TRADE-OFF ANALYSES IN MAJOR INTERCHANGE DESIGN

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Recent expansion of limited-access, high-speed highways has emphasized the need for safely designed interchanges. Frequently, interchanges are designed as modifications to existing designs to increase capacity or as developments from experience of designers. A more analytic approach is needed. In the study reported, existing design criteria are reviewed and evaluated, and a decision-theory approach to design is developed. This approach assesses the relative operational and safety merits of alternative interchange configurations and suggests trade-offs between these merits and the cost of the alternative.

•RELATIONSHIPS among variations in geometric features (such as ramp curvatures, lengths of recovery zones at exit gore areas, and visibility distances to exit ramp noses) and operational efficiency and safety and cost are not well defined. On the other hand, a number of decisions involving trade-offs between cost and operational efficiency and safety have been and are being made in the major interchange design process. The views of practicing design engineers and traffic operations specialists on trade-off analyses, as derived from information gathered for a larger project, are presented with commentary by the author.

PROJECT OBJECTIVES

Since its introduction more than 4 decades ago, the interchange has established itself as an irreplaceable, though sometimes confusing, element of the world's roadways. In particular, the recent expansion of high-speed, limited-access highways has emphasized the need for major interchanges optimally designed to contribute to unambiguous, safe, high-capacity, predictable interhighway access. The key phrase in this assertion is "optimally designed."

Designs of interchanges are often based on evolutionary changes of past designs or on modifications of existing designs to increase capacity. Hence, the newer designs tend to develop from experience and engineering judgment rather than from a ranking of quantifiable alternatives based on performance. The changes seen in recent demands for highway systems suggest that a more analytic approach is necessary.

Consequently, the Federal Highway Administration sponsored the study on interchange design, the principal phases of which were as follows:

1. Preparation of a state-of-the-art document covering major interchange design and operations,
2. Review and evaluation of existing design criteria and constraints,
3. Development of a decision-theory approach to the design of major interchanges,
4. Development of recommendations to minimize operational problems associated with major interchanges, and
5. Determination of the viability of the various freeway-to-freeway interchange configurations for inclusion in adaptive freeway control schemes.

The project was completed in June 1973. The final report and three interim reports are available from the sponsor.

This paper deals with trade-off analyses (costs versus safety and operational efficiency) and is derived from broader information gathered for the overall project. Primarily, it is an exposition of the views (with contrasts) of design engineers, traffic operations specialists, and persons from the research and academic communities on this topic, including present practice and views on the probable and desirable directions of future practices. A presentation of a related "level-of-merit" design concept is also included.

WORKSHOPS

Two 3-day workshops were held at Pennsylvania State University to aggregate the experiences and personal views of practicing engineers and researchers on major interchange design and operations. In most instances, the attendees were intimately involved in or responsible for design policies within their respective organizations. This paper was derived from the workshop sessions on Trade-Offs; Level-of-Merit Concept, led by the author.

TRADE-OFF ANALYSES

Background Information (From Introduction to Session)

Economic evaluation of interchanges, as such, is not a standard problem inasmuch as the interchange is part of a larger freeway project and the project is generally evaluated as a whole. Thus, project economic analysis, for which there are a number of theories and methods (benefit-cost analyses, annual cost methods, rate-of-return methods, interest charges, depreciation, and so on), is not of interest here.

The problem of largest scope in this discussion is the evaluation of alternative configurations, involving road user benefits and road user cost, within the interchange itself. A problem of small scale is the level of investment in the individual components (higher design standards usually cost more) and is the primary subject of interest.

There are relatively few data available that clearly relate operational and safety benefits to costs of the various design features. Accident data are not sufficiently sensitive to the effects of variations in geometrics to be used as evaluative measures, except in a few cases where only gross geometrics are of interest and the data are corrected for exposure.

It appears from interviews with design engineers in a number of state highway departments that very little trade-off analysis is involved in the design process; rarely does the design engineer make a specific decision on whether to increase the design speed of a specific ramp at a cost of X dollars. In a number of states, considerable interest was expressed in defining the relationships between geometric features and operational efficiency and safety; interest in the relationship with cost was not so pronounced.

