the same manner as other major investment decisions. In whatever way has been found to be acceptable to each responsible agency, the gamut of both favorable and unfavorable consequences of the sizing decision need to be identified and evaluated. One such consequence often evaluated in public decisions involving allocation of scarce resources is the economic efficiency of the investment. Economic analysis appears tailor-made to the sizing decision, as the primary impacts are often limited to savings to the user and costs to the highway agency.

Technical literature abounds with information regarding economic analysis and its application to highway investment decisions. Maring (17) and Hutchinson (18) were among those specifically advocating use of economic analysis in highway sizing decisions. Although both presented useful examples to demonstrate their recommendations, effectiveness of those examples was limited by data that were readily available when their work was performed. Publication of the authoritative Manual on User Benefit Analysis by AASHTO (19) has helped eliminate many earlier constraints to effective analysis. At the same time, it must be emphasized that economic analysis still involves a number of important assumptions, any one of which can possibly affect the decision. Sensitivity analyses are recommended for assessing the potential significance of the critical assumptions.

To demonstrate application of economic analysis, a hypothetical situation was defined in which a decision was required between two-lane and four-lane construction on a new 16.1-kilometer highway. Future-year AADT was varied and two ranked hourly volume distributions, as shown in Figure 4, were independently investigated. Details of the analysis are identified within Table 2. Insofar as practical, recommendations and data given by AASHTO (19) were used unflinchingly. Construction and maintenance costs were estimated on the basis of Kentucky experience, and accident costs reported by AASHTO (19) were used.

The criterion chosen to represent economic efficiency was the net present worth of four-lane as compared to two-lane construction. Benefits of the four-lane construction included savings in travel time and accident costs and an increase in the residual value of the investment. Greater costs for the four-lane facility were attributed to those of construction and maintenance as well as increased operating costs occasioned primarily by increased speed.

Figure 7 summarizes the analysis in graphical form. For the standard traffic distribution, two-lane construction is seen to be preferable for future-year AADT's less than about 9,300 vehicles per day. This break-even volume

increased to 9,800 vehicles per day for the alternate traffic distribution. The fact that two different traffic distributions, although having identical K-values and design hourly volumes, had different break-even volumes suggests that factors other than the location of the knee of the ranked hourly volume distribution curve also influence the most economical design.

A comparison was also made between the break-even volumes of Figure 7 and those determined by conventional sizing procedures. In the latter case, the break-even volume depends upon which level of service is selected to represent acceptable congestion in the design hour. The future-year, break-even AADT's for the conventional analysis were determined to be approximately 4,500, 7,400, and 9,300 vehicles per day for "B," "C," and "D" service volumes, respectively. Results from the conventional analysis and the economic analysis thus become comparable only for a level of service ("D") normally considered intolerable for all but exceptional design purposes. The conclusion, therefore, is that, for this example problem and a rather wide range in future-year AADT's, the conventional sizing analysis would lead to a design decision different from that of an economic analysis. Of course, specific numbers reported herein are unique to the given conditions, and generalizations based thereon are to be avoided.

The example of this section has demonstrated application of the techniques of engineering economy to the highway sizing decision. It also has identified at least one situation in which the conventional sizing procedure yields a decision different from one based on the criterion of economic efficiency. The authors are convinced that techniques and data for performing competent economic analyses are readily available and are becoming more sophisticated. Further they are convinced that the economic efficiency of additional-lane investments is one impact that should never be neglected in the sizing decision. At the same time, they are aware that other impacts are sometimes of paramount importance. Who cannot describe a situation where a nearby cemetery, a row of stately shade trees, a bordering park, or any of a number of other situations has served to constrain the size of a highway improvement? The point is simply that economic efficiency, albeit important, is only one of many impacts of the sizing decision that must be evaluated if prudent decisions are to be reached.

SUMMARY AND CONCLUSIONS

A critical examination has been made of the conventional method for highway sizing, that is, determination of lane requirements. While this method has served admirably in the past, improvements can readily be made that will lead not only to more informed

but also to more easily defensible decision-making.

The fallacy of the conventional method, which determines lane requirements by balancing a design hour volume (demand) against service volumes for the alternative highway sizes (supply), rests with its focus on a single design hour as well as with its orientation to the facility rather than the user. It does not explicitly consider, therefore, the normal reason for increasing highway size, namely, benefits that accrue through time to the user.

Further, some basic premises upon which the conventional sizing methodology is based have been found to be invalid. Many ranked hourly volume distributions ("nth" highest hour plots) do not exhibit discernable "knees," small regions within which their slopes change markedly. Of those that seem to exhibit knees, knee locations vary among observers and are unquestionably and most inappropriately influenced by the number of hours of volume data being examined. Further, knees usually lie outside the normally accepted 30th to 50th highest hourly volume interval. Traffic volume data reported herein offer support to the prior conclusion of others that, at a given location, the K-factor (ratio of 30th highest hourly volume to the average annual daily traffic) cannot be expected to remain constant with time, and, for underutilized facilities, typically decreases as traffic volume increases. Finally, the conventional sizing methodology, while having minimal data requirements and being simple to apply, cannot be expected to necessarily yield the most economical highway size decision.

Similar care and attention should be given to decisions regarding highway size as to other major highway investment decisions. The entire gamut of differential impacts, including such factors as the degradation of parks and historic places, aesthetics, noise and air pollution, etc., should, if possible, be evaluated. Of particular importance to this evaluation is the economic efficiency of the highway investment.

The capacity for using conventional highway economic analysis to aid highway sizing decisions is well-developed and readily available for immediate implementation. Its use is highly recommended as a rational and defensible basis for supporting sizing decisions. However, for those who find this recommendation to be unacceptable, other improvements to the conventional methodology are suggested. The first involves focusing on the user instead of the facility by appropriately changing the abscissae of the ranked hourly volume distribution plots and selecting the design hourly volume at the position of the relocated knee. The second would be more significant but would require a conceptual transition from a single-hour to a range-of-hours

approach. A suitable decision criterion in this situation appears to be the percentage of vehicles during the design life that suffer congestion for the alternative highway sizes. A decision to increase highway size would be justifiable when the percentage of vehicles suffering congestion on the smaller facility was considered unacceptably large by the design agency.

