TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA-RD-73-82	2. Government Accession No.	3. Recipient's Catalog No. PB 232 136

4. Title and Subtitle MAJOR INTERCHANGE DESIGN, OPERATION, AND TRAFFIC CONTROL Vol. 3. Appendixes H-M	5. Report Date July 1973
	6. Performing Organization Code
7. Author(s) J.I. Taylor, R.A. Olsen, J.C. Hayward, W.L. Raymond, Jr. and R.S. Hostetter	8. Performing Organization Report No. TTSC 7315
9. Performing Organization Name and Address Pennsylvania Transportation and Traffic Safety Center Research Bldg. B University Park, Pennsylvania 16802	10. Work Unit No. FCP 31P2-502
	11. Contract or Grant No. DOT-FH-11-7795
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration Washington, D.C. 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code T-0081

15. Supplementary Notes

FHWA contract manager: C. R. Stockfisch (HRS-33)

PRICES SUBJECT TO CHANGE

For table of contents of this report, see Vol. 1 (FHWA-RD-73-80).

16. Abstract

The objectives of this research project were to develop improved design procedures and guidelines for major (i.e., freeway-to-freeway) interchanges through the examination and analysis of existing design procedures and current freeway operational characteristics. Pertinent information was gathered through a review of the literature, conversations with and workshop participation by practicing design engineers and traffic operations specialists, and through written questionnaires.

The criteria and guidelines used in the design of major interchanges at both the overall configuration level and the individual component level (such as entrances, exits, lane drops, major forks) are reviewed; conclusions and recommendations for future practices are stated. Freeway traffic control systems are examined in the context of major interchange design and operation, and the implications of various systems are explained.

A methodology for interchange evaluation using decision theory and tradeoff analyses is presented, with example applications. Extensive case studies of a lane drop and exit ramps at a major interchange are described to illustrate the manner in which the recommended guidelines might be applied in practice. Two sample "Fact Sheets" illustrating the manner in which design experience information might be disseminated to the design community are included.

A bibliography of over 200 pertinent references accompanies the report. This report is in 3 volumes. The other volumes are:

FHWA-RD-73-80. Vol. 1. Text of Report
FHWA-RD-73-81. Vol. 2. Appendixes A-G

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U S Department of Commerce
Springfield VA 22151

17. Key Words Major Interchange, Freeways, Freeway Control, Highway Design, Freeway Operations, Design Policy, Design Procedures, Decision Theory	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22151.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-69)

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APPENDIX H

LANE DROP CASE STUDY

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FIGURES

TABLES

APPENDIX H: LANE DROP CASE STUDY

Introduction

Based on the results of the workshop questionnaires on lane drops and relevant state-of-the-art information, the following discussion provides an introductory framework for the cast study analysis.

Cases I-V

In the workshop questionnaire, the participants were requested to rank the alternative lane drop configurations in order of preference and assign a relative numerical measure of merit based on safety and operations to each alternative. In general, the results of the statistical analyses indicate that the experts' responses have a significant level of agreement. For Case I (see Figure H-1), the mainline lane drop is preferred, and is the alternative used most often in current practice.

For Case II, pictured in Figure H-2, Alternative A is also rated highest by the experts. Yet, in actual Case II design situations, Alternative B is used most often.

Although A is the preferred alternative in Case III (see Figure H-3), the preference for B is nearly equal to that for A. Additionally, the merit ratings of the two alternatives are nearly equal. Again, however, B shows a clear dominance in current usage.

In all three cases, the mainline lane drop is the preferred alternative. The right lane drop at the exit follows, with slightly smaller rank and merit values. Alternative C, the left lane drop at the right side exit terminal is the least preferred alternative. Its merit ratings for all three cases are of similar magnitude; approximatley one-third of the ratings for A and B. This pattern does not change regardless of the number of lanes for the mainline or exit roadways.

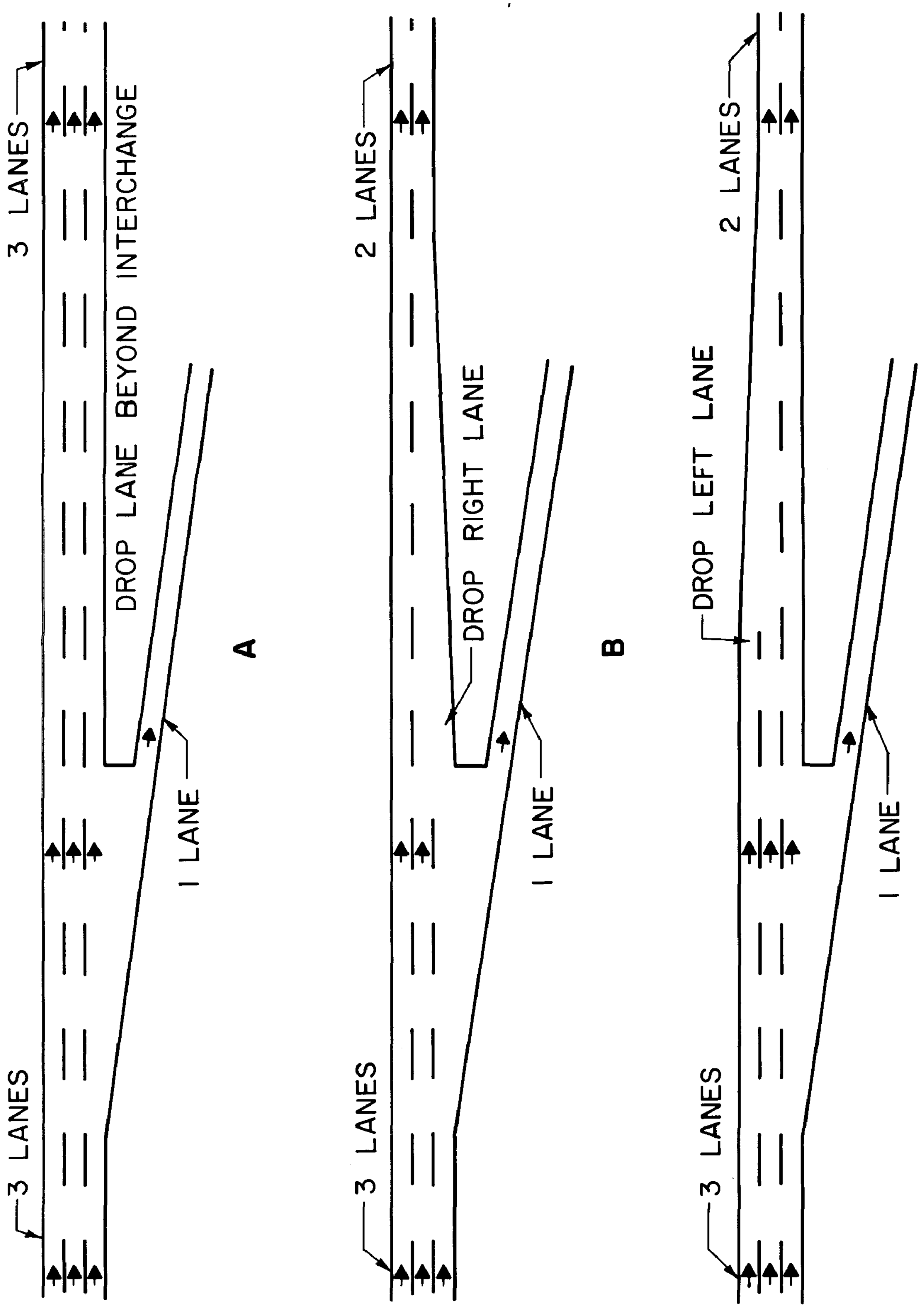

Figure H-1. One-Lane Exit, Reduction for Three Lanes to Two on Mainline

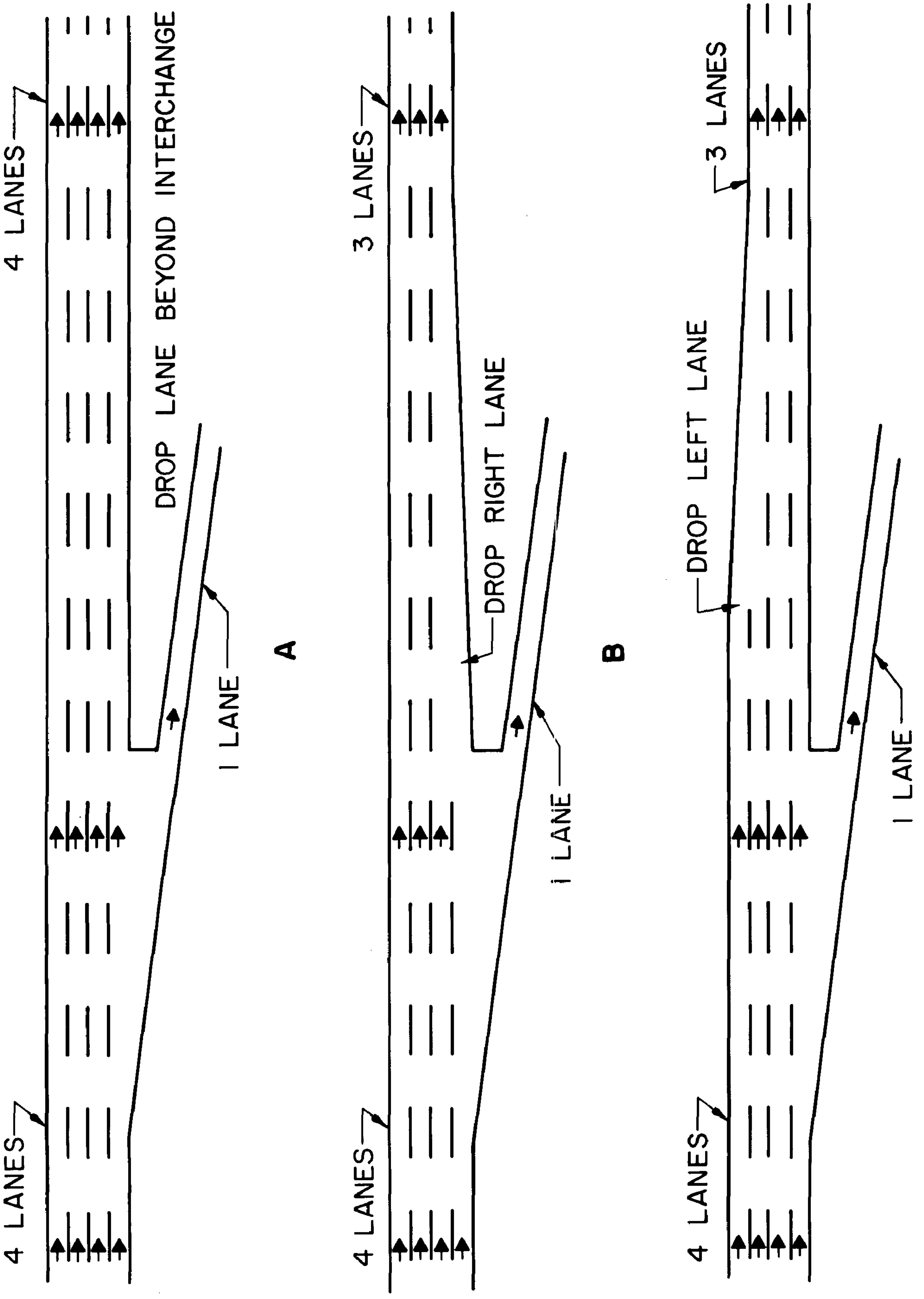

Figure H-2. One-Lane Exit, Reduction from Four Lanes to Three on Mainline

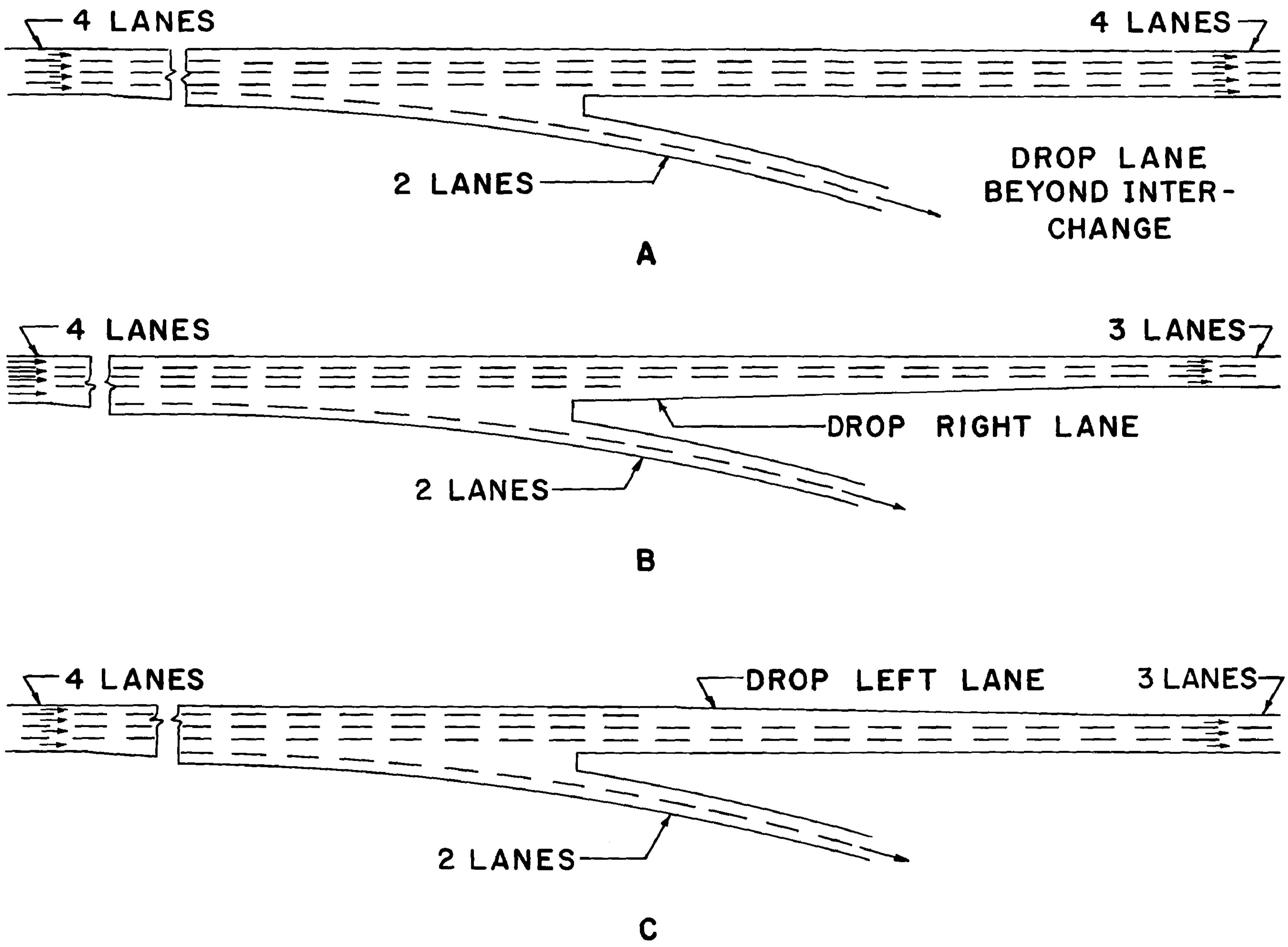

Figure H-3. Two-Lane Exit, Reduction from Four Lanes to Three on Mainline

The research literature also indicates a preference for the mainline lane drop. However, the basis of comparison in some of the studies may be seriously questioned. For example, the type and lengths of recovery areas and distances to adjacent conflict points are frequently not considered -- or at least their consideration is not reported. Because the conditions are variable, the possibility exists that invalid comparisons of lane drop operations and safety data are made in those studies.

The more recent state highway policy positions on lane drop location state that mainline lane drops are preferred, as represented by recent revisions to a number of design manuals Still, this preference is not stated in the majority of the state manuals reviewed; in fact, they rarely discuss lane drop design in detail. A few manuals present their standard designs for lane drops adjacent to exit terminals.

In Case IV, illustrated by Figure H-4, the experts unanimously selected the right lane as the lane which should be dropped for the mainline lane drop. Unfortunately, it is not clear whether the left mainline drop is preferred over the lane drop at the interchange. However, no respondent qualified his answer by denoting the right or left lane in selecting Alternative A in Cases I-III. Further, one engineer notes that his state design agency prefers the mainline lane drop regardless of side because of their experience with lane drops at the interchange. The AASHO "Yellow Book" also states that the left is less desirable than the right mainline drop, but either is preferable to the interchange lane drop. It is reasonable, then, to conclude that the left mainline drop is preferred over the interchange lane drop.

Although Case I involves a three-lane freeway, and Case IV a four-lane freeway, the results for Case IV are assumed to hold for Case I.

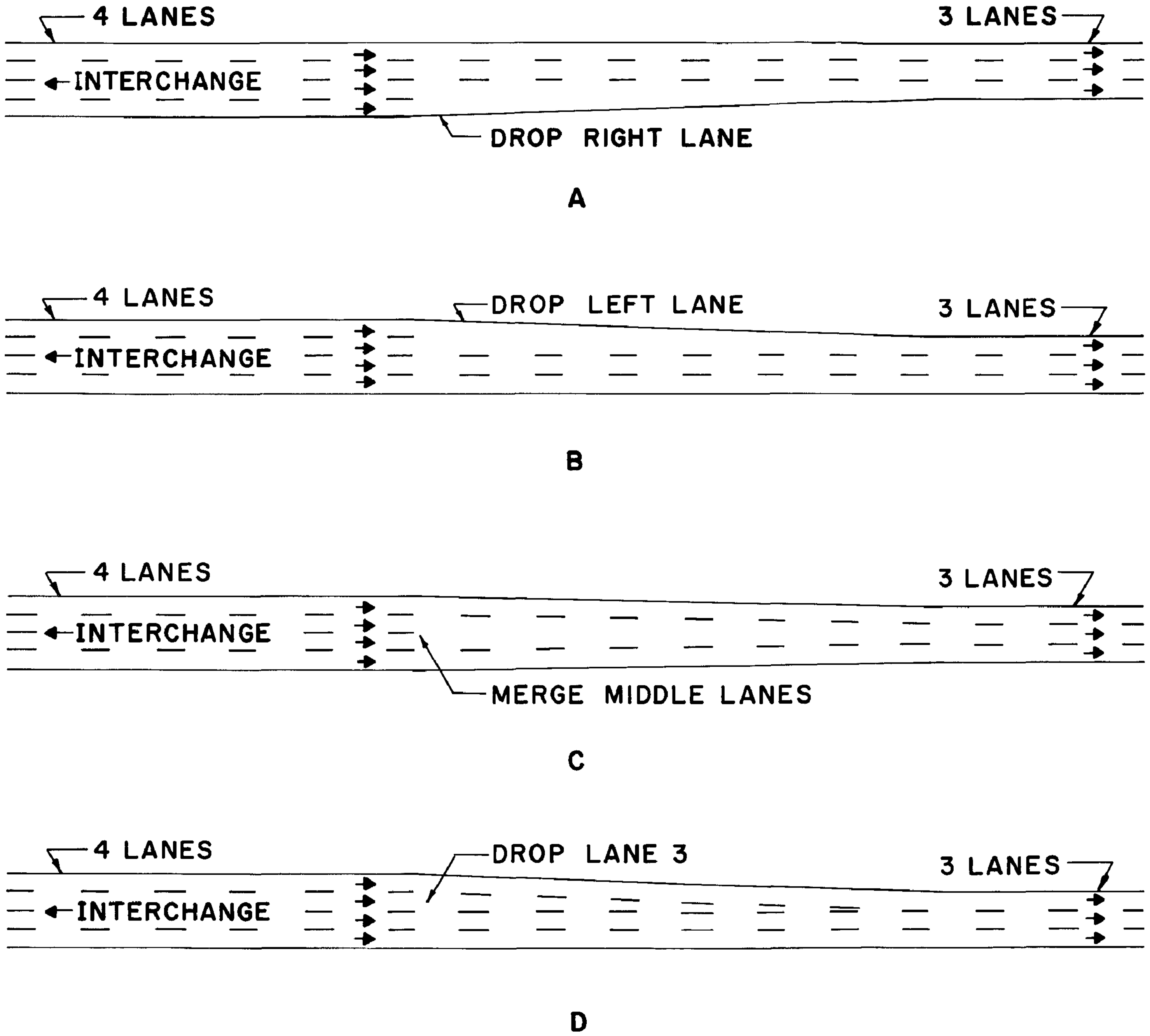

Figure H-4. Mainline Lane Drops

There are two reasons why this assumption appears to be valid. First, the pattern of the results indicate that the difference between three or four lanes is not significant in determining lane drop design policy. Further, one expert states that there is no difference in lane drop design between a six-lane and eight-lane freeway.

Seventy percent of the experts select a length between 1,000 and 3,000 feet for the distance between the prior interchange entrance ramp and the start of the lane drop tapered section. A value of at least one-half mile is specified in two state manuals. Seventy percent of the experts also feel that the lane should usually be dropped beyond the influence of a freeway-to-freeway interchange.

Comments by the experts indicate speed differentials or lane distributions are important considerations in the decision of the proper lane to drop. These characteristics appear to have areal differences. More importantly, not much seems to be known regarding these characteristics of the traffic stream in relation to lane drop operations.

In Case V (two lane drops at a major fork), the two alternatives shown in Figure H-5 are judged nearly equal in terms of safety and operations, with A slightly favored by the experts. With this case being the only exception, about 96 percent feel that, ideally, lane drops should occur at major forks. In the literature and discussion sessions, major forks were mentioned as possible but not always practical locations for lane drops. (For one thing, frequently there are no major forks in the vicinity of the proposed lane drop.) None of the design references present standard designs for Case V.

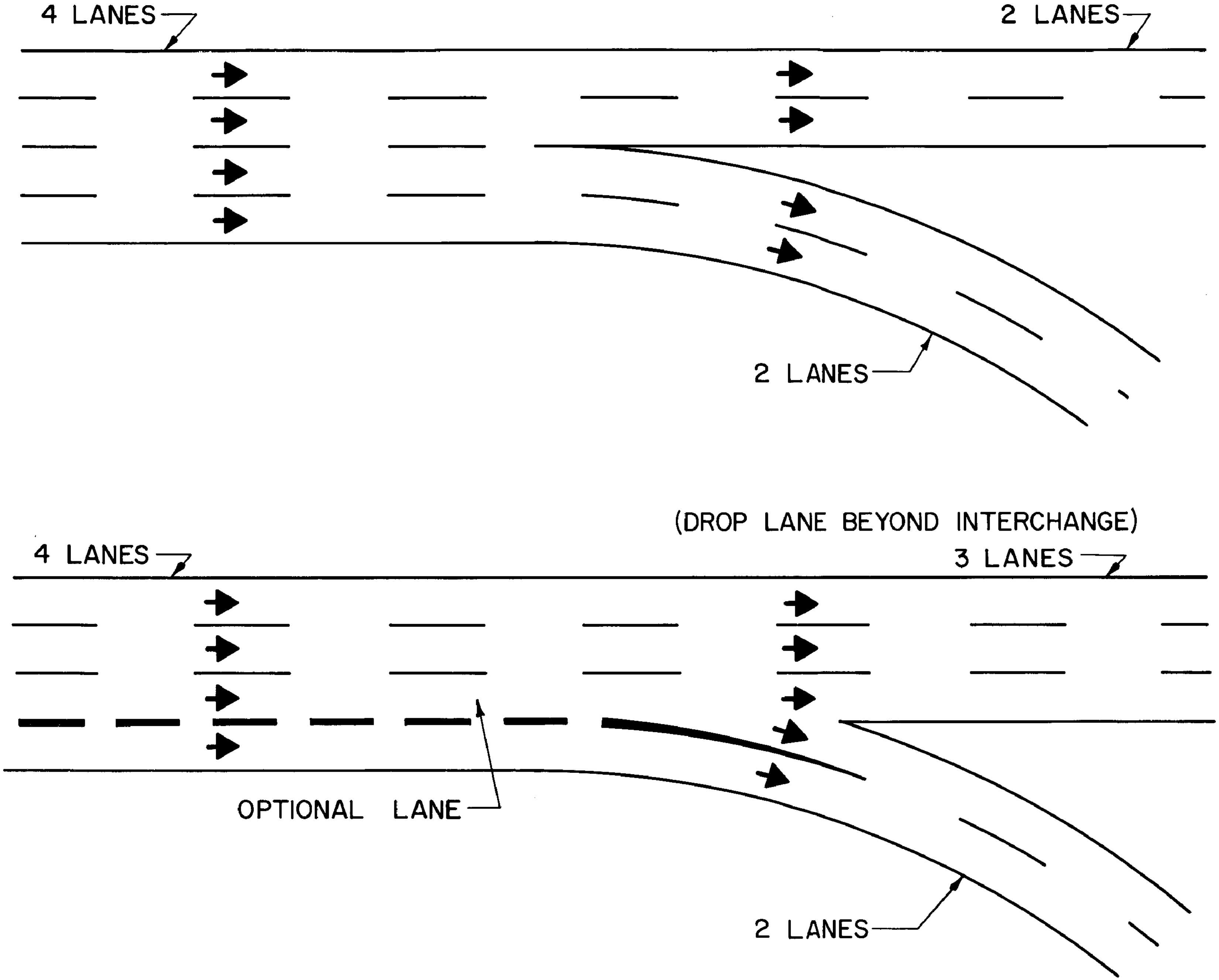

Figure H-5. Major Fork, Reduction from Four Lanes to Two on Mainline

Recovery Area Design

The preferred taper ratios for mainline lane drops cover a large range in values, as indicated in Table H-1. It is interesting to note that seven out of fifteen respondents answered with identical taper ratio values for both speed categories. Since the mean has no special significance, the mode of each category might be interpreted as the most preferred ratio. For the minimum ratio at both speeds and the desirable ratio at 60 miles per hour, the mode value is 50:1. At 70 miles per hour, the desirable ratio has a mode value of 100:1. However, there is much less agreement for this value than for the previous three categories; accordingly, the median value of 70:1 may be more representative than the mode value.

Very little information can be found covering mainline lane drop recovery areas. Two state design manuals suggest taper ratio values equal to the design speed of the freeway. These values are slightly flatter than would be indicated by the results discussed above.

For the recovery area of a lane drop adjacent to an exit gore, the results in Table H-2 indicate that a tapered section is preferred over full-width lane followed by a tapered section. A value of 50:1 is representative of the taper ratios provided for both recovery area alternatives. The median value of the wide range of full-width lane lengths is 800 feet.

This analysis indicates that the values presented in the AASHO "Red Book" are quite severe. Further, the figure presented for the lane drop adjacent to an exit gore is for an exit lane drop which involves the mainline right lane extending into the exit ramp -- no auxiliary deceleration lane is provided. In the AASHO "Blue Book" the

TABLE H-1

TAPER RATIOS FOR THE MAINLINE LANE DROP RECOVERY AREA

Experts	Alternatives A	 B
1	70:1	
2	35:1	
3	50:1	
4	50:1	
5	30:1	
6		150', 50:1
7		1,000', 50:1
8		1,000', 50:1
9	50:1	
10	100:1	
11		800', 70:1
12		1,000', 50:1
13		360', 30:1
14	50:1	
15	55:1	
16	X[a]	

---

[a] No value provided.

TABLE H-2

RECOVERY AREA VALUES FOR LANE DROPS AT THE INTERCHANGE

	Design Speed			
	60 MPH		70 MPH	
Experts	Minimum	Desirable	Minimum	Desirable
1	70[a]	100	70	100
2	35	50	35	50
3	40	50	50	50
4	50	50	--	--
5	50	80	80	100
6	40	75	50	100
7	50	100	50	100
8	40	50	50	60
9	50	70	50	70
10	60	90	70	100
11	40	50	50	75
12	50	50	50	50
13	50	50	50	50
14	25	40	35	55
15	70	70	70	70

---

[a] Values are ratios, e.g., 70:1.

taper values are approximately one-half the values indicated above, but the full-width lengths are larger; on the order of 1,000 feet.

Most of the state manuals which present exit recovery area design recommendations do so by providing standard designs. The State of Washington, for example, provides extensive information in the form of typical figures for right side exits and lane drops. This manual also permits design flexibility, in that the length of the full-width portion of the recovery area may vary from 0 to 650 feet. While Washington utilizes a 50:1 taper ratio, Texas specifies a 100:1 taper as the desirable value and 50:1 as the minimum. Generally, the recovery area design values presented in the reviewed manuals exhibit a variance similar to those given by the experts.

The experts emphasized the importance of signing in lane drop situations. Yet the literature and workshop commentary seem to indicate that effective signing techniques are not universally provided.

Recommended Lane Drop Design Guidelines

Because of the basic nature of the lane drop, an unexpected lane change and/or merge at high speed is required. The fundamental objective of the designer should be, then, to maximize the probability that through vehicles in the dropped lane are able to complete a lane shift safely, with a minimum of flow disruption. The guidelines must be consistent with that objective.

In the workshop commentary, the importance of driver considerations is repeatedly intimated by the experts. In addition, the consideration of the drivers' task at the approach and merge is consistent with the above objective; therefore it is adopted as the standpoint of the guidelines.

The guidelines provide preferred design configurations and a list of important operation and design conditions, such as horizontal curvature and merge task parameters. The effects of variations in these conditions on the design of freeway lane drops is discussed. The purpose of the guidelines is to provide a framework for the evaluation of the pertinent design and operation conditions for a proposed design configuration in a particular design situation. Table H-3 presents a list of the topics considered in utilizing the guidelines.

The considerations cannot all be quantified or assigned relative weights in this report; consequently, an experimentally-derived formula for lane drop design cannot be presented here. The guidelines, however, are not intended to replace the design engineers' judgment and expertise, but to supplement his knowledge. Engineering judgment supplies the sensitivity in the design process which cannot be provided through rigid design specifications. In this respect, the engineer should regard the guidelines as aids which enable him to determine the compatibility of a proposed configuration for a particular design situation.

A basic assumption in the development of the guidelines was that the roadway conditions for a particular design situation are more or less set and the lane drop must be fitted into the total design. Site-specific conditions may be controlling factors in some design situations. Thus, it is entirely possible that the generally preferred alternative, the right mainline lane drop, may not be the proper choice in a given situation.

Three other alternatives are: (1) a left mainline lane drop; (2) a lane drop adjacent to a right-side exit of an interchange; and (3) a lane drop at a major fork. Major forks appear to be somewhat

TABLE H-3

GUIDELINE CONSIDERATIONS

I. Driver Expectation
    A. Decision points
    B. Right side orientation
    C. Continuous movement for through traffic
II. Warning and Decision-Making Task
    A. Signing
    B. Delineation
    C. Visibility
        1. Pavement contrast
        2. Lighting
        3. Sight distance
    D. Number and complexity of decisions
III. Lane Change Task
    A. Upstream gap sampling
        1. Rear visibility
        2. Rear sight distance
    B. Maintenance of vehicle position in lane
        1. Roadway alignment
        2. Distance to recovery area
    C. Lane change
        1. Critical gap size
        2. Judgment of closure rate
        3. Lane speeds and volumes
        4. Truck volumes

IV. Forced Merge Task

A. Upstream gap sampling

1. Rear visibility

2. Rear sight distance

B. Maintenance of vehicle position in lane

1. Roadway alignment

2. Length of recovery area

3. Crossing construction joints

C. Merge

1. Critical gap size

2. Judgment of closure rate

3. Lane speeds and volumes

4. Truck volumes

D. Emergency recovery

1. Structures

2. Shoulder

V. External Considerations

A. Stage construction

B. Costs of lane extension

C. Overall mainline operation

1. Lane distribution at various volumes

2. Capacity

3. Distances between lane drop and entrances and exits

4. Ramp volumes

D. Policy constraints

ideal locations for lane drops, but are not always "available" where a lane drop is desired. Hence, this alternative is not discussed further in the guidelines.

The alternatives should be examined in order of preference: right mainline lane drop, left mainline lane drop, and right lane drop adjacent to an interchange exit. However, the final decision to use any particular configuration must rest with the design engineer, since he provides the judgment of relative importance among the varying considerations encountered in the design.

The following design guidelines were formulated through a synthesis of the information available from the questionnaires, workshop discussions, research literature, and design manuals. First, each of the considerations listed in Table H-3 is discussed; then lists of advantages and disadvantages (relative and individual) of each of the three alternatives are presented.

General Considerations in Design of Lane Drops

Driver Expectation

The first consideration dealt with is driver expectation. Although the basic lane drop occurrence is generally unexpected, there appears to be a difference in the level of driver surprise between lane drops at the interchange and past the interchange. The driver regards the interchange as an area of complex maneuvers and, therefore he is less likely to be surprised with the lane drop at the interchange.

Because of the right side orientation for merge and diverge maneuvers in urban areas, the driver is more likely to be surprised at a left lane drop. In addition, the driver generally views the left lanes as accommodating higher speed through traffic. The provision for continuous movement of through traffic is important in this respect.

Warning and Decision-Making Tasks

To aid in the driver's decision-making task, proper warning of the lane drop must be provided in terms of information systems. Signing of lane drops is one of the most important factors to be incorporated in any given design alternative. Clearly, the drivers in all lanes should understand the nature of the impending lane drop. Delineation techniques complement signs in warning the driver of the lane drop. Existing information systems do not appear to be entirely satisfactory in terms of their effectiveness.

A second factor to be considered in design is the visibility of the lane drop or taper area. At some warning point, visibility of the lane drop should be available with signing -- permitting the driver to relate the sign to the roadway geometry. Therefore, the engineer should strive to locate the lane drop where proper signing and visibility can be provided simultaneously.

As noted before, the interchange is a decision point with signs and conflict points. The inclusion of a lane drop there requires the driver to process more information and make his decision in a shorter period of time than at the mainline lane drop; the severity of the problem is a function of the overall complexity of the interchange. The design engineer should not locate the lane drop where it severely complicates the driver's decision-making process.

Lane Change Task

It is desirable that the lane shift be made prior to the tapered area; otherwise, the driver is put in a forced merge situation. Basically, the driver's lane change task requires sampling gaps in the adjacent lane while maintaining proper longitudinal and lateral vehicle placement. The rear visibility or field of view is more limited at left side drops, than at a right lane drop. Since the roadway's horizontal and vertical alignment can restrict rear sight distance, the roadway alignment is an equally important consideration in the evaluation of this aspect of the lane change task.

Horizontal and vertical curvature coincident with the lane drop also complicate proper lane maintenance by the driver as he samples upstream flow. The whole task is a continuous process. If the vehicle's speed is 60 miles per hour during the gap-search process, it must be remembered that the vehicle will travel nearly 900 feet in ten seconds. Sufficient distance must be provided from the lane drop warning point to the beginning of the taper in order to increase the probability of a safe lane change.

The lane change depends on the driver acceptance of a gap. Certainly, higher volumes (with lower speeds) result in smaller gap sizes in each lane. Further, the driver's judgment of vehicle closure rates is limited; particularly from the rear and at high speeds. Thus, relative lane speeds should be considered in terms of speed differentials between adjacent lanes. Moreover, a truck's lane change task requires a much larger gap size due to its limited acceleration capability. These three driver and traffic characteristics (visibility, gap acceptance, and relative lane speeds) require consideration in the decision as to the proper lane to be dropped.

Forced Merge Task

If the driver has not changed lanes prior to the tapered area, he is forced to execute a merge at that point. In this maneuver, the driver is in a critical situation. As the task requirements on the driver become more demanding, the effects of the related geometric and traffic influences become more pronounced. Since he continues to sample upstream flow, the conditions affecting his rear view are still important. Clearly, it is more difficult for the driver to maintain proper vehicle position in the taper on a curving roadway alignment. The tapered section should be long enough to provide distance for acceleration and merging or emergency deceleration, but short enough for the driver to recognize it as a lane drop. It appears that the taper ratio should be 50-70:1.

Because of the forced nature of the merge at this point, the size of the acceptable gap decreases. The number and severity of potential vehicle conflicts are related to lane speeds and volumes and truck traffic. As before, these considerations apply to the decision of the lane to be dropped.

In situations where a vehicle is not able to merge into the adjacent lane, an emergency recovery area should be provided. Lane drops at structures not only do not provide the emergency area but restrict movement with concrete abutments or railings. Shoulders should be designed to allow the driver to maintain control of his vehicle and enter the traffic stream. Careful consideration should be given to roadside obstructions near the tapered area.

External Considerations

There are, of course, lane drop design considerations external to the driver task. In a program of stage construction, a first-stage left lane drop with a widened median appears to be more appropriate than a right lane drop. Costs involved in the eventual lane extension are a real consideration, and favor initial completion of the right lane so that "final" design entrance and exit ramp configurations can be constructed in the first stage.

Proper consideration should be given to the overall mainline operation.

- A left lane drop might disrupt a smaller number of vehicles than a right lane drop over an equal period of time, but they will be moving at higher speeds.
- Excess mainline capacity on the approach to a lane drop located past the interchange is inherent. This excess capacity permits favorable lane distribution within the preceding interchange and improves operations at the lane drop.
- Successive conflict areas are important in determining weaving and flow stability. Therefore, the engineer should consider the distances between the lane drop and adjacent entrance or exit ramps, and the traffic volumes on these ramps. For instance, the distance from the last interchange entrance ramp to the lane drop should be in the range of 1,000 to 3,000 feet.
- Policy and administrative effects are practically undefinable in general terms. Because of this and the variance in dominant conditions, it is not practical or realistic to recommend the exclusive use of any one alternative.

Advantages and Disadvantages of Alternative Configurations

Right Mainline Lane Drop

Advantages:

- Less driver surprise than left lane drop because of right-side orientation of drivers.

- Allows for continuous movement of high-speed through traffic in left lane.
- Greater rear visibility or field of view than left lane drop.
- Usually less hazardous than left lane drop due to lower speeds in right lanes.
- "Spreads" the decision points; less demand on driver than interchange lane drop.
- Smoother overall flow and larger capacities because of more favorable lane distribution than at interchange lane drops.

Disadvantages:

- Disrupts a larger number of vehicles than the left drop.
- Usually, smaller gap sizes occur in right lanes due to higher volumes at lower speeds. (Truck volumes compound this problem because of the larger gap sizes required.)
- Less appropriate than left lane drop in stage construction because of interchange reconstruction and alignment change requirements.
- Less driver expectation of existence than at the interchange.
- More expensive than interchange lane drop because of lane extension.

Left Mainline Lane Drop

Advantages:

- Disrupts a smaller number of vehicles than right lane drop.
- Usually, larger gap sizes occur in left lanes due to lower volumes at higher speeds. (Greater advantage realized due to lower number of trucks in left lane.)
- More amenable to stage construction than right lane drop.
- "Spreads" the decision points, less demand on driver than interchange lane drop.
- Smoother overall flow and larger capacities because of more favorable lane distribution than interchange lane drop.

Disadvantages:

- Lower driver expectation than right lane drop because of right-side orientation of drivers.
- Interrupts high-speed through traffic.
- Limited rear visibility.
- Usually, higher speeds in left lanes increase hazard due to driver's limited judgment of vehicle closure rates.
- Lower driver expectation of occurrence than at the interchange.
- More expensive than interchange because of lane extension.

Right Lane Drop Near Exit Terminal

Advantages:

- Lower driver "surprise" element because he recognizes interchange as an area of complex maneuvers.

- Less costly than mainline lane drop as no lane extension required.
- Allows for continuous movement of high-speed through traffic in left lane.
- Usually, less hazardous than left lane drop due to lower speeds in right lanes.

Disadvantages:

- Increases difficulty in driver decision-making because of the increased information and task load.
- Usually, smaller gap sizes occur in the right lanes due to higher volumes and lower speeds. Depending on configuration, entrance and exit ramp traffic may compound this problem. (Truck volumes also compound the problem because of the larger gap sizes they require.)
- Smaller capacity and poorer operations through the interchange area may result.
- Less appropriate than left lane drop in stage construction because of interchange reconstruction and alignment change requirements.
- Disrupts a large number of vehicles than the left drop.

<u>Common Considerations:</u>

- Can signing and visibility be provided simultaneously?
- Does the mainline's horizontal and vertical alignment restrict rear sight distance?
- Can sufficient distance be provided from the lane drop warning point (concurrent signing and visibility) to the beginning of the recovery area taper for a safe lane change?

- Can sufficient distance be provided for the recovery area with a taper ratio of 50 to 70:1?
- Is construction joint design coincident with pavement lane markings?
- Can sufficient emergency recovery area be provided away from structures or roadside obstructions?
- Is the shoulder area sufficient to allow the driver to control his vehicle and re-enter the traffic stream?
- Is there sufficient distances between lane drop recovery areas and entrance or exit terminals to allow for stable flow and operations?

Lane Drop Case Study

This analysis of an existing freeway section provides an illustration of the practical application of the lane drop design guidelines. In addition, the analysis provides insight into the importance of the consideration of the driver's viewpoint and tasks. Further, it illustrates the difficulty of determining the relative importance of the many roadway and operating considerations.

While the guidelines recommend the mainline lane drop as the initial choice (assuming the major fork option is not available), this analysis does not involve a new design situation and therefore, the guidelines' order of consideration is not required. Generally, the context of this analysis is a discussion of the compatibility of an existing lane drop configuration and the guideline considerations.

The data presented here were collected during visits to the site and the cognizant PennDOT district office. The roadway data were provided by the design engineers in the form of design plans, profiles, and miscellaneous notes.