On the other hand, a number of decisions involving trade-offs between costs and operational efficiency and safety have been and are being made somehow. These range from the decision not to use diamond configurations for major interchanges through the elimination of loop ramps for turning movements with large volumes to requirements for 50-mph turning roadways for 70-mph through roadways.

Generally, the higher design standards cost more, yet we keep upgrading the standards. (This assumes some sort of cost analysis, but it is not obvious how these decisions are made.)

Many of the less-than-optimal designs and features found on old interchanges resulted from compromises for cost reductions. Today, on the other hand, cost factors seem to be a lesser constraint in the selection and evaluation of alternative component configurations and in the development of design details either because the designers now see a stronger relationship between their design details and the resultant operation and safety or because they are willing to spend more than previously to obtain these desirable ends.

Interviews with engineers from the various state highway departments, conducted within this project, indicate that feedback from operations analysts is usually poor and frequently nonexistent, except for those interchanges that are almost hopelessly inadequate for their opening.

In addition, some highway engineers observe that in recent years final designs are based less on a combination of optimal features than on the necessity to choose among the least objectionable constraints. They are particularly troubled by the fact that local sociopolitical groups, who possess meager information about or experience with roadway design, can force changes (e.g., provision of local access within a major interchange) that seriously impair operations and safety.

Workshop Questionnaire

After the preceding introductory remarks, a set of discussion questions was posed to the workshop participants. These were followed by a period of open discussion and distribution of a questionnaire. The participants were asked to complete and return the questionnaire the next day, thereby giving them an opportunity to discuss the subject further among themselves and to consolidate their thinking. In general, the questions were nearly the same as those presented for discussion. The questions, with answers received, are given in the Appendix.

As can be seen, interest in and necessity for economic analyses decrease somewhat as the design decision becomes more and more specific. This is logical in that the alternative costs become relatively smaller and the overall project constraints are rather well set by the time the design details are selected. A number of respondents indicated that more economic analyses would be desirable but that appropriate methodology was not available. However, there is no clear mandate for the development of this methodology.

Also, some of the answers indicate that "engineering judgment" is the most used decision-making procedure on including "desirable features." It is perhaps surprising, and certainly encouraging, that only about a third of the respondents indicated that their organization had adopted the policy of simply meeting certain minimums.

It is apparent from some responses that experience is the prime input to the design decision process, although considerable attention is being paid to accident record analyses and pertinent research results.

LEVEL-OF-MERIT CONCEPT

As mentioned, cost and some measure of operations and safety are two major trade-off factors receiving consideration in the selection of alternative component configurations (such as left versus right ramps or single versus double exits) and in the specification of design dimensions (design speed for a given ramp, length of acceleration lane in a given situation, etc.). In development of a final interchange design, a number of these trade-off decisions are made, although, perhaps, not consciously.

Design engineers are asked, Is it more desirable, from an operations and safety viewpoint, to provide a single exit (with subsequent branching for left and right movements) or two individual exits? The answer is almost unanimously, Single. However, when then asked which configuration should be established as a design standard to be rigidly adhered to, the answer becomes somewhat less definite, and "hedging" will be noted. Obviously, the hedging comes about because designers feel there are situations in which the single exit should not be selected, and this is often because, in that situation, the double exit could be achieved at considerably less cost.

The same types of questions and answers can be applied to other design features, such as right versus left ramp or length of acceleration lane. In other words, there are known desirable features, but something less is often used because of some cost factor. Designers claim it is impossible to give a set answer to any of these types of questions, which will hold across all situations. A major reason for this is that they are trying to assess cost and merit measures at the same time and, as the combinations are nearly infinite, so are the "correct answers."

It appears, then, that, because no definite universal answers can be had when the two factors are considered together, it would be helpful to decision-makers if they could assess the two factors (cost and operations and safety merit) individually with some degree of certainty and then make their decision on the basis of relative costs and relative merits.

Assessing relative costs will usually be possible although sometimes with considerable difficulty if the alternatives are such that a major portion of the interchange design is involved (such as a decision on a right or left exit). In the case of designating the length of an acceleration lane, the cost analysis may be very simple (if only a little change in earthwork quantities and pavement length is required) or somewhat difficult if the longer lane will also interfere with downstream features, require a larger grade separation structure, etc.