REFERENCES

1. Peabody, L. E. and Normann, O. K., "Applications of Automatic Recorder Data in Highway Planning," *Public Roads*, Vol. 21, No. 11, Jan. 1941, pp 203-222.
2. Cron, Frederick W., "Highway Design for Motor Vehicles -- A Historical Review: Part 2, The Beginnings of Traffic Research," *Public Roads*, Vol. 38, No. 4, March 1975, pp 163-174.
3. Highway Research Board, Committee on Highway Capacity, "Highway Capacity Manual -- Practical Applications of Research," 1950, U.S. Government Printing Office, Washington, D.C.
4. Matson, Theodore M., Smith, Wilbur S., and Hurd, Frederick W., *Traffic Engineering*, McGraw-Hill, New York, 1955.
5. American Association of State Highway Officials, *A Policy on Geometric Design of Rural Highways*, American Association of State Highway Officials, Washington, D.C., 1966.
6. American Association of State Highway Officials, *A Policy on Design of Urban Highways and Arterial Streets 1973*, American Association of State Highway Officials, Washington, D.C., 1973.
7. Werner, Al and Willis, Terry, "Cost-Effective Level of Service and Design Criteria," *Research Record 699*, Transportation Research Board, 1979, pp 1-7.
8. Walker, William P., "Trends in the 30th-Hour Factor," *Bulletin 167*, Highway Research Board, 1957, pp 75-83.
9. Bellis, W. R. and Jones, John E., "30th Peak Hour Factor Trend," *Research Record 27*, Highway Research Board, 1963, pp 1-13.
10. Reilly, E. F. and Radics, R. D., "30th Peak Hour Factor Trend," *Research Record 199*, Highway Research Board, 1967, p 78.
11. Chu, Benjamin P., "Michigan's Statewide Traffic Forecasting Model, Vol III -- Design Hour Volume Model Development," Michigan Department of State Highways and Transportation, Nov 1972.
12. Cameron, Neville, "Determination of Design Hour Volume," The University of Calgary, Department of Civil Engineering, Calgary, Alberta, May 1975.

13. Glauz, William D. and St John, Andrew D., "Recreational Travel Impacts -- Procedures for Dealing with the Impacts," Interim Report prepared for U.S. Department of Transportation, Dec 1977, Midwest Research Institute, Kansas City.
 14. ITE Technical Council Committee 6F-2, "Reexamination of Design Hour Volume Concepts," *ITE Journal*, Vol 48, No. 9, Sep 1979, pp 45-49.
 15. DeVries, Norman R., "The Role of Design Hour Volume in Highway Planning and Design," Working Paper, Wisconsin Department of Transportation, Nov 1975.
 16. Crabtree, Joseph D., "Design Hour Volume: A Critical Look at Present Methods for Determining Number of Lanes," Unpublished Student Paper, College of Engineering, University of Kentucky, Aug 1979.
 17. Maring, Gary E., "Weekend Recreational Travel Patterns," *Technical Report No. 18*, Feb 1971, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.
 18. Hutchinson, Bruce G., "Economic Criterion for Highway Capacity Determination," *Transportation Engineering Journal*, Vol 98, No. TE3, Aug 1972, pp 465-475.
 19. American Association of State Highway and Transportation Officials, "A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements, 1977," 1978, American Association of State Highway and Transportation Officials, Washington, D.C.
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FIGURE 1. TYPICAL RANKED HOURLY VOLUME DISTRIBUTION (STATION 16)