Description of the Freeway and Interchange

The section of roadway under consideration is a portion of southbound Interstate 79, or Pennsylvania Legislative Route 1016, in Allegheny County. This section of freeway lies in the outlying areas southwest of Pittsburgh. At the time of this writing, the freeway south of the Kirwin Heights Interchange is open for traffic, but the portion leading north to Western Pittsburgh is incomplete (see Figure H-6). The Canonsburg Interchange, not shown on Figure H-6, is located 7.5 miles south of the Bridgeville Interchange. The design speed of the

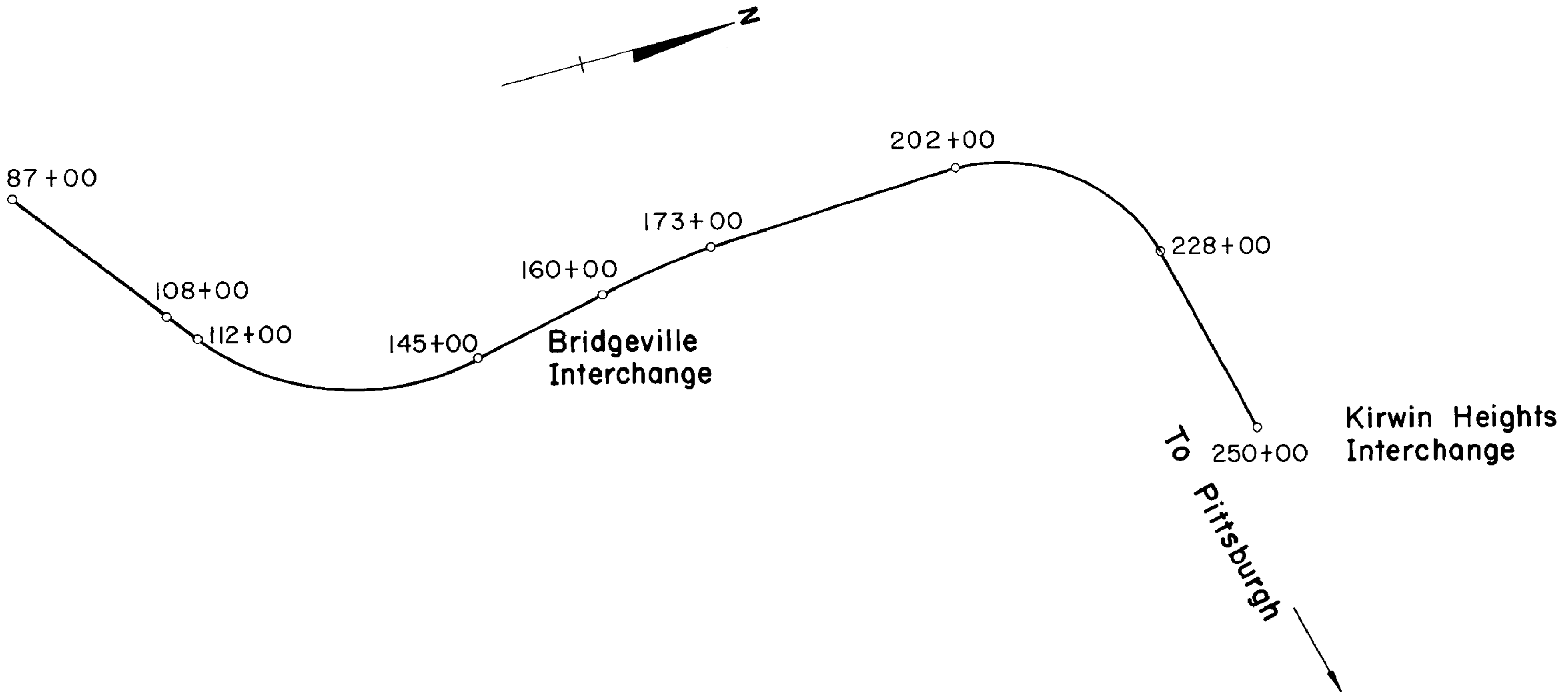

Figure H-6. Line Schematic Plan of I-79

freeway is 70 miles per hour and the posted speed limit is 65 miles per hour. Three basic lanes of I-79 approach the Bridgeville Interchange from the North and two lanes lead away. The horizontal alignment is shown in Figure H-6 and the vertical alignment in Figure H-7. In Figure H-6, the circled points and numbers correspond to station numbers where points of curvature and tangency begin.

At the Bridgeville Interchange, the freeway passes over Pennsylvania Legislative Route 545, or Pa. 50, which is a four-lane highway at the interchange. One right exit ramp and one right entrance ramp serve the freeway's southbound lanes.

Critical Analysis of the Bridgeville Exit Lane Drop

In accordance with the outline in Table H-3 and the ensueing discussion, this analysis is centered on the unfamiliar driver as he travels south at 65 miles per hour on I-79. Again, since this is not an analysis of a new design, driver expectation considerations are deferred until they are appropriate in the discussion.

The warning perception and decision-making tasks occur in the approach to the lane drop. In Table H-4, the signing sequence is given in terms of the sign legends, corresponding figure numbers, approximate distance to the lane drop, and the lateral location of the sign. The size and shape of signs which are not shown are similar if not identical to those signs indicated. Figures H-8 through H-11 show the approach roadway to the interchange. Figure H-12 clearly shows the exit lane drop at Station 155, where the right mainline lane is extended into the exit ramp and no auxiliary deceleration lane is provided. The first indication of animpending lane drop is sign #2, which directs the through traffic to the left lanes.

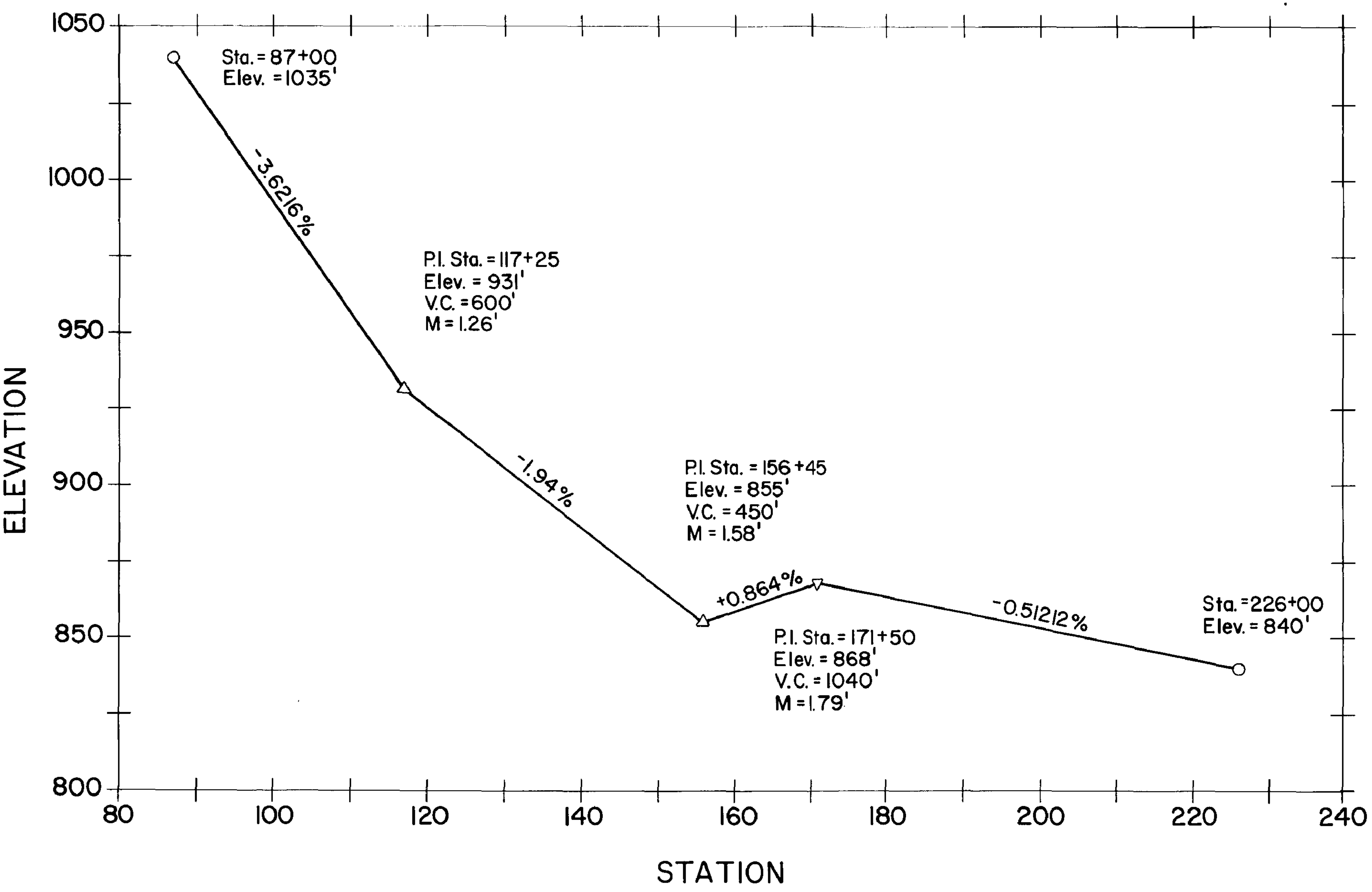

Figure H-7. Profile of I-79 Southbound Lanes

Figure H-12. Sign 8 and Exit Lane Drop at Station 155

Figure H-13. Signs 9 and 10 at the Exit Gore and Emergency Recovery Area

Figure H-10. Signs 5 and 6 and View of Bridge at Station 173

Figure H-11. Sign 7 and Overpass at Bridgeville Interchange at Station 160

Figure H-8. Sign 2 and View Looking South at Station 202

Figure H-9. Sign 4 and View Looking South at Station 178

TABLE H-4

SIGNING SEQUENCE TO BRIDGEVILLE LANE DROP

Sign Legend	Figure Number	Color Legend/ Background	Distance to Lane Drop (Miles)	Location
1. PA 50 EXIT 1 MILE BRIDGEVILLE	Similar to Sign #6	White/Green	1.0	Right Shoulder
2. THRU TRAFFIC KEEP LEFT	8	White/Green	0.9	Right Shoulder
3. PA 50 BRIDGEVILLE EXIT 1/2 MILE	Similar to Sign #6	White/Green	0.6	Right Shoulder
4. RIGHT LANE EXIT ONLY	9	Black/Yellow	0.5	Right Shoulder
5. BRIDGE FREEZES BEFORE ROAD SURFACE	10	Black/Yellow	0.4	Right Shoulder
6. PA 50 BRIDGEVILLE RIGHT LANE	10	White/Green	0.4	Right Shoulder
7. BRIDGE FREEZES BEFORE ROAD SURFACE	11	Black/Yellow	0.2	Right Shoulder
8. EXIT 25 MPH	12	Black/Yellow	0.0	Ramp Right Shoulder
9. EXIT (Arrow) 11	13	White/Green	0.0	Exit Gore
10. (Arrow) 25 MPH	13	Black/Yellow	0.0	Exit Gore

Sign #4, the only warning sign for the lane drop, is one-half mile before the lane drop, affording the driver nearly 28 seconds to complete a lane change (at 65 mph). However, limited effectiveness of "EXIT ONLY" signs is reported in the literature.

Pavement delineation consists of solid white lane lines as seen in Figures H-12 and H-13. They delineate the exit lane and right edge of mainline lane number one. Amber reflective markers are posted on the right side of the ramp and on the exit gore. (The shiny areas outlying the exit lane in Figure H-11 are caused by the moisture on the pavement.)

The visibility of the lane drop in terms of sight distance is limited to some extent by the combination of bridge railings, a horizontal curve with a radius of 7,700 feet, and a crest vertical curve with a length of 1,040 feet. The crest occurs near Station 171 and the sight distance is assumed to be 1,600 feet. The freeway and lane drop are not lighted. The concrete pavement and asphalt shoulder provide sufficient surface contrast.

Is there sufficient warning to provide the driver advance knowledge of the exit lane drop? There is sufficient warning for the exit, but marginal warning for the exit lane drop itself. One criticism is the lack of a lane drop warning sign at the point where the geometric situation becomes visible -- each confirming the other. Advance understanding of the configuration is especially important for the exit lane drop. Regardless of the side, the unknowing driver will not expect a basic freeway lane to simultaneously change its function and direction. In other words, the visibility of the lane drop is not sufficient as a warning if the driver does not clearly understand the various tasks to be performed at the exit. In a sense then, the main criticism is the configuration itself.

Assuming the driver begins his lane change task at Station 171, there is sufficient rear visibility and sight distance for the upstream gap sampling. While the roadway alignment is curved, this should not be a major problem for average road surface conditions. However, the bridge areas are potential skid areas as noted by Signs 5 and 7 in Figures H-10 and H-11, and this will increase the hazard of the lane change task in some instances. The distance to the lane drop from this point provides approximately 17 seconds for the lane change maneuver.

The safe completion of the lane change task depends on the lane distribution of speed and traffic volumes. Data based on counts and studies for these parameters at this site are not available. Even so, they would be of limited value since the existing volumes are not representative of the design volumes for the completed I-79.

The forced merge task arises if the through driver discerns the situation too late, or if he is unable to change lanes earlier because of unacceptable gaps in the adjacent lane. There is adequate rear visibility and sight distance. In order to turn the lane into the ramp, a horizontal curve with a radius of about 2,900 feet and superelevation of 1/2 inch per foot are provided. This can be seen in Figure H-12, where the mainline is a tangent section and the drop lane diverges to the right. Hence, the late lane-changing through driver must resist the physical tendency of the vehicle to follow the exit lane.

The forced merge recovery area is not easily defined in this configuration, but it is assumed to be the section of lane from the start of the white lane line to the exit nose in Figure H-12. The length of this area is approximately 200 feet, which is clearly inadequate. In this area the driver must cross solid lane lines, construction joints, and worn shoulder material (possible evidence of acceleration over the shoulder). While there is a paved, 10-foot wide shoulder, the emergency recovery area -- the gore -- is restricted by the exit gore post delineators and signs. Another major inadequacy of this exit lane drop configuration is that it does not provide at least a short paved section of lane beyond the gore nose for a continuous merging maneuver.

As noted before, the freeway is not open to the north beyond the Kirwin Interchange. As a result, traffic volumes are light on the freeway at present. Not surprisingly, discussions with the district engineers indicate that the lane drop has not been a serious accident location. This fact, of course, does not necessarily mean that the exit lane drop is not a hazardous location.

External considerations relevant in this exit lane drop situation include the possible ill effects of weaving in the two right lanes on the approach to the exit terminal. Policy requirements in terms of design standards contained in the highway design manual of Pennsylvania do not exist for lane drops at exits (or at a location between interchanges).

Critical Analysis of Lane Drop Alternatives

Two preferred alternatives are the mainline lane drop and the major fork lane drop. As no major fork occurs at or just beyond the Bridgeville Interchange, the following brief discussion addresses itself to an analysis of the alternative of a mainline lane drop located ten to thirty stations past the entrance ramp terminal, or at Stations 132 to 112.

As shown in Figures H-6 and H-7, the lane drop would be located on a positive grade and at a horizontal curve to the right. The curve condition would restrict the driver's forward and rear sight distance. Historically, unfavorable operations have been reported for lane drops at horizontal curves. In addition, truck acceleration characteristics on the 1.94 percent grade should be considered in terms of the lane change and merge. The emergency recovery area is limited on the right due to the side slope and guardrail. Thus, "moving" the lane drop to this curved section past the entrance ramp does not appear desirable.

An external consideration; an auxiliary truck climbing lane, beginning at Station 108, provides a third lane for slow-moving vehicles on the 3.6% grade which begins near Station 117 (see Figure H-7). The truck climbing lane is added at a point only 400 feet beyond the point where the lane drop might have been located (end of horizontal curve), as shown in Figure H-6. Clearly, a lane drop followed by a lane "add" in the 400 foot section is a poor design. Therefore, consideration should be given to extending the three lanes to the point requiring the auxiliary lane.

Cost considerations appear to have been the major factors in the evaluation of the alternative lane extension to the truck climbing lane. Referring to Figures H-14 and H-15, the necessary substantial cuts and fills would involve large construction costs for the extension. Another cost-related factor is the length of the extension -- 4,700 feet from the Bridgeville exit, the location of the existing lane drop. Further, in the present situation, reconstruction of the entrance ramp terminal, shown in Figure H-14, would be required, at additional cost.

Figure H-14. Bridgeville Entrance Terminal at Station 142

Figure H-15. View Looking North from Station 108 (Southbound Lanes)

An example of the use of the guidelines, in a worksheet format, for this situation is given in Table H-5. The relative merits of the existing configuration and three alternatives, as framed by the guideline considerations, are represented by pluses (better) and minuses (poorer). It is important to note that this evaluation of the alternatives is site-specific. Other sets of entries would be made for other sites since they would vary by specific alternatives, areal considerations, unquantified relationships of the various considerations, and engineering judgment.

Recommendations

Based on the overall site analysis, corrective recommendations are as follows:

1. Erect a lane drop sign - "RIGHT LANE MUST EXIT" - at Station 165 near the point of lane drop visibility.

2. Reconstruct the exit gore and terminal area to provide a deceleration lane and a tapered area adjacent to the gore with a taper ratio equal to 50:1. (The distance from the end of taper to the entrance terminal would be 700 feet.)

3. Provide lighting for the exit terminal and lane drop. Support devices should be in accordance with new safety-oriented techniques.

4. Conduct a feasibility study for the lane extension of 4,700 feet to the truck climbing lane at Station 108. Evaluate the operations of the reconstructed lane drop after 1-79 is completed in terms of accident data or other safety effectiveness measures and mainline and entrance ramp volumes. If the lane is extended, determine the compatibility of the lane drop design at Station 87 with these guidelines. A possible significant part of this study should be the

TABLE H-5

RELATIVE MERITS OF THE CASE STUDY ALTERNATIVES

	Interchange (Right-Side)		Mainline (Stat. 132 to 112)	
	Existing (Exit Drop)	Gore (Adjacent)	Left Lane Drop	Right Lane Drop
I. Driver Expectation				
A. Decision points	+	+	-	-
B. Right side orientation	+	+	-	+
C. Continuous movement for high-speed traffic	+	+	-	+
II. Warning and Decision-Making Task				
A. Signing	-	-	-	+
B. Delineation	-	-	+	+
C. Visibility				
1. Pavement contrast				
2. Lighting				
3. Sight distance	+	+	-	-
D. Number and complexity of decisions	-	-	+	+
III. Lane Change Task				
A. Upstream gap sampling				
1. Rear visibility	+	+	-	+
2. Rear sight distance	+	+	-	-
B. Maintenance of vehicle position in lane				
1. Roadway alignment	+	+	-	-
2. Distance to recovery area	+	+	-	-
C. Lane change				
1. Critical gap size	-	-	+	+
2. Judgment of closure rate	+	+	-	+
3. Lane speeds and volumes	-	-	+	-
4. Truck volumes	-	-	+	-

TABLE H-5 (Continued)

	Interchange (Right-Side)		Mainline (Stat. 132 to 112)	
	Existing (Exit Drop)	Gore (Adjacent)	Left Lane Drop	Right Lane Drop
IV. Forced Merge Task				
A. Upstream gap sampling	-	+	-	-
1. Rear visibility				
2. Rear sight distance				
B. Maintenance of vehicle position in lane				
1. Roadway alignment	-	+	-	-
2. Length of recovery area	-	+	+	+
3. Crossing construction joints	-	+	+	+
C. Merge				
1. Critical gap size	-	-	+	+
2. Judgment of closure rate	-	+	-	+
3. Lane speeds and volumes	-	-	+	+
4. Truck volumes	-	-	+	-
D. Emergency recovery	-	-	+	-
1. Structures				
2. Shoulder				
V. External Considerations				
A. Stage construction	-	+	+	-
B. Costs of lane extension	+	+	-	-
C. Overall mainline operation	-	-	-	+
1. Lane distribution at various volumes				
2. Capacity				
3. Distances between lane drop and entrances and exits				
4. Ramp volumes				
D. Policy constraints	+	+	+	+

consideration of traffic operations and accidents during winter at the bridge locations.

Discussions with PennDOT district engineers reveal that future planned improvements include lighting and reconstruction of the exit gore to provide a larger recovery area. These actions are at least consistent with the recommendations above.

Conclusions and Recommendations for Further Research

It has been stated that lane drop design decisions are affected by a number of important considerations and, hence, engineering judgment must play a key role in the design decision process. But there is an argument for the adoption of "standard" designs based on the need to provide for driver expectation of impending lane drops. The occasional necessity for deviation from the following suggested design statements is, of course, acknowledged.

1. The right mainline lane drop is preferred.
2. The mainline lane drop should be located 1,000-3,000 feet past the preceding entrance ramp terminal.
3. A 50-70:1 taper ratio (for a 12-foot lane, 600-840 feet long tapered sections) should be used for the lane drop recovery area.
4. The numbers of mainline and exit ramp lanes are relatively unimportant considerations in the decision on lane drop location.
5. The driver's task to safely complete the lane shift with a minimum of flow disruption should be the primary consideration in lane drop design.

6. Effective warning systems -- proper techniques concurrent with lane drop visibility of the overall geometry (sight distance, delineation, pavement-shoulder contrast) are critically important and should be designed as an integral part of the lane drop configuration.

7. The exit lane drop should not be an acceptable alternative lane drop configuration. (At a minimum, adequate recovery areas should be provided.)

8. Past research studies of alternative lane drop configurations must be reviewed carefully, as frequently they do not properly isolate and identify the effects of critically important and <u>variable</u> conditions.

9. Lane drops located on horizontal and vertical curves should be avoided because of restricted visibility (forward and rear) and increased maneuvering problems.

10. The guidelines presented in this appendix are useful as design aids.

The guidelines, unfortunately, do not contain statements of the finite or relative values for each of the considerations.

Further research is clearly necessary in the areas of sign legends, relationships between signing and visibility distances, and lane assignment techniques to provide effective warning systems for mainline lane drops and lane drops adjacent to exit gores.

APPENDIX I

A FACT SHEET APPROACH TO DISSEMINATING FREEWAY DESIGN EXPERIENCE

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INTRODUCTION

Problem Statement

The field of freeway design deals with large, expensive, and often complex end products. Due to the permanency and limited number of these projects in one design jurisdiction, very little experimentation is possible. For this reason, the highway design engineer must supplement his own experience with the knowledge of others. There are two principal sources of such knowledge:

1. Academic research studies, which frequently concentrate on developing generalized design guidelines through synthesis of operational experience over a large number of sites.
2. The design experiences (with feedback on subsequent operational characteristics) of his peers in specific situations.

A problem arises, however, in the dissemination of information from past design experience. While the findings of research studies are usually published and distributed through governmental or institutional channels; actual design experience of individual engineers often is not collected, organized or made available to those who would find such material useful.

All of this points to the need for a method of gathering, indexing, assembling, and publishing information which will permit the freeway designer to evaluate his design in comparison with past experience in a number of similar situations. This comparison would indicate to him which aspects of the previous case studies were similar to his present situation. Based on his knowledge of the outcomes of these other case studies, the freeway designer could assess the probable outcome of utilizing various alternative design configurations.

The idea for a documented case history "book of fact sheets" was conceived at the workshops conducted as a part of this project. (See Appendix C for an agenda and list of participants.) From the opinions expressed, several goals for such a system were established:

1. The information gathered should be catalogued or indexed as to the specific type of design configuration to allow the design engineer to quickly narrow down the number of cases for review.
2. The information should be concise. Ideally, all the information for a single site would be placed on one or two pages.
3. Finally, some sort of central clearinghouse will be needed to assemble and distribute the information received from the various organizations dealing with freeway design.

While this paper is concerned mainly with Items 1 and 2 above, some attention is given to Item 3 in the Comments and Conclusions section of this appendix.

Objective

The objective of the study described in this appendix was to develop a sample format for indexing and reporting the experiences of design engineers, as related to specific freeway design configurations, in such a manner that other designers might derive benefit from the earlier experiences.

Method

To determine what information is essential in describing the design input and operational characteristics of a specific site, an example of one such site, a two-lane entrance ramp in Omaha, Nebraska, was studied in depth. An example of the final fact sheet for this case is presented at the end of this report. From this specific case the more general format has been developed.

A second fact sheet, developed around a larger scale design experience, an entire interchange in Illinois, is also included to demonstrate the wide applicability of the concept.

SAMPLE STUDY

Location and History

The site used as an example is the Douglas Street (US 6/75) entrance ramp to I-480 in Omaha, Nebraska, as shown in Figure I-1. This location was chosen because of one of the authors' familiarity with it and the accessibility of information concerning it. This particular location is also appropriate because information in each stage of the process proposed in the formulation of a typical fact sheet was available.

Route I-480 is a major urban freeway in Omaha, varying from four to six lanes wide. Beginning approximately 1.5 miles upstream from the merge point under study, I-480 becomes an elevated freeway. The Douglas Street entrance ramp merges with eastbound I-480 at the west end of the Missouri River Bridge. At present there are three other bridges over the Missouri River connecting Omaha and Council Bluffs.

Since its construction in 1966, this entrance ramp and the Interstate route it merges with have served three varying functions. To fully understand some of the design decisions that were made it is necessary to be aware of the changes in paths of through traffic in Omaha over the study period. These are illustrated in Figures I-2, I-3, and I-4.

When first constructed, the entrance ramp carried all eastbound traffic passing over the bridge into Iowa. This included cross-country traffic on Interstate 80 and local traffic on I-480, all of which was routed on the one-way pair of Dodge and Douglas Streets through the central business district of Omaha and across the Missouri River Bridge into Council Bluffs, Iowa.

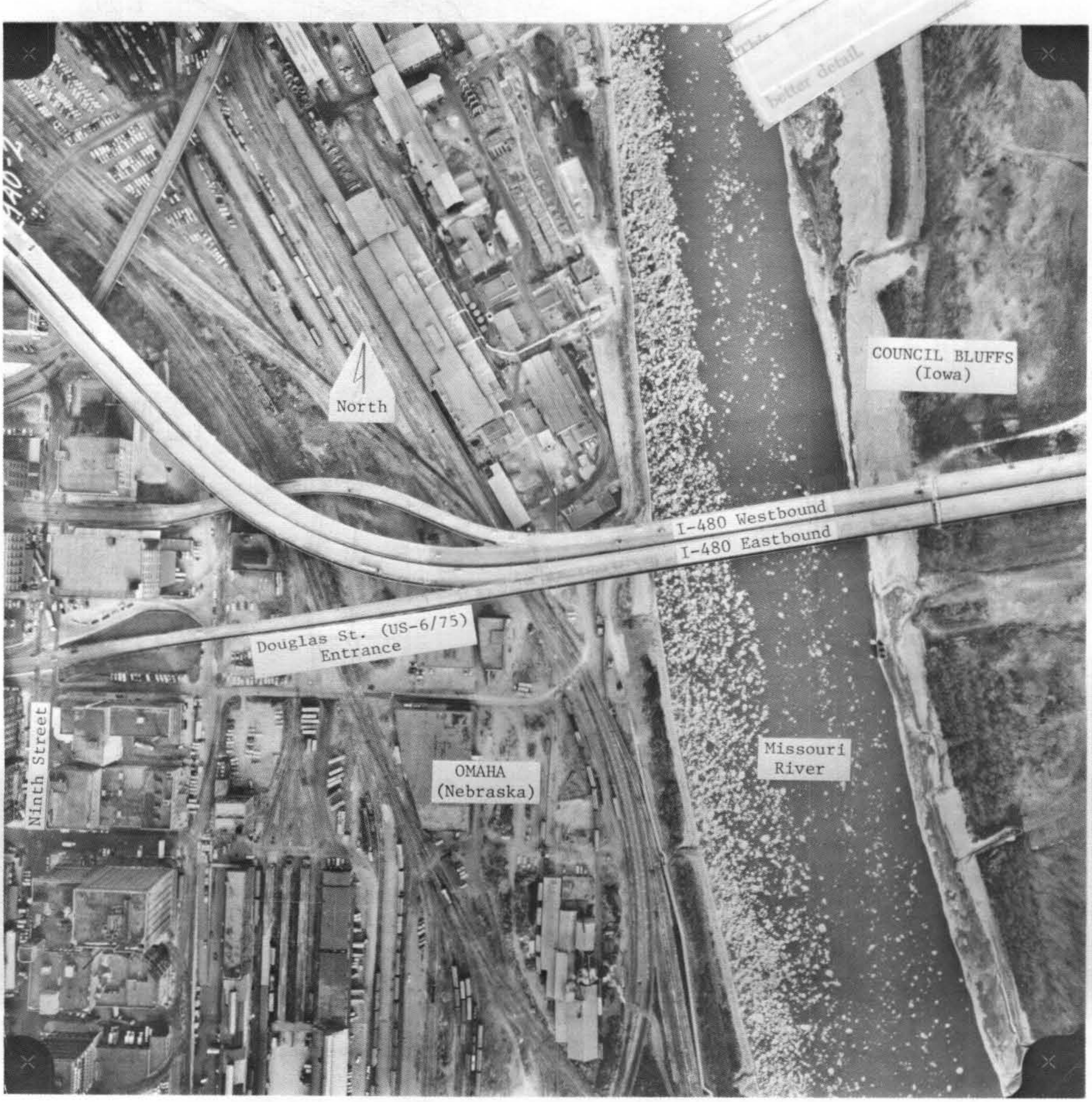


Figure I-1. Study Location

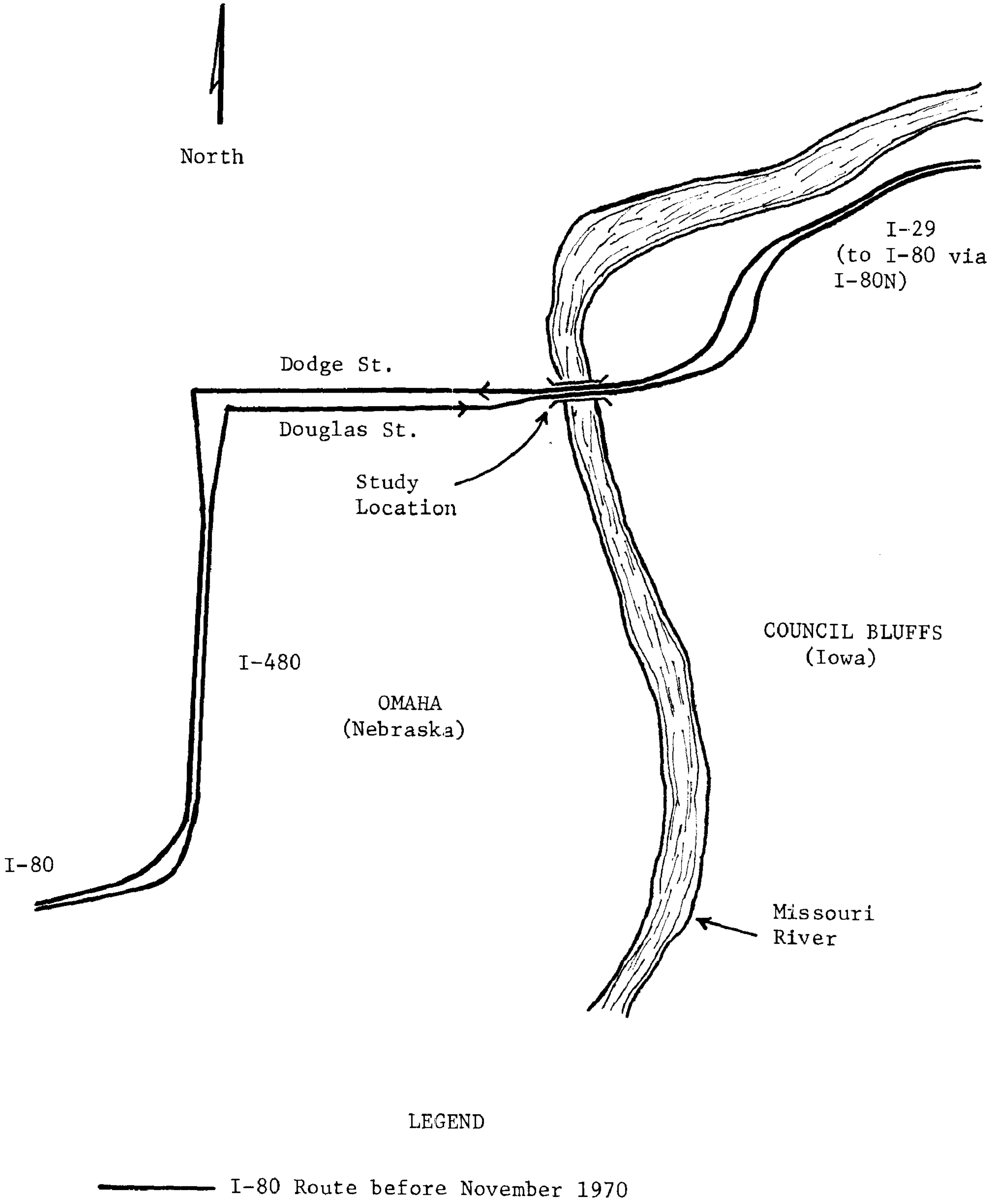


FIGURE I-2. Interstate 80 Route Before November 1970

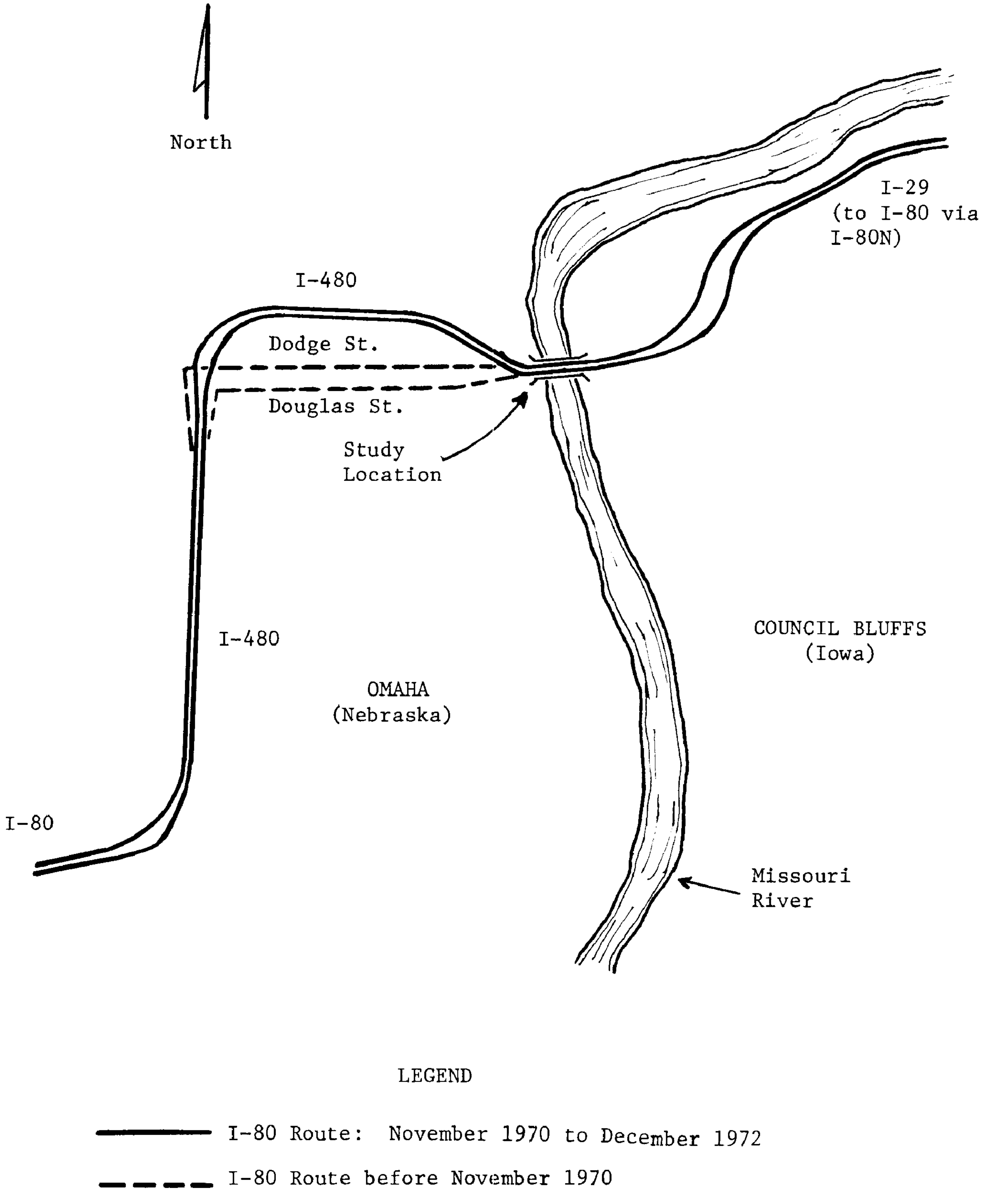


FIGURE I-3. Interstate 80 Route: November 1970 to December 1972

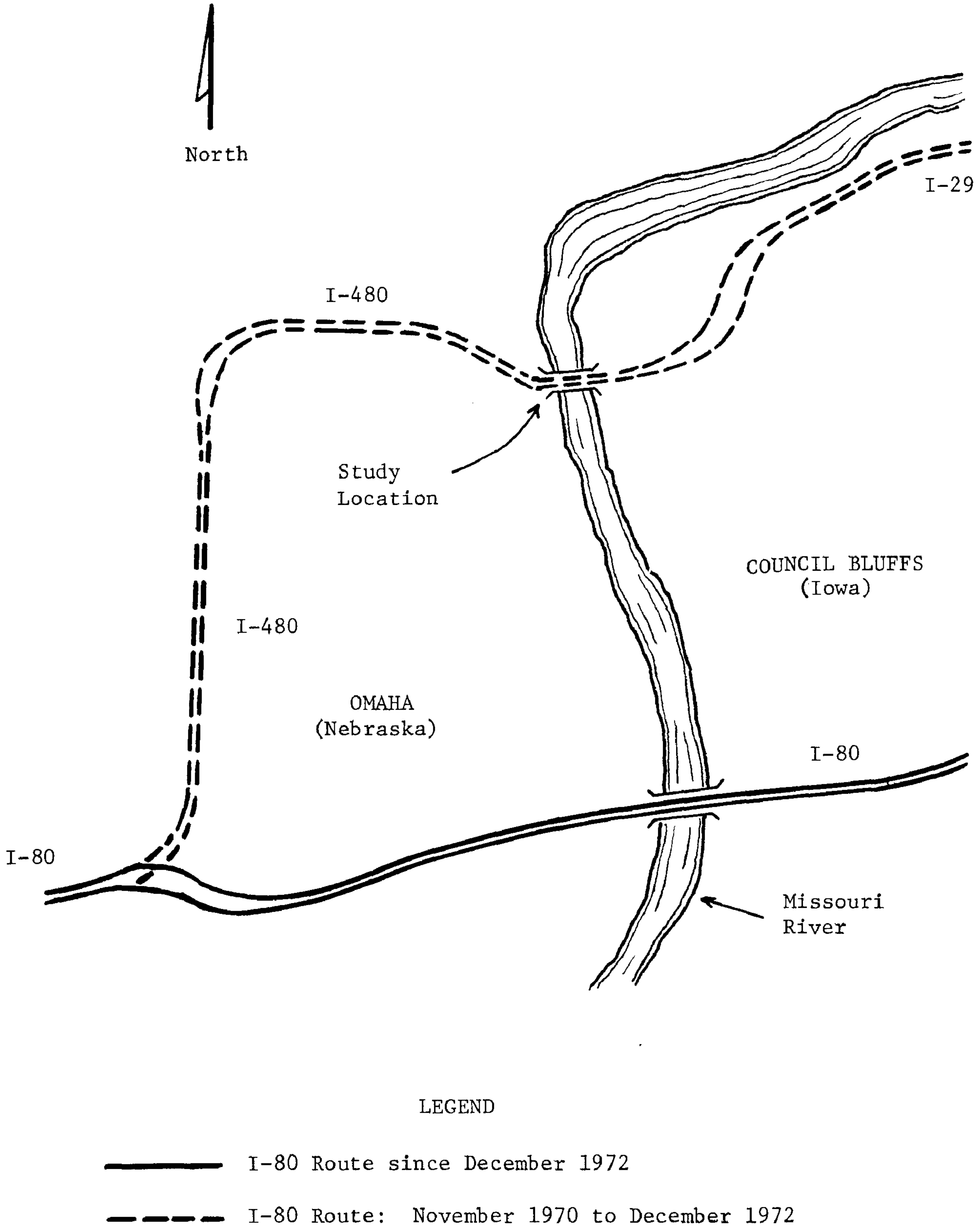


FIGURE I-4. Interstate 80 Route Since December 1972

In October of 1970 the elevated section of I-480 was completed, eliminating the need for through Interstate traffic to use the one-way pair of Dodge and Douglas Streets. At this time the Douglas Street entrance became a true entrance ramp as opposed to a through route.

The current situation developed in December, 1972, when the remaining section of I-80 was opened to traffic. Through traffic on I-80 is no longer routed over I-480 and past the merge point under study.

While the completion of the I-80 route to the south of this location should remove the I-80 traffic from the location of this study, the I-480 route remains an important link between the Omaha and Council Bluffs central business districts and is also a connection between Omaha and Interstate 29 in Council Bluffs. Commuter traffic remains quite heavy.

Design Parameters and Limits

When designed in 1962, it was estimated the I-480 bridge would carry an immediate average daily traffic of 30,830 vehicles. Projections for 1984 were an average daily traffic figure of 76,000 and a design hour volume of 8,665. Table I-1 is a comparison of estimated and actual traffic volumes. Further design input listed the number of trucks to be 4 percent of the total volume, a directional split of 63 percent, and the design speed was set at 50 miles per hour. The combined population of the municipalities connected by this section of urban freeway was approximately 360,000 at the time of design.

