COST-EFFECTIVENESS TECHNIQUE FOR ANALYSIS OF ALTERNATIVE INTERCHANGE DESIGN CONFIGURATIONS

Joseph A. Wattleworth, Department of Civil Engineering, University of Florida; and Jerry W. Ingram, Florida Department of Transportation

•AT THE present time highway designers generally have inadequate means for selecting the most cost-effective configuration for a given set of traffic volumes. Frequently the designer simply seeks out a configuration that meets the requirements and selects that one. There is a need for a procedure that can be quickly used by a designer to compose alternative interchange design (or redesign) configurations and that considers the cost of each configuration as well as the effectiveness of the interchange. In addition, it would be highly desirable if the procedure would allow the designer to use the results of the analysis of one configuration to lead him to the next logical configuration, thereby giving him the capability of a sequential design process.

This report develops a cost-effectiveness methodology for the analysis and comparison of alternative interchange configurations. The methodology is presented in the framework of a case study of the interchange of Fla-436 and I-4 north of Orlando, Florida.

CHARACTERISTICS OF THE INTERCHANGE

At present this is a conventional diamond interchange. Interstate 4 is a 4-lane divided freeway, and Fla-436 is also a 4-lane divided arterial street in a semirural area. All interchange ramps are 1-lane, and an inadequate signal system is in operation. The interchange is currently overloaded during the morning and afternoon peak periods, and a high traffic growth rate (approximately 8 percent yearly) is expected. One major variable in the traffic projections is the possible construction of the proposed Beltline Expressway that will essentially parallel Fla-436. Therefore, traffic projections were made under 2 assumptions: that the Beltline Expressway was built and that it was not built. The inability to predict a single set of future design volumes was one of the factors that led to the development of the cost-effectiveness methodology.

STUDY PROCEDURE

The basic procedure that was utilized in this study is a general systems approach. Described briefly, the initial step is to define the objectives of the study and to analyze the alternative systems that might satisfy those objectives. The general objective of this particular analysis is to select the geometric design-operations alternative for the interchange of I-4 and Fla-436 that will provide the required traffic capacity at minimum cost. All alternative solutions, referred to as candidate systems, are compared to determine which alternative will best meet the existing traffic demands and also sustain future demands and which will do so at a minimum cost. Comparison of alternatives was done on the basis of a cost-effectiveness analysis, where effectiveness was defined in terms of the total interchange capacity (expressed as equivalent ADT entering the interchange). The most important characteristic of a systems approach is that it in-

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volves the consideration of all alternatives and their analyses and comparison to determine the most effective or optimal candidate system.

Model to Determine Effectiveness of Each Candidate System

Each geometric configuration alternative was evaluated in terms of the total peak-hour capacity, that is, vehicles/hour. There are 2 reasons for using peak-hour analysis rather than 24-hour capacity analysis:

1. Peak-hour capacity must be adequate in order for the interchange to operate efficiently during these periods; and
2. The afternoon peak-period traffic pattern is generally substantially different from the morning peak pattern.

A linear programming model, which had been developed earlier (1), was used to establish the peak-hour capacity of each alternative. Basically, this model solves for the peak-hour interchange capacity of any configuration subject to 2 types of constraints:

1. The volume using any interchange element does not exceed the capacity of the element; and
2. The traffic entering the interchange is properly distributed among all of the possible movements.

The capacity is the maximum peak-hour volume that can enter the interchange.

Utility of Interchange Analysis Model

The model determines the maximum peak-hour (entering) volume a particular interchange configuration can accommodate before congestion develops at a critical location within the interchange. The model also identifies the critical element that limits the total interchange capacity. With this model, the highway engineer can then select a new design configuration that provides an increased capacity for the critical element; and, thus, the new configuration will have a greater capacity. The model, then, can be used to determine the appropriate sequence of geometric improvements and the capacity of each alternative interchange configuration. Thus, the designers who use this model can determine a set of geometric improvements that will increase the capacity of an interchange and the order or relative priority that should be given to each improvement.