The problem, then, will be to assess the relative level of merit provided by the alternative configurations, or the alternative design dimensions, and then to choose among the alternative levels of performance and the corresponding costs.

Assuming, for the moment, that the specification of alternative merits is possible, the designer is then in a much better position to select the final design. This will still be a highly subjective process, depending largely on the designer's engineering experience and judgment; a benefit-cost analysis is not being suggested.

An example will illustrate the concept. Assume the conditions given in the following:

Configuration	Merit Rating	Additional Cost (dollars)
Single exit (on right)	10	3,000,000
Double exit (both right)	8	2,000,000
Double exit (right and left)	3	0

If the total interchange cost (with double exit, right and left) is estimated at $40,000,000, which configuration should be selected? If the total interchange cost (with double exit, right and left) is estimated at $7,000,000, which configuration should be selected? Now assume the ratings are changed to 10, 8, 6; which configuration should be selected?

The fact that different configurations might be chosen under these differing conditions points up the problem of setting definitive configuration selection criteria. Even in this simple example (in practice, other considerations, such as maintenance costs, road user costs, and the like, would also enter the decision-making process), it is not possible to select a single, "always correct" answer.

The merit ratings give some insight to the question, How much better? It is agreed that a single exit is better than one incorporating right and left exits, and therefore using a design incorporating a single exit justifies a higher cost, but how much higher? First, one must determine how much "better" one configuration is than another. The merit ratings, if available, could provide some feel for these qualitative comparisons.

Each time a decision has been made in the past, the designer did go through some similar assessment of the relative merits and costs. The merit ratings, if they can be developed in a credible and acceptable manner, will provide some basis for a rational choice. They would provide a means by which the decisions could be made more consistently by each designer, and more consistent designs could be obtained from various designers.

As another example, assume that a speed change lane (acceleration) from a turning roadway with a design speed of 40 mph to a through roadway with a design speed of 70 mph must be designed. The "Blue Book" suggests that this acceleration lane be 1,000 ft long. Suppose, due to situational considerations, a speed change lane 800 ft long would be $500,000 less expensive than one 1,000 ft long; which should be selected?

Obviously, a judgment on the importance of that missing 200 ft is required. This assessment is usually made on the judgment of the design engineer. Suppose, however, that credible merit ratings are available: 8 for 1,000 ft and 7.5 for 800 ft. Would this affect the decision in a different manner than if the two ratings were 8 and 4? Would not this degree of specificity help the designer in making this decision?

The next question, obviously, then, is, Can the merit ratings be developed in a manner such that they will be respected and accepted by the design community? It is proposed that the approach to the development of these ratings include a combination of physical analyses, experimental research, and the operational experience of design engineers and operations specialists.

Workshop participants were asked to rate various exit-ramp configurations (Fig. 1) to illustrate the feasibility, and problems, of deriving consensus expert judgmental evaluations. The procedure was as follows. A value of 10 was to be given to the most desirable alternative, and then the other alternatives were to be rated against that one on the basis of operations and safety. (Totally unacceptable designs were rated 0.) Costs were to be considered later and were not to be a factor here. For the configurations shown in Figure 1, the participants were to assume a single-lane turning roadway on four-lane freeways with a DHV for each turning movement of 1,000 vph. The participants were also to rate alternative lengths for an acceleration lane of a major interchange. Turning roadway design speed was 40 mph, through roadway was 70 mph. (Blue Book value is 1,000 ft.) DHV was 1,000 vph. A tabulation of the ratings is given in Table 1.

When the results were tabulated, the participants were categorized into three groups: design engineers, traffic operations specialists, and academic and research. This allowed us to note any differences of opinion among these three areas of expertise.

It is interesting to note that all three groups selected configuration E as the best and considered the left exit designs the least desirable. The traffic operations specialists gave slightly lower ratings to the loop ramp configuration (C) than did the design engineers. Although the sample is small, the results tend to indicate that those who work with the "product" on a day-to-day basis feel that even more effort (and money) should be expended to eliminate second-choice design features.