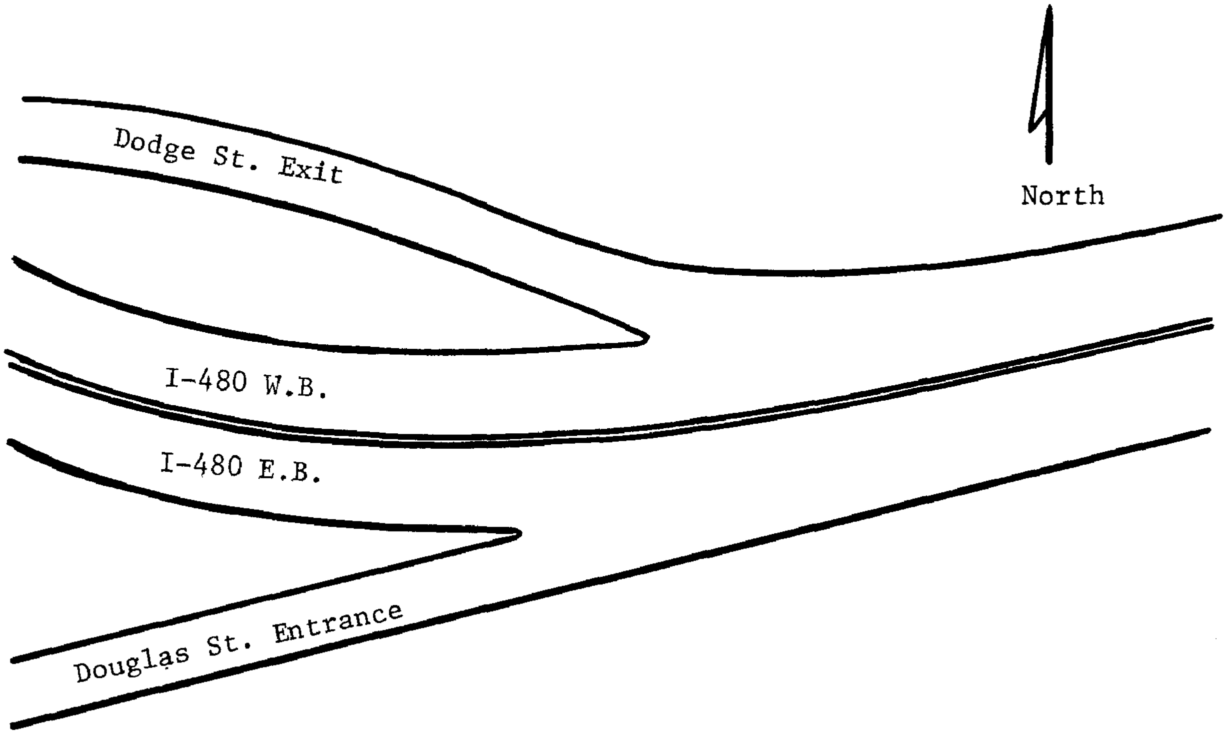
In addition to these design criteria, location of a railroad track leading to the docks of several warehouses along the Missouri River in

TABLE I-1

ESTIMATED AND ACTUAL ADT VOLUMES

Year*	Dodge St. Exit	Through I-480	Douglas St. Entrance	Total
1962	15,415	-	15,415	30,830
1970	23,000	-	23,000	46,000
1971	11,500	22,100	13,400	47,000
1973	-	-	-	40,000
1984	-	-	-	76,000

*1962 - Estimated traffic at time of construction
1970 - As counted before through I-480 lanes opened
1971 - As counted after through I-480 lanes opened
1973 - As counted after parallel I-80 route opened
1984 - As projected at time of design



LOCATION OF VEHICLE VOLUME DATA

Omaha placed special restrictions on the elevation of the lower end of the ramp. (See Figure I-1.)

Final Design Configuration

In order to carry the heavy interim traffic consisting of all eastbound bridge traffic, a two-lane entrance ramp with 15-foot lanes was decided on. The ramp was designed to merge with the three-lane elevated section of I-480. The bridge itself is of sufficient width (96 feet) to carry only four lanes of traffic in each direction.

In order to cross the railroad tracks at Ninth Street at grade (while maintaining the tracks at the proper elevation for the nearby warehouse docks) and rise to the I-480 bridge level at the merge point, it was necessary to utilize a six percent grade on the entrance ramp. This relatively steep grade with an at-grade crossing, was selected as an alternative to lengthening the ramp to go over the railroad tracks.

The documentation of specific design checks concerning levels of service and minimum geometric standards for this location is almost nonexistent. The configuration can be checked, however, at several points by the use of existing standards at the time of design (1962 - 1964). One of these checks involves determining the desirability of using the relatively short (650 feet) six percent grade. Design standards list a "desirable maximum" ramp upgrade of seven percent. (AASHO, 1957)

At the time, it was realized that while automobiles would have relatively little trouble accelerating from 25 mph on Douglas Street to a comfortable merge speed, the problem for trucks accelerating on the upgrade would be appreciable. While no auxiliary speed-change lane was constructed for the trucks, the two-lane ramp would permit a truck to stay in the right-hand lane, which eventually becomes the added lane on the bridge structure. By the trucks remaining in the right-hand lane, automobiles could use the other ramp lane to attain a speed which would permit them to merge with the through traffic. As noted above, the total number of trucks for the entire configuration was estimated to be only four percent of the total volume.

Snow sensors and heating cables were installed in the ramp at the time of construction to offset adverse climatic conditions. The extent of use of these devices is unknown to this writer.

Another design check involves comparing the capacity of the roadway to actual or projected volumes. During the first step of the staged construction, the entrance ramp design volume of all eastbound traffic was approximately 2,200 vehicles per hour and a two-lane ramp was considered acceptable.

A level of service of operations can be determined based on the future design year and current year traffic volumes. The 1984 design year parameters were estimated to be a DHV of 8,665 and a directional split (D) of 63 percent. This implies an eastbound design hour volume of 5,450 vehicles (0.63 x 8,665) on the four lanes downstream from the merge point.

At the time of design, the 1965 edition of the Highway Capacity Manual was not yet in use but is referred to in this section for a relative comparison. Table 9-1 of the above publication gives a maximum service volume of 5,600 vehicles per hour for a 70 mph average highway speed and a Peak Hour Factor of 0.77 at Level of Service "D." Because the level of service criteria in the Highway Capacity Manual is based on the reduction in operating speed incurred by increased traffic volumes, adjustments must be made for attainable average highway speeds less than the base value of 70 mph. While the design speed of the configuration is 50 mph, the weighted average highway speed for the overall highway facility is estimated to approach 60 mph. Applying this value to Table 9-1 (HCM) gives a maximum service volume of 4,900 vehicles per hour at Level of Service "D." This indicates that because the projected volume is greater than the maximum service volume at "D," the Level of Service will be "E" (nearing full capacity) by 1984.

In addition to this "across all lanes" volume check, the merge capacity can also be calculated using current methods. By following the method described on Page 226 of the 1965 Highway Capacity Manual a ramp volume of 2,630 and a through volume of 2,820 gives a merging volume of 1,900 vehicles. This is slightly less than the full capacity volume for merging of 2,000 vehicles per hour. From these checks it appears that the design configuration will be operating at Level of Service "E" by the future design year (1984).

Similar checks can also be performed to determine the level of service for the most recent complete traffic data as collected in December, 1972. By assuming that the hourly volume is proportional to the ADT, a total hourly volume of 5,360 may be calculated. Applying the 63 percent directional split leaves an hourly volume of 3,390 vehicles eastbound. The maximum service volume is 2,880 at Level of Service "C" and 4,900 at Level of Service "D," indicating that in 1972 the design configuration was operating at Level of Service "D." Since this time the opening of a parallel route has reduced these volumes sufficiently (see Table I-1) to revert to Level of Service "C."

The closing of one of the through lanes (Figure I-6) eliminates the need for determining the merging characteristics as calculated for the design year. The number of lanes up- and downstream from the original merge point are now equal.

Evaluation of Operating Characteristics

While functioning as the only entrance to I-480, this design configuration worked quite well, even with the average daily traffic reaching approximately 23,000 vehicles.

With the opening of the through lanes of I-480 the ramp volume was reduced to an average daily traffic of 13,400 vehicles. It was apparent, however, that traffic from Douglas Street was having some difficulty seeing and merging with the through I-480 traffic. Evidence of this came to light mostly in the form of public expression of concern over "close calls" at this location.

There appeared to be two causes of the merging problem:

1. The six percent grade, coupled with the parapets on the ramp and elevated section of roadway, prevent the two streams of traffic from seeing each other until they are very near the merge point.
2. Shortly downstream from the merge point, the width of the bridge is sufficient for only four lanes of traffic. Since the two-lane ramp merges with three through lanes, this necessitates a lane drop very near the merge point.

With this configuration, during peak volume periods when vehicles occupied the three through lanes a majority of the time, the addition of two lanes of merging traffic without proper warning created a major problem. This was compounded by the reduction in the number of lanes from five to four shortly after the merge.

A review of the accident records indicates that since the opening of I-480 to through traffic in November, 1970, five reportable accidents occurred which were directly related to the merge problem. Figure I-5 is a collision diagram showing the relative location and circumstances of these accidents. The relative infrequency of accidents in comparison to the adverse public opinion may be due to the behavior of the drivers during peak traffic hours when the amount of merging traffic is highest. At this time the bulk of the ramp traffic is comprised of commuters who are somewhat familiar with the problem and possibly exercise more caution than someone who is less well acquainted with the location.

Other indications of traffic problems at this location are limited. The utilization of erratic maneuver or similar studies is greatly hampered by the lack of an observation post from which the merging traffic may be viewed.

Remedial Action

Faced with what they considered to be a legitimate public complaint, Nebraska Department of Roads officials set about determining what remedial action could be taken. Relying on operational changes only, the decision was made to close one lane of either the ramp or through roadway in order to move the lane drop to a less hazardous location. Because the two-lane ramp had been initially designed to carry the total I-480 eastbound traffic and now was carrying only local merging traffic, a first consideration was to close a lane of the entrance ramp. Before making any changes,

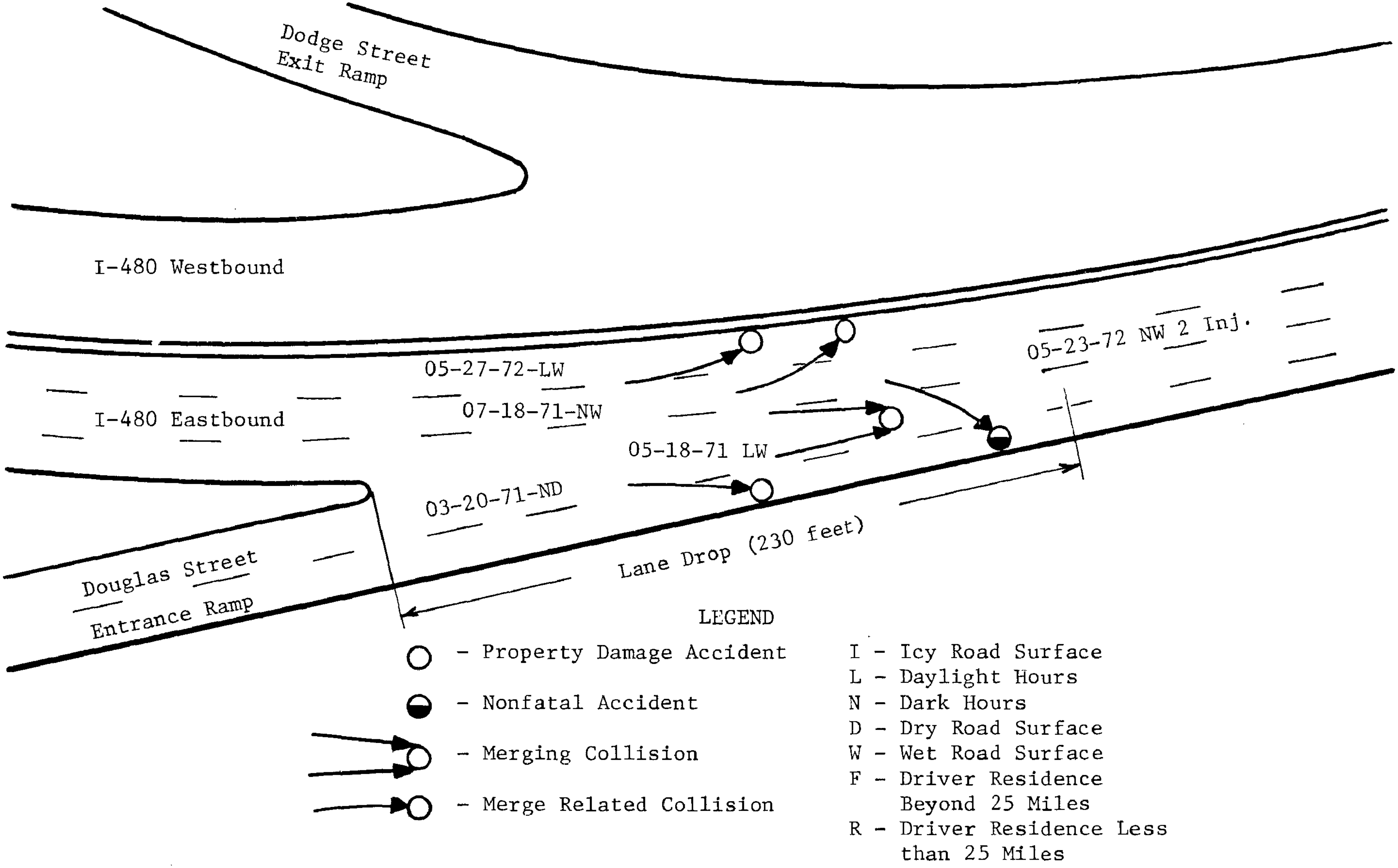


FIGURE I-5. Collision Diagram

however, an eight-hour volume count by lane was performed at the merge point. The results of this traffic study are shown in Table I-2. As expected, the 4:00 p.m. to 5:00 p.m. and 5:00 p.m. to 6:00 p.m. periods reflected a heavy commuter traffic flow.

Examination of the traffic volumes by lane indicated that, contrary to what had been expected, the through lane closest to the merging traffic was actually carrying a relatively light traffic volume. This was probably due to the tendency of local drivers to avoid the right-hand through lane which was affected most by the merging traffic.

Based on these traffic counts it was decided that closing of the low volume lane of I-480 would not appreciably degrade operations on the through roadway and would be a better solution than creating a single lane entrance. Late in 1972 pavement markings and signs were installed to discourage drivers from using the I-480 lane nearest the entrance ramp. The changes are shown in Figure I-6. Sufficient time has not passed since then to adequately judge the effectiveness of these changes.

TABLE I-2

HOURLY VEHICLE VOLUMES

at I-480 EB & US-6/75 EB (Douglas Street)
Omaha, Douglas County, District 2
Wednesday, May 31, 1972

Time	South Lane	North Lane	Total	South Lane	Center Lane	North Lane	Total	Total
11am-12	448	264	712	156	384	185	725	1437
12-1	453	277	730	123	398	172	693	1425
1-2	478	287	765	119	387	215	721	1486
2-3	529	304	833	124	406	211	741	1574
3-4	503	364	867	127	592	339	1058	1925
4-5	999	771	1770	176	1049	674	1899	3669
5-6	885	650	1535	220	832	545	1597	3132
6-7pm	397	230	627	204	558	232	994	1621
Total	4692	3147	7839	1249	4606	2573	8428	16267

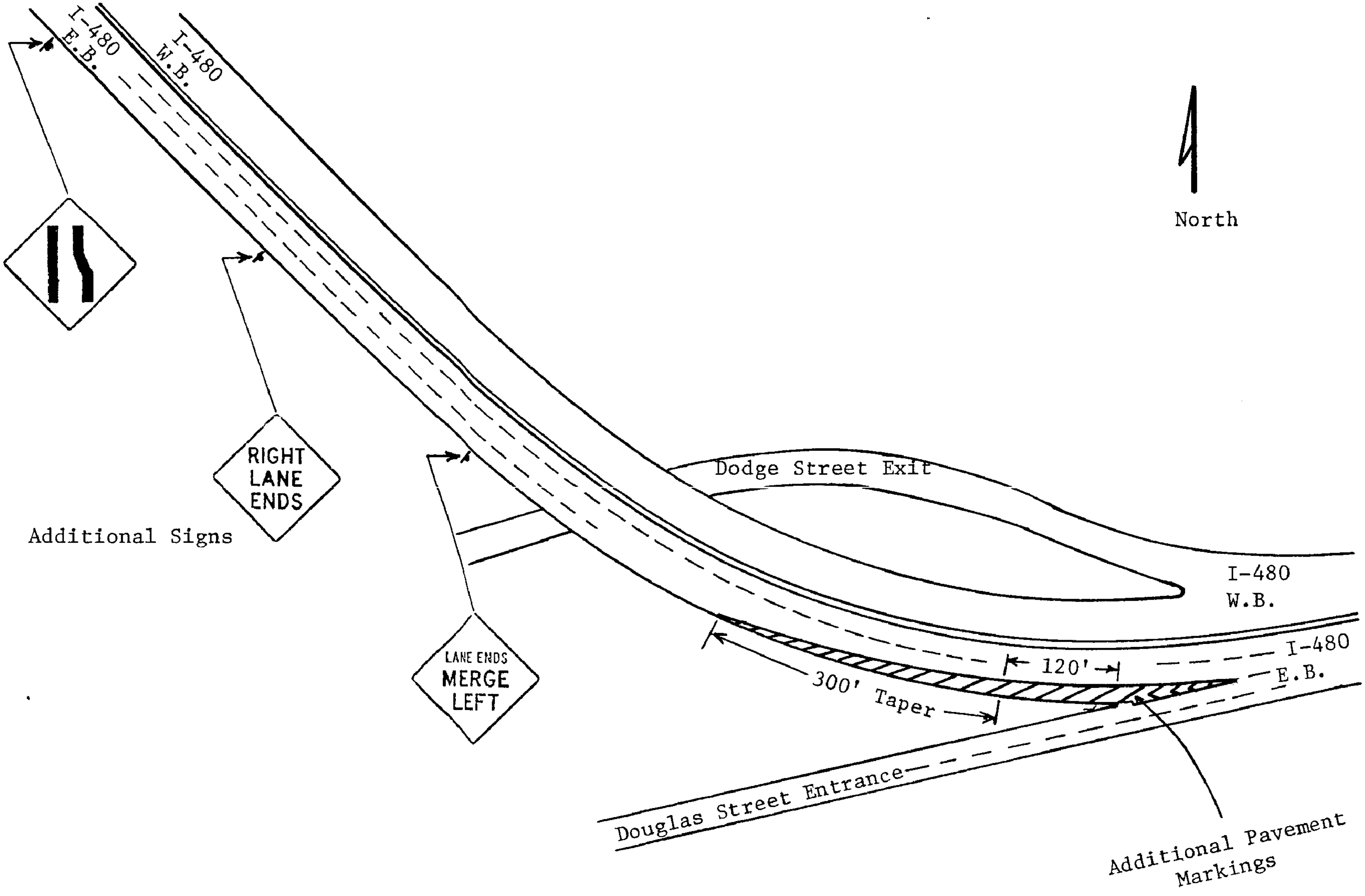


FIGURE I-6. Corrective Measures

FACT SHEET FORMAT DEVELOPMENT

Using the above study as an example, a concise format for assembling the assorted information can now be proposed. This format should include the information needed for indexing, comparing, and evaluating the design configuration.

Indexing Information

It is this writer's purpose to suggest a form for the index rather than construct the entire indexing system. Suggestions for further study concerning an indexing system are given in the Comments and Conclusions section.

Two subsystems should provide access to these individual case studies. The first of these will essentially group all design configurations by type. For example, all experiences dealing with left-hand exits would be titled: "Exits, Left-Hand" and filed as such.

The use of key words will provide a reference system concerning design considerations rather than design configurations. For example, the fact sheet user may wish to review all cases involving sight distance problems on entrance ramps. Rather than reviewing all cases filed under "Entrance Ramps," he could instead find "Sight-Distance" and "Entrance Ramps" in the key word index and thereby select only those entrance ramp cases where sight distance was evaluated.

Comparative Information

The next portion of the case study review should contain the necessary information for the designer to be able to compare his design situation with that of the case study.

Before listing some of these items it may be appropriate to discuss two types of design criteria. The concept of this paper is based on the need for supplying information on peer design experience to the individual who has encountered a new problem in freeway design. These problems usually arise when some constraint is placed on the design project, such as a heavy turn volume, lack of adequate right-of-way, or some similar situation. It is at this point that standard design features, such as right-hand exits and entrances and single-lane entrances, must be abandoned because they do not satisfy the existing conditions. For this reason it is obvious that in addition to the "General Design Features," these limiting conditions, referred to in this paper as "Special Conditions," must be included in the reporting format.

Listed as General Design Features should be projected traffic volumes, proximity of upstream and downstream exits and entrances, percentage of trucks, directional split information, design speeds and the number of lanes downstream and upstream. Also included should be information concerning the general area (such as whether it is urban or rural) and the type of traffic expected (such as the proportions of commuter or through traffic). These general criteria for the Omaha study are listed in the section entitled General Design Features in the fact sheet at the end of this appendix.

The special conditions for this study were twofold. First, due to staged construction the entrance ramp was designed as a two-lane ramp to initially carry the entire eastbound bridge traffic prior to construction of the through roadway upstream. Secondly, the grade on the entrance ramp was governed by the elevations of the railroad tracks at the bottom of the ramp and the elevated roadway at the top. These points are discussed in the Final Design Section above and are summarized on the "Fact Sheet."

The specific design criteria listed in the "Fact Sheet" for the Omaha study are probably not sufficient to describe all types of design configurations (i.e., lane drops, left exits, etc.). To list all possible design criteria is beyond the scope of this study. What is intended here, however, is an attempt at ordering the types of information that would go into the preparation of a fact sheet.

Final Design Description

After listing the design parameters the final design configuration should be described. Dimensions and distances should be included if they are critical in describing the configuration. In addition to this description, a sketch or photograph should be added to further clarify the situation.

Operational Evaluation

The next section of the fact sheet should contain an appraisal of how the design configuration performed after being opened to traffic. This assessment may have to be of a subjective nature, based upon the opinion of various highway officials. Other than these opinions, very little evidence is usually available on which to judge the adequacy of a design configuration. The determination of adequacy is suggested by this author as subject matter for further study.

If the design is determined as adequate, this "fact" would be entered on the fact sheet and this portion of the fact sheet would be complete.

However, if the design operated less than optimally, the fact sheet should contain information concerning how it was judged as such and what if anything was done to correct the situation. In general, it appears that public opinion and a high accident rate may be the predominant indicators of a lower performance design configuration. Other factors such as the results from erratic maneuver or "near miss" studies will provide further operational information, if available.

After listing the problems incurred, any remedial action taken to improve the situation should be explained. In the Omaha study, for example, traffic was discouraged from using one of the lanes of the through roadway (I-480). This action was determined on the basis of a lane-by-lane vehicle count which indicated that the closing of the one through lane would not hamper the freeway's operation appreciably.

Ideally, a subsequent evaluation of the "success" of the remedial measures would follow. In this instance the data are not yet available.

Lessons Learned

The final section of the fact sheet should contain the designer's comments concerning what he felt was learned in this design experience. These comments may refer to both better-than-expected and worse-than-expected results, and should treat individual design considerations such as sight distance, grades, lane drops, etc.

COMMENTS AND CONCLUSIONS

Further Study Needs

While this appendix sets forth a format for the Fact Sheet, further study will be needed before this system can be put into use. This will include developing a system for indexing all design configurations and preparing a list of key words for referencing specific design considerations. A pilot study in which several Fact Sheets are prepared and then distributed to designers throughout the profession for their criticism may be required to assess the potential benefits.

Conclusions

The success of this type of design aid is dependent on several factors. Each Fact Sheet must contain sufficient information to describe the design configuration fully. From the sample study it is apparent that the amount of information available decreases with time due to changes in key personnel and a general lack of documented design decisions. For this reason the analysis of a design configuration should be performed as soon as possible after it has been implemented in order to preserve the details concerning design decision. Also, the organization which will be needed for assembling, publishing and distributing the Fact Sheets may wish to supply data collection teams to ensure the quality and consistency of the reports.

Participation in the program must be on a large scale basis to provide a sufficient number of comparative reports on all types of design configurations.

EXAMPLE FACT SHEET 1

Entrance Ramp, Two Lane

Location:

- US 6/75 (Douglas Street) entrance ramp to Route I-480 at Missouri River Bridge connecting Omaha, Nebraska, and Council Bluffs, Iowa.

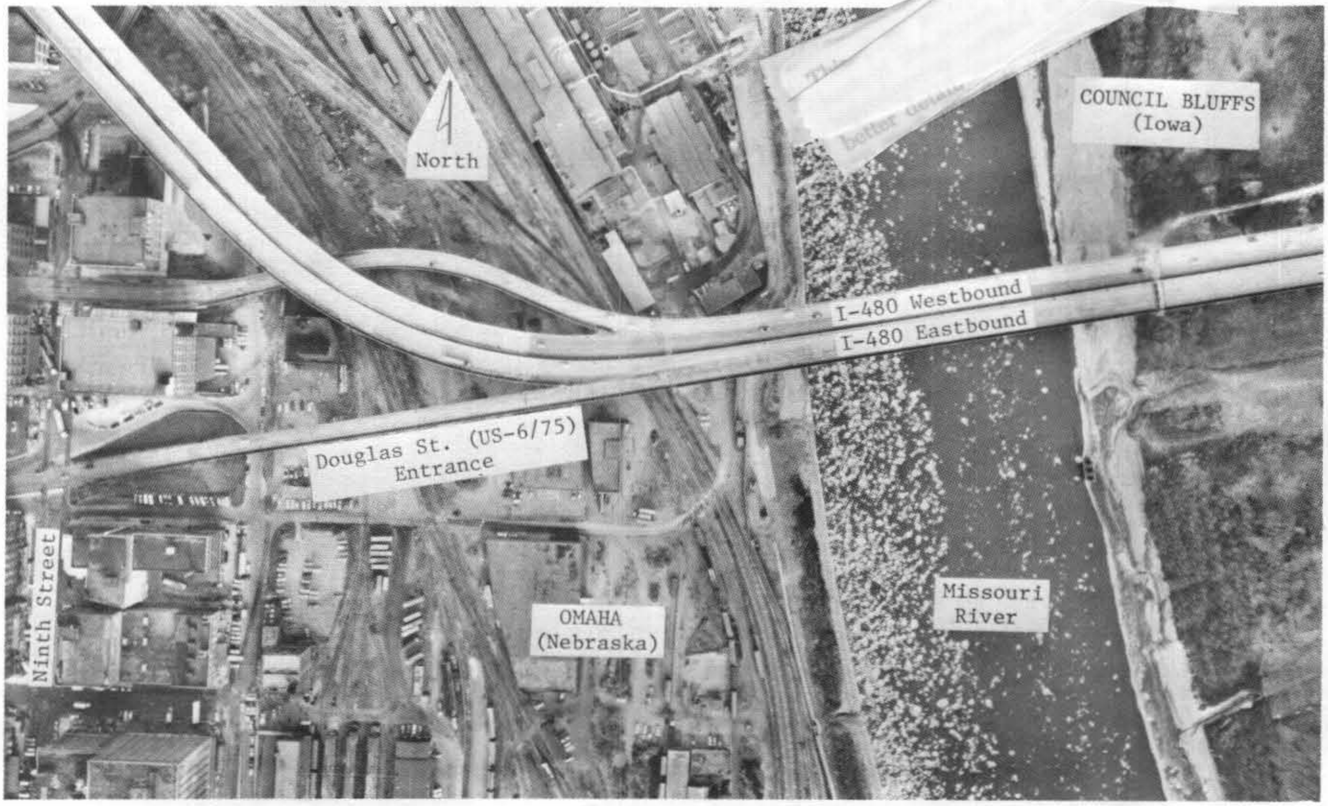


Figure 1. Location

General Design Features:

- Average Daily Traffic on the bridge at the time of design (1962) -- 30,830 vehicles. All eastbound traffic to be carried solely on the entrance ramp.
- Projected volumes for 1984 -- ADT of 76,000 and DHV of 8,665. Entrance ramp DHV of 2,630.
- Trucks = 4%
- Directional Split = 63%
- Design Speed, through road = 50 mph
- Nearest Exit -- 0.35 miles downstream
- Nearest Entrance -- 0.39 miles upstream

- Area Type -- Urban with heavy commuter traffic
- Combined population of muncipalities = 360,000

Special Conditions:

- Due to staged construction, the entrance ramp was required to carry all eastbound bridge traffic until completion of the upstream through lanes.
- The bridge is limited to four lanes in each direction.
- The elevation of the bottom and the length of the entrance ramp were dictated by the location of railroad tracks at Ninth Street at the beginning of the ramp. (See Figure 1.)

Final Design:

- See Figure 1.
- The ramp is on a 6% upgrade and has two 15-foot lanes.
- There are three through lanes prior to the merge and four lanes, total, after the merge.
- There are 3-ft. solid parapets along both the elevated freeway and bridge.

Operational Evaluation:

- After the through lanes were opened, a merging problem was created by the limited sight distance; a result of the grade on the entrance ramp and the parapets on the roadways.
- The reduction in the number of lanes soon after the merge point added to the problem. Evaluation based mainly on public opinion and accident records. (Figure 2 shows the accidents definitely traced to the merging problem.)

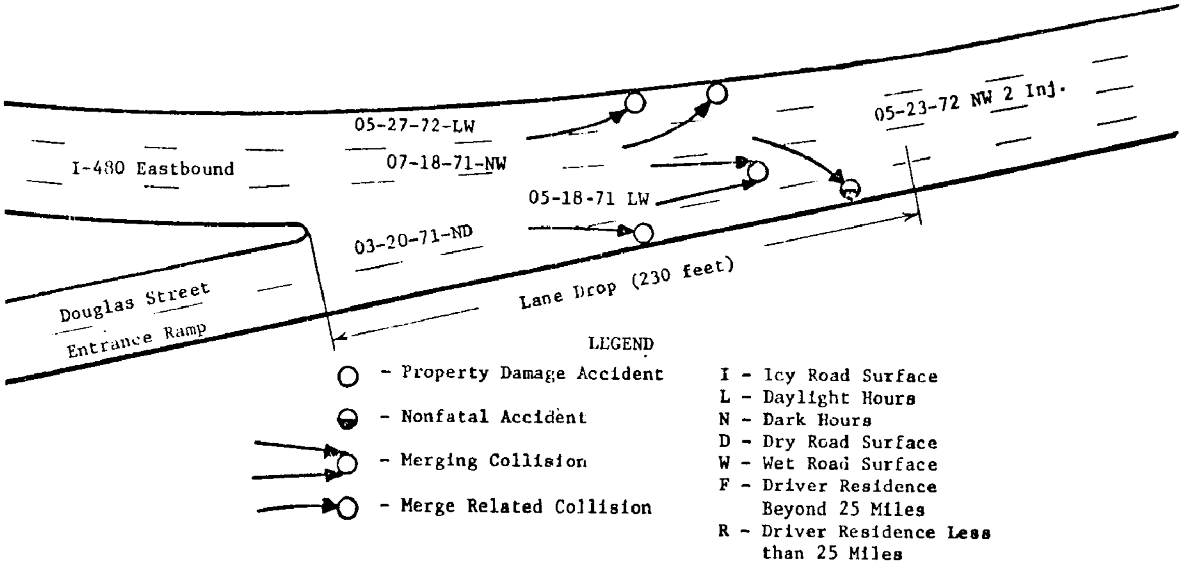
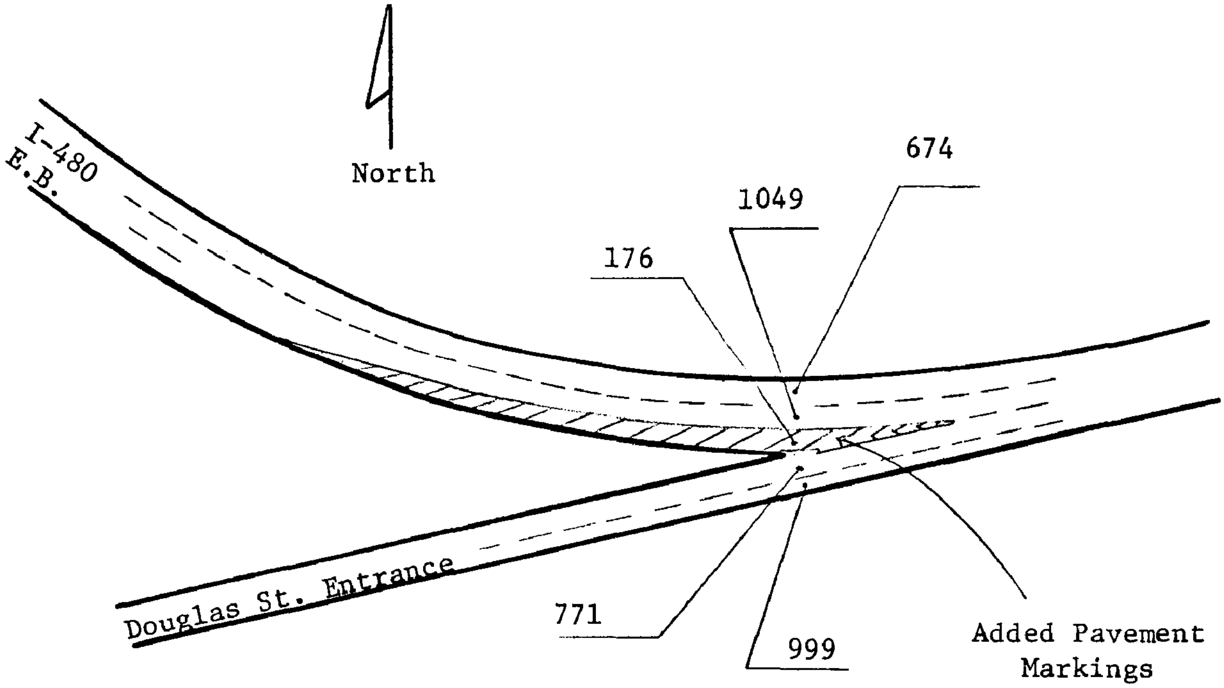


Figure 2. Collision Diagram

Remedial Action:

- A lane-by-lane vehicle volume count was made to determine the actual traffic distribution. The results of this count are shown in Figure 3.
- Based on this traffic data, pavement markings and signs were installed to discourage through I-480 traffic from using the lane nearest the entrance ramp. The pavement markings are shown in Figure 3.



Afternoon peak-hour volume counts before pavement markings were added.

Figure 3. Volume Counts and Corrective Measures

Evaluation After Remedial Action:

- Not available at this time.

Lessons Learned:

- Lane Drop. The lane drop very near the merge point (see Figure 2) was unsatisfactory. A decision on a second maneuver (lane change due to lane drop) was required immediately after completion of the first maneuver (merge), with virtually no time for information processing. Remedial action at this location included moving the lane drop -- eliminating the merge. (See Figure 3.)
- Grades, Entrance Ramp. The relatively steep grade (six percent) was a major factor in the unsatisfactory operations. It added to the merge problem created by the restricted sight distance and sudden lane drop.

- Sight Distance. Sight distance at the merge point was not sufficient. It was restricted by the use of parapets on the entrance ramp and elevated through roadway. This problem was compounded by the fairly steep (six percent) grade on the entrance ramp.

- Entrance, Two Lane. The two-lane entrance ramp did not function adequately. It might have functioned better if the lane drop had been moved further downstream and the rear and forward sight distances had been longer.

Key Words for this Fact Sheet:

- Entrance Ramp
- Grade
- Lane Drop
- Sight Distance
- Two-Lane Entrance

EXAMPLE FACT SHEET 2

Cloverleaf Interchange Complex

Location

A full cloverleaf interchange with collector-distributor roads was selected for the interchange at the intersection of three highways (Interstate 270 and Illinois 203 and U.S. By-Pass 40 and 66) and four railroad tracks, at essentially the same point. See Figure 1 on page I-38 for a general highway map of the area surrounding the interchange. The map was made in 1965.

General Design Features

The highways in the area are still essentially the same. A few new residences and two mobile home parks (approximately 200 units) have been built in the immediate area of the interchange since the map was made. There are now no service facilities in the immediate area surrounding the Interstate 270 and Illinois 203 Interchange; but there are several service facilities at the interchanges of Interstate 270 and Illinois 3 and Interstate 270 and Illinois 111, which are 1.7 and 1.5 miles respectively from the subject interchange. Interstate 270, the Illinois 203 Interchange, and the Illinois 3 Interchange were opened in 1962; and the Illinois 111 Interchange was opened in 1963. Granite City, which is two miles south of Interstate 270, is the predominant city in the immediate area of the interchange. Interstate 270 is the north by-pass around St. Louis, Missouri. (The Interstate 270 and Illinois 203 Interchange is four miles east of the Mississippi River.) The terrain in the area is level.

See Figure 2 on Page I-39 for a plan of the subject interchange. Before Interstate 270 was opened to traffic, U.S. By-Pass 40 and 66 was the dominant east-west route in the area (it is now primarily a local and service road, its bridge across the Mississippi River is closed; the route is designated as FAP 5 on all figures contained in this report). In addition to providing route continuity to both the Illinois 203 and FAP 5 traffic and access to Interstate 270, the particular interchange also serves some of the local traffic.

The particular design incorporated is unique in this area because of the collector-distributor roads, and the primary purpose the roads serves (i.e., continuing Illinois 203 and FAP 5 through the Interstate without having to utilize an at-grade railroad crossing for them, either before, or after, crossing Interstate 270). The interchange is several miles from the heavily populated areas near St. Louis, and the curbed islands between the Interstate and the collector-distributor roads are unusual for this area.

The Interstate 270 and Illinois 203 Interchange was not chosen for evaluation because it was known as a problem location; rather, it was studied because of its uniqueness.

Volumes

See Figure 3 on Page I-40 for the composite 1971 average daily traffic at the subject interchange and two other near-by interchanges, also on Interstate 270. The ADT's at the two near-by interchanges (at Illinois 3 and Illinois 111) are also given to aid in explaining the traffic distribution in the area. 1971 ADT's are used because accident data are also from, and prior to, 1971.

The following comments pertain only to the subject interchange. The east-west traffic distribution on Interstate 270 is almost equal. The Peak Hour Design Volume is 12% of the ADT. The percentage trucks on Interstate 270 varies from almost 50% of the total traffic during the early morning hours to as little as 8% during peak hours; the percentage is taken as 12% during the design hour. On Interstate 270, approximately 25% of the ADT is trucks. The truck percentage on Illinois 203, FAP 5, the collector-distributor roads, and the ramps is much less than on Interstate 270. Although the ADT on Interstate 270 increased over 75% between 1966 and 1971, the ADT's on Illinois 203 and FAP 5 decreased.

Speeds

See Table 1 on Page I-41 for posted and observed speeds. The interstate spot speed study was not conducted at the subject interchange; however, the people responsible for the operation of the Illinois 203 Interchange feel that a study there would yield essentially the same results (they cited the "unwritten law" by which law enforcement officers allow drivers 5 MPH over the posted speed limit). The speed study was conducted at a site near the subject interchange, and was made during the daytime.

Levels of Service

On Interstate 270, level of service B exits throughout the interchange during the peak periods (level of service A is present during most of the day). For the merging of the collector-distributor roads and the interstate, level of service A exists; and for the diverging of the interstate and the collector-distributor roads, level of service A is also present. The service levels for the remainder of the interchange are comparable to those which exist on the Interstate.

Horizontal Curvature

See Table 2 on Page I-43 for horizontal curve information. Curve data is shown for the Interstate 270 main lines, the ramps, and pertinent points on the collector-distributor roadways. In this area, because of occasional snow and ice in the winter months, a maximum superelevation rate of 0.08 foot per foot is used. The superelevation rates used for some of the curves appear to be a little low; however, the entire interchange is comfortable to drive at the posted speeds, and no apparent problems attributable to the low rates have been discovered.

Vertical Curvature

See Table 3 on Page I-44 for vertical curve information. The elevations of the collector-distributor roads are controlled by the Interstate 270 roadways, and thus differ in elevation from the roadways only because of transverse slope. Adequate stopping sight distance has been provided throughout the interchange.

Roadway, Ramp, and Shoulder Widths

See Table 4 on Page I-45 for roadway, shoulder and ramp widths. Width information is shown only for particular cross-sections where a significant change occurs, or terminates. Note that the collector-distributor roads are 22 feet wide between the center two ramps on each side of the Interstate.

Acceleration and Deceleration Lanes

Deceleration lanes 580 ft. long are provided for the exiting Interstate traffic, and 800 feet acceleration lanes are provided for the entering traffic.

Signing

On Interstate 270, there are "Illinois 203 -- Granite City -- Exit 3/4 Mile" and "Illinois 203 -- Granite City -- Right Lane" signs on both approaches to the interchange (the latter signs are about 1,000 feet from the beginnings of the deceleration lanes). Signing for each of the six exits (from Interstate 270 to the collector-distributor roads and from the collector-distributor roads to the ramps) is mounted on trusses. See Figure 5 on page I-46 for the locations of the six trusses, and see Figure 6 and 7 on pages I-48 and I-49 for photographs of four of them. The signs on the trusses are illuminated at night. On Interstate 270 and the collector-distributor roads, all of the route and destination signs pertain to Illinois 203 and Granite City.