The steps involved in the use of the model for the analysis of an interchange are as follows:

1. Identify all reasonable types of interchange configurations, such as diamond, cloverleaf, partial cloverleaf, and directional, that are to be considered as possible solutions (this step is a function of the designer's general knowledge of the interchange area);
2. Set up the interchange analysis model for a first trial interchange configuration of one of these types (this may be the existing interchange configuration);
3. Solve the model to determine the total capacity of that interchange configuration and the critical interchange elements that limit the total capacity, e.g., those elements on which the volume equals the element's capacity;
4. Revise the design configuration of the interchange to provide increased capacity for the elements that are found to be critical.
5. Repeat the steps of modeling a new interchange configuration, solving the model to determine the critical elements, revising the design configuration, modeling the new configuration, and so on until an interchange configuration of adequate capacity is found or until no further improvements are feasible; and
6. Repeat steps 2 through 5 for each appropriate type of interchange configuration.

This step-by-step analysis ensures that for a given type of interchange each configuration considered has a higher capacity than the configuration previously considered. It also ensures that, at each step, the capacity of the critical interchange element is increased, and it allows the designer to focus his attention on the critical elements.

CANDIDATE SYSTEMS

Five alternate interchange configurations or candidate systems were analyzed to determine the maximum capacity of each during both the morning and afternoon peak hours; many of the systems had several variations included in the analyses.

The following section describes the candidate systems and discusses the geometric improvements in proceeding from one candidate system to another. The final variation of candidate systems II, III, IV, and V involves the modeling of Interstate 4 as a 6-lane freeway (at present, it has 4 lanes). This occurs at the step after the capacity of one or both of the 2-lane directional sections of I-4 becomes the critical interchange element.

The analysis of one configuration of one particular candidate system provides a capacity value for the configuration and identifies the interchange element that limits the capacity of the interchange. This, then, allows the designer to select the next configuration that provides a higher capacity for the critical element, and, hence, each configuration has a higher capacity than the preceding one.

CASE STUDY: I-4 AND FLA-436 INTERCHANGE

This section presents the case study that was conducted on the interchange of I-4 and Fla-436 north of Orlando, Florida. Six general candidate systems were considered, and the analysis included 17 specific candidate systems. Within each type of candidate system, the analysis of one candidate system led to the selection of the next until all feasible improvements had been made.

Capacity Analyses

For each of the 17 systems, a morning peak-hour capacity (total volume entering the interchange) and an afternoon peak-hour capacity analysis was conducted. It was assumed that the volume during each peak hour was 10 percent of the total volume entering the interchange. Thus, it was possible to determine an equivalent ADT by simply multiplying the lower of the 2 peak-hour capacities by 10. The equivalent ADT, which is also in terms of vehicles entering the interchange, was used as the measure of effectiveness of each interchange configuration (candidate system). The equivalent ADT, then, is the total daily traffic that can enter the interchange without causing any of the capacities in the interchange to be exceeded in either of the peak periods. Figure 1 shows the geometric configurations, and Table 1 gives a description of each system and the results of the capacity analysis for each.

Candidate System I—Candidate system I represents a slight improvement over the existing configuration and operation of the interchange of I-4 and Fla-436. In candidate system I, new signalization is considered so that the 2 closely spaced signals at the ramp terminals can be coordinated. This will also permit the use of the 4-phase, 2-overlap signalization that has been found to be highly efficient for diamond interchange signalization (2). In candidate system I, no reconstruction of interchange elements is considered.

Under this type of operation, the capacity during the morning peak hour is 5,991 vph, and the critical capacity element is the entrance ramp in the southwest quadrant. That is, for the given volume distribution in the morning peak period, the volume using the entrance ramp in the southwest quadrant exactly equaled its capacity, while the volume on each of the other geometric elements was less than its capacity. In the afternoon peak period the capacity was found to be 5,418 vph, and the critical capacity element was the exit ramp in the southeast quadrant. Because the afternoon capacity is lower than the morning capacity, the equivalent ADT is 54,180 vehicles, and the geometric element that restricts this value is the exit ramp in the southeast quadrant.

Candidate System II—Several relatively minor modifications of the existing geometric design configuration were considered. In each of the 4 variations of candidate system II, the improved signalization of candidate system I is assumed to be installed and in operation.