In general, the academic and research group was not so critical of the left exit designs as the other groups. A possible interpretation is that the academic and research group bases its opinions primarily on conceptual principles and that, in fact, actual operations and safety at left exit ramps are even poorer than might be anticipated.

The results of the ratings of the alternative lengths of acceleration lanes are given in Table 2. Again, it can be noted that the three groups are essentially in agreement, and the design engineers are slightly less critical of substandard design.

It is also interesting to note that the Blue Book has a median rating of 9, which indicates that the participants believe this value to be adequate. A slightly higher value is reported for 1,200 ft, but then it tends to drop off again as the length is extended further. From comments, it would seem this dropping off is due to concern for the excessively long merging area that might result or the possibility that drivers might temporarily believe the lane was not going to be dropped.

The use of group medians in Tables 1 and 2 masks the rather wide range of individual ratings, as the "outliers" are lost in this process. As examples, the ratings for configuration A in Figure 1 ranged from 0 to 7, configuration D from 3 to 10, and configuration E from 7 to 10. These large discrepancies may indicate an interpretation problem on the part of some of the respondents or differences in past experiences with the various designers. Hence, the use of the Delphi method (1) or some similar technique for arriving at consensus opinion is suggested for future studies of this type.

Further Introductory Remarks

Before beginning the open discussion, it was further pointed out that, if these merit ratings can be set for alternative configuration choices and for design dimensions, the possibility for specifying different levels of merit for entire interchanges exists. For example, for a major interchange, the designer could specify that all configurations and design dimensions have merit ratings of 9 or better, whereas for a less important interchange configuration and dimensions with ratings of 7 might be acceptable.

Hence, these merit ratings could be used to select individual design features through comparison of relative merits and relative costs or as a means to ensure design features consistent with the importance of the interchange and, if desirable, consistent within a given interchange.

This last statement leads to another question: Is it ever desirable to purposely degrade a design feature so that the level of design will appear to be consistent to the driver? In other words, is it better if the driver encounters marginal quality throughout the interchange than if he observes high quality in all places in the interchange except at one critical site? Will he be deceived into thinking he is on a better grade facility than he is?

Figure 1. Exit-ramp configurations.

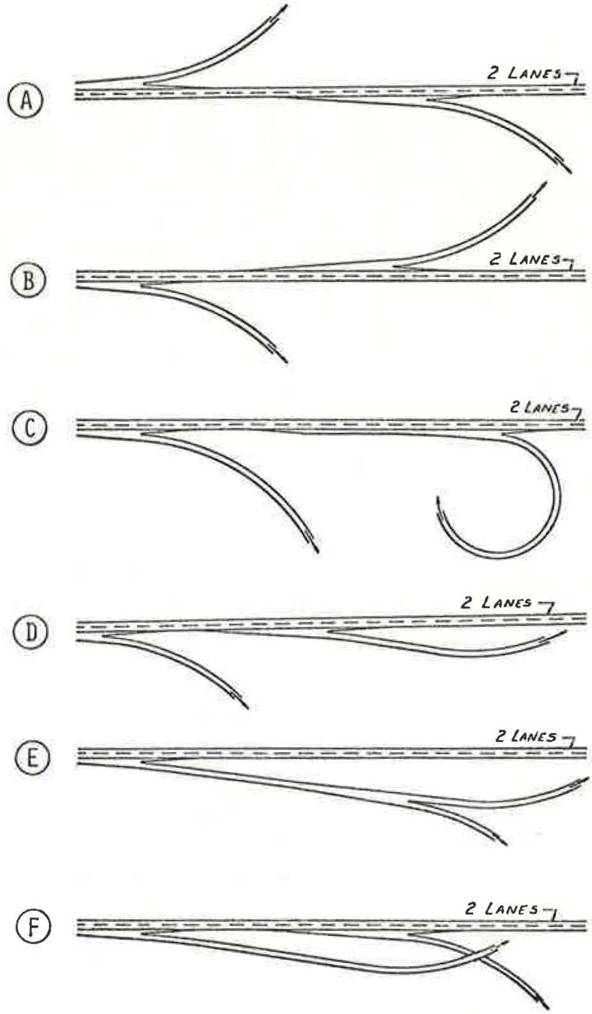

Table 1. Median ratings for exit-ramp configurations.