The signing for the remainder of the interchange is also good; and considering the fact that there are four connecting legs to the interchange, the total number of signs have been held to a practical limit. The signing which now exists at the interchanges of Interstate 270 and Illinois 203, Illinois 3, and Illinois 111, was installed under a single contract in 1965.

Accidents

See Table 5 on page I-47 for 1971 accident data, and see Figure 5 on page I-46 for accident locations for 1970 and 1971. A property damage accident is any reported accident in which an injury or fatality does not occur; and a personal injury accident is any accident in which at least one person complains of an injury, but no fatalities occur. Of the sixteen accidents which occurred at the interchange in 1971, seven were property damage only, eight involved personal injury, and there was one fatal accident (in which a pedestrian was involved). Also, of the sixteen accidents, twelve occurred on Interstate 270, one occurred on a ramp, and three were recorded on the connecting roads.

For 1970, there were six property damage and seven personal injury accidents at the interchange. Of the total of thirteen, seven occurred on Interstate 270, two occurred on ramps, three were on the connecting roads, and one was on a collector-distributor road. In 1969, there were nine property damage, one personal injury, and one fatal accident (nine of the accidents were on Interstate 270, and the other two were on the connecting roads). In 1968, there were seven property damage and four personal injury accidents (ten occurred on Interstate 270 and the other one occurred on a connecting road).

Comments

Comments by all the people contacted concerning the operation of the interchange were favorable. A state trooper said that most of the people who used the interchange were from the local area, and thus were familiar enough with its operation that very few problems existed.

The responsible traffic engineering people were very satisfied with the operational qualities of the interchange. They feel the interchange will satisfactorily handle several times the present traffic volumes.

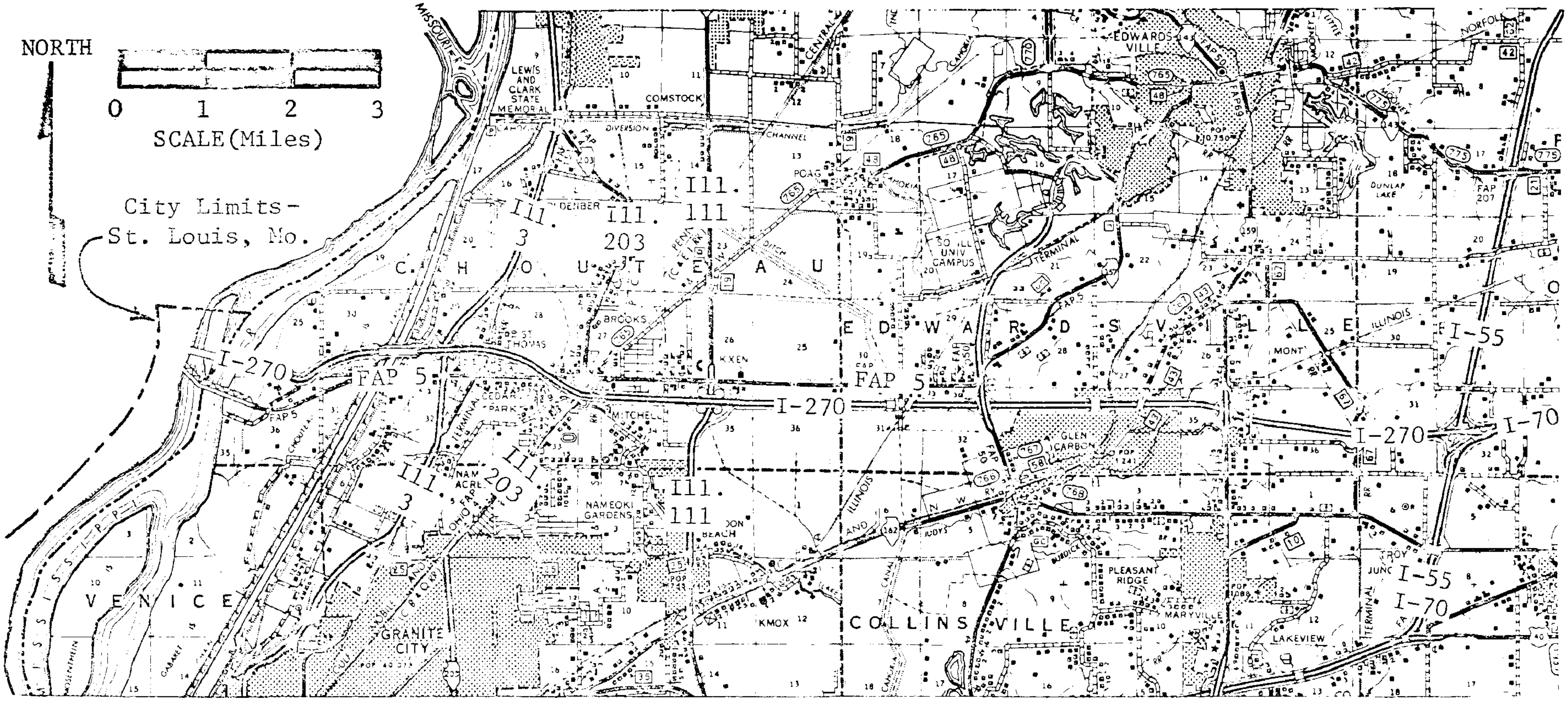
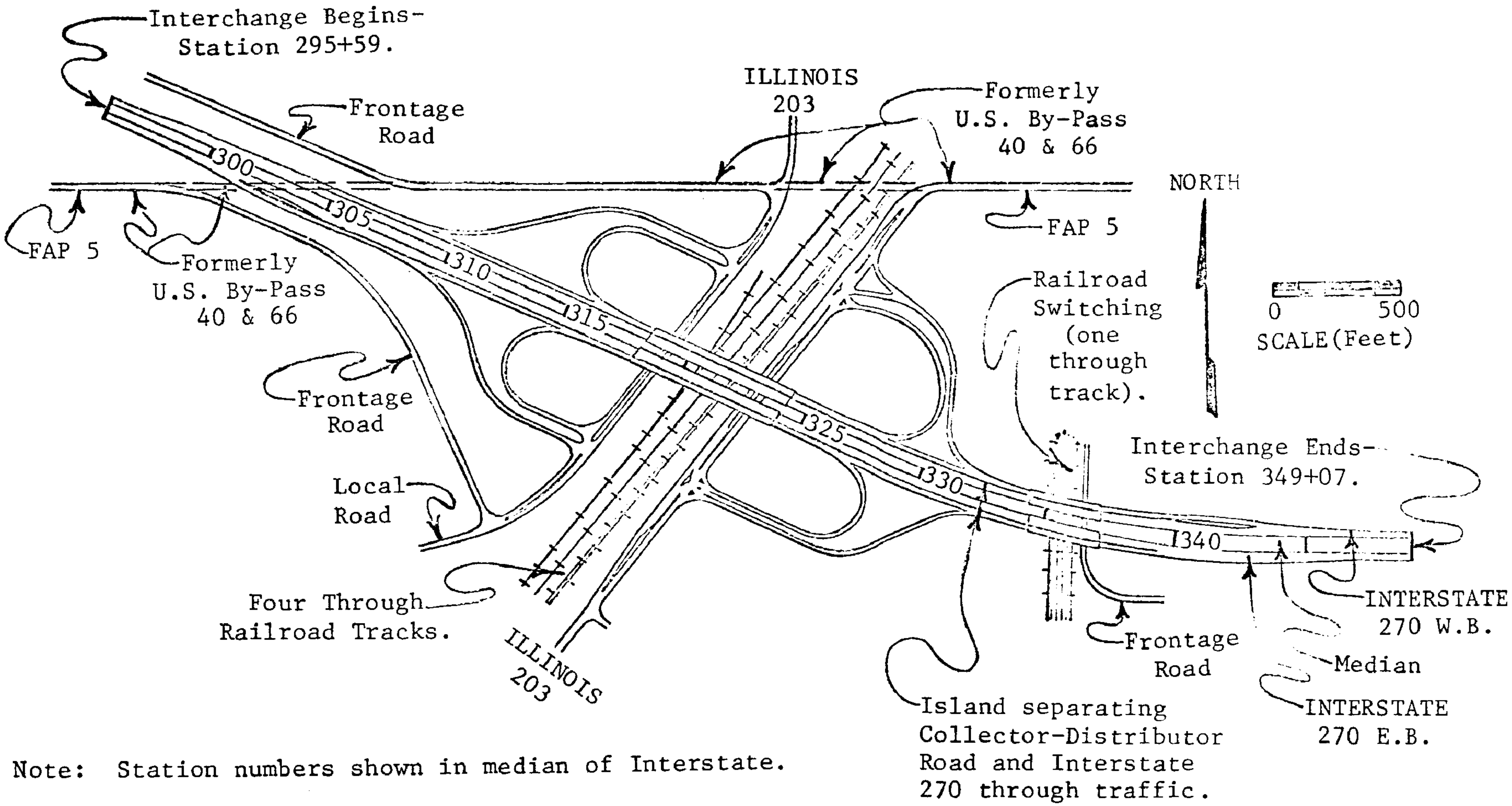
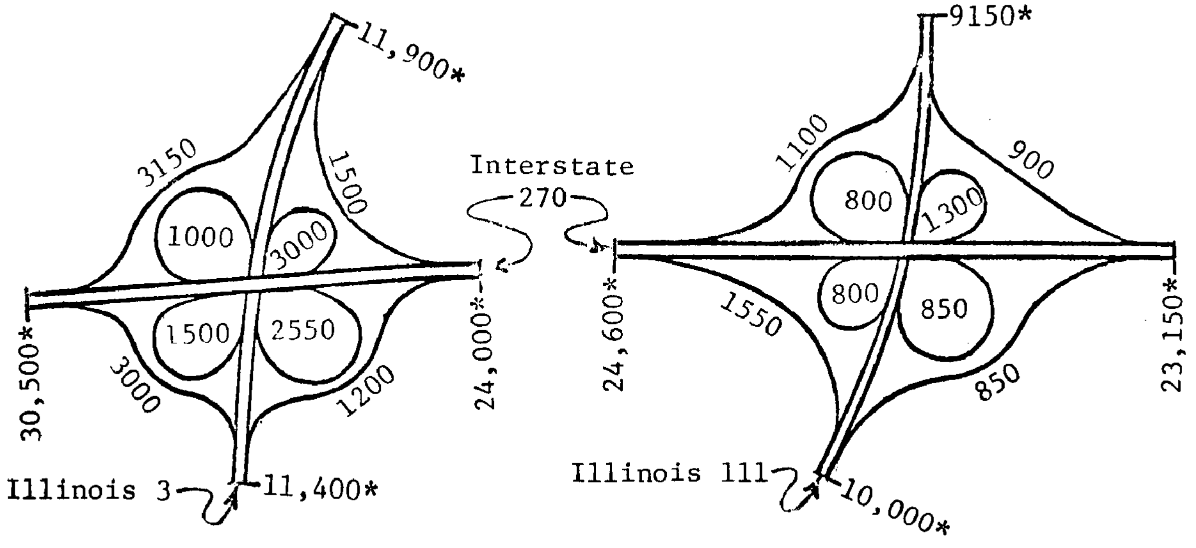


Figure 1. General Highway Map of Area Surrounding Interstate 270 and Illinois 203 Interchange



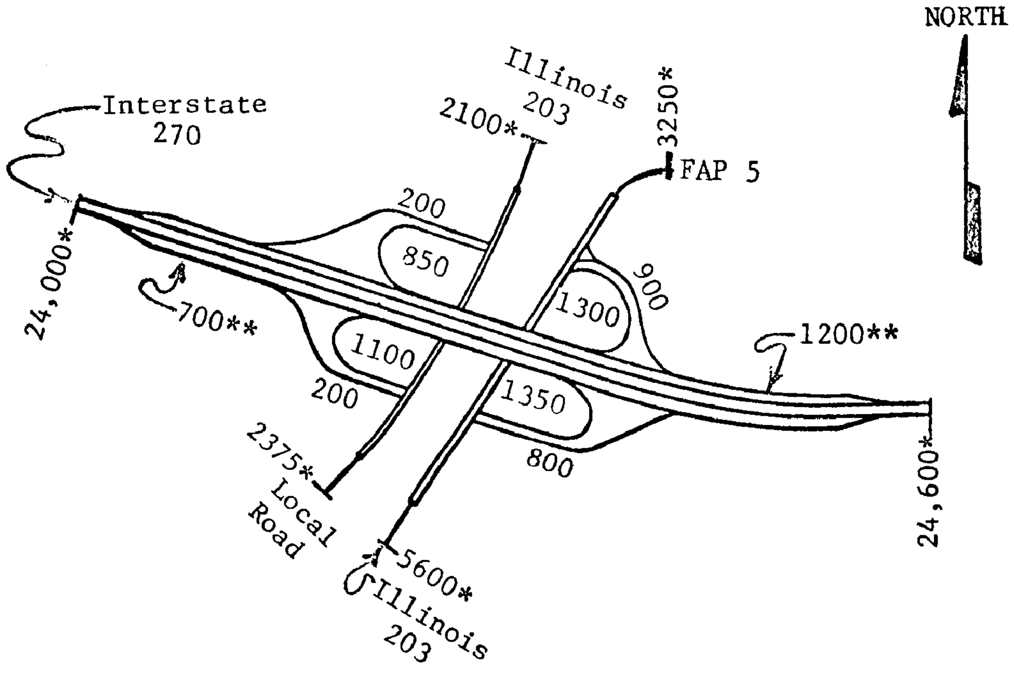
Note: Station numbers shown in median of Interstate.

Figure 2. Plan of Interstate 270 and Illinois 203 Interchange



Illinois 3 Interchange

Illinois 111 Interchange



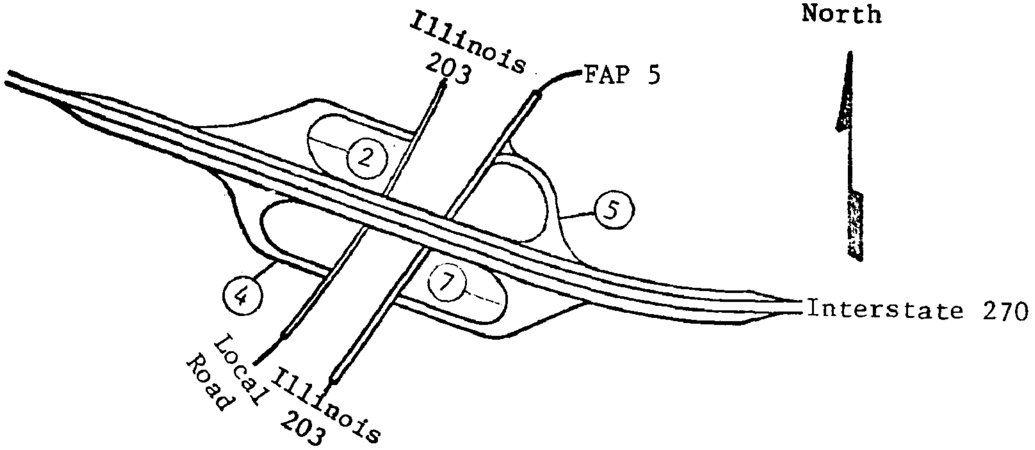
Illinois 203 Interchange

* Both Directions Combined.
** On Collector-Distributor Road.

Figure 3. Composite 1971 Average Daily Traffic

TABLE 1

POSTED AND OBSERVED SPEEDS

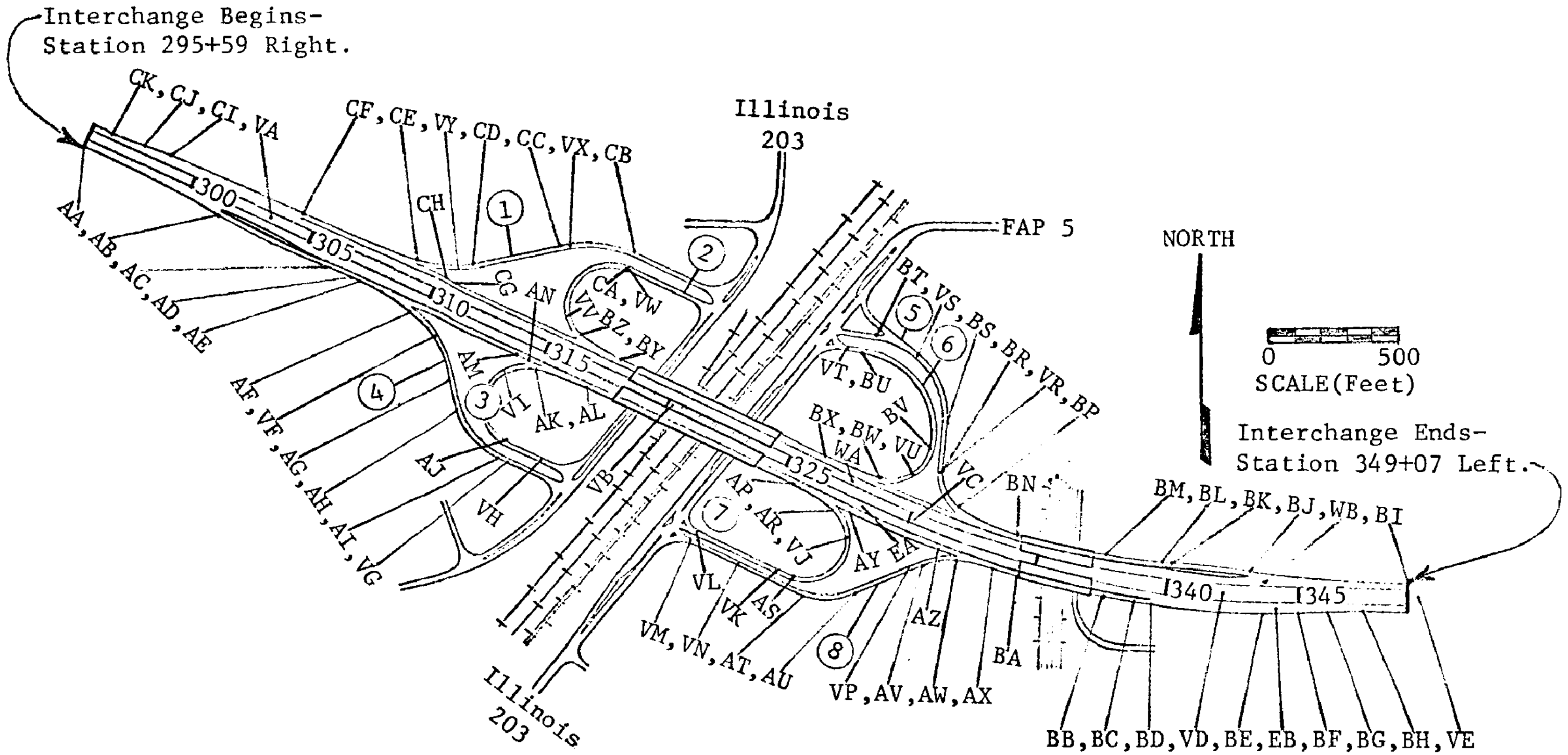


Interchange Plan

Posted Speeds	
Location	Speed (MPH)
Interstate 270	70*
C-D Roads	50
Ramp 4	35
Ramp 7	25
Ramp 5	25
Ramp 2	25

*55 MPH for trucks over 4 tons and vehicles towing trailers.

Observed Interstate Spot Speeds			
	Speed (MPH)		
Percentile	Passenger Cars	All Vehicles	Trucks Over 4 Tons
15th	61.9	57.8	
75th	73.5	71.9	
85th	75.8	74.7	68.6
Average Speed of all Vehicles = 65.7 MPH.			



Notes: Circled numbers above (1 through 8) are ramp numbers.
Station numbers shown in median of Interstate.

Figure 4. Plan of Geometric Design

TABLE 2

HORIZONTAL CURVE DATA

Curvature Point*	Station**	Length (Ft.)	Radius (Ft.)	Super-elevation (Ft./Ft.)
AA=PC	295+59	581	6273	
AB=PRC	301+40	443	2865	
AC=PRC	305+83	119	1910	
AD=PT	307+01			
AE=PC	307+30= 0+00 R4	226	1080	0.06
AF=PCC	2+26 R4	294	430	0.06
AG=PT	5+21 R4			
AH=PC	6+40 R4	277	310	0.06
AI=PT	9+17 R4			
AJ=PC	2+91 R3	456	150	0.08
AK=PCC	7+47 R3			
AL=PT	9+47 R3 =317+04	200	1910	0.08
AM=PC	314+05	50' Rounding		
AN=PT	314+55			
AP=PC	325+60= 0+00 R7	172	690	0.08
AR=PCC	1+72 R7	434	150	0.08
AS=PT	6+06 R7			
AT=PC	5+74 R8	201	230	0.06
AU=PT	7+76 R8			
AV=PC	10+69 R8	135	230	0.06
AW=PCC	12+04 R8			
AX=PT	13+26 R8 =333+48	122	1080	0.06
AY=PC	327+85	350	2981	0.02
AZ=PT	331+28			
BA=PC	334+46	336	3820	0.02
BB=PCC	337+78	115	1174	0.02
BC=PRC	338+90	61	1174	0.02
BD=PRC	339+50	426	3086	0.02
BE=PT	343+69			
BF=PC	344+94	114	1526	
BG=PRC	346+08	136	1526	
BH=PT	347+44			

Curvature Point*	Station**	Length (Ft.)	Radius (Ft.)	Super-elevation (Ft./Ft.)
EA=PC	328+25	1609	3820	0.02
EB=PT	344+18			
WA=PC	327+52	1609	3820	0.02
WB=PT	343+78			
BI=PC	349+07	586	6273	
BJ=PRC	343+20	302	6668	
BK=PT	340+11			
BL=PC	339+76	215	1910	0.02
BM=PCC	337+56	346	3820	0.02
BN=PT	334+06			
BN=PC	334+06= 0+00 R5	236	690	0.08
BP=PCC	2+36 R5	158	150	0.08
BR=PT	3+93 R5			
BS=PC	5+75 R5	465	310	0.06
BT=PT	10+40 R5			
BU=PC	1+91 R6	493	300	0.06
BV=PCC	6+84 R6	251	150	0.08
BW=PCC	9+35 R6			
BX=PT	11+53 R6 =326+13	218	1910	0.08
BY=PC	317+73= 0+00 R2	163	690	0.08
BZ=PCC	1+63 R2	436	150	0.08
CA=PT	5+99 R2			
CB=PC	3+82 R1	279	430	0.06
CC=PT	6+62 R1			
CD=PC	9+94 R1	241	430	0.06
CE=PCC	12+35 R1			
CF=PT	17+01 R1 =304+35	465	6200	0.06
CG=PC	310+80	50' Rounding		
CH=PT	310+30			
CI=PC	298+85	114	1526	
CJ=PRC	297+71	136	1526	
CK=PT	296+35			

*Refer to Figure 4 on page I-42 for curvature point location.

**Stationing is from Interstate 270 centerline unless station number is followed by an "R" and a number which designates a ramp station.

TABLE 3

VERTICAL CURVE DATA

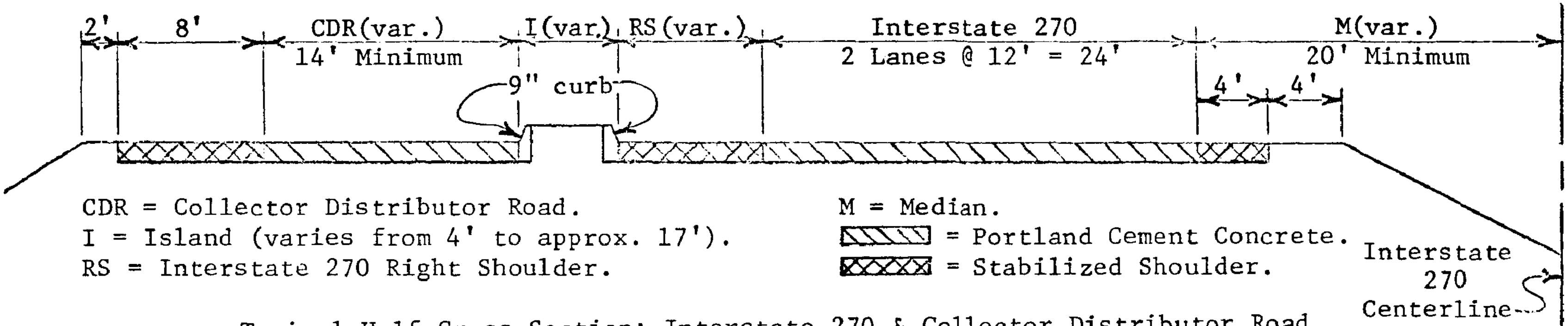
Point of Intersection*	Station**	Elevation (Ft.)	Length (Ft.)	Grade(1) (%)	Grade(2) (%)
VA	303+25	413.40	500	-0.20	+3.00
VB	320+20	464.25	1440	+3.00	-0.72
VC	330+17	457.07	400	-0.72	-0.48
VD	342+15	451.32	1000	-0.48	-3.00
VE	349+56	429.09	400	-3.00	-0.20
VF	3+48 R4	432.47	200	+1.45	-2.07
VG	9+50 R4	420.00	300	-2.07	+2.30
VH	1+50 R3	424.34	240	-1.00	+3.70
VI	6+29 R3	442.06	200	+3.70	+3.44
VJ	2+85 R7	453.33	200	-3.00	-6.00
VK	6+75 R7	429.93	150	-6.00	-3.00
VL	10+00 R7	420.18	120	-3.00	+0.80
VM	1+00 R8	419.65	120	-0.80	+3.00
VN	3+00 R8	425.65	100	+3.00	+4.00
VP	10+15 R8	454.25	200	+4.00	+0.90
VR	3+89 R5	452.55	300	-0.90	-5.50
VS	8+75 R5	425.82	310	-5.50	+0.70
VT	1+34 R6	427.04	180	-0.70	+4.00
VU	7+97 R6	453.56	200	+4.00	+2.05
VV	2+50 R2	444.12	150	-4.85	-5.50
VW	6+00 R2	424.86	350	-5.50	+1.00
VX	6+25 R1	416.86	300	-1.90	+3.41
VY	10+54 R1	431.48	200	+3.41	-1.40

*Refer to Figure 4 on page I-42 for point of intersection location. Points of intersection for curves on Interstate 270 are shown in the median on Figure 4 because both the eastbound and westbound roadways are at the same elevation.

**Stationing is for Interstate 270 unless station number is followed by an "R" and a number which designates a ramp station.

TABLE 4

ROADWAY, RAMP, AND SHOULDER WIDTHS



CDR = Collector Distributor Road.
I = Island (varies from 4' to approx. 17').
RS = Interstate 270 Right Shoulder.

M = Median.
▨ = Portland Cement Concrete.
▩ = Stabilized Shoulder.

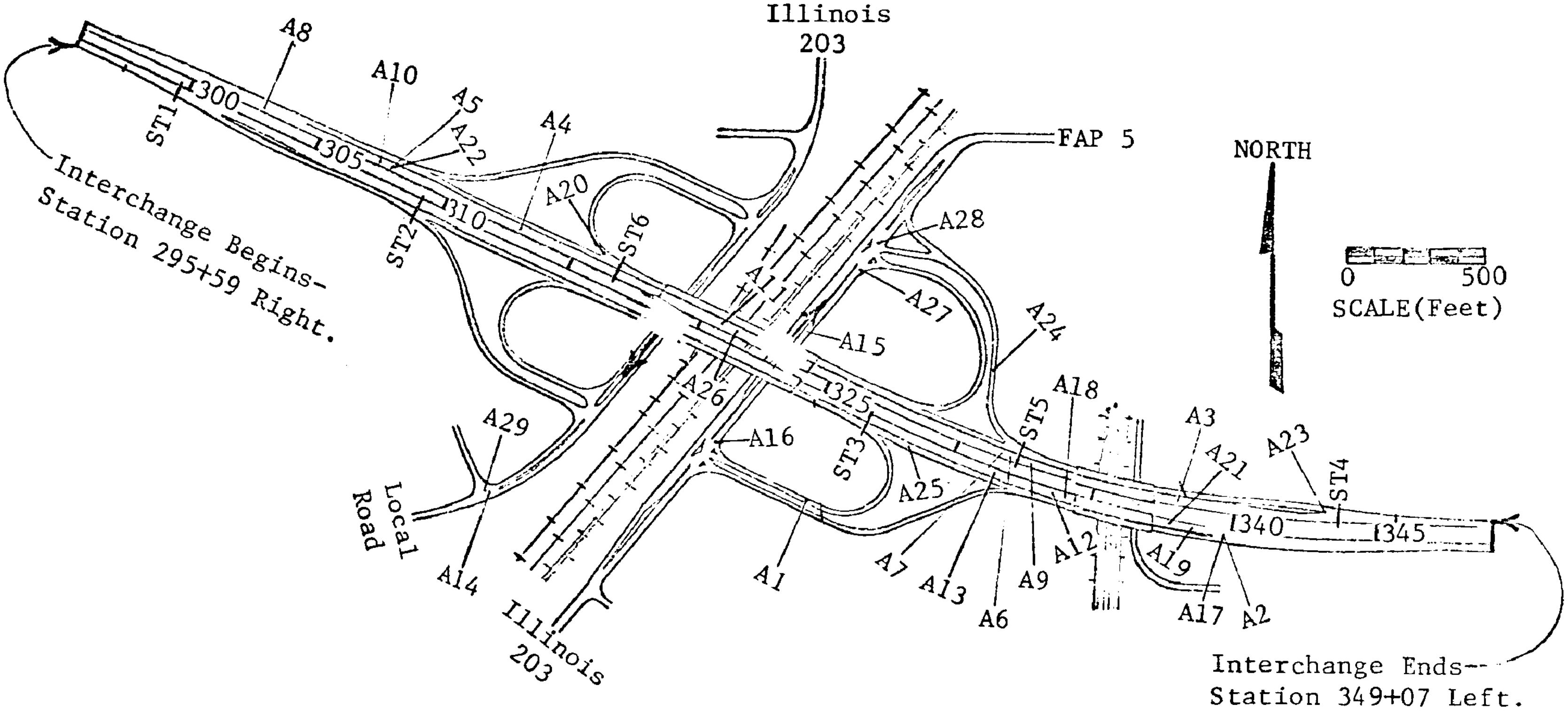
Typical Half Cross Section: Interstate 270 & Collector Distributor Road

Notes: All of the eight ramps are 16 feet wide.
Widths of island and Interstate 270 right shoulder are approximate.

Pt.*	Station**	Width (Feet)		
		M	RS	CDR
AA	295+59 Rt.	20	8	-
CK	296+35 Lt.	20	8	-
AB	301+40 Rt.	20	6	15
	302+12 Rt.	20	2	14
	304+35 Lt.	20	2	14
	304+72 Rt.	20	20	14
AD	307+01 Rt.	20	12	14
	308+32 Rt.	20	12	14
	310+55 Lt.	20	12	14
	314+30 Rt.	20	6	14
	315+06 Lt.	20	12	14
AL	317+04 Rt.	20	6	22
BY	317+73 Lt.	20	6	22
AP	325+60 Rt.	20	6	22
BX	326+13 Lt.	20	6	22
AY	327+85 Rt.	20	10	16
	329+35 Lt.	22	10	16
AZ	331+28 Rt.	23	8	16
BN	334+06 Lt.	26	6	14
BA	334+46 Rt.	26	6	16
BM	337+56 Lt.	28	6	14
BB	337+78 Rt.	28	6	16
BD	339+50 Rt.	29	2	14
BL	339+76 Lt.	29	13	14
	342+47 Lt.	31	2	14
BJ	343+20 Lt.	32	6	15
BH	347+44 Rt.	32	8	-
BI	349+07 Lt.	32	8	-

*Refer to Figure 4 on page I-42 for location of point. For points which are not designated by letters, refer to station number.

**Stationing is from Interstate 270 centerline.



Notes: Station numbers shown in median of Interstate.
A1 through A16 designate 1971 accident locations.
A17 through A29 designate 1970 accident locations.
ST1 through ST6 designate sign truss locations.

Figure 5. Plan of Signing and Accident Locations

TABLE 5

1971 ACCIDENT DATA

Accident Number*	Hour	Weather	Road Surface Condition	Number of Persons Injured	Number of Persons Killed	Type of Collision	Vehicle Direction	Maneuver	Driver Residency
A1	10-11A	Rain	Ice/Snow	0	0	Fixed Object-Off Rd.	West	Skidding due to road cond.	Out State
A2	10-11P	Snow	Ice/Snow	4	0	Sideswipe-Same Direction	East East	Skidding due to road cond. Going straight ahead.	Out State Out State
A3	12-1A	Clear	Dry	1	0	Fixed Object-Off Rd.	West	Avoiding animal.	County
A4	6-7P	Clear	Dry	0	1	Rear End-Both Moving	West West	Going Straight ahead, struck ped. on road. Going Straight ahead.	County County
A5	7-8A	Rain	Wet	0	0	Fixed Object	West	Changing traffic lane.	County
A6	6-7P	Clear	Dry	0	0	Sideswipe-Same Direction	West West	Avoiding Deer. Going Straight ahead.	Out State Out State
A7	6-7P	Clear	Dry	0	0	Sideswipe-Same Direction	West West	Avoiding Deer. Going Straight ahead.	Out State Out State
A8	3-4P	Clear	Dry	1	0	Sideswipe-Same Direction	West West	Going Straight ahead. Going Straight ahead.	Out State Out State
A9	3-4A	Clear	Dry	1	0	Fixed Object	West	Going Straight ahead.	County
A10	3-4P	Clear	Dry	3	0	Fixed Object-Off Rd.	West	Going Straight ahead.	Out State
A11	6-7A	Snow	Ice/Snow	0	0	Fixed Object	West West	Going Straight ahead. Going Straight ahead.	County County
A12	9-10P	Clear	Dry	1	0	Sideswipe-Same Direction	East East	Going Straight ahead. Going Straight ahead.	Out State County
A13	12-1A	Clear	Wet	1	0	Fixed Object-Off Rd.	East	Going Straight ahead.	State
A14	5-6P	Clear	Dry	0	0	Turning	North North	Going Straight ahead. Making left turn.	County County
A15	12-1P	Clear	Dry	0	0	Sideswipe-Same Direction	North North	Going Straight ahead. Changing traffic lane.	County County
A16	8-9A	Clear	Dry	2	0	Turning	North West	Going Straight ahead. Merging from ramp.	County Out State

APPENDIX J

CLASSIFICATION AND INTERCHANGE INVENTORIES

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FIGURES

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APPENDIX J: CLASSIFICATION AND INTERCHANGE INVENTORIES

Interchange Classification Techniques

Background and Needs

The prospectus originally furnished on this project stated that "research is needed which will provide the design engineer with a systematic approach to major interchange design." Later it continued, "some recent designs have suffered the title 'a can of worms' because this type of design does not fit a conventional classification and is often the result of years of compromises in finalizing the design." Most descriptive writeups on interchange classification are primarily discussions of various configurations which could be utilized in handling intersecting freeways. The AASHO (1957) "Redbook" devotes pages 494-515 to discussion of types and varieties of interchanges. As soon as specific sites enter the discussion, however, it becomes clear that interchanges are seldom duplicated in exact detail in any "standard" configuration.

The prospectus also stated, "the operational characteristics, if measured, would provide an indication of how well a facility was accomplishing its function of safely moving traffic. The measured operational characteristics in conjunction with the interchange costs would facilitate the economic analysis which would give designers a more rational approach to future designs." And later, ". . . while there is evolution in major interchange design, it is based more on experience and engineering judgment than on research with the measured performance of existing interchanges. . . . Much of the design work appears to originate independently of experience in different areas of the country."

Part of the purpose and scope statement in the original prospectus was: "considering the great lack of written information on freeway-to-freeway interchanges, a classification scheme should be developed to encompass the interchanges now in operation and in the preconstruction stage. . . . A judgmental evaluation of the various design configurations and practices should be made wherever possible--the purpose being to delineate the relative merits in meeting the functions of the major interchange."

The statement of work in the prospectus included "develop a comprehensive classification scheme of major interchanges including new designs not yet constructed," and "review the operational problems associated with major interchanges and provide recommendations that will minimize the operational problems." This latter task implies that standardization of interchanges or parts of interchanges would be possible if enough information were available in the proper form to allow setting of optimal standard designs.

It seems clear from the prospectus, that its writers considered a comprehensive classification system both of potential value to designers and feasible in a practical sense. This section considers these points and possible alternatives to a classification system as such, which might be considered in filling the needs of designers and others concerned with road system design.

There have been studies of interchange classification systems, such as that of Takebe (1969) which presented a catalog of interchange types based on the systematic arrangement of basic forms of ramps and ramp patterns. A number of other interchange classification techniques (e.g., Leisch, 1971, 1972) have been proposed, but there are serious problems with systematic attempts to analyze every possible pattern of interchange composition through theoretical systemization. In practice, the various finished patterns have been derived by means of trial and error or evolution and engineering experience to fit specific requirements of the site. An analysis of existing designs might be more productive for use in design activities if it were related more closely to the processes by which the configuration was actually produced.

Objectives of Classification Schemes

A classification scheme or descriptive technique for interchanges and their variations would be most practical and useful if a variety of objectives were met. The system should:

1. Provide the designer with relevant details of a wide variety of previous solutions to specific design problems for consideration in solving a given problem.
2. Provide historical data on specific features and appurtenances related to safety, operations, maintenance, life, repairability, and appearance. This must permit updating of files periodically to allow predictive modeling of various features in regard to operation or long term cost.
3. Present selected past proposed solutions which, although not constructed, may provide useful ideas in a given problem. Data may have been developed in preliminary design phases of rejected solutions which will be useful for later planning and design work for other sites.
4. Provide data on relative costs and other advantages and disadvantages of the possible alternative solutions to a given problem. This would allow more objective decision making based on trade-off information, even though trade-offs can not always be stated in dollar values. The decisions remain human functions, not automatic ones, however.
5. Aid in standardizing those aspects of design which are important in driver behavior as shown by previous experience with a given

design aspect. Conversely, where satisfactory performance does not appear to be related to variations of certain features, greater flexibility is allowed the designer.

6. Provide information for possible modifications or reconstruction where operations are currently substandard or inappropriate compared to traffic inlets and outlets (a bottleneck or excess localized capacity).
7. Facilitate maintenance by showing location of signs, fences, guardrails, luminaires, etc., and histories of each on performance, damage type, frequency of failure, and repair delay and cost.
8. Make use of data from all regions of the U.S. and from foreign experience. Common terminology, definitions, and procedures would be necessary for (and facilitated by) widespread application.
9. Be of reasonable initial cost and favorable benefit-cost ratio in the long term.
10. Be readily accessible to potential users, with reasonable personnel and training demands.

Alternatives in Classification or Description Schemes

The alternatives to a comprehensive, formalized classification system include:

1. A detailed inventory of existing and proposed designs in the form of a computer graphics system which allows display and comparison of a wide variety of solutions to a given problem in a short period of time and provides amplifying information in various accessible levels of detail. This alternative has been explored and is reported as the MIDCAS feasibility study later in this section.

2. A film inventory of existing roads and interchanges with a method for rapid access to any given roadway plus a cross-indexing system which allows location of a specific type of problem or a solution to a specific set of design problems for comparison. A film inventory probably should include both aerial views of complex roadway networks and driver's-eye views of all roadways and ramps. Existing photolog systems are discussed later in this chapter.
3. A "design catalog" which illustrates common and proposed solutions to specific design problems. Designers would be able to consider a reasonable number of "standard" designs which would be usable with or without minor modifications for adaptation to local conditions. Such a catalog would aid development of a common nomenclature and would encourage use of solutions which are in accord with driver expectations. It would be limited to ramps and intersections and could not include large amounts of detail if it were to be kept to a practical size. It has also been suggested that a design catalog could be useful in public planning meetings for illustrating a proposed solution where a model or perspective drawings do not yet exist. This alternative is not discussed further in this document.
4. Increased frequency and utilization of design seminars and design workshops in which current methods and problems are disseminated effectively throughout the country with a minimum of delay and ambiguity, and with emphasis on timely, relevant problems in decision making and implementation. Such workshops may need to be supplemented by design newsletters aimed at a specific design community--a small, well-defined population, distributed nationwide.

5. An expanded set of definitions to supplement and standardize the references used by schools, consultants, for planning, and in construction groups, to make the present system of informal classifications more consistent throughout the country and more useful for publication and for comparative uses. Several glossaries have been used for highway engineering purposes but none is both universally used and comprehensive. It seems likely that this alternative is actually a desirable supplement to any system and, though not a major aid in designing as such, probably is necessary for improved communications and thus improved dissemination of design-related information. Most formalized or computerized systems would provide standardized terminology since their operation depends upon explicit definition of the elements involved (e.g., see "Definitions of Roadway Segments" used for illustration later in this chapter). Techniques which do not contain a text format, such as photologging, do not attack the problems of terminology directly.

Descriptors Versus Classification

Rather than a comprehensive classification scheme of major interchanges, it seems more appropriate to consider an interchange descriptor system which is basically an inventory of existing (and perhaps proposed) designs, including objective statements of the operational characteristics of all types, the cost, and rationale for unusual features, plus the characteristics of traffic, turning volumes, weather, and local driver idiosyncrasies in behavior or route preference. It seems logical that such a detailed inventory would make use of computerized storage and graphics and be maintained by a single central agency for use by designers as they deem necessary through remote access devices. In this concept, the basic design process remains one of logic, experience, and judgment, but objective evidence becomes accessible to supplement experience and memory of details, both for use in designing and for ensuring "good" designs are accepted by the decision makers and the public where costs may be questioned.