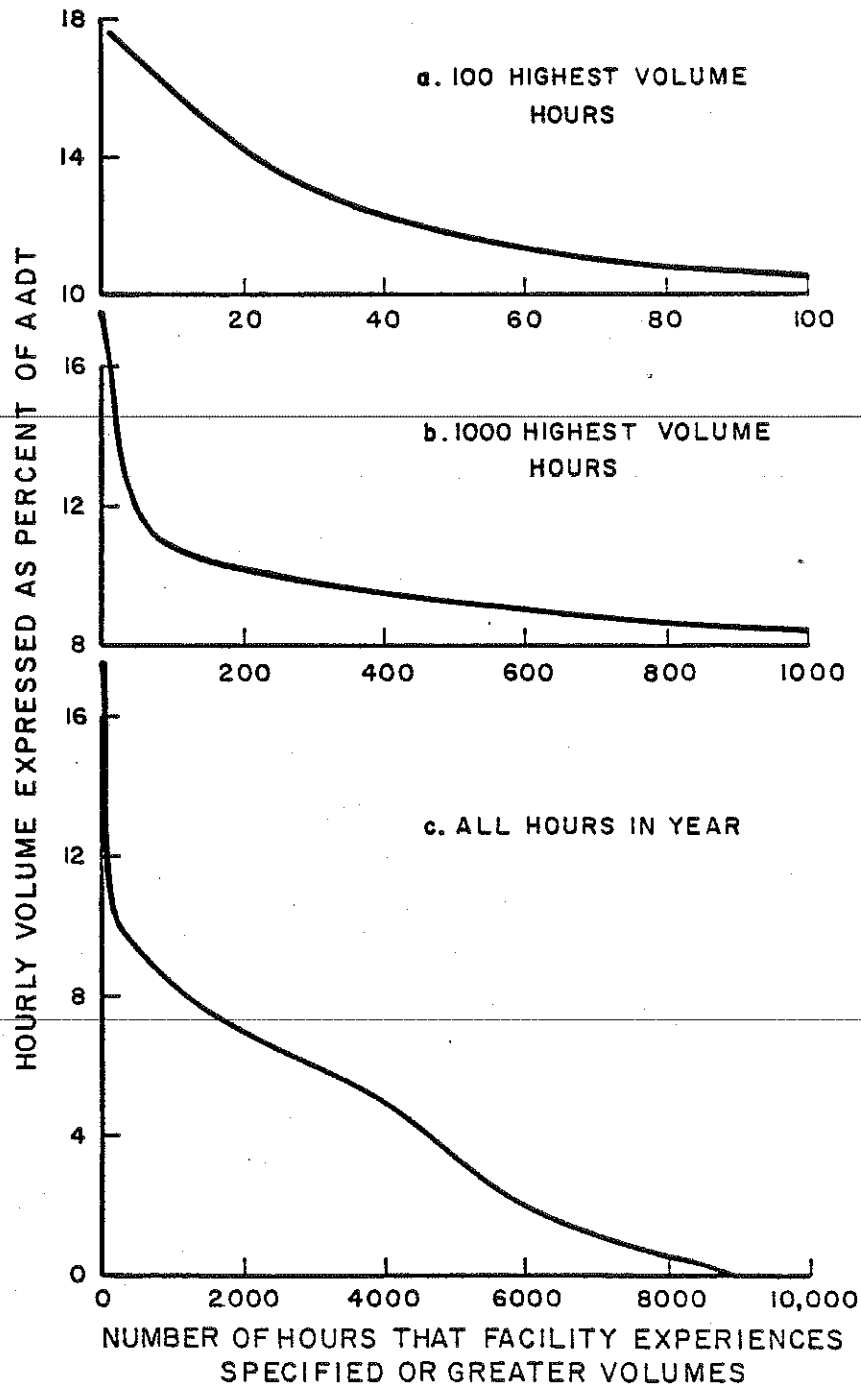


FIGURE 2. RANKED HOURLY VOLUME DISTRIBUTION SHOWING INDISTINCT KNEE (STATION 46)

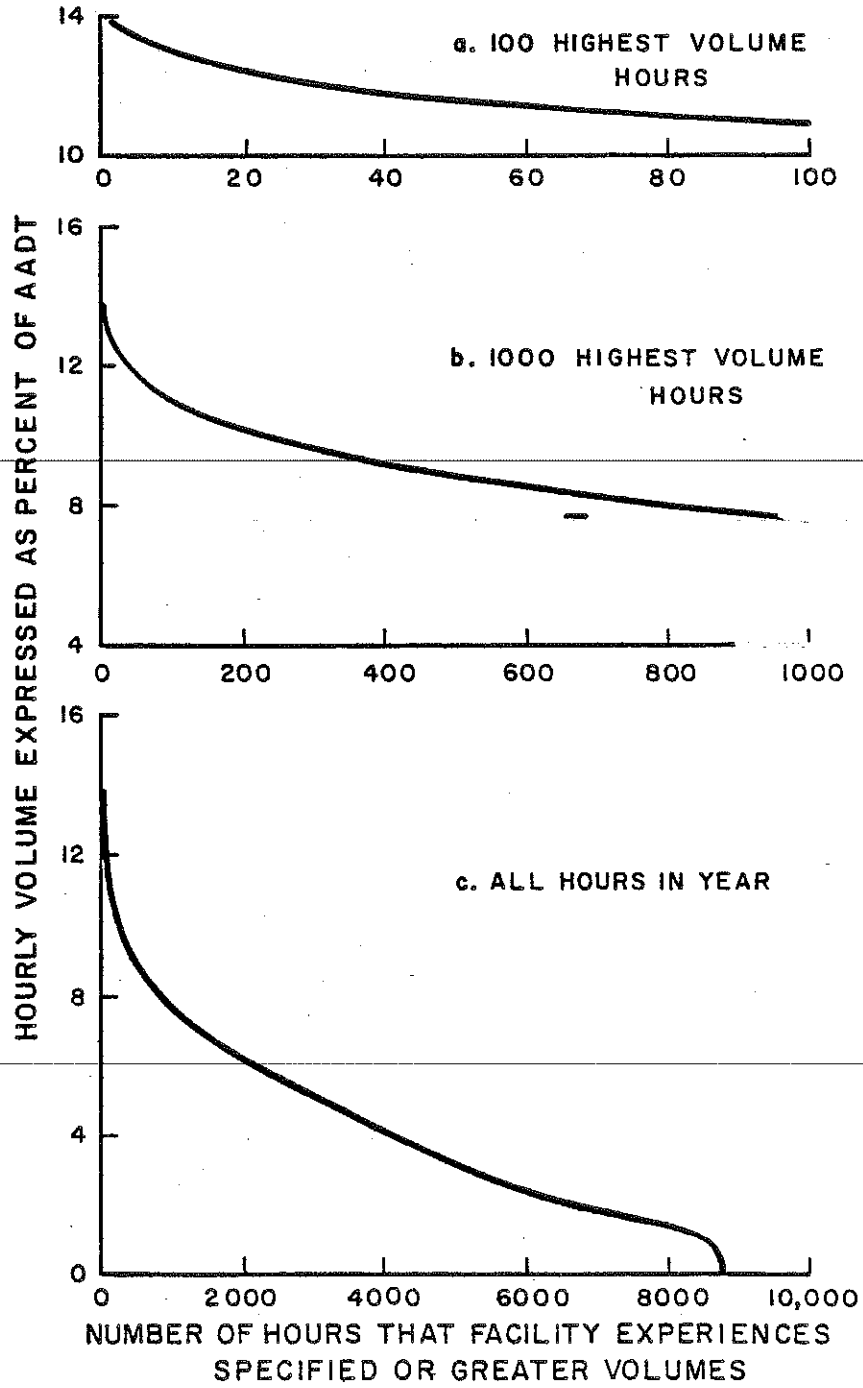


FIGURE 3. TYPICAL RANKED HOURLY VOLUME DISTRIBUTION SHOWING SEGMENTED QUADRATIC MODEL OF BEST FIT (STATION 7-S B)