In the morning peak period, the east-to-south left-turn movement is very heavy and merges with the heavy west-to-south right-turn movement on the southbound entrance

Figure 1. Geometric configurations of candidate systems.

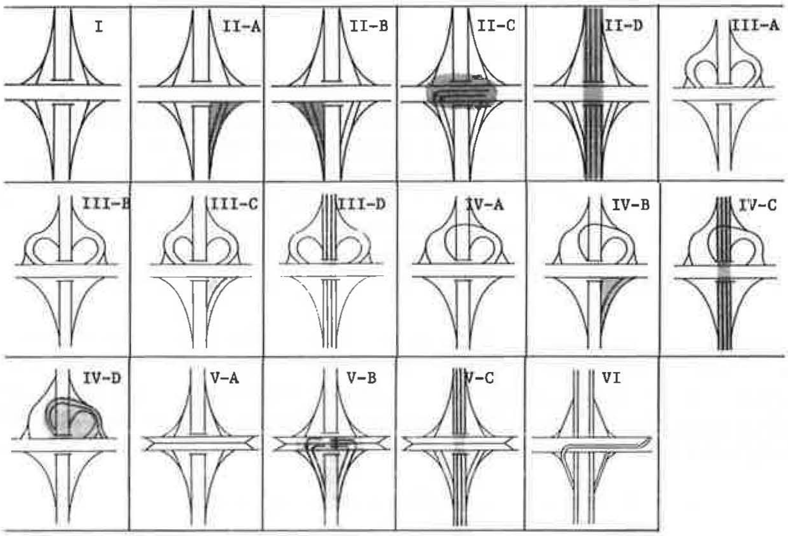

Table 1. Description of candidate systems and summary of traffic analyses.

System	Description	a.m. Peak-Hour Capacity	a.m. Critical Element	p.m. Peak-Hour Capacity	p.m. Critical Element	Equivalent ADT (entering)
I	New signalization to develop 4 phase-2 phase overlap	5,991	Entrance ramp in S.W. quadrant overloaded	5,418	Exit ramp in S.E. quadrant overloaded	54,180
II-A	Signalization plus 2-lane exit ramp and double left turn for S.W. movement	5,991	Entrance ramp in S.W. quadrant overloaded	8,233	Signalization overloaded	59,980
II-B	Same plus 2-lane entrance ramp in S.W. quadrant	6,686	Signalization overloaded	8,233	Signalization overloaded	66,860
II-C	Same plus additional approach lane east and double left for E.-S. movement	9,000	Southbound lanes of I-4 overloaded	9,417	Northbound lanes of I-4 overloaded	90,000
II-D	Same plus widening I-4 to 6 lanes	9,855	Signalization overloaded	10,438	Signalization overloaded	98,550
III-A	Partial cloverleaf design; all ramps 1 lane	6,376		8,506	Exit ramp in S.E. quadrant overloaded	63,760
III-B	Same with extra lane on east approach of Fla-436	9,000	Southbound lanes of I-4 overloaded	8,506	Exit ramp in S.E. quadrant overloaded	85,060
III-C	Same with 2-lane exit ramp in S.E. quadrant	9,000	Southbound lanes of I-4 overloaded	9,416	Northbound lanes of I-4 overloaded	90,000
III-D	Same with I-4 widened to 6 lanes	9,197	Signalization overloaded	10,611	Eastbound lanes of Fla-436 overloaded	91,970
IV-A	Flyover design; all lanes 1 lane	9,000		8,506		85,060
IV-B	Same with 2-lane exit ramp in S.E. quadrant	9,000	Southbound lanes of I-4 overloaded	9,416	Northbound lanes of I-4 overloaded	90,000
IV-C	Same with I-4 widened to 6 lanes	9,456	Flyover ramp overloaded	12,804	Northbound lanes of I-4 overloaded	94,560
IV-D	Same with 2-lane flyover ramp	13,500	Southbound lanes of I-4 overloaded	12,804	Northbound lanes of I-4 overloaded	128,040
V-A	3-level diamond interchange	5,991	Signalization overloaded	5,977	Exit ramp in S.E. quadrant overloaded	59,770
V-B	Same with 2-lane exit ramp in S.E., 2-lane entrance ramp in S.W.; double left turn for E.-S. movement	8,913	Southbound lanes of I-4 overloaded	9,417	Northbound lanes of I-4 overloaded	89,130
V-C	Same with I-4 widened to 6 lanes	11,783	Entrance ramp in S.W. quadrant overloaded	10,810	Eastbound lanes of Fla-436 overloaded	108,100
VI	Relocation of 2-lane flyover ramp; I-4 to 6 lanes; 2-lane ramps in southern quadrants	11,982	Entrance ramp in S.W. quadrant overloaded	9,890	Signalization overloaded	98,900