A new tool of this kind may be met with some skepticism both among large design firms, whose feeling is that experience has taught most of the necessary lessons, and among small design groups who feel they do not have major design problems. For this reason, a careful evaluation of the potential of a computer graphics interchange descriptor system must include more than opinions from operating design engineering groups. On the other hand, there is a tendency among the advocates of computer systems to promise more than can be delivered in a reasonable time and with practical costs, so that the feasibility of such an inventory must be coupled with a cost-benefit analysis before it can be implemented on a large scale. It must be clear, however, that a computer graphics descriptor system is not a computerized design system: it is a much simpler, concise, and limited compilation of data which would be useful for design and other highway-related uses.

Whether computer graphics are appropriate for the descriptor system as it is envisioned here depends on the extent of programing and computer time charges involved. It is possible, in concept, to exploit the accounting and storing capabilities of the computer and couple them with the talents of an experienced designer to develop a design which fits precisely into the economic, operational, topographic, and social requirements of any environment. Because much of the input data which serve as models or criteria for design choices are unstable or controversial (such as land values, convenience, worth of historic features, local ecology, etc.), criteria which enter into the design comparison may not be fixed well enough for a mathematical algorithm which produces the "best" solution to a given set of problems and constraints. Comprehensive, formalized computerized design systems have been explored (see Walker, 1972; May and James, 1973; Beilfuss, 1973; NCHRP, 1972) but "automatic design," though feasible, is still beyond the present state of development. Rather than being an automatic design technique, the interchange descriptor system would provide a systematized listing of the considerations that go into the design process from a number of existing instances so that comparisons to the situation under study could be made. The trade-off process, although not bypassed, would be simplified by presenting facts in standardized form, as much as possible, for more direct comparison of the pros and cons of any given configuration, ramp type, or variation from "standard." A descriptor inventory system would provide a common "hopper" for collection of known facts as they become available. Improved data, new techniques, and further data can be added at any time it seems desirable.

A Recent Theoretical Analysis of Interchanges

Takebe (1969), in his theoretical analysis of interchange composition, illustrates the complexity of describing all possible configurations in intersection roadway patterns. That paper contains a summary of the basic patterns which shows 193 different patterns. Takebe states "these are substantially all of the basic patterns practically usable, except for asymmetric patterns. . . ." Although 78 of the patterns were said to be found in the literature of existing interchange structures, it has already been pointed out that a very large portion of all practical interchanges are asymmetric because of local requirements and land use patterns.

Takebe lists a variety of interchange maneuvers, ramp sequence arrangements, ramp forms, and ramp connection configurations. He has assigned codes to each of these various types and has suggested that the various combinations of types can be evaluated in terms of undesirable, good, better, or best. It seems likely that, in most cases, the sole source of such evaluations is meant to be subjective impressions by experienced designers. Thus Takebe's analysis, although it is more thorough than previous attempts at classifying interchanges, illustrates the two basic problems in classification: the system must be complicated to include all the possible variations, and the evaluation of the relative merits of the various configurations is still a very crude and unorganized process. Takebe's study makes it obvious that practical usefulness of such complicated classification schemes will very quickly suggest computer storage and access systems, coupled with graphic displays.

Another serious problem in Takebe's analysis is illustrated by Figure 4-1 (his Figure 8) showing schematics of two interchanges which appear very different but which Takebe says are "topologically identical." Since the drivers negotiating these two interchanges meet entirely different conditions of ramp length, sight distance, radius of curvature, and distance between successive ramps, there are bound to be wide operational differences even though they are topologically identical. A classification scheme which has no distinction between these two patterns, which are very different from the operator's viewpoint, raises questions as to why a classification scheme is desired. Perhaps the most important answer is that classification should be useful for predicting or describing operational characteristics.

The foregoing discussion is not meant to discount the efforts of Takebe, but rather to indicate a need to extend them into a more useful tool for the designer. The design process often is one of fitting ramps into an area with many constraints, rather than one of selecting a pattern for the entire interchange. Thus the classification scheme which allows retrieval of operational characteristics of various types of ramps, in the context of a

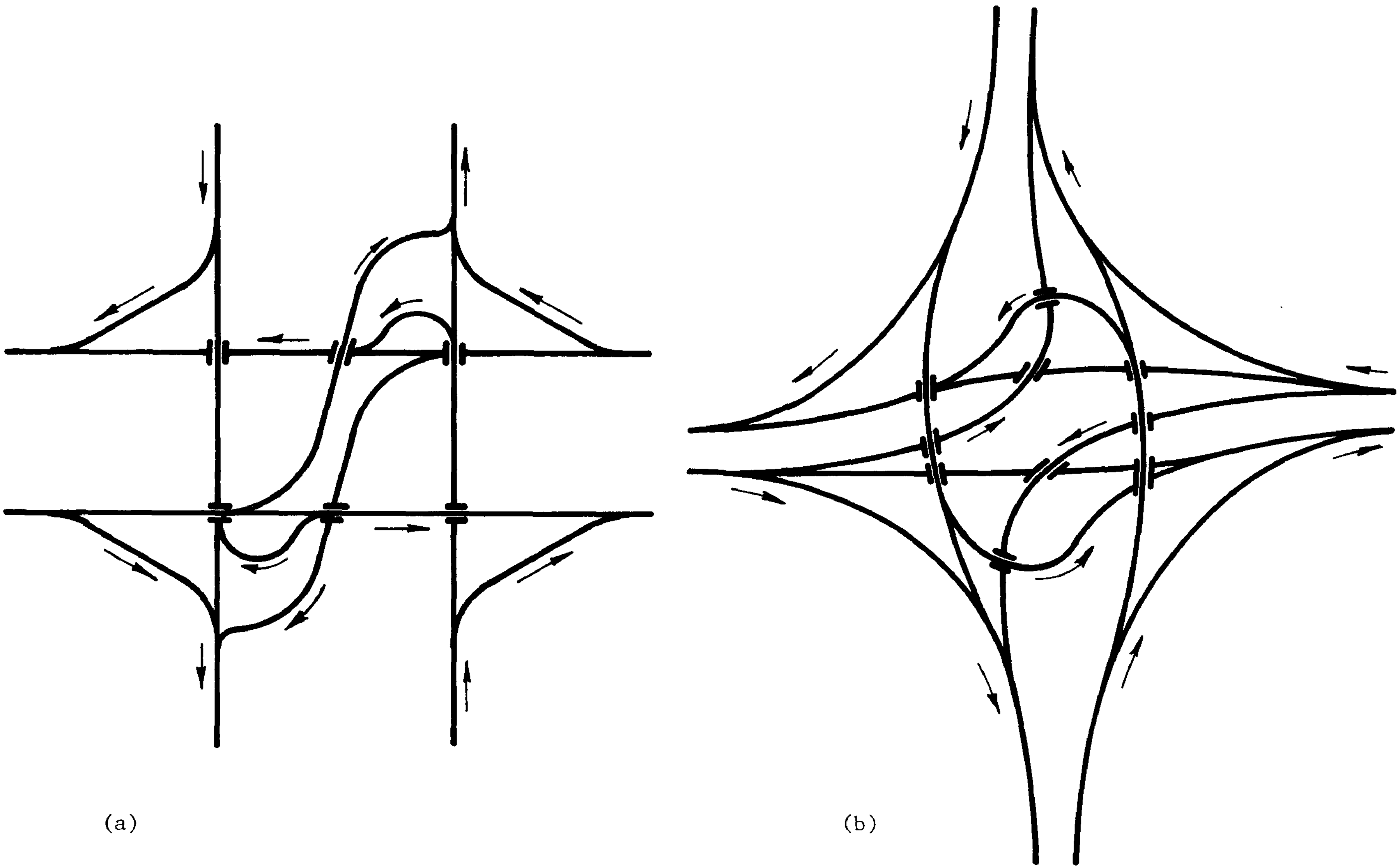

Figure J-1. Deformation of Pattern of 2DD(out) 2DS(out) [from Takebe] variety of interchanges, would enable a designer to avoid those features which have proven to have poor operational characteristics and to select those with conditions conducive to smooth operation. A catalog of possible configurations, such as presented in Takebe's Appendix I, may be useful to the designer in preparing preliminary sketches since it contains a large number of possible configurations which might otherwise not be attempted in a particular solution. However, a formalized system of developing and cataloging the operational characteristics, cost, maintenance, and accident histories should be added so that the designer is better able to consider the tradeoffs in various alternative configurations.

Although undoubtedly there are examples of "classical," perfectly symmetric cloverleafs or directional interchanges, they are not common and are generally not feasible in urban or highly developed areas. Intensive land use is accompanied by points with social and historical interest or by political pressures which usually require compromises of various types, modifying the classical designs and sometimes making them all but unrecognizable. Practicing design engineers on the higher levels, however (based upon the reaction of participants in workshops held during this project), maintain that there really are only three types of interchanges: the cloverleaf, the directional, and the diamond; moreover when the interchange is freeway-to-freeway, diamonds and often even cloverleafs are considered inappropriate for the high volumes and speeds. Since there are at most three types of interchanges (except for truly unique designs such as the "turbine" of Breuning (1958)), it no longer makes sense to discuss classifications of interchange types, but rather the variations among interchanges, or the ways they vary from the basic one, two, or three types. The variations often consist of changes in ramp location, "minor" variations in geometry, and patterns of exits and entrances necessary to accommodate local requirements of land use, volume variations, local access, and esthetics.

Since any freeway-to-freeway interchange requires at least four through movements and eight turning movements plus local access, the number of variations among the ramps or turning roadways immediately becomes large. A large number of relatively small variations dictates a great amount of detail and complexity if the minor variations are going to be compared, each one to each other, for operational qualities, cost, and similar characteristics of interest to designers, planners, and decision makers. There are many anecdotes, though little formal evidence, to indicate that certain "minor variations" in geometry, signing, or driver decision points can have strong influence on traffic flow, safety, or convenience. The increasing complexity of highway networks as parts of societal systems make it highly desirable that formal evidence be gathered for orderly and economical development.

Accidents and Geometric or Traffic Characteristics: A Recent Study

A paper by Browner (1971), based on the analysis of geometric and traffic characteristics of the interstate system in terms of accidents by Cirillo et al. (1972), clearly illustrates the problem of operational analyses which attempt to relate accidents to geometric and other characteristics of roadways and intersections. Data were collected from 20 states over the period from 1959 to 1965. A total of 2,287 study sections resulted, of which 1,411 actually were used in interchange modeling. A study unit was defined as one component of a study section such as a loop or other ramp. Approximately 74,000 study units were received from the 20 states but were culled down to 44,835 study units for a variety of reasons. Over 100 variables were tested in the pilot modeling in this project to determine those variables which were relevant to accidents. There were 13 types of study units, including five ramp-type units, four types of speed change lane units, and four types of mainline units. Many of the roadways, though they were interstate highways, were designed to older specifications. The intersection types included full and partial cloverleafs, three-leg or trumpet intersections, full and half diamonds, and full slip-ramp diamonds. Major interchanges probably would not now be considered to include any of the diamond interchanges.

In spite of the relatively large number of variables and data points considered in this study, specific conclusions were difficult to arrive at. There were problems in techniques of reporting, differences in methods of collecting data, differences in design standards and execution of construction, and many other variables which were not taken into account but which may ultimately prove relevant to accident frequencies. In the study by Cirillo et al. (1972), over 100 variables in geometric and traffic characteristics were considered but many major factors such as driver behavior, vehicle condition, and weather conditions were not considered. The most important single result is a very low fraction of variance in accidents which can be explained by geometric variables. This percentage varies from 5% to 20% on specific study units, and probably has a maximum of about 9% on interchanges as a whole. Because of the already high standards for interstate construction, they concluded, changes in geometrics should not be expected to change the accident picture appreciably.

The average daily traffic (ADT) gave the highest simple correlation of any variable tested with the number of accidents. Accidents increase with the traffic volumes until the traffic volumes starts to approach capacity, then the accident rates go up rather sharply, especially when level of service F (stop and go) is approached.

Other conclusions were that, although commercial vehicles are involved in fewer accidents than their proportion of traffic, they probably increased accident rates because they add to the congestion (larger sizes) and they negatively influence automobile driver behavior. Also, drivers of out of state vehicles were found to have fewer accidents than their proportion of the total traffic, implying that lack of familiarity is not especially important when good design standards have been set.

Although the death rate on interstate highways is less than half that of the average of all highways and less than one-third of that on rural or secondary roads, the high vehicle-mile rates on interstates will continue to contribute a large number of total fatalities and injuries.

The study by Cirillo et al. (1972), as detailed as it was, is still insufficient to determine the long-term effects of specific design variables and combinations of design variables and other conditions on accident rates. It seems unlikely that ADT can be kept below the high accident rate values in many areas. Other techniques will be necessary for reducing accidents.

It is important to note that, with many of the geometric variables, the correlations showed some effects opposite to those expected from common expert engineering judgment. While there is undoubtedly a portion of such conclusions which is based on inadequate models or insufficient sample sizes, there is probably a significant number of cases where engineering judgment is not sufficient, especially when such judgments are made from data collected remotely. It is very likely that important variables or special circumstances are not included in the data. It is also possible that the logic followed in forming certain conclusions from engineering judgments is erroneous. More likely, erroneous conclusions result from lack of full consideration of all relevant input information. These are the kinds of findings which are most likely to be important in a long-term effect on safety in the design community: if engineering judgment is found to result in erroneous conclusions among the most experienced designers, there undoubtedly are a large number of areas where less experienced designers in more remote locations are making greater numbers of errors. A more comprehensive, continuously updated system of data gathering and analysis would allow discovery of fallacious engineering assessments and discovery of variables which may not currently be considered important or are not properly weighted in determining specific judgments. This is obviously a complex undertaking requiring considerable investments in time and money before any payoff can be expected. However it promises to provide substantial payoffs which can not be obtained in less ambitious programs.

Design Community Reaction to Classification Schemes and Standardization

Standardization and classification were discussed as two topics within one session in each of the two workshops held for this project. In general, the representatives of the design community tended to feel that there should be some standardization of ramp design and some aspects of interchange component design but no strict adherance to one or more "standard" interchange designs. It may be possible to standardize many interchange parts or patterns to some extent, and then mix the parts as necessary to provide a suitable solution to a given interchange problem.

A major objection to standardization is that it tends to result in the setting of minimums and the subsequent building to those minimums rather than to better standards, even where they might easily be met. Standardization tends to stifle free thought, although from the driver's point of view, routine-appearing solutions are usually desirable.

A participant from California felt that it is not now possible to get specific ammunition to fight for a standard. Whereas many decisions used to be made intuitively, there is now greater legislative and public pressure to justify more expensive designs. In many cases the data to justify "better" design solutions are not available. He pointed out that there is not enough information to build a good case for many decisions which have already been made. Desired traffic projections have become meaningless in many metropolitan areas, so that freeways and interchanges are built for specific portions of the demand rather than to meet some future demand level. This is done while maintaining a sense of balance in economics and in other considerations, but attempting to build a whole facility which will operate at a consistent level throughout.

A participant from Pennsylvania felt that standardization probably could come first in the form of desirable guidelines, perhaps with a listing of priorities such that the best designs can be held as a goal, with certain lower levels of design permitted where necessary, and a minimum design specification which should be met at all costs. In those cases where minimum designs cannot be met, serious consideration should be given to cancelling at least that part of the project entirely. In a few recent cases, ramps which could not be designed to reasonable standards were omitted so that specific turning movements could not be made within those interchanges. The definition of "reasonable" was not established and must depend upon operational data and criteria.

Designs which have been used in the past have met with certain objections even though they seem to work reasonably well. For example, Texas uses an X-pattern ramp which presents signing problems and raises several objections from a theoretical viewpoint. However they have fairly good operational records and seem to provide service equivalent to more elaborate designs in view of the present demand. Should the demand increase, however, it is possible that serious operational problems would be encountered.

Standard configurations would eliminate many of the problems in signing since the standard would be developed with signing in mind from the beginning. However, standards which are formulated in great enough detail to include signing do not allow for variations in terrain, soil, and problems of right of way which often are important.

Standardization probably should start from the point of view of the driver, so that as he looks ahead he receives the proper impression of the upcoming situations related to his changing speed or lanes and his turning movements. Since this kind of consideration would require standardization of vertical as well as horizontal curvatures, it seems unlikely that true standardization can ever be implemented. Features, such as elevated approaches to an intersection to provide the driver with more of a plan view of exits, can only be recommended, not required.

While it may not be possible to standardize all aspects of an interchange configuration, there are specific problems in sight distance and obstruction of line of sight which can be predicted. For the most part, these already are familiar to the experienced designer, but the total configuration from the viewpoint of the driver may not be appreciated from drawings alone and may require various types of models or design aids.

While standardization of configurations may not be practical, it was agreed that there are still areas where standardization of terminology would be useful. Ramps, connecting roadways, indirect versus direct ramps, and similar terms may cover more than one meaning, and some are used with different meanings in different parts of the country. It is likely that standardization of such terms will require a sustained and active effort, including the use of seminars where specific configurations are discussed to illustrate the differences and the specific meanings.

It was pointed out during the workshop that standardization can be interpreted in two ways: the driver may know what to do through standardization of design, or he may know from provision of standard techniques for insuring good visibility and sight distance. Thus he may know how to drive a given design because "right turn ramps always come before left turn ramps," or he may know how to obtain information for negotiating specific designs. Once again there was no clear source of data for determining "successful" designs or for objective comparison of alternative design solutions: a notoriously unfortunate operation will become known to be design community, but the features responsible for the problems may be harder to identify.

There are many specific features of existing roadways for which there are no good data on operation. For example, there is very little known about the capacity of loops, both one lane and two lane. One two-lane loop in Long Island handles 1500 vph, far above manual guidelines. Loops may provide large savings in construction costs compared to direct ramps. If the weaving problem is eliminated through the use of collector-distributor roads, it is possible that the additional cost for directional ramps is not necessary for the relatively small increase in traffic flow they allow. A variety of independent studies have been made on specific features of this type across the country, but there has been no coordinated attempt to compile this kind of information in a central data bank which would allow comparisons of various features. Thus the trade-off evaluation is made based on the experience of the individuals involved, usually with little hard data to substantiate the value of specific features which "facilitate" flow or "improve" operation.

The Federal Highway Administration representatives felt that significant advances had been made in the last few years in standardizing some desirable features of entrances and exits. Interchanges are seldom designed without providing for all movements, regardless of demand. These ramps tend to be in more standard locations in an interchange, and left off-ramps are generally prohibited. California has a standard policy of use of collector-distributor roads, standard radii, and similar standard components in the cloverleaf.

Standardization may lead to the use of costly features where they are not actually required. For example, in high density traffic with many heavy trucks, overhead sign bridges often must be supplemented with median or shoulder signing. To require such multiple signing everywhere would be very costly.

With regard to the inventory system, two questions were raised: to what extent will an inventory system support design efforts, and what other benefits would arise from inventory system. It seems clear from accident investigations that it is the interrelationship of several features, not a single element, which contributes to accidents. Routine accident reporting seldom considers such interrelationships.

One of the consultants felt that an inventory could ultimately be used for driver training and even driver licensing to insure reasonable behavior in interchanges. He pointed out, however, that a comprehensive system could provide data which might be used against the highway authority in court cases where a feature has clearly shown itself to be hazardous. While such uses are conceivable, the identification of hazardous locations is obviously a first step toward remedying such conditions, and this is a standard function of a highway agency which is currently being more widely accepted. For example, a recent decision of the California Supreme Court* against the state held that a design to the accepted standards of 1942 was outdated by 1972: when the state knows or should have known that changed physical conditions have produced a dangerous condition it must act to correct it. A systematic procedure for identifying such problems and at least scheduling corrective action seems to be a necessary legal defensive requirement. New York and Illinois courts also have accepted the concept of liability for changed conditions.

A detailed classification system or complicated inventory was generally felt to be useful for research purposes, but too complicated or time consuming to utilize in design tasks. This kind of conservative reaction is understandable, but new tools often take considerable selling, even where they are enthusiastically utilized after a transition period. It was pointed out that, although the computer requires a large amount of detailed data in complicated, coded formats, the user requires only a knowledge of which buttons to push to obtain pictures and text, and he never encounters the vast majority of the data which is required by the computerized system. Designers are not programmers nor should they be, but a programmer can ease the task of the designer and provide him a means of obtaining information which is not otherwise available to him in a convenient form.

It was suggested that the new capacity manual is a large volume which is neither convenient nor simple to use; there is danger of an inventory system or classification system also being too cumbersome for its practical benefit. A system based on computer graphics obviously must be user-oriented and self-instructing to avoid such a possibility.

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*Baldwin v. California, 491P. 2d 1121 (1972).

It was pointed out that accident clusters which have already been identified might be evaluated in terms of physical features present to provide information on combinations of features which are undesirable in general, though not obviously so from outward indications. A new, national standard on such accident analyses could be maintained without a form of inventory, although the inventory would include this information. Any reconstruction because of poor accident records would obviously require more than information from a computer file. Detailed investigations and analyses of the site would obviously be necessary, even though suggested solutions may be derived from inventory data.

In the second workshop session on standardization and classification it was pointed out that there is a lack of information as to what is "good" driver behavior and performance in negotiating an interchange (and elsewhere). The operation on any segment depends on the segments preceding and following it rather than just the segment itself. Thus it is important that any analysis of roadway systems allow for inspection of the site and other areas near the site which may have influenced driver behavior. Pinpointing accident locations by reference systems which are available to both the involved motorists and the inventory analyst are obviously important for any studies of causation.

There were several other comments suggesting that the details of history and the fine-grain information of construction details may not generally be useful to design engineers. It was agreed, however, that there is no source of feedback on the operations of specific road segments except through "experience". Some agencies make it a policy to have design staff visit and review finished projects to provide some operations feedback; most do not make any provisions for any regular, direct feedback from operations to design.

Another topic brought up in the workshop was the fact of driver experience and habits which vary on regional basis. Even with the recent greater communication and greater amounts of travel, regional variations are a fact of life to be considered in setting standards for driver interpretation and behavior which might have been derived by "averaging" typical requirement from widely dispersed sources. Although some of this variation could be included as local descriptive information on an inventory, there is a limit to the number of variables which can be covered.

There was considerable discussion of design philosophy: is a given interchange type assumed and modified, or are individual problems solved and then combined to an overall unit? Some agencies begin with a cloverleaf and work upward if necessary, and others assume a directional interchange and work downward toward less expensive configurations. Although design basically attempts to eliminate all bottlenecks, the natures of the interchange and the cross-country freeway are different, so that interchanges inherently become impedances. The question remains as to what degree of impedance is acceptable for a given cost.

Improving feedback may require face-to-face meetings, but a more formal system such as an inventory might also be useful as a common basis. There is a continuing problem of exposing young designers to past projects, including past mistakes. Such training programs really have not been analyzed or objectives in this area established. The design process is seldom the idealized one of connecting two proposed roadways with optimum conditions for traffic. Many times the designer is forced to live with a number of accomplished decisions on details. Given these constraints, an inventory would be useful if it could offer instances of designs which met some of these constraints and continued to operate in a satisfactory manner, as well as some which were not satisfactory because of some specific combination of conditions.

Highway planning is obviously an extremely complex process. It was suggested that, until each man in this planning process can appreciate the positions of all the other people involved, there can be no progress towards a smoothly working system. Although pressures may be strong, decisions which have already been made are sometimes not irrevocable in the light of strong evidence, and the decision not to build at all when only a poor design is possible remains to be considered.

Taragin of the Federal Highway Administration described a German group of professionals who attempt to look at proposed designs from several points of view to provide this kind of integration. This is a new procedure, and its long-range effectiveness has not yet been established, although there is great enthusiasm about its potential. The problems are basically those of communicating a large number of details to and from groups with diverse backgrounds. While sketches, workshops, drawings, hearings, and models are used to facilitate such communications, the problems are by no means solved in terms of conveying concepts and problems in reasonable time to provide satisfactory understanding among these groups.

A post-session questionnaire was administered after each of the sessions on standardization and classification. A general description of the opinions expressed on these questionnaires follows.

Standardization was generally felt to apply to only about half of the general features of major interchange. "Standardization" may not have any meaning to the drivers, even if it is practiced on the design level. Those aspects which effect driver expectancies should be treated in as uniform a manner as possible, but it is not practical to standardize all shapes and configurations. Although it is generally felt that standardization does make a difference in driver behavior, there is no definitive evidence to support this or to define the degree of standardization or consistency which is desirable.

If a number of standards were adopted, it would be necessary to adapt these standards for local conditions and details. The workshops were divided on whether adaptation would compromise the standards, essentially making them meaningless on the whole. Definitions and further data are obviously necessary before such questions can be resolved.

The opinion of the workshop participants was also approximately evenly divided on the idea of a formal classification system or detailed inventory. Generally, the classification system was not seen to fill any obvious needs, while the inventory was considerably more acceptable as a helpful concept. A conversational classification system was felt to be sufficient. It was generally agreed that an inventory system is necessary for meaningful research in several areas of interest to design. Direct use in design or location tasks was mentioned, but not by the majority of respondants.

The next topic considered by the workshop was improvement of the feedback provided to designers. Here it was agreed that the computerized inventory system would be useful, although in-depth investigation teams and site visits by designers or periodic feedback from traffic operations to designers were also mentioned.

The addition of computer graphics to a computer inventory was not felt to be necessary, although about half indicated it was desirable. This is somewhat surprising, since the discussion made it obvious that sketches begin to appear very early in conversations about design features, especially interchanges. It does not seem probable that a system without computer graphics would be as acceptable as one with this capability, providing the graphics are an integral part of the system and are not added at large additional expense.

When asked whether a computer inventory system would be cost effective, the workshops tended to be negative: approximately half said no, half said yes or maybe. The concern was basically for the cost, based on experience with overruns in a few computer-based projects in the past.

The concept of a federal reference system or computer data bank on all interchanges was somewhat more acceptable. There was some concern regarding the handling of regional problems, but the major concern was that individual agencies would be slow to make use of a federal system on a regular basis. It was emphasized that such a system would have to be convenient for users and well designed to encourage its use. The fact that information exists is not sufficient; there must be a concerted selling effort to overcome a natural tendency to use established methods and less sophisticated techniques. As mentioned previously, this kind of a conservative reaction is understandable and expected. A system must be able to offer benefits which are obviously greater than those of the present system without increasing the costs or involving any inconvenience in obtaining the new information.

Stored-Image Roadway Inventories

Photologging

Photologging, the systematic filming of finished roadway at short intervals, provides much of the information needed for planning, problem analysis, maintenance, and similar concerns related to highways. While photologs usually cover all roadways, they can be useful in the study of interchanges as a separate or integral part. The discussion is included here to illustrate a technique of detailed description which is already well developed and practical. An extended interchange photolog, on a nation- or world-wide basis, is a viable alternative to a more formal system of classification, although photologs lack the quantified data and cross referencing which are desirable.

Several State Highway Departments (Baker, Case, & Hulbert, 1971) began filming their state highways as early as 1965. The film logs have been used by many groups, and the highway divisions are generally well satisfied with the results. Uses include various checks and surveys of speed zones, school zones, curve symbols and recommended speeds, channelization, sign location, accident sites, landscape planning, driveways, drainage patterns, guardrail locations and sequences, and the location of buildings. These films are available for administrative, maintenance, traffic engineering, and planning uses, and are updated as new construction or modifications to the highways are made. New uses are continually found for the film records,* and they may be useful in evaluating past designs or for refining proposed designs. Interchanges make up a small part of the photolog but access is convenient. The designer can "drive through" an interchange photolog, but detailed data must be sought elsewhere.

The photolog records are made on 16mm or 35mm color negative film with one frame every 1/100 of a mile (52.8 feet). Color is considered necessary, but opinion on film size is divided. A wide-angle lens usually is used, and the filming is often done at about 40 mph, although up to 70 mph is attainable under special conditions. The camera is mounted in a standard sedan or light van with suitable electrical equipment installed. The camera may be mounted in front of the passenger seat and aimed through the windshield,

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*A Second Seminar on Optical Instrumentation for Highway Engineers was planned for 11-12 April 1973, too late for inclusion in this report. Sessions were planned for reports of aspects of photologging including use in North Carolina, West Virginia, Canada, U.S. Forest Service, urban San Diego, and Washington. Proceedings can be obtained from SPIE Seminar Registration Committee, Box 288, Redondo Beach, California 90277. FHWA and ITE were Co-Sponsors. Further information can also be obtained from W. T. Baker, FHWA Office of Traffic Operations.

often 2° or 10° to the right of parallel with the roadway. The film is tripped by an impulse usually derived from the speedometer cable with frequent manual cross-referencing to the existing mile markers or other reference systems existing in the road system.

The filming usually requires a driver and a camera operator, although Montana has used a single operator/driver. Since filming is done in both directions, each mile of highway results in 2 miles of filming or 200 frames. Filming can be done at rates of up to 40 miles of highway per operating hour, or 300 miles of highway in a single day. Averages are considerably less than this, obviously. In most cases the film is commercially processed and then edited in the negative before printing. The films are prepared for filing in 100-1,000 ft. rolls or in cartridges with approximately 100 feet of film or 40 miles of highway in each cartridge. The films may be viewed or printed on standard 16mm or 35mm microfilm projectors and reader-printers. Single frames may be studied and rapidly located in equipment such as the Kodak Recordak Lodestar 16mm microfilm projector and the Vanguard Motion Analyzer.

The cost of the systems varies depending on film size and equipment. The addition of a data section on each frame raises both the utility of the finished film and the price for equipment. Prices vary from approximately $12,600, for 16mm film without a data block, up to about $200,000 for 35mm with extensive data (e.g., the California system) printed on each frame. Although these costs are very rough since most are based upon initial implementation of new systems, it appears that the choice of film size results in a 2:1 overall cost difference, but addition of a data block on each frame can also double costs.

California has made use of photologging since 1968. The image of a data panel is added to each frame through a series of mirrors and an Adtrol Photo-Digital recording system which places 15 rows of binary coded decimal (BCD) numbers in the top of the picture. A fifth wheel is used for measuring distance and triggering the camera, but the inconvenience associated with the fifth wheel makes the great distance accuracy (± 0.5%) of questionable value.

BCD data appearing at the top of each frame are large enough to be read from the 35mm frame without equipment if necessary, although a Vanguard Motion Analyzer projector is normally used. It allows projection at any rate up to 24 frames per second and provides a feeling of motion along the roadway from 0 to 800 mph. The BCD information includes the date, county, route number, district, and odometer reading. Additional data may be entered directly from a control panel during the film making.

Film, after editing, is kept by each district while the negative and a second copy are usually retained in the state highway headquarters. Each district in California has 50 to 80 rolls of film, with 40 to 64 miles of its assigned highways per roll, and a Vanguard projector. The headquarters film library consists of 30,000 miles of filming on 686 rolls with an average of 44 miles per roll. A duplicate set costs approximately $20,000.

The districts in California claim that they can get 85-90% of all the data needed for traffic accident analysis in intersections from the films, saving approximately five hours of field work for each hour of viewing. The legal section is able to provide conclusive photographic evidence of the conditions of roadways which often results in the court throwing out cases brought against the department. Nearly every group viewing the photolog has found some use that can save them time and money. In California, the average benefit-cost ratio is estimated at 4 to 1 in the various uses. In addition to state employees, city and county officials, outdoor advertising firms, and private traffic researchers have found the photolog valuable.

The Washington State Department of Highways also has a photologging program and 35% of the 5,000 state highway miles was filmed by the end of 1971. This system is installed in a van and uses a Flight Research System. The camera aims through the window 55 inches above the ground, aligned two degrees to the right.

Montana also does photologging with a 35mm format. Using 35mm color negative master, it is possible to produce either 35mm or 16mm positives, and individual prints can be made in either color or in black and white from any frame.

The Montana system is operated by a single operator and driver. This one man can photolog an average of 250 miles a day, gathering notes with a small tape recorder during the logging operation for coordination later with the films.

In Montana, the films are stored in 100-foot rolls which cover approximately 16 miles of highway in one direction of travel. A book of primary highway maps becomes the directory for locating any specific portion of the highway and the roll of film containing it.

Montana has found that the photolog is particularly valuable after a highway has been rebuilt and claims for damages are made by the property owners. In litigation, the photographic evidence supports the engineer's testimony in court and becomes a source of evidence which often results in a favorable verdict for the highway department.

A bonus feature was found in the Montana system, when it was discovered that the negative aerial reconnaissance and mapping photographs in Montana's files could be copied onto microfilm and used in the same reader-printer which is needed for the photologging system. Montana has 50,000 9" x 9" aerial negatives, and approximately 5,000 negatives are added to the files each year. The quality of the microfilm reproductions is suprisingly good, and all the aerial negatives were microfilmed at a cost of less than $1,000, requiring a very small amount of storage and much better accessibility. For high quality prints, a microfilm printer copy is sent along with the negative roll to the commercial printers for positive identification of the frame desired.

Arizona developed the ALISS (Accident Location Identification and Surveillance System), which is a computerized record system used with the 16mm photolog (the Highway Optical Data System) to provide a computerized roadway inventory file which is periodically updated. A data panel is included in the bottom quarter of the Arizona photolog film frame. It includes route number, route direction, date, altimeter, gyrocompass, clock, speedometer, and two mechanical counters which indicate the state milepost system number and distance in miles for each exposure.

The Arizona traffic engineering section developed a computerized record system for traffic control devices and aids. It was found that in the older manual records, approximately 40% of the data were invalid. The Highway Optical Data System (photolog) is used to bring the sign records up to date. The mainline sign file consisted of 38,000 records. This was validated and updated to the date of the photography, and coded in a computer storage system in less than 90 days using summer-aids or students who had no previous experience in this work. Compared to past records of updating by conventional field survey of signs, it was estimated that there was a saving of 5 months of time and $24,000 using the photolog system. A civil engineering technician supervisor and an electronic technician are assigned full-time to operate, maintain, and modify the equipment, and to provide for the film processing and storage.

Table J-1 compares some of the costs and features reported by six states using photolog systems. Many additional states have begun photologging

TABLE J-1

PHOTOLOGGING OF STATE HIGHWAYS IN SIX STATES, 1971

State	System	Highway (mi)	Filmed (Nov 71)	Crew	Film	Filing mi (1-way)	Data on Film	Reader Equip	Equipment Cost	Total Cost (1-way mi)	Rerun Cost (1-way mi)
Arizona	(own design)	5,400	100%	2	16mm	100' spools (up to 40 mi ea)	Bottom	Vanguard Motion Analyzer, Lafayette APA-200	$45,000	$4.00	$1.90 (1 print)
Oregon	Flight Res. (in part)	7,739	100%+*	2	16mm	100' cartridges (40 mi ea.)	No	Kodak Recordak Lodestar	$12,600	$3.25	--
New Jersey	(own design)	2,200	100%+*	2	16mm	200' rolls (80 mi ea.)	No	Kodak Recordak Motormatic, LW Data Analyzer	--	--	--
Montana	(own design)	13,000	50%	1 + tape recorder	35mm	100' rolls (16 mi ea.)	No	3M-400 Reader-Printer	$49,000	$3.77	--
Washington	Flight Res.	5,000+	35%	2	35mm	200' rolls (32 mi ea.)	No	3M-400 Reader-Printer	--	--	--
California	Microlog	14,700	100%	2	35mm	400' rolls (64 mi ea.)	Top	Vanguard Motion Analyzer	$232,000	$7.89	$4.43 (2 prints)

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*Reconstruction has also been refilmed.

and new systems are being developed, so that costs and techniques listed in Table 4-1 can only be rough indications of these features. Approximately 36 states have or are planning photolog record systems.

Time-Lapse Television

The time-lapse video mode is differentiated from the continuous video mode in that the recording tape travel speed is reduced, recording fewer frames in a given time period. When the tape is played back at normal speed the action is faster than normal.

This time-compression feature is useful for studying long-term changes or low frequency events as well as for storing a series of views along a roadway. Unlike film, video recording have serious resolution problems which limit legibility of small signs and license numbers. No processing is required, however, so that instant replay and retakes are routine. The cost tends to be higher with video recorded inventories, though tapes are reusable where a permanent record is not needed.

Time-lapse video recording does have potential for studying operations or physical features of interest to the designer where time compression is desired. Recording speed reduction ratios of up to 61:1 have been used. This ratio is useful for following the progress of construction, since a full week's work can be viewed in less than 45 minutes on a finished tape. Other intermediate time ratios have been used such as 29:1 for hazardous rural intersection monitoring, and 5:1 or 3:1 for medium and heavy traffic volumes. A recording ratio of 5:1 permits five hours of recording tape to be played back in one hour at normal speed. This is probably the most useful single speed for time-lapse recording, allowing most of the information that is usually obtained from field studies to be extracted from the tape.

In one study (Baker et al., 1971, p. 33-38) a total of 22 separate items of data were extracted from a 5:1 time-lapse video tape, including traffic volume per lane, number of weaving manuevers, encroachments within the gore area, vehicle classification, and pedestrian-vehicle conflicts. It was estimated that a crew of ten men would be required to obtain this data by field means. Only one field man was necessary for the video recording, and data reduction was accomplished by two men in an office during one 8-hour day since they could replay the tape as many times as necessary to extract the desired information. Obviously the time compression and the portability of such systems make them very useful for presentation to public groups or officials, eliminating the need for site visits.

In this study, a 10-speed Odetics model VTL310 was used. The complete system cost was approximately $4,000. Improved equipment is continuously being developed for such special applications. Some units, e.g., Flight Research Inc. of Richmond, Virginia, provide commercially available units which include an odometer or other data within each frame. A standard reel of video tape is 2,400 feet in length and lasts one hour at normal speed. Up to 61 hours of recording is thus possible with a 61:1 time-lapse ratio in automatic equipment.

Major Interchange Design Computer Access System (MIDCAS)

Introduction and Objectives

Up to the present time, the design of major highway interchanges has been dictated mostly by site- and task-specific considerations. To be sure, some highway planners benefit from previously conceived and implemented designs, and experienced designers usually are able to make sound decisions in novel situations, given enough study, but at this time there is no facility available for the systematic comparison of extant highway interchanges on a nationwide basis. Local studies, such as May and James (1972) on the cost effectiveness of adding lanes to freeways, can provide some of this data, but a more generalized system is needed for broad use. Such a system would obviously facilitate highway planning and design in that previous designs could be evaluated, copied in part or whole, rejected, or at least assessed on good and bad design features. A comprehensive inventory of physical interchanges would also incorporate operational, historical, and cost data which would be valuable in decisions related to various design alternatives. The MIDCAS approach is intended to keep equipment and programing costs low compared to the ultimate benefits. Potential benefit is expected not only for the engineer but for those interested in driver behavior and community development as well, since the test of a design is its ultimate operation, safety, and public satisfaction. The available hardware base described below allows not only rapid comparison of behavioral and engineering design parameters in text form, but it presents visual, diagramatic comparison as well. This is not a computer design system, but an aid to the designer and others utilizing computer storage and graphics.

The MIDCAS is an on-line, interactive computer graphics storage and display system designed to allow easy access and comparison of interchange design features, both as schematic diagrams and in the form of listings of relevant operational, engineering, and behavioral parameters and data collected on a number of major highway interchanges.

Background

In practice, the design of any connecting roadway is not done in isolation. Through a series of sketches and modifications, the set of interacting paths are integrated into a workable scheme. One of the basic problems in designing a classification or descriptor system is that there is no single, straightforward, step-by-step procedure by which designs are developed. If the basic steps could be enumerated and put in a hierarchy of some type (as discussed in another chapter of this report), then it would be possible to structure a descriptive system based on these steps with provisions for integrating the various steps and for combining the intermediate outcomes of each step.

It will become obvious when the details of the descriptor system are discussed, that it will be extremely difficult to simplify this system so that it can be used without reference to tables, computer output devices, or sketches. A system of "levels" of descriptor is intended to simplify the extraction of any one type of data for a specific design consideration. Briefly, levels start with the interchange as part of a highway network (level 0), proceed to the interchange and its turning maneuvers (level 1), through individual turning maneuvers (level 2), individual ramp or feature specifications (level 3), to historical and detailed maintenance data on each feature (levels 4, 5, 6, etc.).

While the complete descriptor in coded form may fill several pages, the descriptor level which is of interest for any specific decision or criterion consists of only a line or two which can be decoded with reasonable effort from the coded version, or displayed on the system graphics terminal in either pictorial form or as descriptive text. In either case, a paper copy on anything displayed of the graphics terminal can be obtained immediately.

There are at least two approaches to solving design problems: the solution of individual problems by means of a computer program which integrates the requirements and shows the possibilities, and a detailed inventory of existing interchange descriptions and a method for showing existing designs which most completely fill the requirements of a new situation. It is likely that the most versatile system would combine some features from each of these approaches, but it is unlikely that a truly "computer-designed" interchange will ever become feasible in view of the large number of interacting variables usually present.

The inventory-matching technique requires the detailed specification of all of the major existing interchanges with a complete discussion of the costs of construction, the advantages and disadvantages in operation and maintenance, and the amount of land and type of structures required. In this way, for example, maximum use of experience can be made, and such things as the solution of the intersection of two roadways which make a very small angle to each other can be considered separately from those in which the intersection angles are close to 90°. While the number of interchanges which now exist is not extremely large, interchanges from other countries can supplement such an inventory even to the extent of displaying mirror images of the left-hand traffic interchanges from Japan and Britain. Computer graphics displays rotate in space at the command of 3 simple controls so that left-hand and right-hand patterns are immediately interchangeable.

It is possible that an inventory-matching technique could be of such a scope as to be manageable without computer assistance. It is possible to design a system of flow charts or cross references which would allow selection of solutions which have been tried in the past for specific problems. While this would not necessarily include all the possible combinations and configurations, it is very likely that the ingenuity displayed in the total number of existing exchanges could be made more readily accessible to designers with everyday problems. Such a paper-based system provides significant disadvantages in expanding, editing, and up-dating, however, and it would be likely to cost more than a machine-based system in a short period of time.