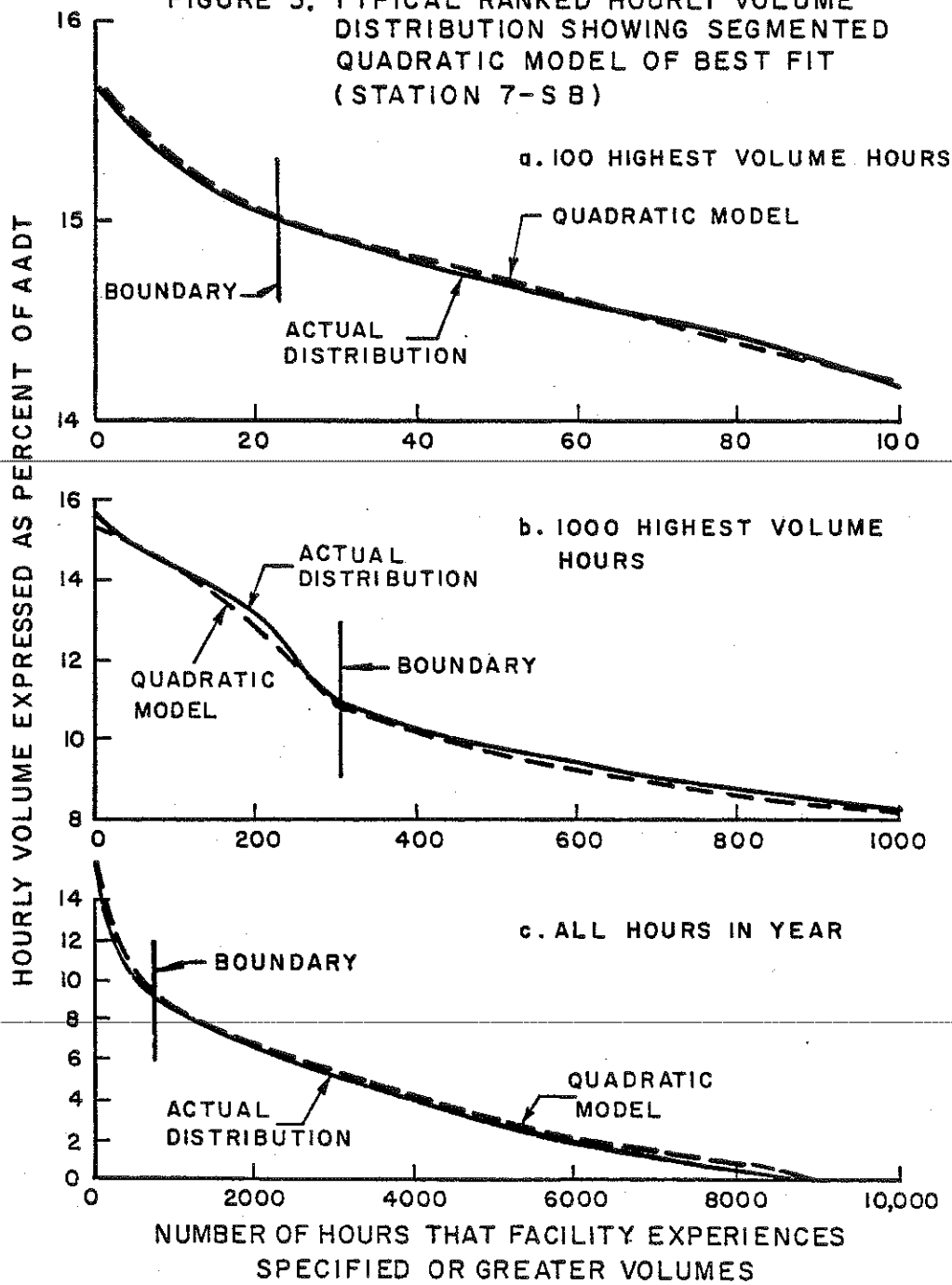


FIGURE 4. RANKED HOURLY VOLUME DISTRIBUTIONS FOR EXAMPLES

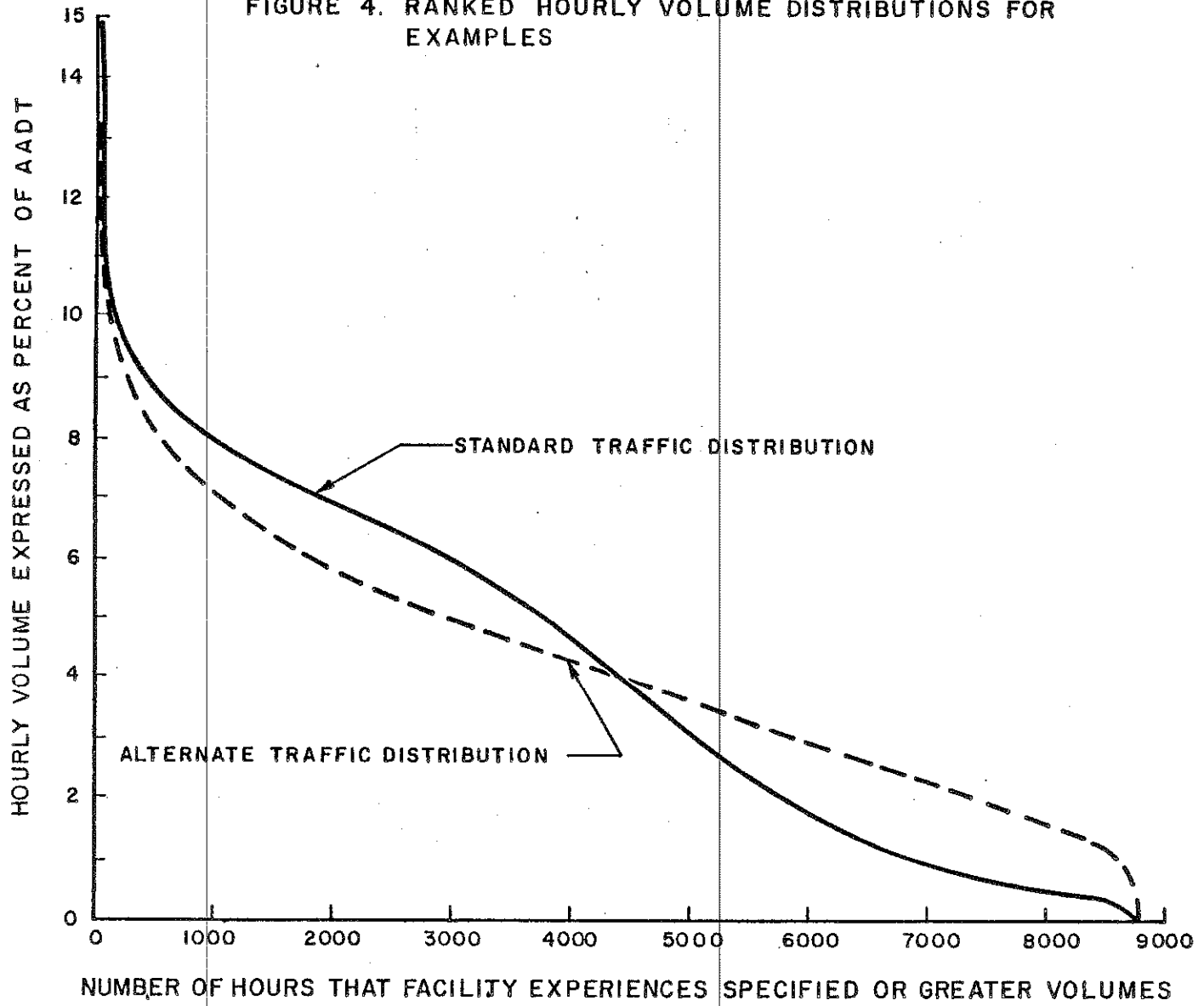


FIGURE 5. RANKED HOURLY VOLUME DISTRIBUTIONS FOR BOTH USERS AND THE HIGHWAY

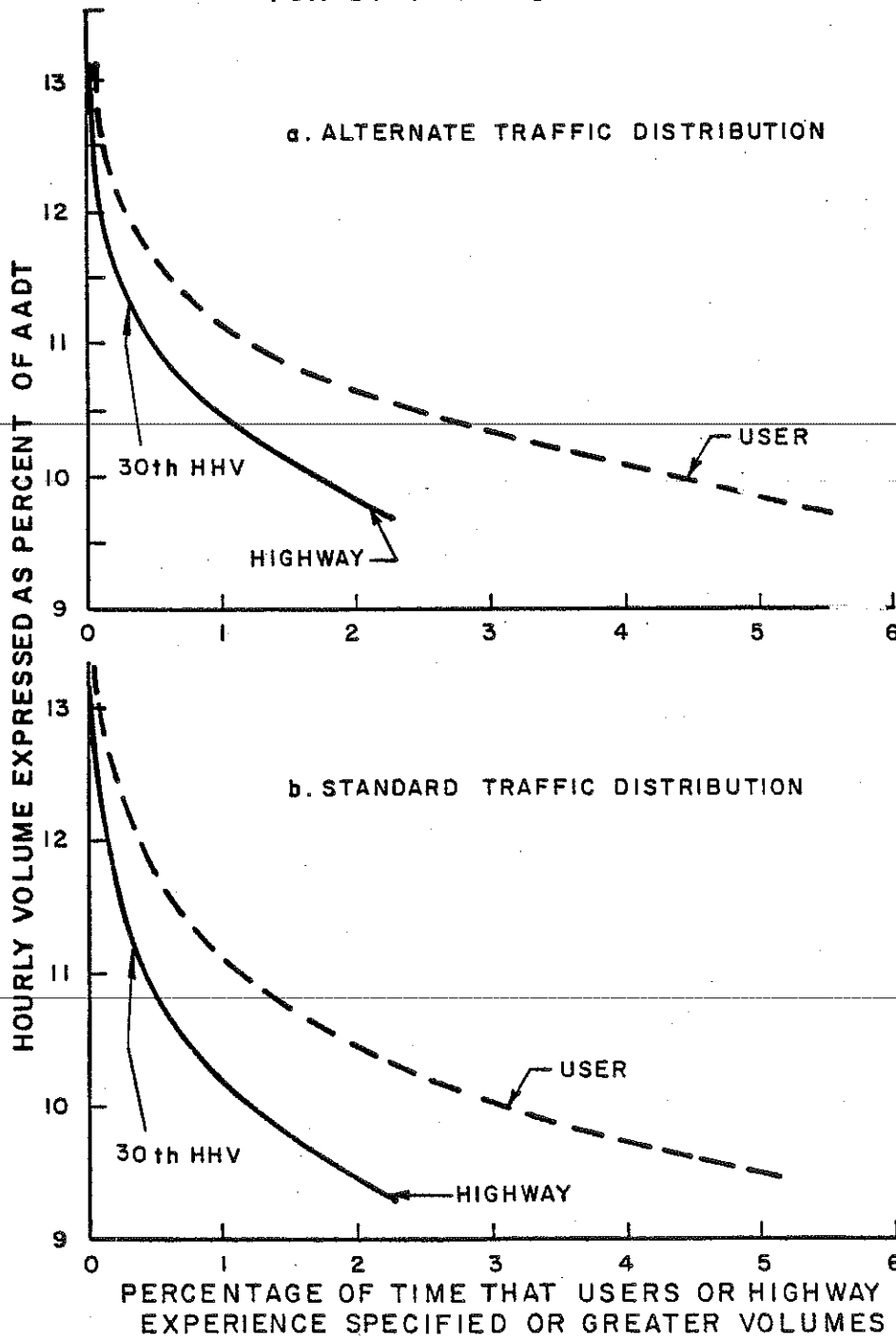


FIGURE 6. INFLUENCE OF TRAFFIC VOLUME ON CONGESTION OF TWO-LANE, EXAMPLE HIGHWAY

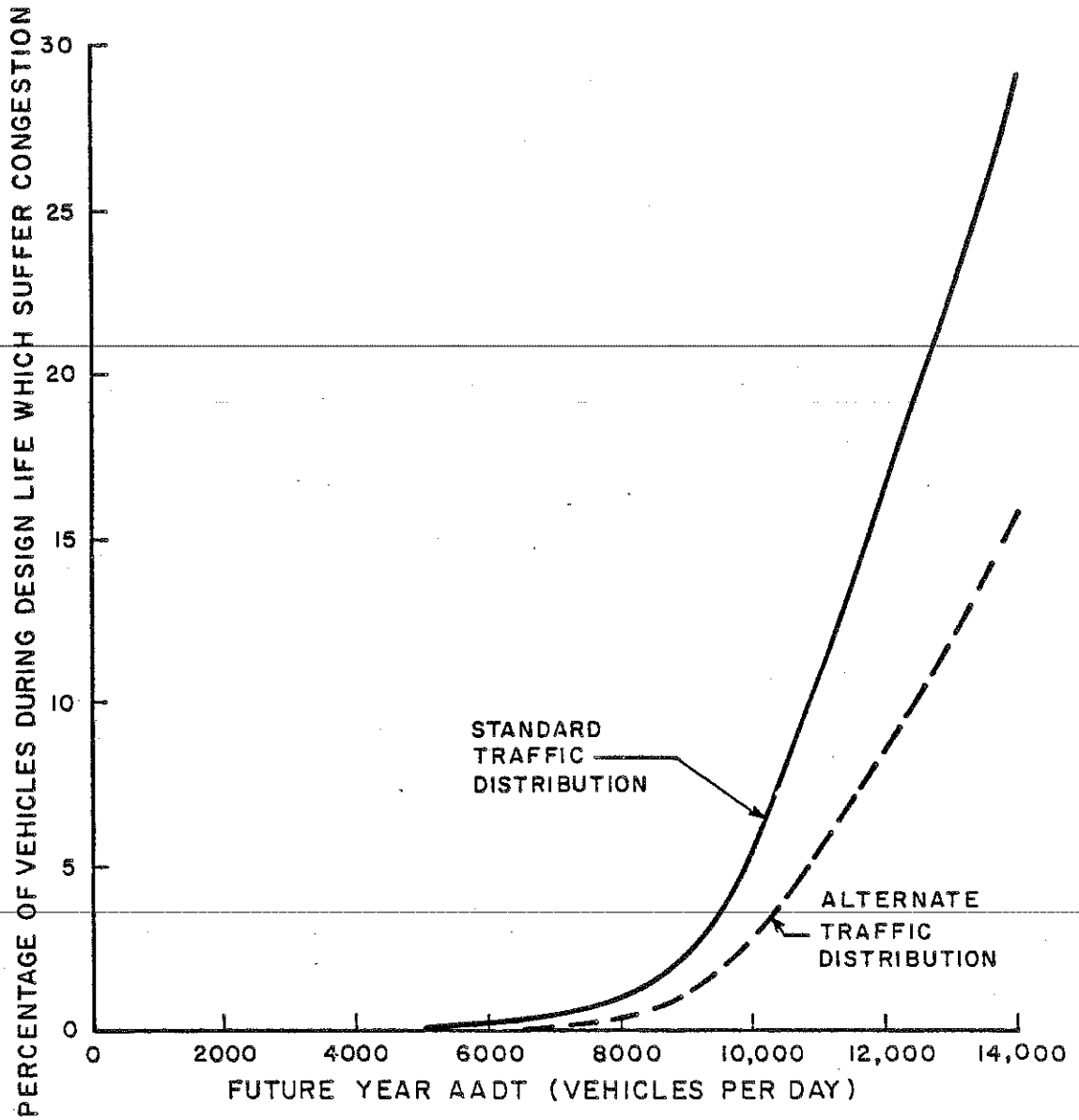


FIGURE 7. ECONOMIC EFFICIENCY OF FOUR-LANE
VERSUS TWO-LANE CONSTRUCTION IN EXAMPLE

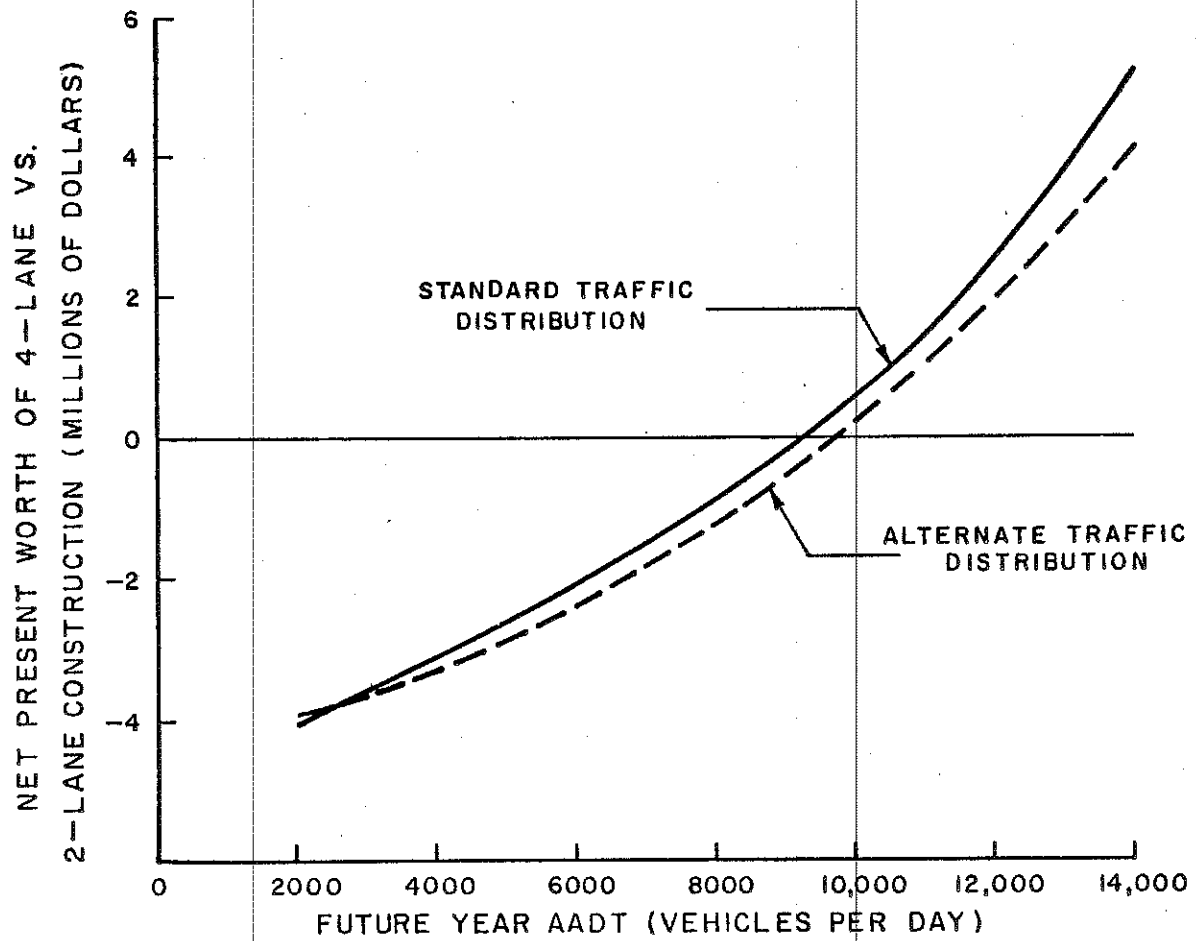


TABLE 1. EXISTENCE AND LOCATION OF KNEE FOR RANKED HOURLY VOLUME DISTRIBUTIONS

	GRAPH OF 100 HIGHEST VOLUME HOURS	GRAPH OF 1000 HIGHEST VOLUME HOURS	GRAPH OF ALL HOURS IN YEAR
Percentage of Graphs with Discernible Knee (Total for 4 Observers)	83.8	86.2	91.2
Average Rank of Hour at Location of Knee			
Range for 4 Observers	6.6 to 9.9	47 to 82	310 to 620
Segmented Model	19	110	360
Percentage of Knee Locations within 30th to 50th HHV Interval			
Average for 4 Observers	0.6	33.3	0.0
Segmented Model	11.1	0.0	0.0

TABLE 2. ASSUMPTIONS IN ECONOMIC ANALYSIS EXAMPLE

TRAFFIC

1. Growth of 3% compounded annually
2. Composition of 85% cars, 10% single-unit trucks, 5% combination trucks
3. Directional split of 55% in direction of greatest flow
4. Ranked hourly volume distributions as shown in Figure 4

ROADWAY

1. Uninterrupted flow in rural area
2. Design speed of 96.6 km/h and speed limit of 88.5 km/h
3. Length of 16.1 kilometers with 3.66 meter lanes and 3.05 meter shoulders
4. No access control but four-lane highway has median
5. Paved surface