ramp in the southwest quadrant. The capacity of this 1-lane entrance ramp and the left-turn capacity of the east-to-south movement are both potentially critical. In the afternoon peak hour, the heavy south-to-west movement makes the capacities of both the 1-lane exit ramp in the southeast quadrant and the left-turn movement off this ramp potentially critical. The improvements considered under candidate system II are relatively minor geometric changes to increase the capacities of these critical elements.

Candidate System II-A—The previous analysis indicated that the capacity of the exit ramp in the southeast quadrant limited the equivalent ADT of candidate system I. Consequently, candidate system II-A is similar to candidate system I but has a 2-lane exit ramp in the southeast quadrant. Because of the heavy left-turn volume using this ramp, a double left turn is also provided for those left turns. The shaded area shown in Figure 1 indicates the area changed from the previous candidate system; Table 1 gives the results of those changes. No changes occurred in the morning peak-hour capacity, for no attempt was made to increase it. However, the capacity of the afternoon peak period increased to 8,233 vph. The morning peak-hour capacity is now lower and determines the equivalent ADT, which is 59,910 vehicles per day.

Candidate System II-B—The entrance ramp in the southwest quadrant was the geometric element that limited the equivalent ADT in candidate system II-A. Consequently, in candidate system II-B this ramp is widened to a 2-lane ramp. All of the previous improvements are retained in this candidate system. The capacity of the morning peak period was increased to 6,686, and that of the afternoon peak period was unchanged. The improvement raised the equivalent ADT to 66,860 vehicles.

Candidate System II-C—In both peak periods under candidate system II-B, the capacity was restricted by the capacity of the signal system. Consequently, the improvement incorporated into candidate system II-C is to add an approach lane on Fla-436 from the east and to provide a double left turn for the east-to-south movement. This changes the critical lane volumes in the signalization constraint and increases the capacities of both the morning and afternoon peak periods to 9,000 vph and 9,417 vph respectively. The equivalent ADT is 90,000 vpd, and the capacity of I-4 south of the interchange limits the capacity in both the morning and afternoon peak periods.

Candidate System II-D—In candidate system II-D, I-4 is widened to 6 lanes. This will increase both the peak-period capacities. The morning peak-hour capacity is 9,855 vph, and the afternoon peak-hour capacity is 10,438 vph; the equivalent ADT is 98,550 vehicles per day. At this point in the analysis, the capacity of both peak periods is limited by the capacity of the signalization. All reasonable improvements in this area have been made, and candidate system II has been fully exhausted.

Candidate Systems III, IV, V, and VI—Each of these systems represents a new general configuration (Fig. 1 and Table 1).

Candidate System Capacities and Future Volume Projections

The relative effectiveness of each candidate system can be seen by plotting the projected future volumes and superimposing on this figure the defined 24-hour capacity for each system. This is shown in Figure 2. The 20-year forecast with and without the Beltline Expressway enables the designer to determine which candidate system will be capable of accommodating the future demands. The year in which each candidate system will fail to efficiently accommodate the expected demand is given in Table 2.

Cost Analysis

The cost of each of the alternative configurations was estimated by using prevailing unit cost figures that were provided by the Florida Department of Transportation. Table 2 gives a summary of the cost analysis and also indicates which of the configurations have the disadvantages of requiring substantial additional right-of-way or requiring major reconstruction of the interchange.

Cost-Effectiveness Analysis

A cost-effectiveness analysis is, in general, conducted to ensure that in the selection of a preferred system the greatest return is obtained for the capital invested. Cost-

Figure 2. Traffic demand projections and relation to equivalent ADT capacities of candidate systems.