The computer-aided design of interchanges, while more complicated than the inventory-matching technique, is well within the realm of possibility with today's computers (see Walker, 1972; NCHRP 20-8, 1972; Beilfuss, 1973). At this point it is assumed that the time advantage alone probably would not justify computerized designs since hearings, reviews, and approvals are more limiting than the drafting time requirements. The larger number of considerations which can be integrated by a computer seems to promise a more rational and economical solution to the extremely cumbersome series of detailed solutions. Once a ramp is chosen in any design, the choice of other ramps between roadways is somewhat restricted. When two ramps or roadways cross the same area, it becomes necessary to elevate, depress, or reroute one or both of the roadways. The cost of level separation versus circumventing can be estimated in terms of structures and roadway lengths. Where a level change is required, a minimum ramp length is dictated for moving from one level to another. In the same way, given any assumed design speed, the change of direction of a given angle requires a minimum arc length and radius of curvature. Acceleration and deceleration tapers depend on curvature, grade, exit speed, number of lanes diverging, and other factors. Most of these factors are predictible, within limits, in a given situation, and a mathematical model to solve such interacting requirements should be possible.

Summaries of operational characteristics can be modeled on the computer as well. For example, weaving areas are generally undesirable. If an operational "price" can be assigned to each of the weaves of various lengths (in terms of accidents, tie-ups, maintenance, public complaints, etc.), the disadvantage can be weighed against other costs such as a more elaborate ramp design. As the distance between conflicting ramps increases, what was a weave now becomes two separate maneuvers. While there is no exact cutoff point for every situation, such things as number of lanes, grade, angle of entrance or diverge, etc., can be used to formulate a model for predicting operational disadvantages. May and James (1972) have developed a systems analysis for optimal expansion of certain California freeways based on cost effectiveness. While this is somewhat more specialized than a computer based inventory, some of their data and techniques would probably be valuable in developing such an inventory.

Computer-aided design in the broader sense of computer-calculated solutions to new problems is a separate, more complex, and largely independent possibility well beyond the scope of the current project. The MIDCAS demonstration project which is described in this section is intended to illustrate the more practical computer graphics inventory and data access concept which can be implemented on available equipment with minimal programing investments. It offers promise of more objective, rational, and defensible decisions during the design process without restricting the engineer's creative activities and without the imposition of strict procedures or additional rules upon the design community.

Hardware--ADAGE

The hardware used in the MIDCAS demonstration is an ADAGE Model 30 GRAPHICS TERMINAL and associated peripheral equipment manufactured by ADAGE, INC. Boston, Mass. The computer section or "core" has 16k bytes of memory. Other equipment, such as the PDP-9 computes with graphic terminals (Savage et al., 1971), is available. No attempt was made to evaluate the relative merits of the alternatives since the ADAGE system and student operators were conveniently available. Incorporated in this graphics system is a 10" x 10" CRT Scope for schematic and text displays, a disk pack for auxiliary storage, an alphanumeric keyboard (ANK) for input and system control, an Analog Data Tablet for direct on-scope drawing, a teletype with paper tape punch and reader for input and output, and an electrostatic printer for hard copies of any scope displays either diagramatic images or text. Images of any sort displayed on the scope are under the programatic control of any of several devices: light pen, function switches, variable control dials, analog data tablet, and joystick. Figure J-2 shows some of these units for use by the ADAGE operator. Clockwise from the far left they are: printer-plotter, teletype, operator instruction book, function switch box (the two foot pedals are also function switches), joystick, alphanumeric keyboard, graphics display scope, light pen (upper right corner of scope), and variable control dials. The analog data tablet is stored under the table on the right. A polaroid camera is also available for photos of the scope picture. The cabinet on the right contains two disc memory packs.

Operator Control Panel. The Operator Control Panel provides controls for powering the ADAGE Graphics Terminal and initiating the Resident Monitor, an internal control program. It is part of the main equipment frame which is about 3' x 7' and 5' high.

Printer-Plotter. The Printer-Plotter is a high-speed electrostatic device which is capable of printing alphanumeric text as well as graphic data. An important aspect of the printer-plotter is its capability to reproduce a hard copy of any picture which appears on the Graphics Display Scope.

Teletype. A standard Teletype is the primary input-output device of the ADAGE Graphics Terminal and consists of a keyboard and a paper tape reader and punch. The ADAGE Loader is bootstrap-loaded by the paper tape reader in preparation for normal operation. Paper tapes produced by the teletype are used for input to the System Scratch Pad, a temporary storage area. The paper tape punch produces hard copies of information which then can be entered into the system at any time later. Remote Job Entry (RJE) files may be output to teletype, resulting in ADAGE-compatable tapes. Resident Monitor commands are entered via the teletype to control the operation of the system.

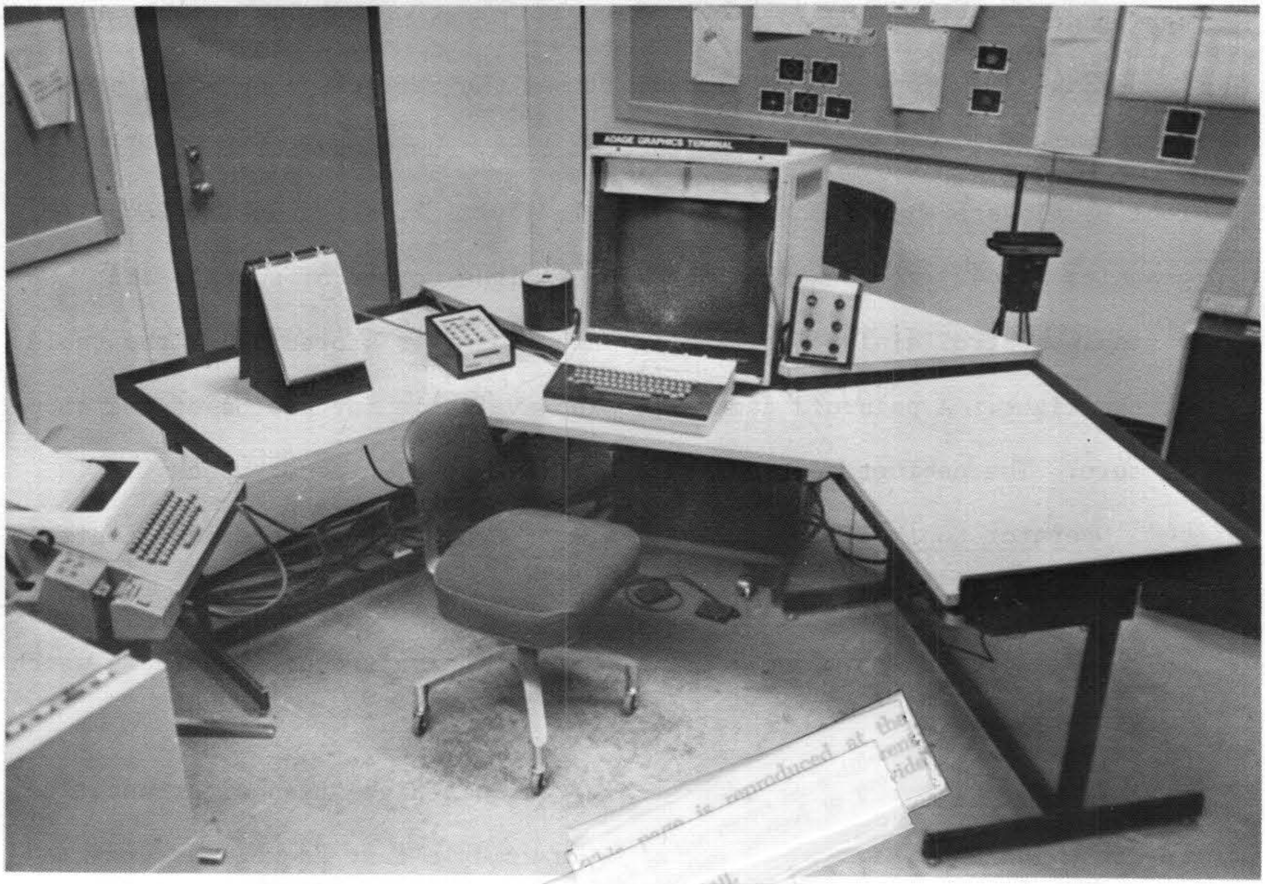


Figure J-2. ADAGE Operator Equipment and Controls

Function Switches. The Function Switches device consist of 16 keys in a small box, and two foot pedals. The function keys and foot pedals are identical in their input capabilities and may be read by a program at any time. The PULSE1 switch, which is mounted on the small box with the function switches, is wired in parallel with the PULSE1 switch on the Operator Control Panel and is useful in controlling or terminating program operations.

Joystick. The Joystick is a device for manually entering three-dimensional information. Two dimensions are obtained by moving the handle in any direction left and right and back and forth. The third dimension input is obtained by twisting the handle.

Alphanumeric Keyboard. This keyboard is similar in function and key layout to the teletype keyboard, except that all 128 of the standard (ASCII) codes can be generated. The keyboard provides a more responsive typing facility than the teletype keyboard and is conveniently located beneath the Scope display.

Graphics Display Scope. The Scope has precision viewing in a 10" x 10" area. All necessary adjustment controls are located behind a panel at the base of the scope. The x-axis is positioned left to right and the y-axis is positioned bottom to top on the scope face. The z-axis is positioned from the back of the scope toward the viewer, and z values are used for intensity control to give depth cuing.

Light Pen. The Light Pen is an input device which is used in conjunction with the Graphics Display Scope. The Light Pen has a fingertip switch on the pen barrel, which when depressed produces a light pen "hit" or computer interrupt each time a light pulse is detected. An operator thus can instruct the computer to operate on any specific part of an image being displayed.

Variable Control Dials. The Variable Control Dials input device consists of a box with six multiple-turn potentiometers. The position of each potentiometer may be sampled by a program at any time. The potentiometers are useful for continuous changing of program variables, such as rotation of displayed images or parts of images around any axes in space, shifting images, or changing scale factors.

Analog Data Tablet. The Analog Data Tablet is a device for entering two-dimensional information. The 10" x 10" transparent glass working surface of the tablet allows sketches, curves, and graphs to be traced for input. The pen's stylus is part of a pressure switch which is engaged by depressing the pen lightly during normal tracing operations; a small click signals activation. The tablet may be used for free drawings or graphic inputs. The pressure switch activation and stylus contact with the tablet are necessary for input to the routine which samples the data tablet and reads the coordinates of the stylus position.

Disk Memory Unit. The Disk Memory Unit allows the attachment and control of random access storage devices. The unit provides for the control of reading, writing, formatting, and status information on programs during development or in routine use. Individual disk packs may be mounted and dismounted quickly as the information requirements of a programmer change.

Equipment Modifications and Alternatives

The ADAGE Graphics system currently active at Penn State University has several additional capabilities above that of the basic system outlined above. Through interfacing with our IBM 370/165, a tremendous calculation and storage capability has been added. In addition, through this interface, a tie-in with a CalComp Plotter is possible, allowing larger and better quality hard copies of CRT Scope images. The relatively large incremental step on the ADAGE Printer-Plotter results in a noticeable zig-zag or step effect on the image which is not seen on the CalComp Plotter or on photographs taken of the CRT Scope images.

Currently under development at Penn State is an add-on capability involving stereo-pairs for true three-dimensional viewing of scope images. This system should represent an improvement over the present three-dimensional viewing capability of the basic ADAGE system in which depth is simulated to some extent by variations in intensity.

The basic ADAGE system outlined in the first part of this section has an approximate cost of $250,000. This includes a 16k memory, scope, disk-driver, electrostatic printer, and peripheral I/O and control devices. The requirement of the MIDCAS system are easily met by this basic system which, in terms of core size, actually represents a higher capability than necessary. An operator training program is being devised which will consist of several Super 8 sound movie cartridges which can be studied at the student's convenience.

It is likely that a less expensive system could be assembled for MIDCAS if a dedicated (single purpose) system with expandable memory were used. Small computers are now performing a large variety of such specialized tasks, with basic systems starting in the modest $25,000-$50,000 range, less programing (in Fortran IV, usually).

The computer program for the ADAGE MIDCAS feasibility study consists of approximately 1000 lines (8") of text on the printer-plotter including liberal commenting and the coordinates of the West Shore Interchange segments. While it has not been developed far enough to be useful in a practical system, the contractor will make copies of the program available to anyone who is interested in this level of detail.

The next sections illustrate the steps an operator goes through in actually producing displays from the computer memory. This seems involved, but requires mastery of only a few rules which appear more complicated on paper than in practice. Before the segments are described and their use discussed, a series of definitions is given. These definitions are fundamental to the success of any inventory system and must be thoroughly examined to assure the unambiguous, comprehensive, and widely accepted terminology necessary for success in a nationwide (or worldwide) system.

General Operating Procedure--MIDCAS on ADAGE

System Power-On and Start Up. To power on the hardware system (ADAGE Model 30 Graphics Computer) the procedure is as follows.

(1) On the Operator's Control Panel (OCP): (a) depress the HALT button, (b) then depress the RESET button.

(2) On the disk drive, after the Power On button is lit, two disk packs are mounted, and BOTH WRITE PROTECT BUTTONS ARE LIT: (a) depress START. (The Ready light should come on and the disks should attain full speed within 30 sec.), (b) THEN TURN THE WRITE PROTECT SWITCH FOR PACKO (right side) OFF. This allows the programmer to change the contents of Disk 0 memory.

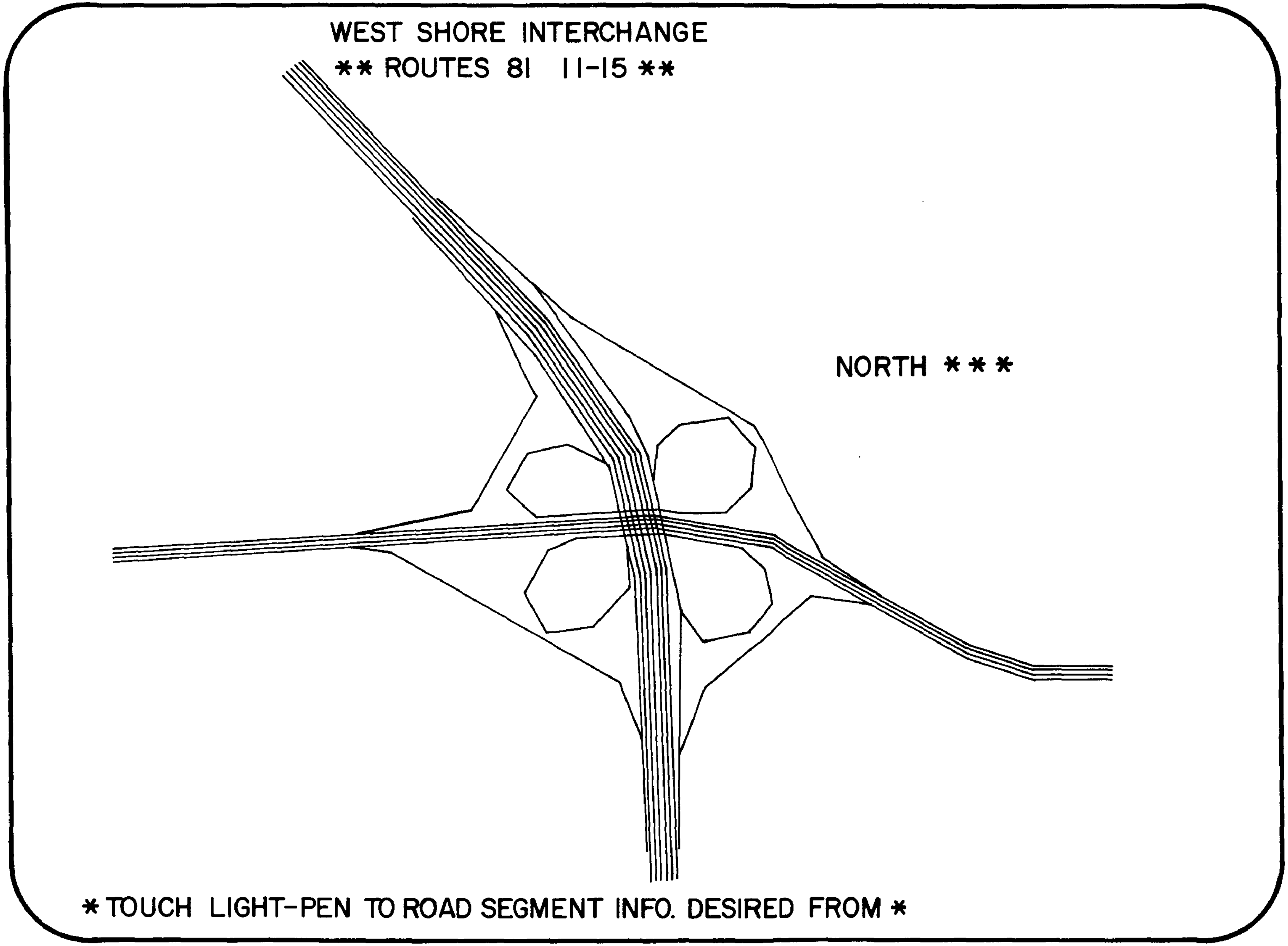
(3) ON THE CRT SCOPE CONSOLE: (a) TURN THE POWER SWITCH ON (WARMUP TAKES APPROX. 1 MIN.)

(4) ON THE OCP (operators control panel): (a) Depress HALT, (b) Depress RESET. (c) Depress RUN, (d) depress THE FAR RIGHT BUTTON ON THE TOP ROW OF BUTTONS, (e) DEPRESS PULSE1. The message MO/DA/YR = should appear on the CRT scope face. If nothing appears turn the intensity up. (If a bright spot appears turn the CRT scope off and call a staff consultant.), (f) TYPE IN THE CURRENT DATE IN THE FORM: 6/14/72

followed by a carriage return (CR). The symbols (CR) will indicate carriage return in the steps below). At this point a message should appear giving the monitor version. If no message appears try step 4 again and/or call a staff programmer.

(5) At the Alphanumeric Keyboard (ANK): (a) Type in RESET ("CRT1", 102)! (b) Type EDIT!, (c) Type 022<(CR), (d) Type 1, - y (CR). This will cause a list of MIDCAS Interchanges to appear on the scope. Select the interchange desired (n) note its code letters and proceed. (e) Type: n, - y (CR) to access the desired interchange program, (f) Type: B (CR), (g) Type: FORTN!, (h) Type: RESET ("OBJPK," 102)!, (i) Type: LOAD ("Interchange code letters", (4,101,102)) (a set of messages should appear, one line of which contains the interchange CODE LETTERS), (j) Type: XXXXX! (XXXXX = interchange's code letters) The Interchange Diagram (Figure 4-3, a schematic of the scope display) will appear on the scope.

MIDCAS Control. [After an operator has powered on the ADAGE computer and accessed the MIDCAS program, a schematic diagram of a major interchange will appear on the screen.] Each line represents a single lane of roadway, not lane boundaries. Each roadway, either single or multilane, is divided into critical road segments, described below, which are delineated by dots at the beginning and end of each segment. A critical road segment represents a portion of a roadway (single or multilane) for which important design and behavioral parameters are available for access. The present version displays all elements as straight lines, though curved lines could be added by more elaborate input procedures.



WEST SHORE INTERCHANGE
** ROUTES 81 11-15 **

* TOUCH LIGHT-PEN TO ROAD SEGMENT INFO. DESIRED FROM *

Figure J-3. Graphics Display of West Shore Interchange Schematic

Operating Procedure.

(1) Schematic Diagram Manipulation

A. 3-Dimensional viewing: The major interchange diagram accessed may be rotated in 3 axes for viewing from any angle. Figure J-4 shows a "helicopter's eye-view" of the interchange approaching from the north on highway 81. The display has also been inverted (left to right) to show how this would work on left-hand traffic. This is a printer-plotter copy with its characteristic zig-zag appearance. The following controls manipulate rotation.

1) VARIABLE CONTROL DIAL A = X-axis rotation

2) VARIABLE CONTROL DIAL B = Y-axis rotation

3) VARIABLE CONTROL DIAL C = Z-axis rotation

B. Scale size (not in present program version): Allows continuous expansion or contraction of diagram size.

(2) Text Road Segment Description

To access the text listing characteristics of a selected road segment the light pen (LTPEN) is employed as follows:

A. Touch the tip of the light pen to the segment desired

B. Press the white button on the side of the light pen

C. The schematic will be replaced with a listing of information on the selected road segment as in Figure J-5, a printer-plotter copy. If not repeat steps #1 and #2 above. The road segment index number will also be typed out on the TTY. Note that some items such as segment and page numbers are "base 8," so that counting is 1, 2, 3, 4, 5, 6, 7, 10, 11 . . . 17, 20, 21 . . . . This can be changed for convenience to the normal "base 10" if desired.

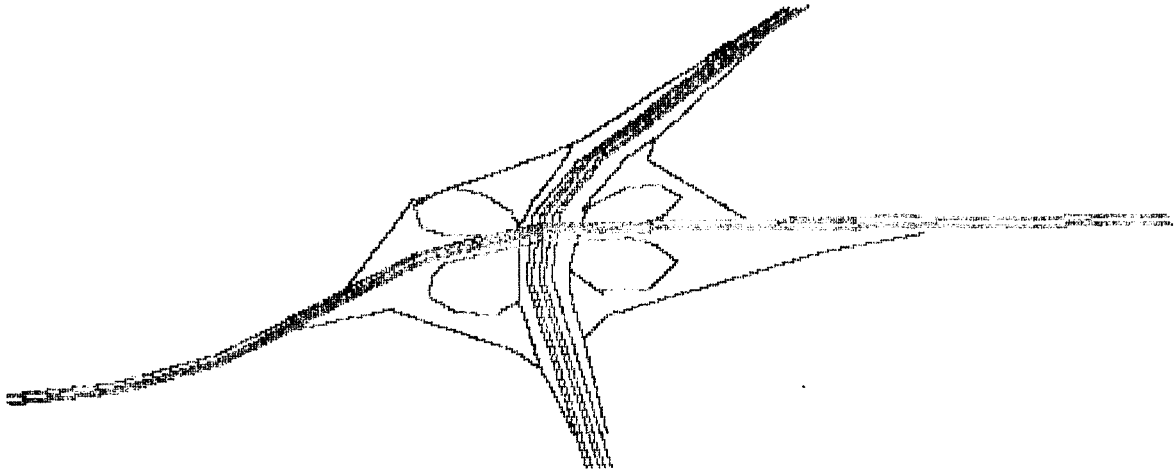
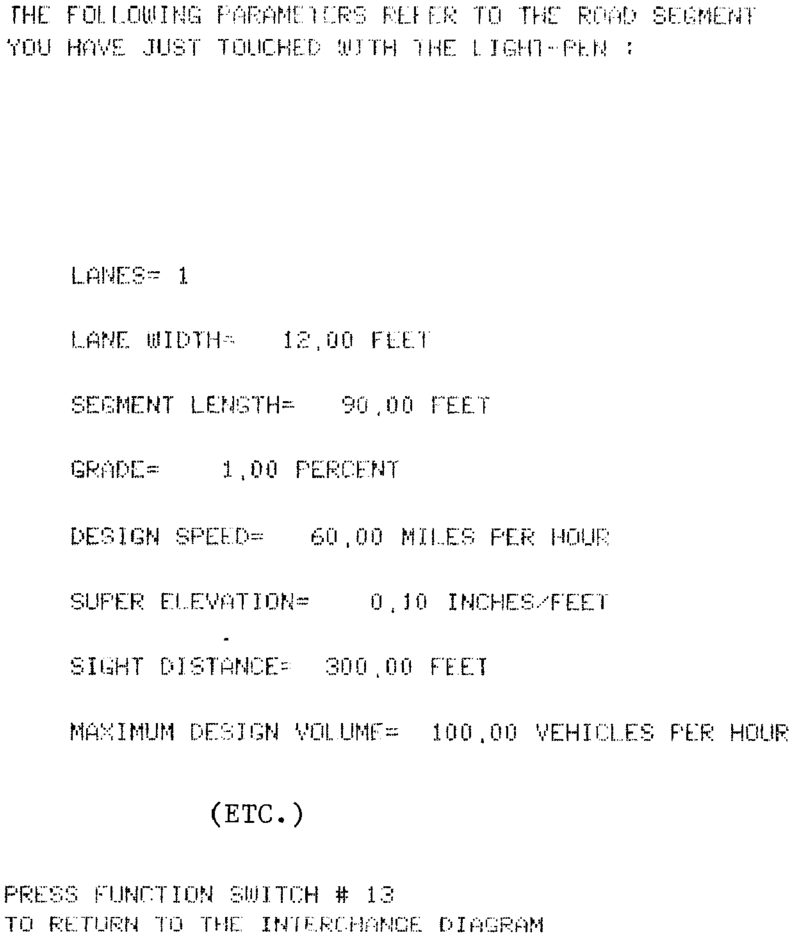


Figure J-4. Inverted Display Viewed from the North on Highway 81



```
THE FOLLOWING PARAMETERS REFER TO THE ROAD SEGMENT
YOU HAVE JUST TOUCHED WITH THE LIGHT-PEN :



     LANES= 1

     LANE WIDTH=    12.00 FEET

     SEGMENT LENGTH=    90.00 FEET

     GRADE=     1.00 PERCENT

     DESIGN SPEED=    60.00 MILES PER HOUR

     SUPER ELEVATION=     0.10 INCHES/FEET

     SIGHT DISTANCE=  300.00 FEET

     MAXIMUM DESIGN VOLUME=  100.00 VEHICLES PER HOUR
```

(ETC.)

```
PRESS FUNCTION SWITCH # 13
TO RETURN TO THE INTERCHANGE DIAGRAM
```

Figure J-5. Roadway Segment Data Display in Response to Light Pen Selection Command

(3) Returning to Diagram

A return to the interchange diagram is accomplished by pressing FUNCTION SWITCH #1. The scope will again display Figure J-3.

Some Definitions of Roadway Segments (Tentative, for demonstration use only)

Acceleration lane - A speed change lane for the purpose of:

a) enabling a vehicle entering a roadway to increase its speed to a rate at which it can more safely merge with through traffic.

b) providing the necessary merging distance.

c) giving the main roadway traffic the necessary time and distance to make appropriate adjustments.

Approach - That portion of an intersection leg which is used by traffic approaching the intersection.

Arterial Highway - A highway primarily for through traffic, usually on a continuous route.

Auxiliary Lane - The portion of roadway adjoining the traveled way for parking, speed change, or for other purposes supplementary to the through traffic movement.

Capacity - The maximum number of vehicles which has a reasonable expectation of passing over a given section of a lane or a roadway in one direction (or in both directions for a two-lane or a three-lane highway) during a given time period under prevailing roadway and traffic conditions.

Collector-Distributor Road - An auxiliary road, separated laterally from but generally parallel to the through roadway, which serves to collect and distribute traffic from ramps or other access roads connecting the major through roadways of an interchange.

Deceleration Lane - A speed change lane for the purpose of enabling a vehicle that is to make an exit turn from a roadway to slow to the safe maneuvering speed after it has left the main stream of faster-moving vehicles.

Direct Ramp - Any road connecting major roadways of an interchange that allows the least possible change in direction in right turns (right lane exit, right lane entry) or left turn (left lane exit, left lane entry) in maneuvering from one major road to another.

Exit Tape - The section adjacent to the main roadway from the widening for an exit roadway up to the point where the ramp proper begins.

Expressway - A divided arterial highway for through traffic with full or partial control of access and generally with grade separations at major intersections.

Freeway - An expressway with full control of access.

Full Cloverleaf - An interchange with a full complement of ramps (all turns provided for) with a separate one-way ramp for each turning movement. Direct left turns are not possible, but rather must use a loop ramp and exit on the right. Drivers desiring to turn left are required to travel beyond the point of the through road intersection and turn right through about 270°. Right turns are accommodated by direct ramps.

Grade - The longitudinal slope of the roadway expressed in percent, (derived from the ratio of height to length).

Gore - The area immediately surrounding the choice point where one road provides two optional directions of travel.

Highway - A way between prominent termini in rural or urban areas where there is comparatively little access or egress.

Intersection - The general area where two or more highways join or cross.

Lane Number - On any roadway, the lane on the extreme right of available, full-width adjacent lanes for the traffic flow in a direction is numbered "1". Other lanes for traffic in the same direction are numbered in an increasing manner from right to left ("lane N"). It is assumed that turning movements most often originate from lane 1, that lane 2 through lane (N-1) are for through traffic, and that lane N is primarily for overtaking.

Loop Ramp - A ramp with a circular shape that connects major roadways intersecting at near right angles. It requires approximately a 270° change in vehicle heading during the transition from one roadway to the other.

Main Roadway (MRD) - The through roadways in an intersection, excluding turning or access roadways.

Median - That portion of a divided highway separating the traveled ways for traffic in opposite directions.

Merge Area - That section where traffic from two lanes blend into a single lane of normal width, usually associated with an entrance ramp.

Ramp - An interconnecting roadway of a traffic interchange, or any connection between highways at different levels, or between parallel highways, on which vehicles may enter or leave a designated roadway.

Ramp Width - The width of a ramp is measured from edge to edge on the pavement intended for constant traffic use.

Road - Any stretch of pavement or strip of land regularly used for moving vehicular traffic.

Shoulder - That portion of a roadway between the outer edge of the through traffic pavement and the curb or the point of intersection of the slope lines at the outer edge of the roadway and the fill, ditch, or median slope, for the accommodation of stopped vehicles, for emergency use, and for lateral support.

Sight Distance - The length of highway ahead to which an object 30" high is visible to the driver.

Speed Change Lane - An auxiliary lane, including tapered areas, primarily for the acceleration or deceleration of vehicles entering or leaving the through traffic lanes.

Super Elevation - The tangent of the angle formed by the intersection of the plane of the road surface with the level plane in a cross-section view. Horizontally curved roadways are superelevated to offset the tendency of vehicles to slide outward under centrifugal acceleration.

Surface Condition - State or characteristics of road: dry, wet, icy, snow-covered, rough, smooth, muddy, traffic-worn, broken surface, etc.

Taper - The ratio of length to width of a speed-change lane which is uniformly increasing or decreasing in width.

Traffic Lane - A strip of roadway intended to accommodate a single line of moving vehicles.

Volume - The number of vehicles that pass a given point on a section of a lane or roadway during a given time period.

Weave, Weaving - The crossing of traffic streams moving in the same general direction, most often involved in merging and diverging. Usually (in a right entrance immediately followed by a right exit) exiting traffic is changing lanes rightward while entering traffic is changing lanes leftward, posing possible conflicts.

Feasibility Study Interchange: An example of some of the data in the catalog of available major interchanges which would comprise the operational MIDCAS system

West Shore Interchange (Routes 81 and 11-15, Harrisburg, Pa.)

To illustrate the use of the suggested MIDCAS system, the West Shore Interchange was divided into 46 "road segments" as indicated in the list below. Each road segment which may be made up of 1 or more "road elements" and represents a portion of a major road, ramp, or collector-distributor (C-D) road which, for engineering, operation, maintenance or driver behavior reasons, is necessarily or conveniently distinct from other segments. The relevant descriptive parameters delineated are individually accessible as described in the section on "General Operating Procedure." Detailed analysis and data shown in this illustrative example are fictitious. Some of the information may be available from existing records, but it is not readily located or accessible. An accurate compilation was not judged necessary for demonstrating the capabilities of the system.

Segmenting the Roadways. The following road segment numbers are those listed by the MIDCAS program upon accessing a particular road segment. The entire list is referred to as "Level 1 text." Each line represents Level 2 data, both as "Level 2 Graphics" (the picture of the sequence of elements) and as "Level 2 text" (a descriptive text on features of that segment as seen in figure 4-5 above). Figure J-6 indicates which portions of the interchange each segment represents.

Each segment is stated in 1 to 4 parts in the form: [Segment number/] [Route or segment name/] [amplifying descriptive data (as necessary)/] [end point station numbers*/]

1. MRD1/ route 11-15/ 2 northbound, 2 southbound, with median/ 00.00-38.50/*
2. MRD1/ route 11-15/ 2 northbound, 2 southbound, with median/ 38.50-48.00/
3. MRD1/ route 11-15/ 2 northbound, 2 southbound, with median/ 48.00-66.50/
4. MRD1/ route 11-15/ 2 northbound, 2 southbound, with median/ 66.50-76.50/
5. MRD1/ route 11-15/ 2 northbound, 2 southbound, with median/ 76.50-85.80/
6. MRD2/ route 81/ 3 northbound, 3 southbound/ 00.00-25.50/
7. MRD2/ route 81/ 3 northbound, 3 southbound/ 25.50-36.70/
8. MRD2/ route 81/ 3 northbound, 3 southbound/ 36.70-45.10/
9. MRD2/ route 81/ 3 northbound, 3 southbound/ 45.10-73.20/
10. Exit taper/ route 81 northbound to direct ramp to 11-15 southbound or collector-distributor/ 04.20-22.50/
11. Gore/ direct ramp to 11-15 southbound and extra lane (collector-distributor)/ 22.50-26.00,00.00-04.00/

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*Some fictitious station numbers have been added for this example.

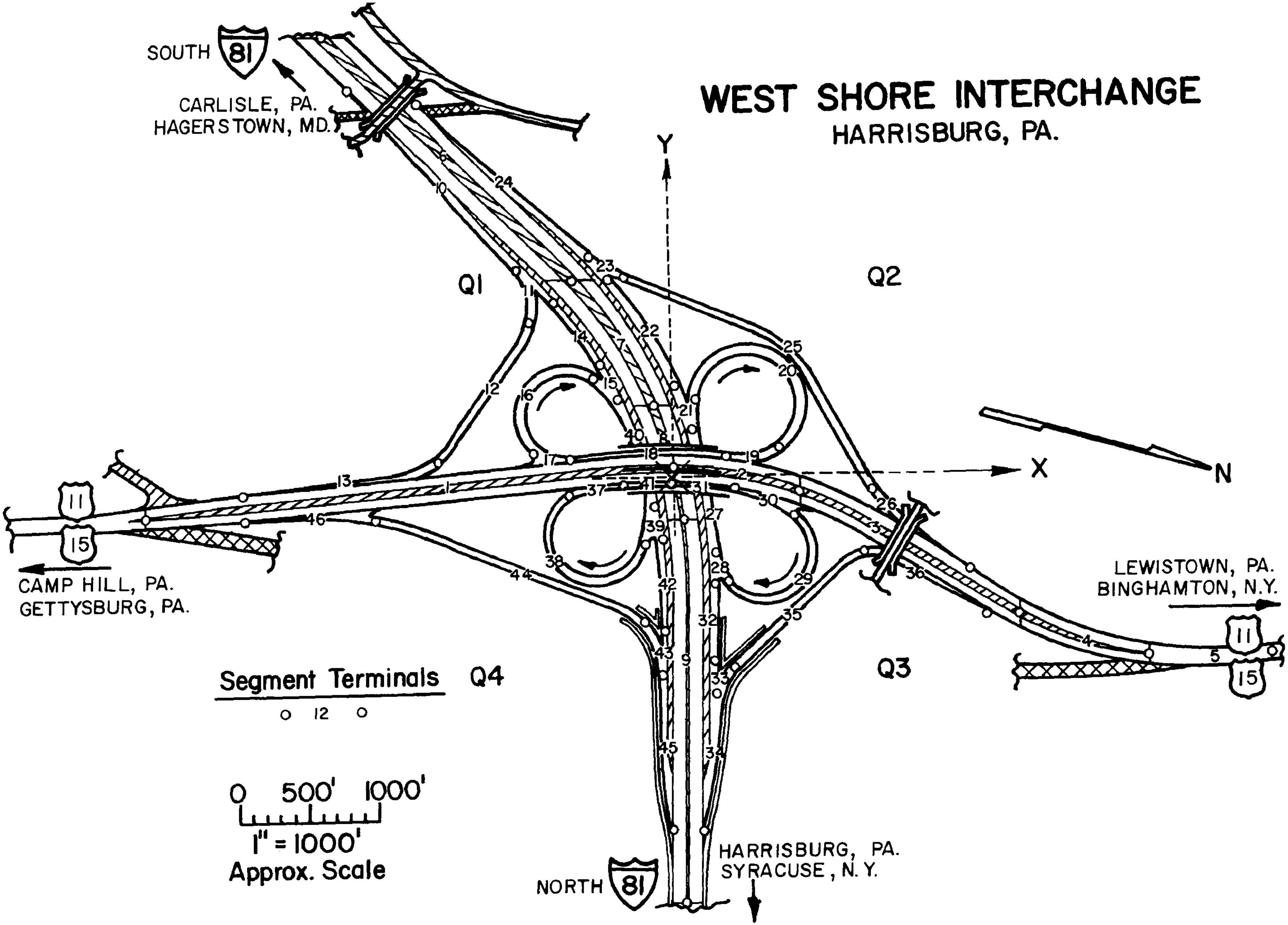

Figure J-6. Segment Numbers for Illustrative Interchange Example

12. Direct ramp/ 81 northbound to 11-15 southbound/ 04.00-16.50/
13. Entrance taper/ to route 11-15 southbound/ 16.50-31.00/
14. Collector-distributor link/ from 81 northbound/ 26.00-31.70/
15. Merging area/ loop ramp and collector-distributor from 81 southbound/ 31.70-34.40/
16. Loop ramp/ route 11-15 southbound to route 81 northbound/
17. Exit taper gore/ route 11-15 southbound to loop ramp/
18. Weave area/ on overpass adjacent to route 11-15 southbound/
19. Entrance taper/ to route 11-15 southbound/
20. Loop ramp/ route 81 southbound to route 11-15 southbound/
21. Gore area/ 81 southbound collector-distributor and loop ramp junction/
22. Collector-distributor link/ to 81 southbound/
23. Merge area/ loop ramp and collector-distributor to 81 southbound/
24. Entrance taper/ to route 81 southbound from 11-15 via direct connecting ramp/
25. Direct ramp/ route 11-15 southbound to route 81 southbound/
26. Exit taper gore/ route 11-15 southbound to direct ramp to 81 southbound/
27. Collector-distributor link/ weaving area/ under bridge adjacent to route 81 southbound/
28. Merge area/ loop ramp and collector-distributor on 81 southbound/
29. Loop ramp/ route 11-15 northbound to route 81 southbound/
30. Exit taper/ route 11-15 northbound to loop ramp to 81 southbound/
31. Weaving area/ loop to 81 on 11-15 northbound on overpass/
32. Collector-distributor link/ from 81 southbound/
33. Gore area/ direct ramp to 11-15 northbound and collector-distributor on 81 southbound/
34. Exit taper/ route 81 southbound to direct ramp and collector-distributor/
35. Direct ramp/ route 81 southbound to route 11-15 northbound/
36. Entrance taper/ on to route 11-15 northbound from direct ramp/
37. Entrance taper/ on to route 11-15 northbound from loop ramp/
38. Loop ramp/ route 81 northbound to route 11-15 northbound/
39. Gore area/ loop ramp and collector-distributor on 81 northbound/
40. Collector-distributor link/ under bridge on 81 northbound/
41. Weaving area/ loop from 81 on 11-15 northbound on overpass/
42. Collector-distributor link/ to 81 northbound/
43. Merge area/ junction collector-distributor on 81 northbound and direct ramp from 11-15 northbound/
44. Direct ramp/ route 11-15 northbound to route 81 northbound/
45. Entrance taper/ on to route 81 northbound from direct ramp/
46. Exit taper/ route 11-15 northbound to direct ramp/

The System in Use

A user interested in a portion of a specific interchange calls up* its level 1 (overall) graphic image by typing in an index code. When he wishes

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*The basic overall and segment displays, segment deletion, and segment text call up were demonstrated on the ADAGE equipment. Much of rest of this discussion is conceptual and has not been programed, although ADAGE equipment would permit such features.

to study a particular feature of one segment in this roadway, such as accident history, cost, or maintenance, he touches the Light Pen to the segment of interest. The level 2 display then shows only that segment, in an appropriate scale, and a text of general descriptive data (as shown above in Figure 4-5). By touching the Light Pen to key words in this text the operator can cause lower levels of detail to be displayed on the topic of interest. Line drawings accompany the lower level texts, where appropriate.

The MIDCAS user may require instances of specific characteristics rather than information on a segment of roadway he already has identified. In this case a search is initiated which matches his list of descriptor levels to those contained in the inventory. The initial output is a number indicating how many instances the search has located. If this number is too small or too large he shortens (less specific) or lengthens (more specific) the descriptor list, respectively. He then cycles through each of the level 1 displays to look at each instance and he may call up those lower levels which may be of interest to him.

Often needs arise, related to signing, accidents, or driver behavior, which logically involve the choice points and the paths a driver may encounter while he negotiates the interchange. A series of "maneuver sequences" are defined in terms of the successive segments which are transversed. Since there are variations in the ways drivers enter, exit, and track on portions of the roadway, provisions are made for ideal or average paths, allowable options, and undesirable (erratic) paths in the maneuver sequences. Expanded sequences may be formed to extend the basic sequence upstream or downstream to study the possible effects of interaction or delayed influences. Thus a site with a high accident rate may be downstream a considerable distance from the road features which actually influence driver behavior in an undesirable way. Upstream or backward expansion of the manuever sequence allows inspection of such features.

Maneuver sequences (Seq) are numbered by convention as follows: M1-M3 are the left turning movement (L), through movement (T), and right turning movement (R), respectively, for the highway which is leading in the direction closest to true North at the point of intersection of the crossing through roadways. M4-M6 refer to L, T, R of the most Southerly roadway (always opposite M1-M3), M7-M9 to most Easterly, and M10-M12 to most Westerly road. More or fewer than 12 are, of course, possible in some interchanges.