	Response Group			
Figure	Design Engineers	Traffic Operations Specialists	Academic and Research	All Groups
A	1	1	3	1
B	2	2	3	2
C	6	4	4	5
D	8	8	6	8
E	10	10	10	10
F	6	6	6	6
Number responding	18	6	7	31

Table 2. Median ratings for acceleration lane lengths.

	Response Group			
Length (ft)	Design Engineers	Traffic Operations Specialists	Academic and Research	All Groups
1,400	10	9	9	10
1,200	10	10	10	10
1,000	9	9	8	9
800	7	6	4	6
600	3	1	0	1
400	0	0	0	0
200	0	0	0	0
0	0	0	0	0
Number responding	18	6	7	31

Questionnaire Results

In addition to the illustrative rating questionnaire handed out during the introductory remarks, a session questionnaire was given to the participants at the end of the discussion, and they were asked to complete it and return it the following day. As in the case of the questionnaire on trade-off analyses, the questions generally paralleled those used to structure the discussion. The questions, with tabulations of the answers, are given in the Appendix.

The answers indicate that somewhat more than half of the participants believe it is possible to derive meaningful merit ratings. The design engineer group was about evenly split, whereas the other two groups were considerably more optimistic.

Assuming that merit ratings should be developed, almost everyone felt that all possible inputs should be used in developing these ratings. A number of the participants indicated that they were "not comfortable" making the ratings, but they provided little information on what would have been helpful. (Signing and lighting conditions were mentioned as other possible information inputs.)

The participants generally felt the level-of-merit design worthy of more investigation and trial but were not optimistic about obtaining a practical design tool.

No clear-cut conclusion can be drawn from the answers to the last question. This is perhaps due to the wording of the question; the comments accompanying the answers indicated that the participants were interpreting this question in a variety of ways.

CONCLUSIONS

Major conclusions in the areas of trade-off analyses and the level-of-design concept as applied to major interchange design and operation and traffic control, based on the literature survey, interviews with individual state highway departments, and the workshop discussions and questionnaires, are as follows:

1. The major interchange design process is very "soft," i.e., it is not possible to formulate a definitive flow chart because a number of considerations impinge on one another and all the data must be in before hard decisions can be made.

2. This state of flux in the design process means that trade-off analyses cannot be pulled out as individual decision-making processes but are interwoven with the total design process. This implies that specific definitive procedures will not be used by the design engineers (at least under the present design methodologies) and that aids or guidelines are more reasonable than rules or computation forms.

3. There is relatively little interest in and feeling of necessity for economic analyses in the process of selecting design details (e.g., the length of acceleration lanes, alternative design speeds for turning roadways, etc.). The author attributes this to the feeling among practicing engineers that there are so many factors to be considered in these decisions, in addition to the constraints they have already built in by selecting an overall general configuration, that economic analysis is just not practical or reasonable. However, it should be noted that at least one state indicated a strong interest in assistance in making these types of decisions.

4. Engineering judgment is the most used decision-making procedure in making trade-off analyses between desirable features and costs. There is an awareness that operational and safety characteristics of alternative configurations differ appreciably and that some cost is justified in providing the better features. The problem of how much should be expended is not solved, however. It appears that very few states follow a design policy of simply meeting certain minimums as published in design manuals.

5. Interest but not enthusiasm was expressed in the level-of-merit design concept; the majority of those questioned indicated that they felt the concept deserving of more investigation, but there were reservations regarding the practicality of the end results. At this time it is not clear whether they feel that it is not even practical to develop guidelines and aids for assessing the relative operational and safety merits of alternative interchange configurations or that it is simply not practical to set up computation procedures to select the most cost-effective alternative.

ACKNOWLEDGMENT

This project was sponsored by the Federal Highway Administration, U.S. Department of Transportation, with the Pennsylvania State University as the contracting agency. The Institute for Research, State College, Pennsylvania, and Gannett, Fleming, Corddry and Carpenter, Inc., Camp Hill, Pennsylvania, assisted in the study entitled Major Interchange Design, Operation, and Traffic Control.