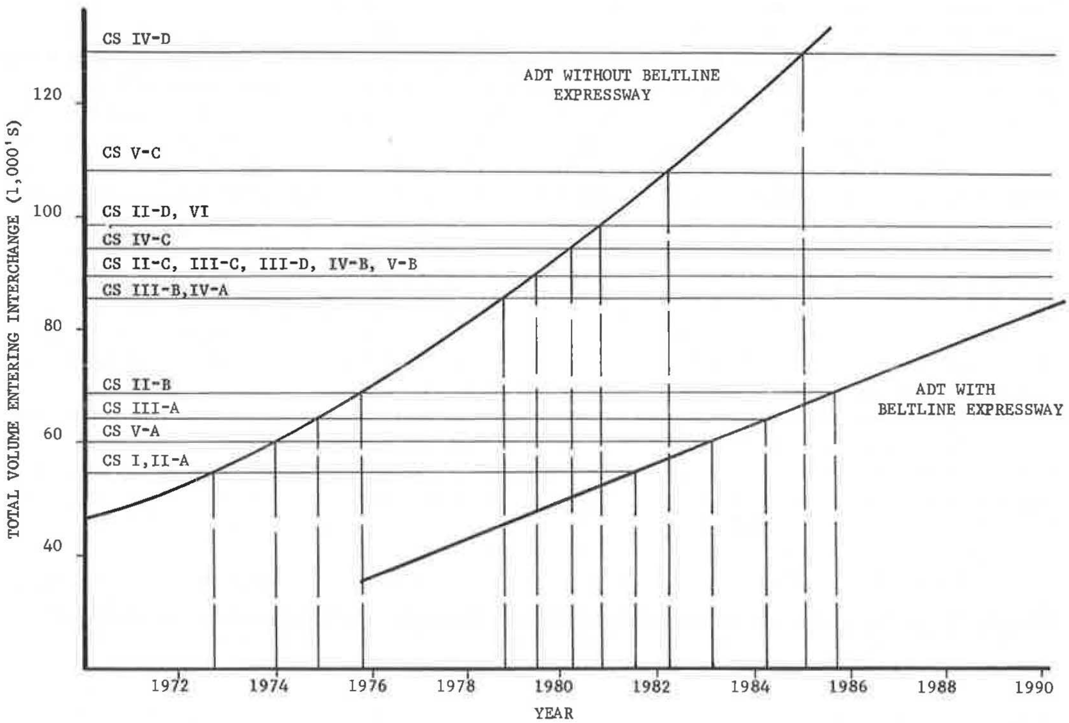

Table 2. Cost and capability of candidate systems.

Candidate System	Year Capacity Reached: With Beltline Expressway	Year Capacity Reached: Without Beltline Expressway	Right-of-Way Required	Major Construction Required	Cost ($)
I	1982	1973	No	No	10,000
II-A	1982	1973	No	No	16,111
II-B	1985	1976	No	No	21,444
II-C	1990+	1979	No	Yes	95,460
II-D	1990+	1981	No	Yes	201,904
III-A	1984	1975	Yes	Yes	2,676,762
III-B	1990	1979	Yes	Yes	2,678,778
III-C	1990+	1979	Yes	Yes	2,684,828
III-D	1990+	1979	Yes	Yes	2,791,272
IV-A	1990	1979	Yes	Yes	2,136,368
IV-B	1990+	1979	Yes	Yes	2,142,418
IV-C	1990+	1980	Yes	Yes	2,248,862
IV-D	1990+	1985	Yes	Yes	2,276,382
V-A	1983	1974	No	Yes	1,382,316
V-B	1990+	1979	No	Yes	1,465,646
V-C	1990+	1982	No	Yes	1,572,090
VI	1990+	1980	No	Yes	1,359,364

effectiveness analyses are conducted in many different ways depending on the purpose of the original analysis. If it has already been decided to undertake the mission that requires one of the candidate systems, the cost-effectiveness analysis frequently involves the selection of the system that meets the system requirements at a minimum cost. This is frequently the case in military applications, but generally in civil engineering applications the specific value of the requirement is not quite so clear. Consequently, the analyses become more complicated and often involve trade-off analyses of the incremental return for an incremental investment.