The format of the descriptive text is: link/seq/link. Any number of links may be added to the ends of a sequence (but the two end links themselves are not displayed on ADAGE). When a seg is expanded, the original links are incorporated into a larger seq, and the next adjacent segment is shown as linking the expanded sequence to the interchange system. For example:

Seq "Mn" (as listed): C/D,E,(F-)*,G/H (only D,E,F,&G are displayed)
Backward expanded Seq "MnX1": B/C,D,E,(F-),G/H
Two element backward expansion "MnX2": A/B,C,D,E,(F-),G/H
Forward expanded Seq "MnZ1": C/D,E,(F-),G,H/I
Two element forward expansion "MnZ2": C/D,E,(F-),G,H,I/J
Expanded in both directions "MnX1Z2": B/C,D,E,(F-),G,H,I/J, etc.
To show options call "MnX0": C/D,E,(L),(M),(F-),G/H
For erratic options call "MnZ0": C/D,E,(F-),(-Q),(-R),G/H
For both option types call "MnX0Z0": C/D,E,(L),(M),(F-),(-Q),(-R),G/H
For both options, double expansion "MnX01Z01": B/C,D,(L),(M),(F-),(-Q),(-R),G,H/I

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* ( ) indicates option, depending upon track followed. Only options of the form (X-) are displayed when basic sequence is called up: other options (X) are displayed in expansion "X0," and (-X) in expansion "Z0".

(X-) indicates common erratic maneuvers <u>exclude</u> this segment, i.e., this segment <u>should</u> be used ordinarily for this maneuver.

(-X) indicates common erratic maneuvers <u>include</u> this segment, i.e., this segment should <u>not</u> be used ordinarily for this maneuver.

The Maneuver Sequences for West Shore Interchange, Pa. are:

M1 Seq: 11N-15N/01,(41),(31-),30,29,28,27,21,22,23,24,06/81S
(Northbound 11-15 turning leftward to 81 Southbound: segments 01. . .06 are displayed)
M2 Seq: 11N-15N/01,02,03,04,05/11N-15N
M3 Seq: 11N-15N/01,46,44,43,45,09/81N
M4 Seq: 11S-15S/05,04,03,02,(01),(-19),(18-),17,16,15,40,39,42,43,45,09/81N
M5 Seq: 11S-15S/05,04,03,02,01/11S-15S
M6 Seq: 11S-15S/05,04,03,26,25,23,24,06/81S
M7 Seq: 81N/06,10,11,14,15,40,39,38,37,(01),(41-),(31),(02-),(-30),03,04,
05/11N-15N
M8 Seq: 81N/06,07,08,09/81N
M9 Seq: 81N/06,10,11,12,13,01/11S-15S
M10 Seq: 81S/09,34,33,32,28,27,21,20,19,(18-),(-17),13,01/11S-15S
M11 Seq: 81S/09,08,07,06/81S
M12 Seq: 81S/09,33,35,36,03,04,05/11N-15N

Conclusions

Through manipulations of levels, searches, maneuver sequences, displays, and texts, the designer (or maintenance engineer, signing section, planner, etc.) can refer to any level of data or any specific feature contained in the inventory. Periodic updating in one central file adds to the historical data and modifies the operational parameters as appropriate. Remote terminals allow personnel in district offices to use the common central storage file to study construction throughout the world without travel and without requiring file updating, except for locally obtained data. Much of the experience of the entire design community is readily available to each agency requiring it in objective, current form. After a period of study on such a system, specific questions will be pinpointed and correspondence or site visits can then proceed on a more definitive, advanced level where judgment and experience are required. The inventory system has shown the engineer where to look and has provided quantitative data (which might not be readily accessible even to the designers of an existing interchange) to help him decide which alternatives are most viable for consideration in his design problem with all of its constrictions.

A static reference system, such as a manual or compilation of photographs, is limited in its versatility, accessibility, comprehensiveness, and in its ability to remain current. Computer graphics systems may, if designed with the user and reasonable costs in mind, provide a tool for optimizing designs based on full utilization of the data and experience of a much larger design community than possible in the traditional approaches or minor variations of them.

APPENDIX K

WORKSHOP DISCUSSION ON DESIGN CRITERIA

William L. Raymond, Jr., Gannett, Fleming, Corddry and Carpenter, Inc.

CONTENTS

FIGURES

TABLES

APPENDIX K: WORKSHOP DISCUSSION ON DESIGN CRITERIA

A major portion of the workshop discussion was centered upon the design criteria for major interchanges, particularly the various design components. The subsequent sections of this Appendix present the pertinent workshop comments on each of the principal items discussed in Chapter 3 of the Report. References to figures having a number beginning with a 3 refer to figures in Chapter 3 of the Report, while a figure with a number beginning with the letter K appears in this Appendix.

Design Speed

In the pre-workshop questionnaire, one of the most frequently mentioned differences between the design of major interchanges and other interchanges was that higher ramp speeds must be maintained. Mr. Housworth (Texas)[1] noted that the cross-country dirver simply does not expect a 30-mph ramp speed at the exit from an 80- or 90-mph freeway. Both Mr. Hall (California) and Mr. Gazda (Illinois) indicated that in rural areas they build cloverleaf interchanges (25- to 35-mph design speed) since they will not have sufficient turning volumes in the foreseeable future to economically justify massive four-level direct connection interchanges (40- to 50-mph design speed).

Left Exits

The results of the workshop discussion and the pre-workshop questionnaire clearly indicated that left-hand exits were held in low regard by

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[1] See Appendix C for a complete list of workshop participants.

the majority of designers. Mr. Housworth (Texas) stated that left exits may not be a problem on lightly travelled four-lane freeways, but with six-, eight- and ten-lane freeways, they create serious weaving problems. Mr. Hall (California) noted that the major problem is on the mainline approach to the left-hand exit, more so than on the ramp itself. He also said that California's experiences demonstrated that where a minor movement exits left at a freeway-to-freeway interchange, poor operating conditions result.

Nevertheless, when it was suggested that left exits be prohibited by federal standards, 82 percent of the participants indicated they should not be banned since there were situations where they were the most acceptable alternative. The questionnaire results indicate that the higher the percentage of left turning traffic in the approach traffic stream, the greater the acceptability of left exits. When more than half the approach traffic or the numbered route turns left, a two-lane turning roadway is required, the left exit becomes a "major fork," and this is deemed acceptable.

It was the consensus of the workshop participants that a long, parallel type deceleration lane should be utilized in conjunction with left exits to afford the turning traffic an opportunity to move out of the high speed lane well in advance of the exit point. Two-lane left exits should be treated as major forks.

Economics plays an important role in the designers' decisions as to whether or not to utilize left exit ramps. When confronted with a savings of $100,000 in selecting a left- as opposed to a right-hand exit in a particular questionnaire situation, over three-fourths of the designers indicated they would not use the left exit. However, if the savings were to be $500,000, sixty percent would use the left exit.

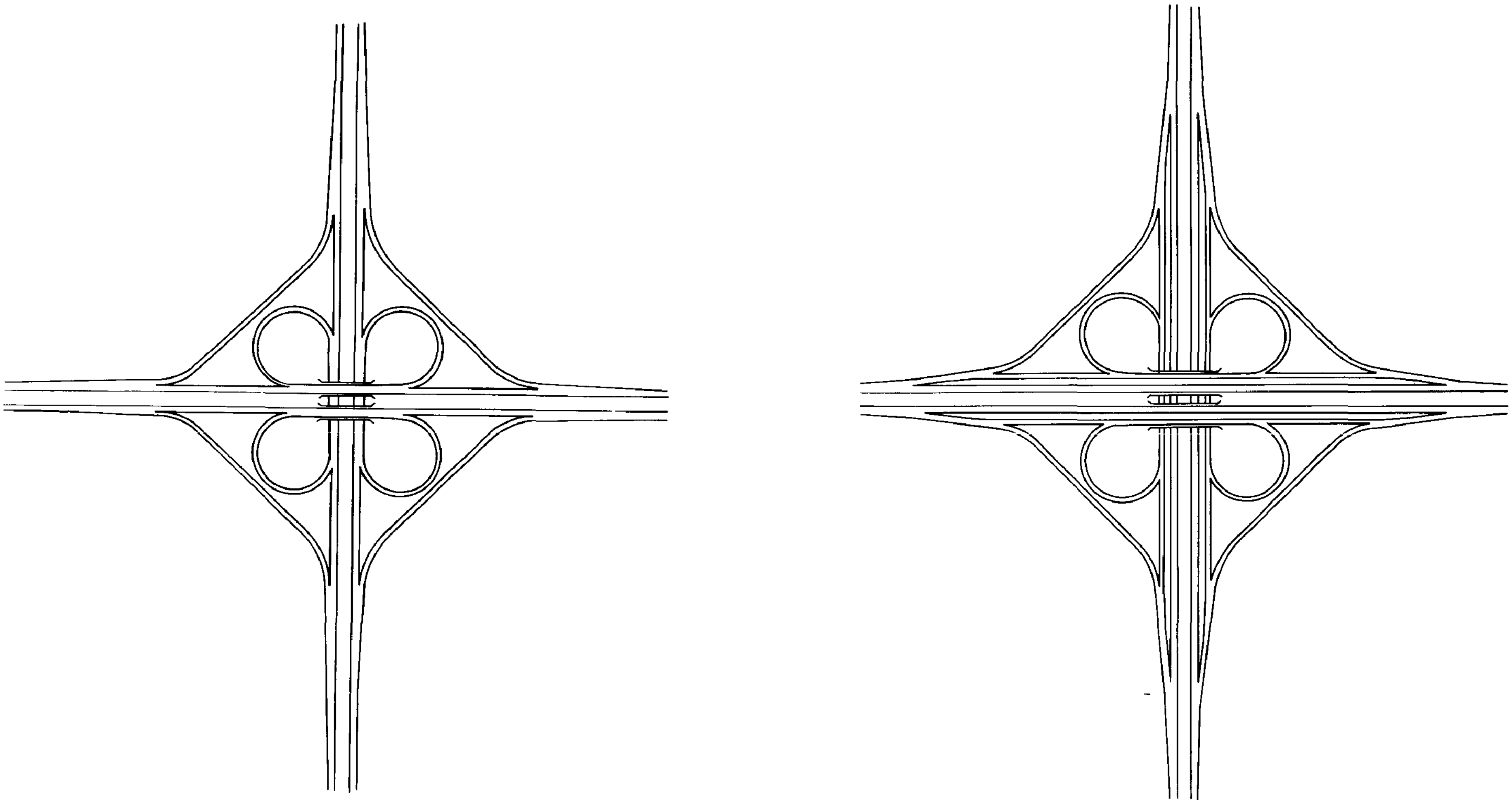
Left Entrances

All the designers at the workshops agreed that entrance ramps from the left having a standard tapered acceleration lane (as shown in Figure 3-3) should almost never be used. However, three-quarters of the workshop attendees considered this design acceptable when an additional full lane is added to the through roadway downstream from the left entrance (as shown in Figure 3-4). The arrangements in Figure 3-4 will operate satisfactorily, it was noted, provided there are no downstream right-hand exits within about a mile of the left entrance which would require "forced" weaving across all the freeway lanes. It was the consensus that the use of left entrances should be restricted to those locations where the entering traffic volume was nearly equal to or greater than the through freeway traffic volume. Under these conditions the entrance ramp would have two or more lanes and at least one additional lane would be required on the freeway ahead. Mr. Hall (California) argued that the speed on left entrance ramps should be comparable to the mainline speed and the merging volume should be on the order of 2000 to 3000 vph. The recommended geometrics for multi-lane entrance ramps are discussed in the subsequent section on Branch Connections.

Loop Ramps

The subject of loop ramps, and particularly cloverleafs for freeway-to-freeway interchanges, elicited lively discussions at the workshop sessions. Mr. Housworth (Texas) stated that only direct connections (including semi-direct) should be used at major interchanges. He said cloverleafs cannot handle the freeway-to-freeway turning movements. Mr. Gray (Ohio) said it should be a "regulation" that you do not exit one freeway to another through a loop ramp. Mr. Gazda (Illinois) strongly disagreed, stating that in his state they do not believe that freeway-to-freeway movements have to be handled by direct connections, and that in the rural parts of the state the minor turning movements can be adequately handled by loop ramps. Mr. Sigal (New York) agreed with Gazda on the condition that weaving be removed from the mainline through the use of collector-distributor roads on both freeways (See Figure K-1). Mr. Gazda replied that from the overall cost-effectiveness standpoint, low turning volumes encountered in rural areas do not justify collector-distributor roads in every case. Mr. Hall (California) indicated they use cloverleaf interchanges with collector-distributor roads in rural areas. In many cases, where traffic volumes are low and no major development is expected, cloverleafs appear to be a workable alternative for 20 or 30 years. He also noted that in addition to the weaving problem, two adjacent loops made it impossible or at least impractical to provide adequate acceleration and deceleration distances. Therefore, collector-roads are mandatory for two adjacent loop ramps. Mr. Housworth said Texas often considers putting in direct interchanges in rural areas with low volumes simply because the cross country driver does not expect 30 mile-per-hour ramps at the end of their 80 or 90 mile-per-hour freeway.

Mr. Loutzenheiser (FHWA) noted that at the "Dynamic Design for Safety Seminars" the question of weaving on major interchanges was discussed at some length. It appeared that the representatives from those states with major urban concentrations were opposed to weaving sections on major interchanges, but that those representatives of less populated states, such as Utah, Montana, etc., did not share this belief. It was Mr.



(a)

Without C-D Roads

(b)

With C-D Roads

Figure K-1. Cloverleaf Interchanges

Loutzenheiser's opinion that perhaps the smaller states were correct in assessing their problem in the way that they did.

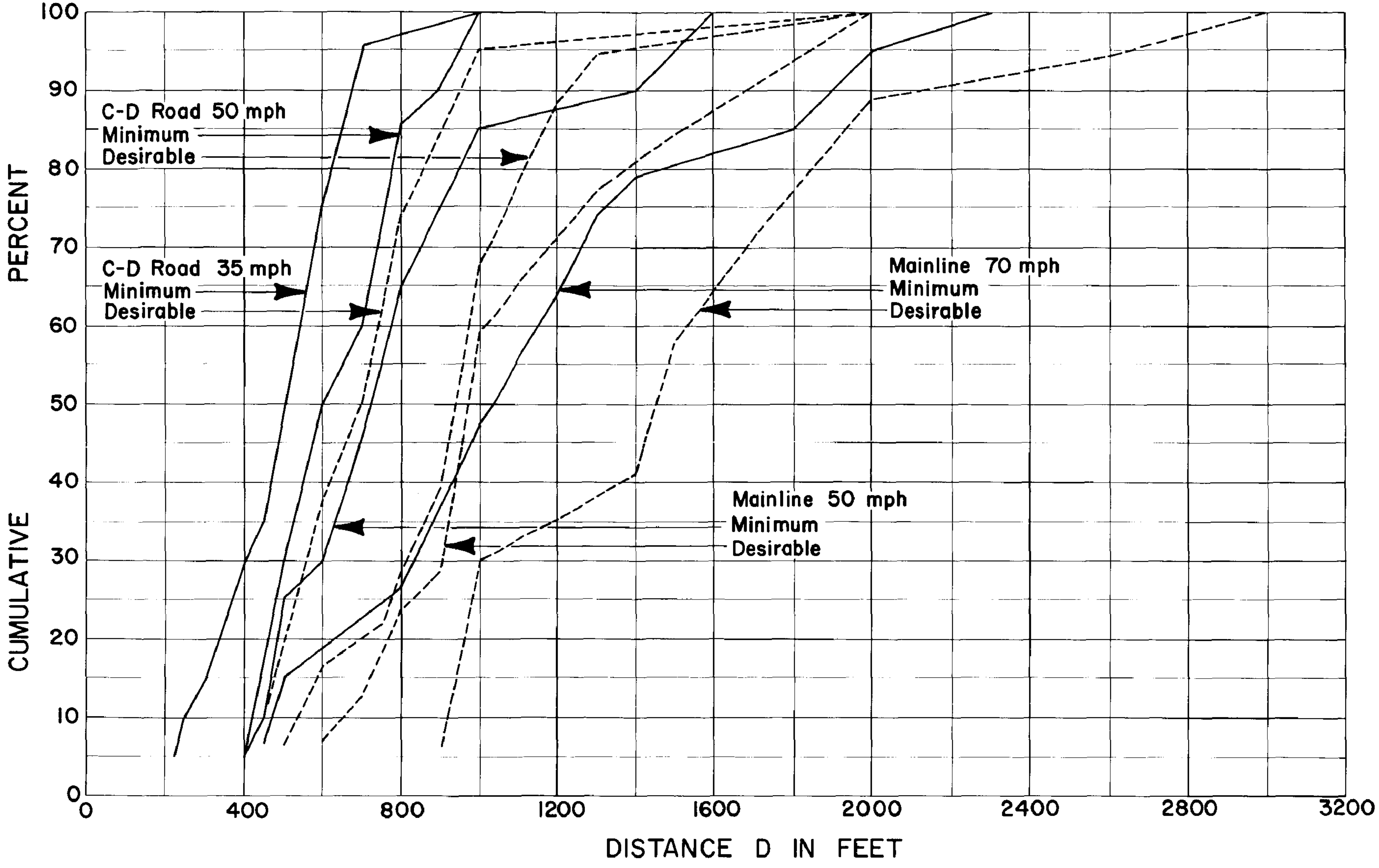
The pre-workshop questionnaire asked the designers to indicate the minimum and desirable weaving distance, D, between entrance and exit noses (as shown in Figure 3-5) for mainline design speeds of 70 and 50 miles per hour, and (in Figure 3-6) for collector-distributor road design speeds of 50 and 35 miles per hour. Figure K-2 shows how the 20 questionnaire respondents answered. The greater variation between the shortest length and the longest length, particularly for the weaving section adjacent to the mainline roadway, indicates that there is little agreement between experienced highway engineers on the specifics of cloverleaf design. The mean values of D indicated by the respondents are shown in Table K-1.

TABLE K-1

MEAN VALUES OF WEAVING LENGTHS
FOR CLOVERLEAF INTERCHANGES

	Minimum	Desirable
Mainline - 70 mph design speed	1000'	1500'
Mainline - 50 mph design speed	700'	1000'
C-D Road - 50 mph design speed	600'	1000'
C-D Road - 35 mph design speed	500'	700'

In addition to low design speeds and short weaving lengths, some of the other problems associated with loop ramps, as indicated by the workshop participants are:



(See Figures 3-5 & 3-6)

Figure K-2. Designers' Preferences for Weaving Lengths in Cloverleaf Interchanges

(1) Restricted capacity - 800 to 1000 vph.

(2) Loops require more maintenance, particularly from trucks riding on the shoulder.

(3) The exit point is not readily visible when it is beyond an overpass structure.

(4) Signing and lighting of loops is difficult.

(5) Truck loads tend to shift on small radius loops.

(6) Terminal geometrics are a problem in a cloverleaf but not in a isolated loop ramp.

Exit Ramps

It was the consensus of the workshop participants that a single exit, as illustrated in Figure 3-7(d), is the most desirable configuration for exits from a freeway. The pre-workshop questionnaire indicated that over 85 percent of the designers used the single exit more than one-third of the time while less than 30 percent stated that they used one of the double exit configurations more than one-third of the time. The major advantages of the single exits noted by the participants were that they greatly simplify signing, reduce driver confusion and hesitation at ramp terminals, and minimize the number of decisions to be made on the mainline. A few designers indicated that the single exit design may result in higher construction and right-of-way costs and that complex routing at an interchange may overload the direction signs.

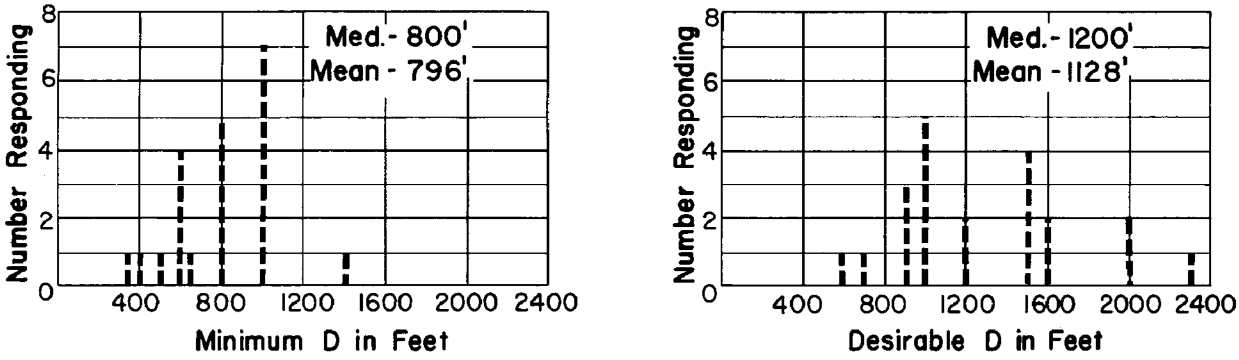
It was noted that with the single exit design, when the exiting volume requires a two-lane exit ramp, a weaving section on the ramp between the exit terminal and the form may be created. The two-lane exit is more complicated and generally costs more than two one-lane exits. It also may be necessary to drop one of the through traffic lanes at the two lane exit for lane balance. However, even with these problems, over 60 percent of the participants still preferred the single exit configuration for two-lane exits over the two exit design.

Mr. Sigal (N.Y.) objected to the two exit configuration shown in Figure 3-7(c), stating that drivers were familiar with interchanges with single exits on the right, with the right turn first and the left turn second. Mr. Housworth (Tex.) said that this is not really a problem because drivers are basically "sign followers" and that most people follow signs without thinking about the shape of the interchange. Mr. Alexander (FHWA) stated that the problem with this logic is that while most drivers are sign followers, there are others who are not. Some drivers will get off on the first off-ramp, then see that it starts turning left, and panic. It is not appropriate, he contended, to design solely on the basis of appealing to "most people."

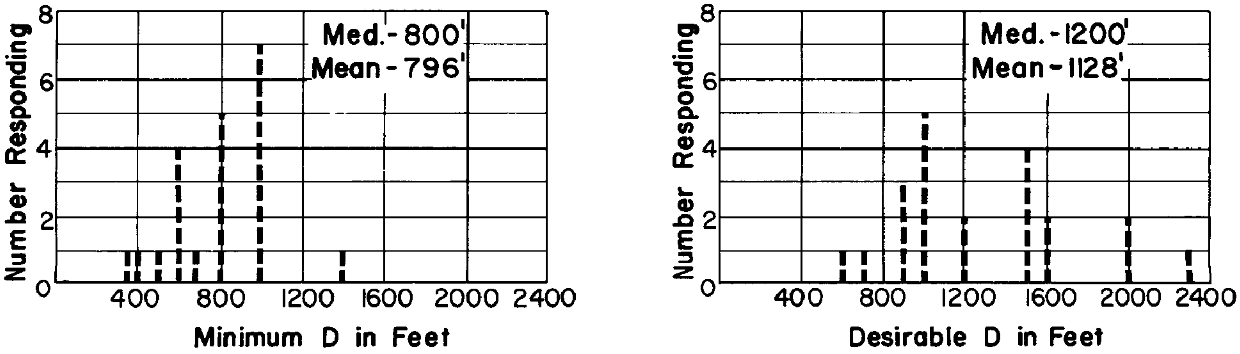
In the pre-workshop questionnaire, the designers were asked to indicate the minimum and desirable distances 'D' between noses for the configurations shown in Figure 3-7. There was little agreement among the 21 respondents, although this may have been due to different assumed design speeds on the mainline. Figure K-3 shows the distribution of these distances and also the mean and median values. It is worth noting that the median and mean values appraoch the AASHO values for an 80 mph design speed, as noted in Table 3-4 -- even for Figure 3-7(d) where the design speed would obviously be considered lower.

Entrance Ramp Configuration

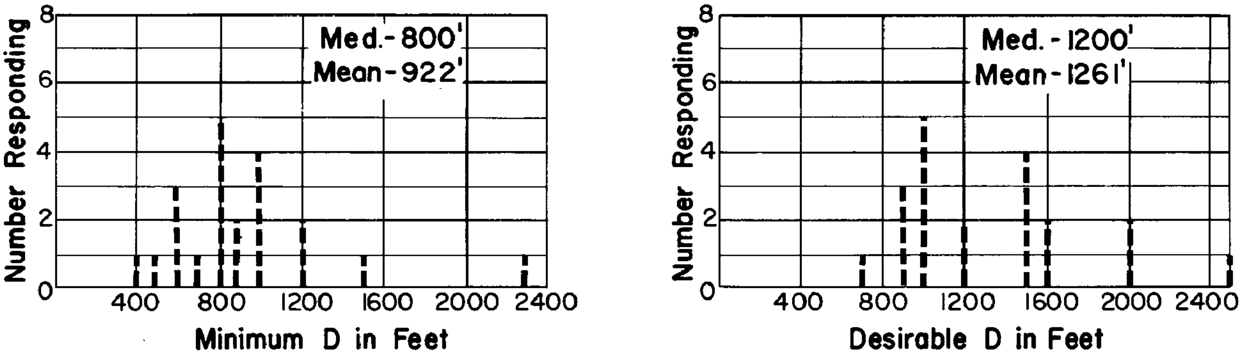
The pre-workshop questionnaire indicated that both the one entrance and two entrance configurations, Figures 3-9(a) and (b), are frequently used but that there was a decided preference for the one entrance design. When the turning traffic volume in Figure 3-9(b) requires a two-lane entrance,



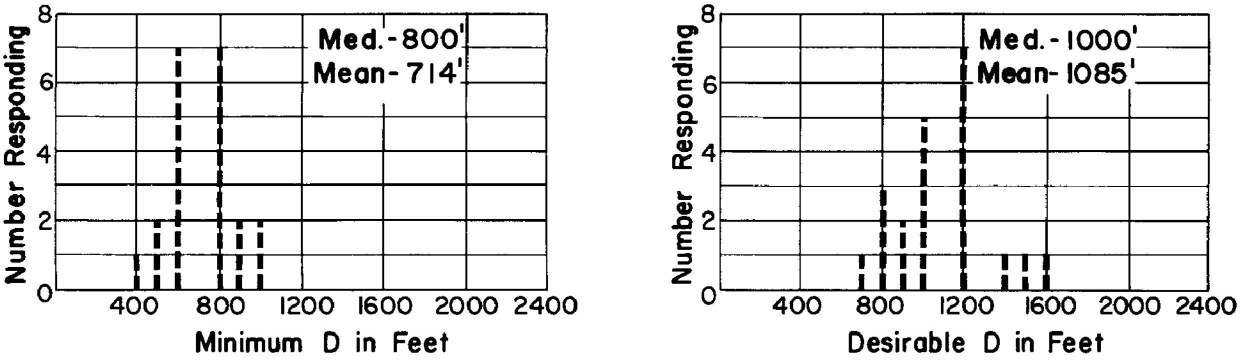
In Figure 3-7(a)



In Figure 3-7(c)



In Figure 3-7(b)



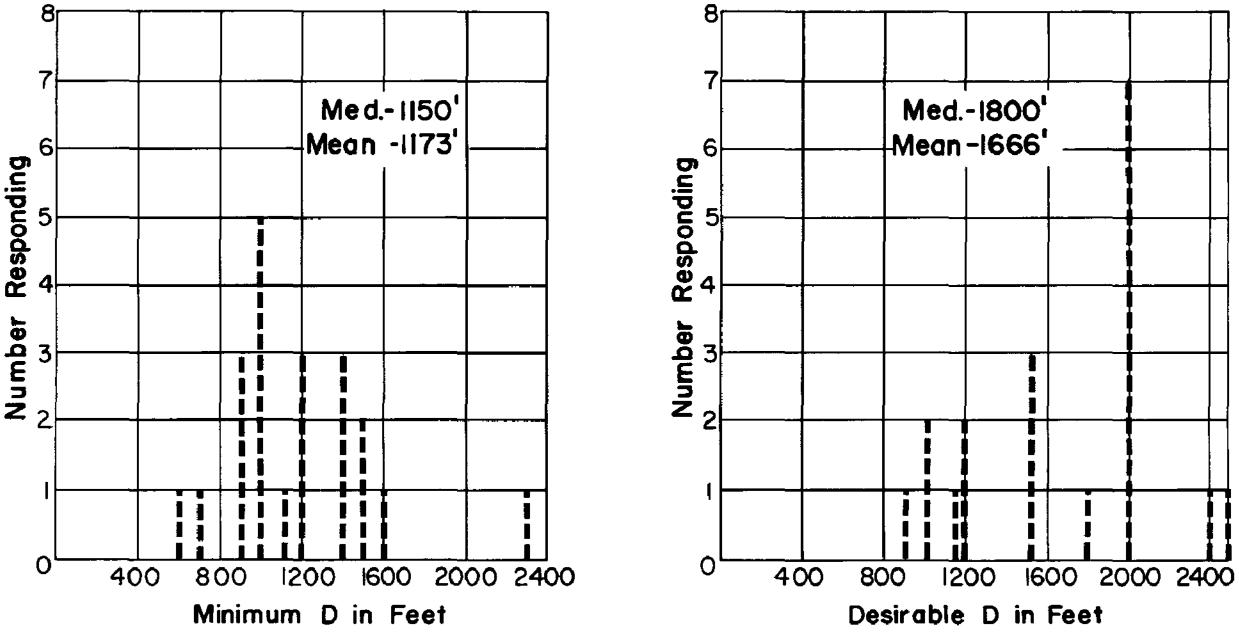
In Figure 3-7(d)

Figure K-3. Designers' Preference for Gore-to-Gore Distances -- Exits more than half the designers still preferred the one entrance configuration. If each of the turning roadways carry 1000 vehicles per hour, several of the participants indicated they would not use Figure 3-9(b) unless another lane is added to the mainline. Mr. Alexander (FHWA) did not see how one could justify not adding another lane if 2,000 vehicles per hour enter (further discussion on this point is included in a subsequent section on lane balance and lane drops). Mr. Sigal (N.Y.) noted that the double entrance configuration does solve many of the problems involved with two-lane, single entrance designs.

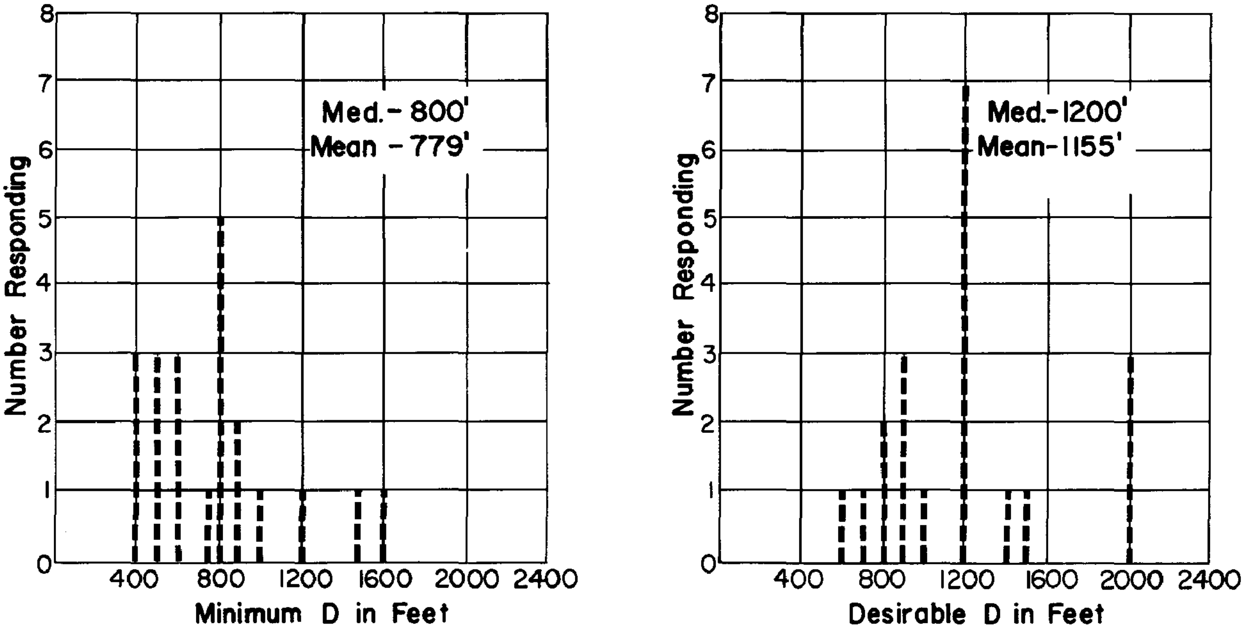
Each of the participants was asked in the pre-workshop questionnaire what they personally considered to be the minimum and desirable distance 'D' between successive entrance ramp terminals shown in Figure 3-9(a) and (b). Figure K-4 shows the distribution of these distances, together with the mean and median values. From these data, it is noted that many of the participants believe the distances recommended by AASHO, shown in Table 3-4, are not long enough for acceptable traffic operation. The great variation in the minimum and desirable distances indicates that the designers and operation personnel do not agree among themselves what these dimensions should be.

Weaving Sections

The majority of the workshop participants were critical of weaving sections on the mainline, judging them poor from both an operational and a safety viewpoint. A few contended that in rural areas with low traffic volumes, 300-500 weaving vehicles per hour and less than 1000 through vehicles per hour, Figure 3-5 would be acceptable if adequate weaving length is provided. Mr. Hall (California) noted that his state was modifying



In Figure 3-9 (a)



In Figure 3-9(b)

Figure K-4. Designers' Preferences for Gore-to-Gore Distances -- Entrances some of their existing cloverleaf interchanges by utilizing the shoulder and striping so they had a free lane for the entrance ramp beyond the exit terminal. The two auxiliary lanes in the weaving area were helping a great deal, he noted.

It was observed that when the loop ramps in a cloverleaf have adequate capacity for the turning traffic volumes, the weaving section on collector-distributor usually operates satisfactorily.

Several designers stated that a principal weaving problem in the vicinity of major interchanges, particularly in urban areas, is the presence of local entrances and exits within less than one-half mile of the major off- and on-movement where the mainline roadway becomes the weaving section. Mr. Biggs (Tex.) stated that in almost every major interchange in Houston an entrance ramp is located approximately 1,000 feet upstream from a major interchange and an exit ramp is located approximately 800 feet downstream from a major interchange. This condition is made worse when two adjacent major interchanges utilize the mainline for the weaving section as in the offset T interchanges shown in Figure 3-10. It was the consensus that this configuration should never be built, even if the weaving length were over one mile long. Mr. Fields (Ohio) indicated that one of the problems associated with using the mainline as a weaving section is the inability to advise the driver of the length available to make the weave and how many lanes he must change to the left or to the right in order to be in the proper lane to make his exit.

Regarding the method and procedures outlined in the Highway Capacity Manual (1965) chapter on weaving, the participants concurred that the weaving section computations were adequate in urban areas but inadequate in rural areas. Mr. Housworth (Tex.) noted that the level of service provided by these computations was not always high.

Lane Drops and Lane Balance

It was emphasized in the workshop that in any discussion of lane drops it is essential to differentiate between basic freeway lanes and auxiliary lanes. It was the consensus that auxiliary lanes which begin at the preceding upstream entrance can be dropped at a major interchange exit without any special lane drop treatment. However, the dropping of a basic through freeway lane requires special consideration, whether it occurs at an interchange exit or beyond the effect of the interchange area.

Figure K-5 shows three geometric configurations for a reduction from three through traffic lanes to two lanes at a single lane exit ramp. Figure K-6 indicates similar lane drops from four lanes to three lanes and Figure K-7 shows lane drops from four lanes to three at a two-lane exit ramp. The participants at the workshop were asked to rank the configurations in each of these figures in order of personal preference. In all three cases the majority favored dropping the through lane beyond the interchange, but 35 percent favored dropping the right lane in Figure K-6 and approximately 45 percent preferred dropping the right lane in Figures K-5 and K-7. Only one of the twenty-seven participants preferred to drop the left lane in each of the three figures.

Mr. Loutzenheiser (FHWA) stated that lane drops are a practical consideration and no formula or equation will help decide where to design the lane drop. Because of geometric and operational specifics, the lane

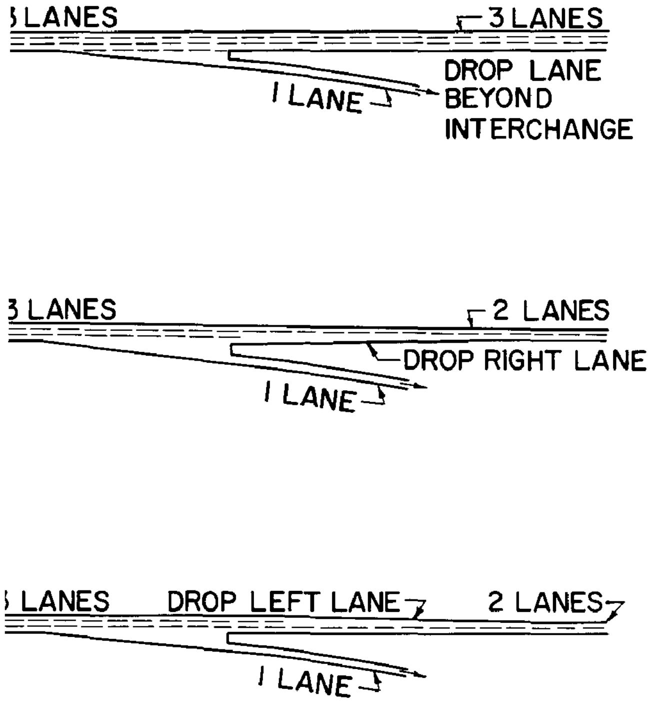


Figure K-5. Lane Drops: Three Lanes to Two, with a One-Lane Exit

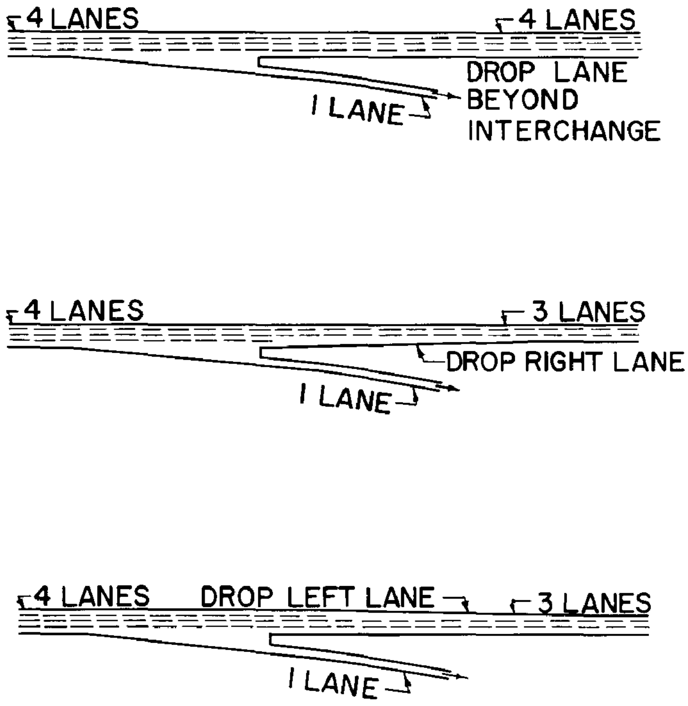


Figure K-6. Lane Drops: Four Lanes to Three, with a One-Lane Exit

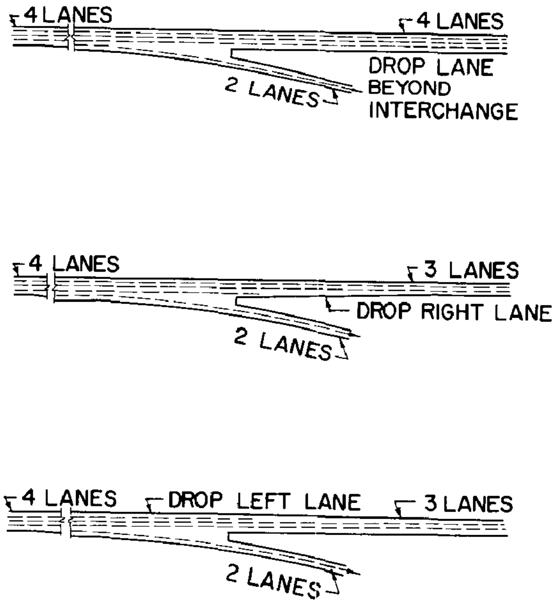


Figure K-7. Lane Drops: Four Lanes to Three, with a Two-Lane Exit drop is usually designed beyond the interchange. Mr. Gazda (Illinois) suggested that one reason for dropping a lane just beyond an exit ramp is that drivers handle the maneuver better because they expect more unusual maneuvers at the exit gore area.