REFERENCE

1. Dalkey and Helmer. An Experimental Application of the Delphi Method to the Use of Experts. Management Science, Vol. 9, 1963.

APPENDIX

Given are the results from two questionnaires, the first on trade-off analysis and the second on level-of-merit design concept. The numbers on the right are the number of participants who selected a given answer.

TRADE-OFF ANALYSIS QUESTIONNAIRE

1. Economic analyses (cost-benefit ratios, rate-of-return methods, etc.) as applied to major interchange design. Please circle the statement you feel most appropriate:
   a. Economic analyses in comparing alternative interchange configurations as a whole
      i. Common practice 5
      ii. Desirable and feasible but not usually carried out 5
      iii. Desirable but not feasible; appropriate methodology not available 3
      iv. Of little practical value; other considerations are determining factors 11
      v. Other 6
   b. Economic analyses in selection of alternative components (loop ramp versus direct connection, collector-distributor roadway versus double exit, etc.)
      i. Common practice 5
      ii. Desirable and feasible but not usually carried out 6
      iii. Desirable but not feasible; appropriate methodology not available 2
      iv. Of little practical value; other considerations are determining factors 12
      v. Other 5
   c. Economic analyses in specification of design dimensions (length of acceleration lane, radius of curvature of loop ramp, etc.)
      i. Common practice 2
      ii. Desirable and feasible but not usually carried out 5
      iii. Desirable but not feasible; appropriate methodology not available 4
      iv. Of little practical value; other considerations are determining factors 17
      v. Other 2
2. How do you reach decisions on "desirable features," such as exclusion of left-hand exits, good visibility of the exit area, uniformity of exiting maneuvers, etc.? (Circle one.)
   a. Decision to meet AASHO Blue Book minimums at all costs 7
   b. Decision not to incorporate (or exclude) certain features at all costs 2
   c. Attempt benefit-cost (or similar) analysis for individual situations 5
   d. Engineering judgment, i.e., no formal analysis of cost factors as such 15
   e. Other 1

3. Can meaningful cost data be obtained for individual components (ramp configurations, length of deceleration lane, etc.)?
   a. Yes; Comment 19
   b. No; Comment 9
4. How do you assess "benefits" to justify extra expenditures for improving on "minimum" design standards? (Circle any appropriate answers.)
   a. Accident record analyses of similar situations 15
   b. Experience in observing similar situations and relating this to extra costs involved 19
   c. Study of research results in these areas 12
   d. Consensus of personnel in your design department 12
   e. Usually use minimum values 0
   f. Other 7

LEVEL-OF-MERIT DESIGN CONCEPT QUESTIONNAIRE

1. Do you feel it is possible to derive meaningful ratings for alternative general configurations (as in the example of the various exit ramp configurations)?
   a. Yes; Comment 18
   b. No; Comment 12
2. Do you feel it is possible to derive meaningful ratings for alternative design dimensions (as in the example of the acceleration lane lengths)?
   a. Yes; Comment 19
   b. No; Comment 11
3. How should the merit ratings be developed, utilizing which inputs? (Circle all you feel apply.)
   a. Physical analyses (acceleration potentials, friction factors, reaction times, etc.) 20
   b. Accident data across alternatives 20
   c. Research studies on driver behavior and preferences 21
   d. Judgment of highway designers and operations specialists 17
   e. Others 8
4. Were you "comfortable" making the ratings requested in the earlier examples?
   a. Yes; Comment 17
   b. No. If no, what additional information would have been helpful? 12
5. Do you feel the concept of using level-of-merit ratings in interchange design is
   a. Feasible? Yes; No; Comment Yes - 14 No - 6
   b. Practical? Yes; No; Comment Yes - 5 No - 11
   c. Deserving of more investigation, better definition, more trial, etc.? Yes; No; Comment Yes - 17 No - 4
6. Is consistency in interchange "quality" important? Should some elements purposely be degraded to make them compatible with the lower standard design-controlling elements?
   a. Yes, usually. Comment 5
   b. Yes, sometimes. Comment 9
   c. No. Comment 13