The measure of effectiveness that is used to evaluate the performance of an interchange is the equivalent ADT or total (entering) capacity of the interchange, and the cost is the initial cost of the improvement (it would also be possible to use annual costs). Figure 3 shows the cost and effectiveness plot of the candidate systems. The equivalent entering ADT's projected for 1991 for the interchange are 78,600 if the Beltline Expressway is constructed and 157,500 if it is not. This will result in a level of service E during peak period. In order to obtain level of service C during peak period, these capacity values should be raised to 100,000 and 200,000 ADT.

The effect of the future of the Beltline Expressway is quite significant. Because the construction of the Beltline Expressway is uncertain, decisions on the improvements to the I-4 and Fla-436 interchange essentially represent gambles on the outcome of the Beltline Expressway. This is a classic case of decision-making under uncertainty, which is the subject of many books in the field of management science.

Figure 3 shows many interesting insights into the decisions involved. First, none of the candidate systems considered will provide sufficient capacity in the event that the Beltline Expressway is not constructed. Candidate system IV-D yields the highest capacity, and the capacity of the 6 lanes of I-4 is reached. To increase the capacity above that of candidate system IV-D would involve the reconstruction of I-4 to 8 lanes. Thus, every consideration should be given to an alternate facility in this rapidly growing area.

If we consider any particular candidate system, it would never be advisable to select a system that costs more and yields a lower capacity than system IV-D. With this in mind, we can greatly narrow the number of candidate systems to be considered. If we start the examination with the least expensive system, we can progressively consider larger expenditures if we consider only systems that produce an increase in capacity for the additional investment. Thus, the only candidate systems that must be considered are systems I, II-A, II-B, II-C, II-D, VI, V-C, and IV-D. Only systems II-D, V-C, VI, and IV-D produce capacities approximately equal to those required to yield level of service C during peak periods (assuming that the Beltline Expressway is built).

The next section presents the recommendations that involve an incremental approach to staging the improvements.

Recommendations

The recommendations that are presented represent a phased approach and are divided into 4 categories: immediate improvements, near-term improvements, medium-term improvements, and long-term improvements (necessary only if the Beltline Expressway is not constructed). Under immediate improvements, relatively inexpensive traffic control improvements are considered; under near-term improvements, minor reconstruction improvements are considered; under medium-term improvement, major construction items that can be made with no acquisition of right-of-way are considered; and under long-term improvements, an item that requires extensive acquisition of right-of-way is considered. The early improvements are also integral parts of later candidate systems.

Each of the improvements should represent one of the cost-effective candidate systems and should be compatible with 1 of the 4 candidate systems that will provide adequate future capacity. The specific improvements that are included in each candidate system can be identified to determine the compatibility of the various systems (Table 3). Candidate system I includes new signal controllers, and each of the other candidate systems also includes this feature; therefore, candidate system I is compatible with an incremental approach to any of the other candidate systems.

Candidate systems II-A and II-B would appear to contain the next increments of improvement—the reconstruction of the 2 ramps in the south quadrants as 2-lane ramps.

Figure 3. Cost-effectiveness of candidate systems.