6. Rolling terrain with 11.3 kilometers level, 3.2 kilometers on a 1 percent grade, and 1.6 kilometers on a 2 percent grade.
7. Tangent sections for 11.3 kilometers and horizontal curvature of 1 and 2 degrees on lengths of 3.2 and 1.6 kilometers, respectively
8. 100 percent of two-lane highway with passing sight distance in excess of 460 meters

ANALYSIS

1. 25-year period of analysis
2. All costs expressed in constant (1975) dollars
3. Discount rate of 5%
4. Hourly time costs of \$3.00 for cars, \$7.00 for single-unit trucks, and \$8.00 for combination trucks
5. Construction costs of \$615,000 and \$957,000 per kilometer for two-lane and four-lane highways, respectively
6. Maintenance cost of \$2,660 and \$4,320 per kilometer per year for two-lane and four-lane highways, respectively
7. Residual value of \$394,000 and \$560,000 per kilometer for two-lane and four-lane highways, respectively
8. Accident costs of \$10.03 and \$8.78 per thousand vehicle kilometers for two-lane and four-lane highways, respectively

APPENDIX

**PROPOSED ALTERNATIVES FOR DETERMINING
NUMBER OF LANES**

DeVries (Ref. 15)

DeVries proposed that, rather than attempting to provide a selected level of service for a single hour of the year, a range of hours falling within the selected level of service should be considered. Such an analysis requires the development of a volume-versus-hour curve and, therefore, requires a continuous or nearly continuous traffic count.

Once the volume-versus-hour curve has been plotted, horizontal lines representing the service volume for each level of service for a particular number of lanes can be overlaid. It is then easy to see which hours of the year will fall into each level of service. The decision regarding the acceptability of the number of lanes must then be made based upon the range of hours falling within the selected level of service. For the chosen number of lanes, this approach generally recommends the same number of lanes as does the traditional approach. This will not always be the case, however. The 30th hour will sometimes fall just outside the selected level of service for the chosen number of lanes. In that case, this method would recommend a fewer number of lanes than would the traditional 30th highest hour approach.

This method has an important advantage over the traditional method, which attempts to represent all the hours of the year by means of a single volume. The DeVries method does not do this. It does not mask the hourly traffic variations throughout the year, but allows them to be considered in the decision-making process. This is a significant improvement and this method is recommended as an alternative to the traditional method.

This method has a drawback in that it is subjective. The designer must decide whether a particular range of hours falling in the selected level of service is an acceptable range or not, and there are no firm guidelines for this decision.

Glauz and St. John (Ref. 13)

Glauz and St. John proposed a user-oriented approach to design as an alternative to the traditional facility-oriented approach. In the traditional approach, the highway is designed so it will be congested no more than 30 hours during the year. In other words, the design insures the facility will not experience congestion more than X% of the time, where $X = 100(30/8760)$. The user-oriented approach states that a typical user of the facility should not experience congestion more than Y% of the time, where Y is a value to be determined. The difference between these two methods can be found in the fact that, during the high volume hours of the year, there are more users on the facility than during the light volume hours. Therefore, in the user-oriented approach, the high volume hours carry increased weight in the determination of a DHV.

This approach is a definite improvement over the traditional approach. The primary purpose of any highway construction or improvement is to provide benefits to the users. Therefore, the design process should focus on the user, rather than on the facility. In addition, the user-oriented approach better recognizes and accommodates the different peaking characteristics of traffic on different facilities. A road with a high peak would have its peak hours carry much greater weight in the design than would the off-peak hours. For a road with little or no peak, the peak hours would carry only slightly greater weight than the off-peak hours. This seems appropriate when it is considered that highly peaked facilities tend to carry much recreational traffic, especially during peak hours. Users tend to value recreational time higher than other time, and vehicle occupancy tends to be higher for recreational travel than for other purposes (Ref 17, p 14). Therefore, these peak hours of recreational travel should exert increased influence in the design.