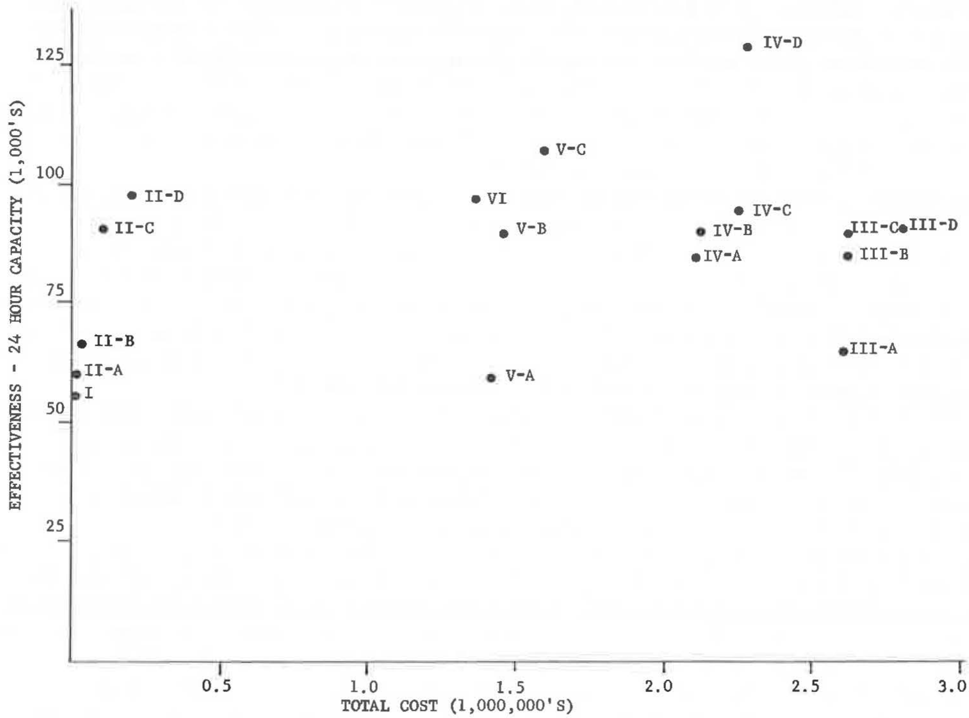

Table 3. Relation of cost-effective candidate systems and improvements.

	Candidate System							
Improvement	I	II-A	II-B	II-C	II-D	VI	V-C	IV-D
New signal control system	X	X	X	X	X	X	X	X
Two-lane exit ramp in southeast quadrant		X	X	X	X	X	X	X
Two-lane entrance ramp in southwest quadrant			X	X	X	X	X	X
Double left turn for east-to-south movement				X	X		X	
I-4 widened to 6 lanes					X	X	X	X
Two-lane flyover ramp for east-to-south movement						X		X
Third level for through movement on Fla-436							X	
Loop ramp in northeast quadrant								X

Each of these improvements is an integral part of all other candidate systems. However, Figure 3 shows that candidate sytem II-C has a substantially higher capacity than candidate system II-B and has only a slightly higher cost. Because of this and because all the improvements in candidate system II-C are relatively minor reconstruction items, this system is selected as the one for the near-term improvements even though the double left-turn addition is not required in 2 of the more advanced systems. The incremental cost of the double left-turn improvement is low. The turn provides a sizable capacity addition and will permit deferring some of the more expensive improvements for a longer time in the future.

The next logical system is candidate system II-D, which involves the widening of I-4 to 6 lanes in addition to the previous improvements. At this point the equivalent ADT is 98,500 vehicles, which is adequate if the Beltline Expressway is built. Thus, if the expressway is built, no further improvements are necessary. If the expressway is not built, further improvements can be considered and candidate systems VI, V-C, and IV-D are the only ones that produce higher capacities. The capacity of candidate system VI is only slightly higher than that of candidate system II-D and would not warrant the large additional expenditures. Therefore, candidate system VI is not cost-effective. If the expressway is not built, its highest possible interchange capacity will be needed; and this will ultimately call for candidate system IV-D. Candidate system V-C is not suitable for phasing into candidate system IV-D, so the decision would be made to go directly to candidate system IV-D.

The recommendations can be summarized as follows:

Improvement Period	Candidate System	Years Required: With Expressway	Years Required: Without Expressway
Immediate	I	Present-1982	Present-1973
Near term	II-C	1982-1990+	1973-1979
Medium term	II-D	Not needed	1979-1981
Long term	IV-D	Not needed	1981-1985

As a practical matter, candidate system IV-D would probably be built in 1979 if the expressway is not constructed and, thus, candidate system II-D would be bypassed.

CONCLUSIONS

The linear programming model of the interchange capacity and the cost-effectiveness analysis provides highway designers with a powerful tool to use in the selection of optimal interchange configurations and in the determination of a phasing program of future improvements. The designer can quickly consider many configurations, and the linear programming model, in fact, helps him determine the next logical configuration when the configuration under analysis has inadequate capacity.

ACKNOWLEDGMENT

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