The Glauz-St. John approach and the DeVries approach can be combined by looking at the number of users that would experience each level of service rather than setting a single Y% of the vehicles that should experience congestion. The designer should look at the number of users that would experience each level of service for each alternative and then select the best alternative from this.

The user-oriented approach is strongly recommended as an improvement over the traditional method. The combined approach is recommended as an even better technique, since it has the advantages of both methods, while eliminating some of the disadvantages of each.

The user-oriented approach has the disadvantage of being subjective in the determination of an acceptable Y% value, the percentage of vehicles experiencing congestion. It also attempts to express the entire yearly traffic distribution by means of a single hourly volume and then designs for that volume. These are some drawbacks of the traditional method that Glauz and St. John have not eliminated.

The combined method eliminates some of these problems since it considers the entire yearly distribution and does not try to summarize it with a single volume. However, the decision process in this method is still subjective, as the designer is asked to choose the "best" alternative based on the number of users experiencing each level of service. His decision as to which is best depends a great deal on his individual judgement.

Maring (Ref. 17)

Maring proposed the use of economic analysis to study the feasibility of providing relatively high levels of service on recreational routes. He made note of two

characteristics of recreational routes that should be taken into account in design. First of all, K-factors appear to be higher on recreational routes than on other rural or urban routes, so it would seem desirable to separate recreational routes for design purposes. Also, vehicle occupancy rates are high for recreational travel, indicating a recreational route could serve twice as many person-trips as a route carrying the same vehicular volume of work trips. "Therefore, consideration should be given to including person-trips served as an item for developing construction priorities." (Ref 17, p 14)

Maring's technique for economic analysis involves first determining the range of hours that would fall into each level of service. This is done for both the unimproved and improved facility and for both present and future traffic. Maring assumed volume was independent of number of lanes provided, stating that research was being done in the area of elasticity of demand. He then determined, for both the present and future years, the number of hours experiencing each possible improvement in level of service (B to A, C to A, C to B, etc.). He then determined a cost differential for each improvement. This was a rough procedure, involving analyses of time costs, operating costs, accident costs, pollution costs, and comfort and convenience. Maring lacked sufficient data to do extensive analyses of most of these. Once these cost differentials had been determined, it was possible to determine a total savings due to the improvement. Maring determined the savings for the present year and the future design year and connected these by a straight line. The total savings were then determined by finding the present worth of the resulting series. Once the total savings had been determined, they were compared to the differential construction and maintenance costs to see if the improvement was economically justified.

This procedure represents a great stride forward in the determination of number of lanes. Maring recommended this procedure for recreational routes, but it could be used for any route. This approach eliminates many of the problems of the traditional method. Since it involves calculation of user benefits, it is inherently user-oriented. It does not focus on a single hour of a single year but rather considers all hours of the present year and the design year. The intervening years are included approximately by means of a straight-line connection from the present year to the design year. Most important, this approach provides a logical, defensible, more objective procedure for determining number of lanes. It is highly recommended for use.

The primary drawback to this method was the lack of necessary data for a complete and thorough economic analysis. The assumption of constant demand was another limitation. Both of these problems pointed to a need for further study.

Cameron (Ref. 12)

Cameron made an attempt to apply the principles of supply and demand to the analysis of transportation services. His procedure involved the development of a price-volume curve and a demand curve. The intersection of these two curves indicates the equilibrium volume for the facility being considered.

The decision-making process begins with the development of a demand curve. This curve shows the relationship between volume and operating cost, i.e., how volume varies with cost. The curve is developed from information about the surrounding area and data on trip purposes as well as from examination of similar situations elsewhere.

Next, a particular facility type is assumed, and, for that type, the capacity is determined, as are service volumes for the different levels of service. A price-volume curve must be developed for that type of facility using the best available relationships between volume and operating costs. The price-volume curve shows how operating costs vary with volume. The intersection of the price-volume curve and the demand curve indicates an equilibrium volume. This volume is compared to the service volume of the assumed type of facility at the desired level of service. If the equilibrium volume falls into the desired or better level of service, then this type of facility is adequate. If not, then another facility type must be examined. Each different facility type will have its own capacity, service volumes, and price-volume curve.

Cameron took an important step by stating that quantity demanded is dependent on quality of service provided. The choice of one design alternative over another will affect the volume using the facility. This is the "variable demand" concept needed for a complete approach to the determination of number of lanes. Cameron expressed the variable demand by means of a demand curve, a process which caused some difficulties. In the construction of a demand curve, it is required that the traffic that will use the facility at any given cost be expressed by a single volume. This ignores the volume fluctuations throughout the year. Cameron uses price-volume demand curves to select a single volume for which to design. This is a questionable procedure. It overlooks traffic fluctuations and requires that the road be designed for a predetermined volume, a procedure which was questioned in the critique of the traditional method.

Despite these shortcomings, Cameron raised some interesting points. He attempted to work variable demand into his design process, and he provided some clues on how this could be handled.

SUMMARY OF AVAILABLE APPROACHES

The different approaches and techniques that have been reviewed can be illustrated figuratively by the three-

dimensional block shown in Figure A-1. This large block is divided into 12 smaller blocks that represent different approaches to the determination of number of lanes. The traditional approach is a single-hour, constant demand, facility-oriented approach. The ultimate approach would consider all hours of the design period, would be user-oriented, and would incorporate variable demand. Therefore, any approach that moves from a single-hour, constant-demand, facility-oriented approach and toward an all-hours, user-oriented, variable-demand approach should be considered for adoption.

The DeVries approach assumes constant demand, is facility-oriented, and considers a range of hours. Glauz's approach is user-oriented, considers a single hourly volume (rather than a single hour), and assumes constant demand. The combined DeVries-Glauz approach takes into account a range of hours, is user-oriented, and assumes constant demand. Maring's method considers all hours, is user-oriented, and assumes constant demand. Cameron's procedure incorporates variable demand, is facility-oriented, and considers a single hour.

FIGURE A-1. APPROACHES FOR DETERMINING
NUMBER OF LANES