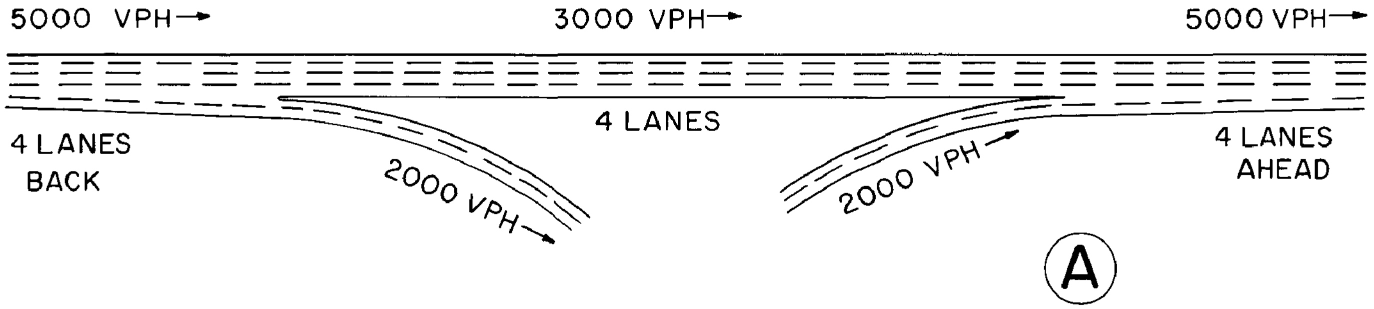
When the lane drop is located beyond the influence of the interchange, it was almost unanimous among the participants that the right lane was the most desirable lane to be dropped. It was noted that the merge from the right was safer and what the drivers expect. It was further argued that the high speed traffic in the left lane should not be disrupted by a lane drop and that rear visibility is poorer when merging to the right as compared to merging to the left.

The few indicating a preference for the left side lane drop noted that there was usually less traffic in the left lane, particularly during off-peak hours, and consequently less lane changing required. It was also pointed out that if a future median lane was to be added ahead, the left side was the natural place to drop the lane.

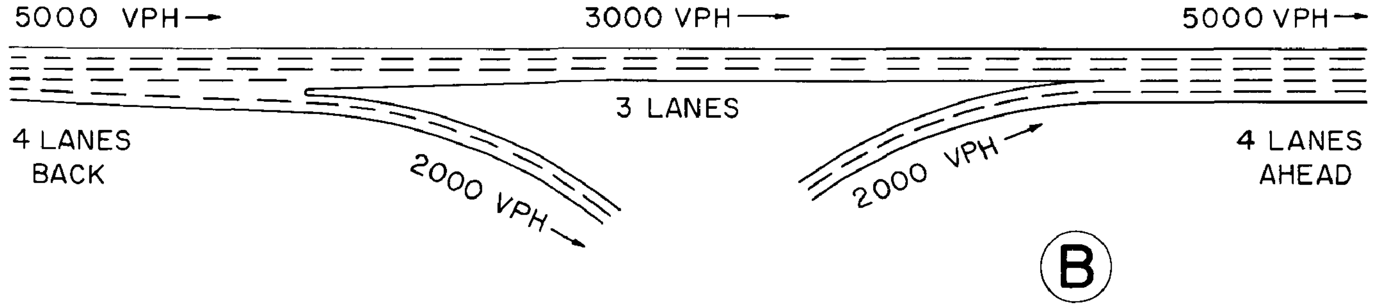
None of the participants favored dropping one of the interior lanes since this puts a squeeze play on all drivers.

There was general agreement that the essential factors for good operational characteristics are good visibility (at least desirable sight distance), tangent alignment, preferably toward the far end of sag vertical curves, and adequate advanced signing to advise the stranger of impending lane drop.

Considerable discussion centered about whether a lane should be dropped at an exit ramp in an interchange if a lane was to be added beyond an entrance ramp. Figure K-8 shows two alternative treatments of a four-lane through roadway at a major interchange with high volume



NO LANE DROPPED



ONE LANE DROPPED

Figure K-8. Lane Balance within an Interchange exit and entrance ramps: Figure K-8(a) has no lane drop, while Figure K-8(b) shows a reduction to three lanes between the exit and entrance ramps. Mr. Sigal (N.Y.) stated he was definately opposed to dropping a lane at an exit and then picking it up at the next entrance. He would carry the same number of lanes through the interchange regardless of the volume. Mr. Hall (Cal.) said that all of the problems in the Los Angeles area have come up in the situation illustrated in Figure K-8(b). Mr. Gray (Ohio) indicated that in the past designs were based strictly on volumes, but now more attention is paid to operations.

A recent gore area study indicated that signing is a problem when lane drops occur in conjunction with exits. Some drivers interpret "EXIT ONLY" signs to mean that if one cares to exit he can do so only from that lane but that the sign does not indicate a lane drop. Mr. Biggs said Texas uses a separate black in white overhead sign reading, "RIGHT LANE MUST EXIT." Texas has discontinued the use of "EXIT ONLY" signs.

A discussion of the geometric design of a lane drop beyond an exit ramp indicated that about half the participants would begin a taper at the ramp nose while the other half would provide a full-width escape lane, varying in length from 150 to 1,000 feet, before starting the taper. Mr. Gazda (Ill.) opined that with full-width paved shoulders (which can serve as a recovery area), the full-width escape lane is not necessary. The taper rate preferred at lane drops varied from 30:1 to 100:1, with 50:1 the most frequently mentioned. One respondent to the pre-workshop questionnaire recommended a taper length equal to the "design speed" times the "lane width." This results in a 50:1

taper for 50 mph design speed and correspondingly flatter tapers for higher design speeds.

Route Continuity

Mr. Hall (California) introduced another variable in interchange design, map relatability, which he defined as the direction the traveler would expect to go. He observed that interchange designers should perhaps consider the driver who expects to make a right turn from consulting his map. The question was posed as to how many people are concerned with map relatability when they drive. Most workshop participants felt that this type of driver represents a small percentage of the freeway user population.

Mr. Fields (Ohio) suggested that lane continuity was more important than map relatability. He argued that once a driver is in a particular lane he prefers to stay in that lane in order to continue on that route. Difficulties arise when a driver is required to change lanes in order to follow a particular route.

Mr. Gazda (Ill.) noted that Illinois relies on pavement jointing to convey messages to the driver. When the through route contains a lower traffic volume than a turning roadway, Illinois designers give the through route the preferential pavement jointing, making the exiting driver cross the pavement joints to get to his destination.

Three alternate configurations for a Y interchange were presented to the workshop participants for discussion. Figure K-9(b) follows the concept of route continuity. Mr. Churchill (Fla.) was of the opinion that it is difficult to make a selection among the alternatives without traffic volumes being known. Mr. Hall (Cal.) stated that the percentage split in volume would be the factor determining which type to

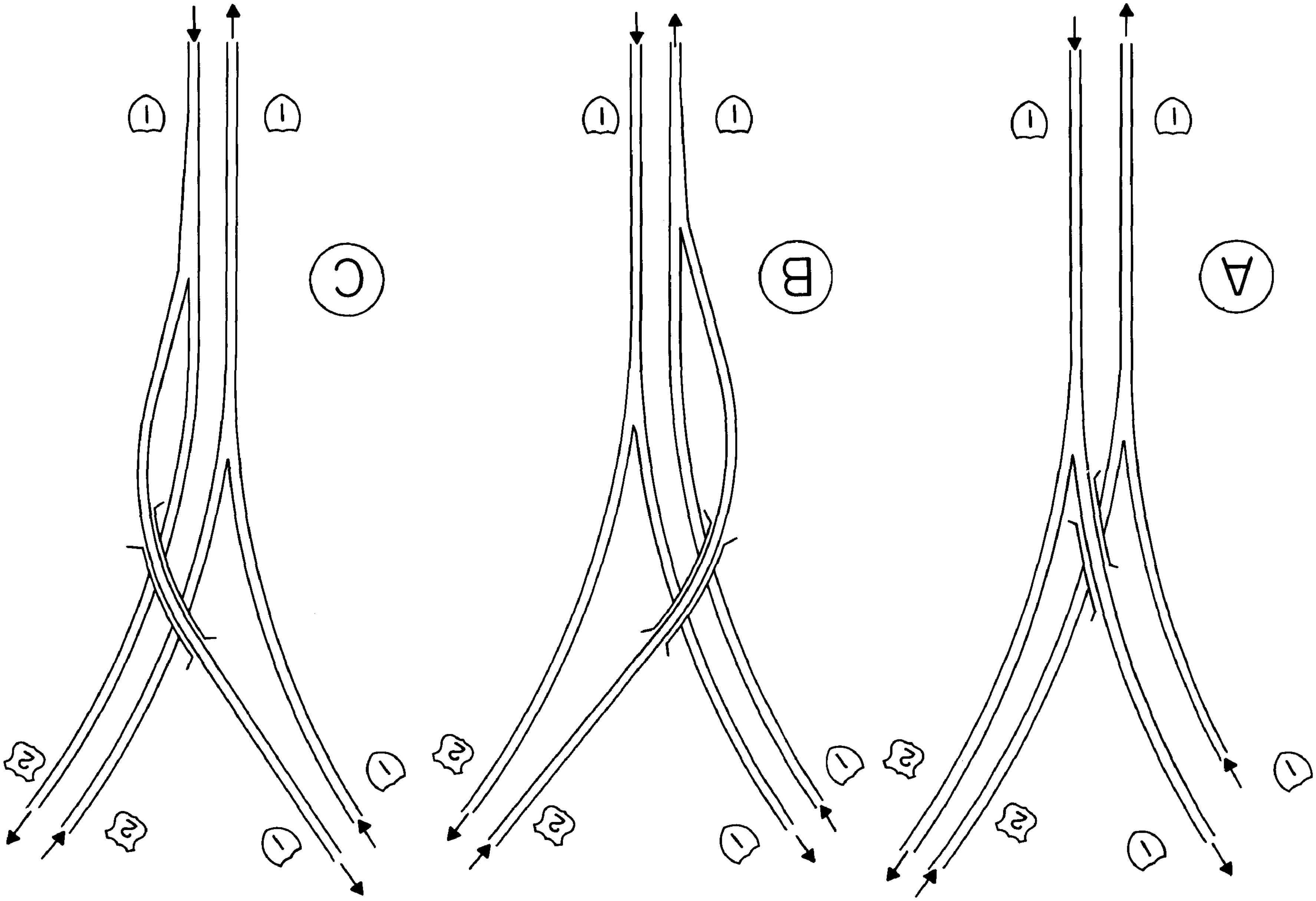


Figure K-9. Route Continuity: "Y" Interchange adopt: with a 50-50 split, he favored Figures K-9(a) or (b); with a 30-70 split favoring Route 2, he preferred the configuration in Figure K-9(c). Mr. Foster (Wash.) indicated that if the volumes were widely divergent, he would design according to volume. However, the character of the two routes also comes into play. If both routes are interstate routes, traffic volume would govern. If one route was interstate and the other a state or federal primary, they would design the interchange so the interstate route appeared continuous. The traffic volumes would have to be extremely high on the secondary route to adopt a design which would make the interstate route appear to exit.

It was noted by Mr. Housworth (Tex.) and seconded by Mr. Kenyon (N.Y.) that visibility plays an important role in whether or not an interchange operates satisfactorily, regardless of route continuity.

Mr. Loutzenheiser (FHWA) defended the route continuity concept, but noted that the current route numbering system is not adequate to adopt this kind of a policy through an urban area. It was noted that with the current practice of utilizing the 200 and 400 series for by-pass interstate routes, a driver following a numbered route may be led directly through a major city rather than directed to a by-pass around the city.

Mr. Loutzenheiser (FHWA) stated that Mr. Leisch's philosophy was based on minimizing lane changes as much as possible and that route continuity would lead to signing which would be more easily understood. He concluded that there is something to be said for route continuity in that it would aid traffic flow, improve efficiency, and reduce accidents if one could attain this kind of continuity.

Exit Terminals

It was the consensus of the workshop participants that for freeway-to-freeway interchanges, where ramp traffic is generally free flowing, the tapered type deceleration lane is superior to the parallel type because it is consistent with the path that most drivers follow. However, there are several notable exceptions where the parallel type is considered the preferred design. These exceptions include the following:

(1) When the mainline roadway is on a horizontal curve and the exit ramp is tangential to the curve.

(2) When the sight distance to the exit area is restricted by either vertical or horizontal curvature and it is desirable to provide a "shadowed" area for the decelerating vehicles off the mainline.

(3) When the exit ramp is a loop, with a considerably lower design speed than the mainline roadway.

(4) For high volume ramps, particularly those requiring multi-lane ramps.

(5) For all exits from the left or high speed lane.

Mr. Gazda stated that Illinois uses the tapered exit terminal for single lane ramps except where a capacity problem exists. When a capacity analysis indicates that the level of service at the exit gore drops below the level of service of the freeway, they provide a parallel auxiliary lane approximately 2,500 feet long, if possible. Mr. Hall indicated that California has used a parallel deceleration lane on congested freeways even though turning volumes were only 700 vph. Operational and capacity advantages can be gained, since in this situation drivers will move into the deceleration lane earlier.

The comment was frequently made that either the parallel or tapered type deceleration lane can be designed to work properly for single lane exits. It was agreed that most multi-lane exits should be designed as major forks.

There was relatively little discussion on the merits of the several types of nose and gore area design. Mr. Churchill (Fla.) noted that there is no need for an excale lane in the gore area when a full-width, flush, high-type paved shoulder is provided adjacent to the mainline roadway. Mr. Gray (Ohio) indicated that the all-paved gore area is significantly better from a maintenance standpoint than an inexpensive paved shoulder material.

Entrance Terminals

It was the consensus of the designers responding to the pre-workshop questionnaire that the taperal type entrance, approximately 1,000 feet long, is the most desirable except where the mainline is on a steep ascending grade and the entrance has a large truck volume. In this latter case a parallel entrance, extended to permit the trucks to attain reasonable operating speed before merging, should be provided.

In the workshop discussion, Mr. McCausland (FHWA) noted that the recent trend toward flush paved shoulders has done away with many of the arguments for the parallel type acceleration lane. One of the warrants in the New York State Design Manual for using the parallel lane is the existence of curbs adjacent to the ramp pavement. With full width paved shoulders, this warrant is negated. Mr. Gazda (Ill.) indicated that his preference for the taper design stems from the 1961 AASHO special study which observes, in part: (1) of the drivers who use speed-change lanes properly, the majority follow a gradually tapered path regardless of the design; (2) many drivers do not know how to use speed-change lanes; and (3) direct taper designs tend to encourage a larger proportion of drivers to use them properly.

Mr. Loutzenheiser (FHWA) remarked that the AASHO Committee revising the "Red Book" tried to get more specific on the choice between the parallel and tapered acceleration lanes and did not succeed. He further observed that with the taper type design, the driver needs a long flat area before he reaches the inside double-line point so that the ramp traffic is practically parallel to, and at the same elevation as, the through traffic. From this position his ability to see and judge the mainline traffic will help to keep him moving ahead and reduce the probability of his stopping. Both Mr. Gazda (Ill.) and Mr. McCausland (FHWA) were in accord that they found no difficulty in using the rear view mirrow when driving a 50:1 taper if the taper extends back beyond the nose.

Most state representatives concurred that with a 50:1 taper, the taper should begin at least 100 feet before the nose, as illustrated in Figures 3-17(b) and (c). Illinois increases this length as the ramp design speed decreases. Mr. Sigal (N.Y.) cautioned that at a 50:1 taper, only four feet of separation are obtained in 200 feet; New York uses 200 feet of 3-degree curve back of the nose and obtains 18.9 feet of separation. Mr. Gazda (Ill.) commented that when a curve precedes the gore nose, drivers tend to cut directly into the traffic stream. By extending the taper as a tangent section back of the nose, the driver becomes properly oriented and uses more of the taper length. Mr. McCausland (FHWA) added that with the taper extended back of the nose, the mainline pavement and shoulder grades control the elevation of the approach ramp, automatically providing adequate rear view sight distance at the approach to the nose.

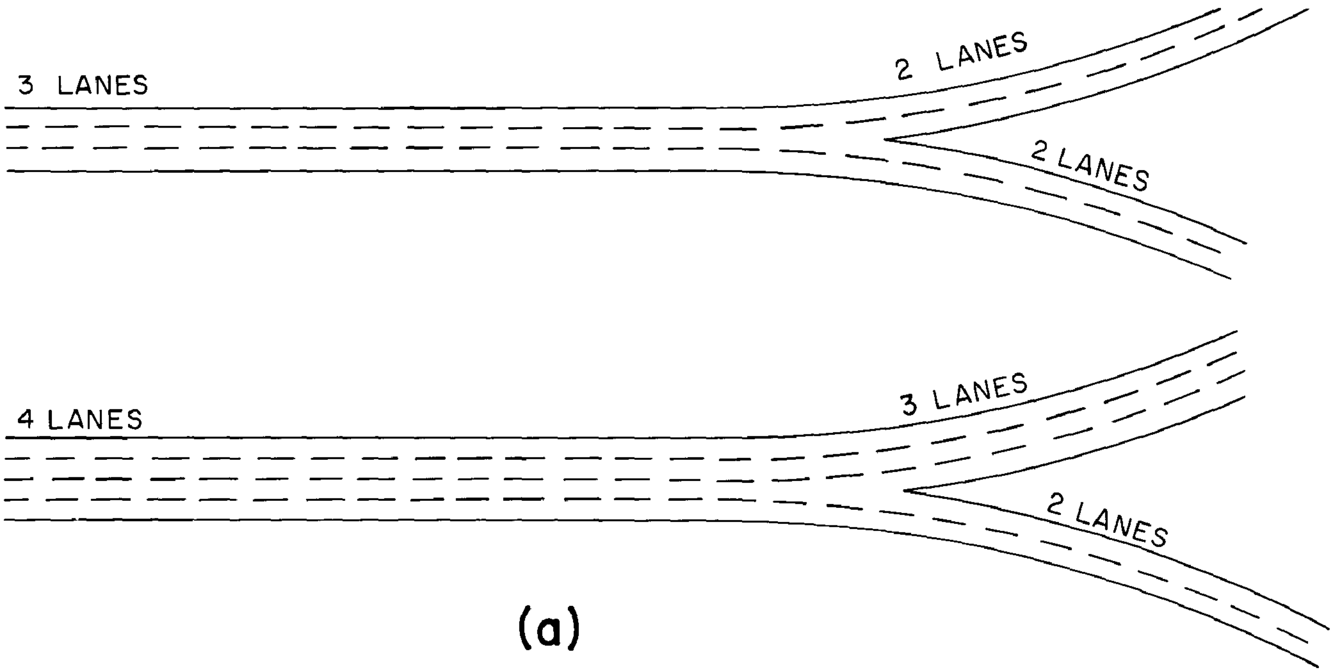
Multi-Lane Exits

The question was raised as to the difference between a two-lane exit ramp and a major fork. Mr. Loutzenheiser (FHWA) indicated that one way to differentiate between the two is the type of design. At a major fork there would be something over and above the conventional design for an exit. Also, major forks usually occur at major interchanges. Mr. Sigal (New York) indicated that at a major fork the two diverging legs are both of freeway standards and the design speeds of the two legs are not reduced for any appreciable distance. Mr. Gray (Ohio) stated that if the basic number of freeway lanes was carried ahead, it is not a major fork. If they are not carried ahead, it is a major fork.

Mr. Hall (California) noted that a full-directional interchange most likely will have two-lane exits. A two lane exit without a parallel auxiliary lane often produces "accident traps." California uses 2,500-foot parallel lanes at two-lane exits.

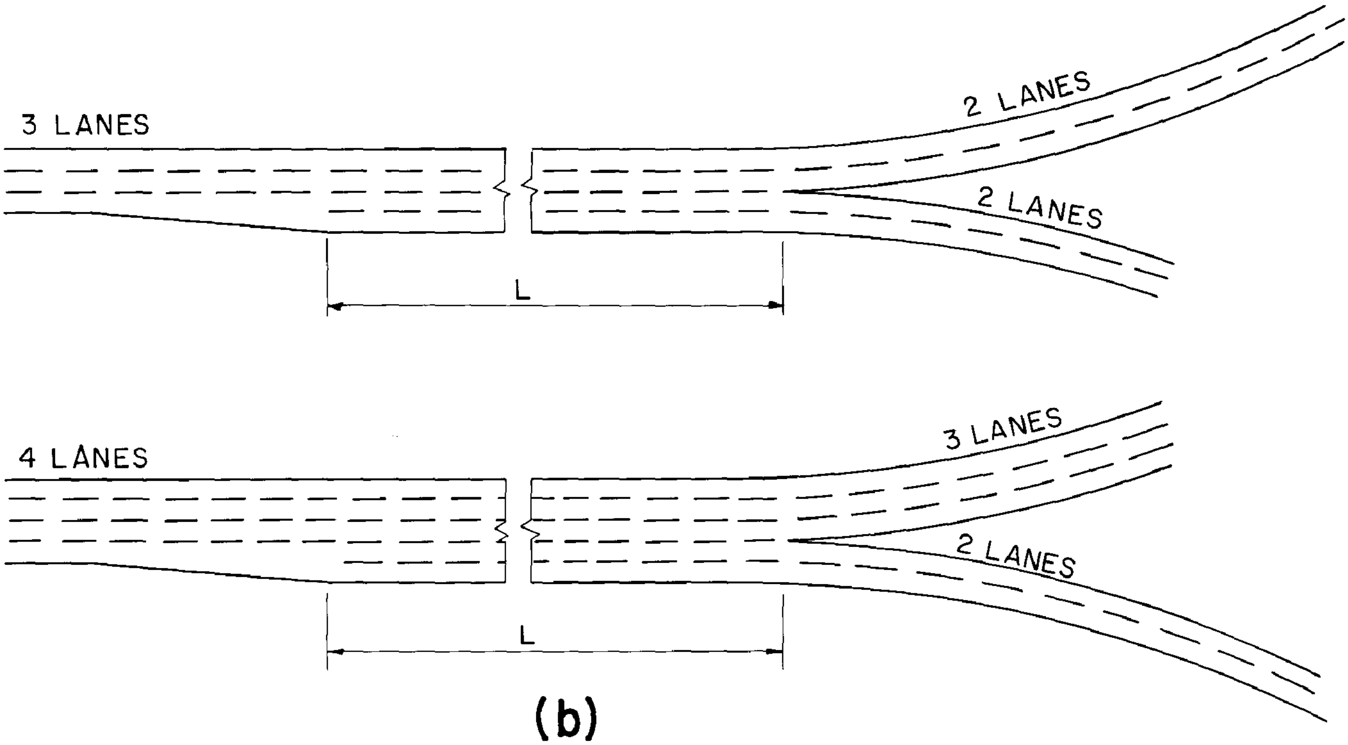
A major concern of the workshop participants was the lane striping (and construction joints) at multi-lane exits. Mr. Gazda (Ill.) indicated that his state continues the lane lines of the preference route for route continuity, adding extra lanes on the right for a right exit and on the left for a left exit.

Mr. Alexander (FHWA) asked whether it was common practice to split three lanes into two two-lane roadways with an optional middle lane. A similar condition may exist where four lanes are split into two- and three-lane roadways. Figure K-10(a) illustrates the optional middle lane. Many of the conferees expressed unhappiness with such a configuration, one reason being that it is difficult to sign. Preference was given to adding an extra lane in advance of the split, as shown in



(a)

OPTIONAL MIDDLE LANE



(b)

NO OPTIONAL LANE

Figure K-10. Major Fork Configurations

Figure K-10(b). Mr. Gazda stated that Illinois uses a length of 1,600 to 2,500 feet of additional lane in advance of this type of split.

Mr. Hall (California) noted that a major problem occuring at multi-lane exits, particularly at major forks, on high volume freeways is the slower moving commercial vehicles in the right lane which do not make the right turn. All other vehicles turning right must weave across these slower moving vehicles creating potentially hazardous conditions. To alleviate this situation, California has developed a special design (shown in Figure K-11) employing a right-exiting left-turn lane for trucks.

Multi-Lane Entrances

The subject of two-lane entrances created considerable discussion in the two workshop sessions. The participants were asked to rank the three merging configurations shown in Figure 3-20. Of the twenty-nine respondents, nineteen preferred the outer lane merge, seven preferred the non-compulsory merge, and only three indicated the inner lane merge as the most desirable. Mr. Hall (California) suggested that the outer lane merge and the non-compulsory merge were not entirely simmilar. Mr. Lins (Maryland) remarked that the public expects the right or outer lane to merge and that the slower moving traffic is generally in the right lane. It was noted that while the outer lane merge has an adjacent full paved shoulder for an escape lane, the vehicle in the inner merge has no escape if a gap fails to materialize. Mr. Gazda (Illinois) observed that when turbulence occurs during peak hours, the inner lane merge accidents are high in number, involve several vehicles, and cause more serious damage because of no escape route.

In the pre-workshop questionnaire, the participants were given a schematic drawing of a two-lane entrance where no additional freeway lanes were

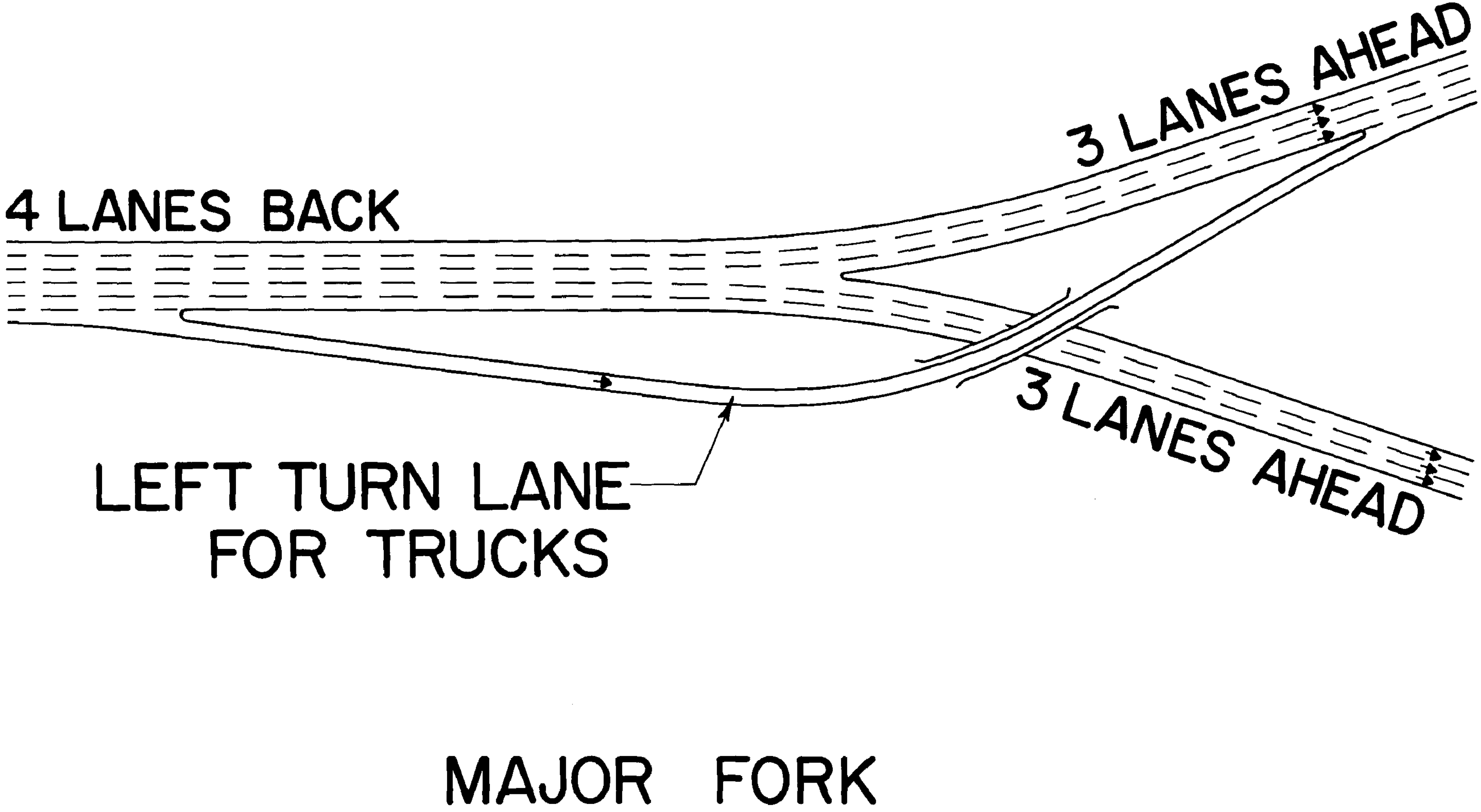
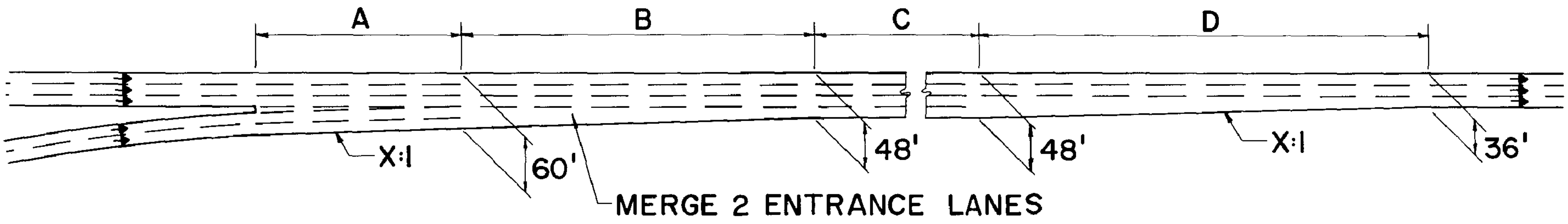


Figure K-11. Major Fork with Truck Lane

provided, and asked to indicate the minimum and desirable dimensions for the various component parts. Figure K-12 shows this two-lane entrance configuration, together with the median, mean, and range of dimensions, both minimum and desirable, as recommended by the participants. There was fairly good agreement that the taper ratio of 50:1 is both a minimum and a desirable standard which governs the dimensions A, B, and C. However, there was a wide range of opinion on the length of the parallel auxiliary lane (dimension C) between the two merging tapers, with minimum values ranging from zero to 2,000 ft.

It was the consensus that the arrangement in Figure 3-32 would seldom be used, for if the turning volume requires a two-lane roadway, it would be almost essential to add at least one lane downstream from the entrance to provide adequate capacity. The two exceptions would be: (1) where the approach volume on the upstream freeway approach does not require three lanes, but an extra lane is carried through the interchange to avoid a lane drop; and (2) in a Y-type interchange where the traffic volume does not warrant a two-lane turning roadway, but this roadway is the continuation of a two-lane freeway roadway with no turning ramps on the immediate vicinity (see the merge in Figure 3-20).

Mr. Hall (Cal.) noted that at two-lane entrances with high volumes in urban areas, both lanes are continued downstream with the outside lane dropped at the first exit and the second lane carried through. Mr. Housworth (Tex.) said his state carries the two-lanes a minimum of 1,800 feet and usually drops one lane at the next off-ramp, with a recovery lane provided Texas has found the recovery lane is very important for satisfactory operations.



RECOMMENDED DIMENSIONS BY WORKSHOP PARTICIPANTS

DIMENSION	MINIMUM			DESIRABLE		
	MEDIAN	AVERAGE	RANGE	MEDIAN	AVERAGE	RANGE
A	500'	475'	200' - 900'	500'	550'	300' - 1000'
B	600'	673'	400' - 1000'	840'	877'	600' - 1200'
C	800'	873'	0' - 2000'	1200'	1450'	500' - 2500'
D	600'	655'	400' - 1000'	600'	795'	600' - 1200'
X (taper ratio)	50:1	50:1	15 - 80:1	50:1	58:1	15 - 100:1

Figure K-12. Dimensions for Two-Lane Entrances

APPENDIX L

TRAFFIC CONTROL FOR MAJOR INTERCHANGES

Robert S. Hostetter, Institute For Research

CONTENTS

APPENDIX L: TRAFFIC CONTROL FOR MAJOR INTERCHANGES

Introduction

The purpose of this appendix is to present a discussion of the feasibility of including major interchanges into freeway control schemes. The problem underlying the need for such an effort is that the congestion frequently experienced at major interchanges often affects connecting freeway links, thereby limiting or negating the control which is exercised upstream of the major interchange. Problems of congestion can be handled either by increasing capacity and/or decreasing demand. Methods for achieving these goals include distribution of costs (**i.e., taxation,** tolls, etc.), land use planning and restrictions, highway construction, and on- and off-freeway control. Although traffic control devices and procedures have long been viewed as a means of enhancing efficiency and safety, the exploration of freeway control as a method of manipulating demand and capacity has barely begun. The requirements for manipulation are, of course, not constant, but rather are generally related to the large fluctuations in demand which occur during peak period as Drew (1968, p. 427) points out, "classical control systems are employed either to make the facility flexible enough to accommodate fluctuations in demand or to reduce the magnitude of the demand fluctuations. Freeway surveillance and control are necessarily limited to the latter." Because of this, it is felt that the concept of freeway control should be broadened to include "non-classical" control methods such as lane exclusivity, corridor control, etc. In other words,the concept of traffic control must be broadened to include various other types of traffic manipulations.

In addition to expanding the concept of control, it is the judgment of the project staff (and shared by many of the design and operations experts who participated in the project workshop) that the point at which freeway control is considered should be earlier in the design-construction-operation process. The fact that congestion at major interchanges reduces or negates the effects of upstream control illustrates the desirability of considering system-wide application of freeway control at early stages of design and planning. Early consideration is in lieu of the more traditional approach of employing control measures only as a remedial treatment over short sections of freeway or at individual "problem" interchanges. This is not to say that freeway control should not be used remedially. On the contrary, the inability to forecast traffic demand over the design life of a facility makes such application of control not only desirable but mandatory on those facilities which are already constructed. As McCausland (1972) has pointed out, there has been a general acceptance of the validity of control concepts involving application of signal control, area-wide surveillance and control from a centralized location, and the use of surveillance system data for activating real-time motorist information systems. Further, there are empirical results available which confirm the general feasibility of such systems. One of the deterrents to design stage consideration of control may be attitudinal. It was suggested in the Design Workshop that there are those in the upper echelons of some state highway administrations who feel that metering, for example, implies substandard design. That this attitude is not shared by the Federal Highway Administration was brought out via reference to a 6-8 month old policy and procedure memorandum (PPM) which indicated that federal participation was available for the installation of conduit for control systems. Further if control systems are part of the total design, the control portions of the design qualify for federal aid. While consideration of control in the planning and design stage is not common, there are indications that some progress is being made. For example, there are projects in both Texas, California, and Washington in which conduit is being provided during initial construction. Also, Illinois has projects in Chicago in which ramp metering is to be designed into the system and used with the onset of operation. Finally, Pennsylvania is designing some sign structures to handle the load for future lane control signing. It was pointed out by one member of the Workshop that in some urban areas it is no longer possible to provide alternate facilities as was done in the past and therefore freeway controls must be designed into the system for the present market. While the negative or apathetic attitudes toward freeway control are being overcome, not all of the problems related to early planning and use of control have been overcome. Some city administrations would prefer that the city street system operates well rather than the freeway system, i.e., since the people who use the freeways are commuters and not local voters and taxpayers. Thus, where a metered freeway ramp may produce a back-up on city streets, a city-state conflict may arise.

In spite of problems such as this, and in spite of the fact that we certainly do not yet know all there is to know about the operation of freeway control system, it was the general consensus of the design and operations experts participating in the Design Workshop, that control should in fact be considered in the design stage and that control should be viewed as a systems problem. Further, the participation of FHWA in funding such efforts and the high probability that control will be required, argue for preparatory steps (e.g., conduit, bridge loads, etc.) being taken in order to reduce the cost and problems of future additions of control hardware. Finally, freeway control concepts should be expanded to include manipulation of demand _and_ capacity, and should be considered as a tool to be used to provide greater flexibility for effectively accommodating changing traffic patterns.

In assessing the feasibility of adapting freeway control technology to the design of major interchanges, we are questioning whether or not the technology is capable of being effectively utilized in such situations. There exists a critical semantic difference between this issue and the more important criterion question, "Will the technology produce the desired effect on traffic operation?" This distinction shapes the discussion which follows inasmuch as it provides a framework for dealing with some of the conflicting opinions and contradictory experiences found in the literature and offered by the experts who participated in the Design Workshop. In the professional literature, despite editorial biases which tend to overrepresent "positive" research results, one can point to antagonistic instances of "relative" success (or failure) in implementing control systems which are functionally identical and are employed under essentially equivalent field conditions.

One could elect to be insensitive to failures and contend that if a control system "worked" at all, it demonstrated that it is "_capable_ of being used effectively," and is therefore, by definition, "feasible." We are, however, concerned not only with "potential" but with expected performance. In short, "capability" serves in the role of a minimum requirement -- a necessary but not sufficient condition for acceptable performance.

Lacking a history of control applications on major interchanges, we must of course rely on extrapolations from controlled non-major interchanges; thus, our feasibility assessments will be, in effect, subjective appraisals and discussions of the likelihood that a given control feature, configuration, system, etc., will produce the intended results when applied to major interchange designs. Our perspective is, then, feasibility from a performance point of view.[1] A major concern in an assessment of feasibility such as we attempted here is the manner in which the available research and experience-based expert opinion information is to be evaluated and used. In some instances, the same type of control system was evaluated using different performance criteria and it is not clear whether different results reflect the differential sensitivity of the evaluative measures, or whether other factors such as geometrics may have produced any intra-study differences observed. Also, in some cases where negative results were obtained, it is not clear whether the "failure" was due to system hardware operational inadequacies or to informational factors.

Designers and researchers have demonstrated considerable ingenuity in deriving figures of merit for operational performance. The Highway Capacity Manual suggests, in addition to capacity, that Level of Service, a qualitative index of flow conditions, be used as the major performance criterion. Wattleworth et al. (1967) stressed the systems

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[1] Cost criteria, while essential to interchange design decisions, are not included in the current feasibility assessment.

approach to evaluation of major interchanges with the maximization of total output under the "highest quality of traffic service" as the best composite criterion. Everall (1972) reviewed some 45 performance measures that could be used in evaluating the effects of alternative solutions to freeway problems. In evaluating the performance of freeway control systems, he specifically identified the somewhat universal use of three basic performance parameters: 1) Total travel time (vehicle or passenger hours), 2) Total travel (vehicle or passenger miles per unit of time, and 3) Number of accidents (classified by severity types per million vehicle miles). In reviewing accomplishments in freeway operations outside the United States, Duff (1971) cites a broad range of criterion indices including establishing a ceiling or critical value for unexpected delay time, reducing driver complaints and irritation, minimization of total time spent in the network, etc.

No matter how sophisticated the engineer becomes in estimating, sensing and detecting traffic parameters such as demand, capacity, speeds, volumes, densities, etc., the most important aspect of the control system is likely to be critical interface in communicating command or advisory messages back to the individual driver in a meaningful fashion. And, assuming that the driver's understanding of the message is in agreement with the intended meaning, there is usually still an opportunity for the individual to compromise the system by failing to behave in the indicated direction. Interestingly enough, qualitative indices of system performance are generally preferred in an apologetic vein despite the fact that they are based upon quantitative traffic features. If drivers are to be expected to use the information presented to them, it must, from their perspective, be meaningful, timely, and credible. This fact dictates that "information" oriented studies be evaluated along with hardware studies.

Several recent efforts have been made in the laboratory to determine driver needs and preferences for freeway traffic information. Dudek et al. (1971) indicated that qualitative information concerning the location and degree of congestion is more valuable to the driver than quantitative alternatives (such as average travel speeds or times between reference points). Moreover, there were indications that such information would be used if it were presented in real time. Heathington et al. (1970), in evaluating information alternatives for the Freeway Driver Information System, also found that drivers preferred to have real-time information on traffic conditions and that descriptive information concerning accidents and speed was preferred to quantitative measures such as travel time or delay.

Two points should be made here:

1) That the measures of system performance that the engineer employs to evaluate freeway operations are not generally preferred by drivers using the system, i.e., several information translation steps may be required.

2) That recent attempts to provide freeway information to drivers (particularly to effect alternate routing) have, by and large, satisfied the requirements for meaningful and timely information if not (from the driver's perspective) credible information.

From a practical point of view, there is no incompatibility in the first point since the engineer can consider the driver's information needs and/or preferences as simply another component of the overall control system to be optimized and continue to evaluate system performance in terms of his own choice of a figure of merit. To the extent that he is successful in this optimization, he enhances the probability of an overall improvement on performance against his selected criterion dimension. The second point is a bit more subtle. We have reached an awareness of meaningfulness and timeliness of freeway information that has found its way into the field, however, we still observe system failures because drivers often times do notdo what they are supposed to do. Closed (via signing) freeway lanes are traveled, posted speed advisories are ignored, "safe" or "large" gaps are rejected while small or hazardous ones are accepted, caution lights are taken as indications to accelerate through an intersection, etc.

Thus, our consideration of feasibility becomes further structured, i.e., in order to be useful to design engineers our assessment of feasibility must be in terms of what we regard as its two principal components -- technology (hardware and systems) and driver behavior. In view of the earlier mention of conflicting expert judgment and the relative success or failure of essentially similar systems, the distinction between technological and behavioral components is not surprising when considered in the context of the rich variety of individual differences in any driver population. In a sort of left-handed manner, this observation really implies that with a few reservations, the scientific and engineering wherewithal exists to develop control hardware which theoretically should be able to optimize any system's operation, given knowledge of the physical limits and capabilities of its components. Since human behavior does not yet lend itself to rigorous, predictable outcomes, such sophisticated hardware systems often fall short of realizing their design goals.

The technological and behavioral aspects of expected performance, then, form the basis for the determination of feasibility of applying control technology to major interchange design. Since there is an infinite variety of design features to major interchanges as well as a rich assortment of control techniques and devices, we shall restrict our discussion to the technological and behavioral impocations of three broad control classifications applied to major interchange design in general. With few exceptions, the problems associated with major interchange design differ little in kind from those of the non-major interchange. Hence, many of the systems employed to control traffic in the non-major setting will yield the same relative success in regulating flow when applied to the major interchanges. One of the major exceptions is the requirement of major interchanges to provide for uninterrupted flow on a multi-lane connecting link.

While it is not our intention to provide a comprehensive summary on freeway control techniques since several relatively recent state-of-the-art documents exist (Drew, 1968; Duff, 1971; Wattleworth, 1971; Everall, 1972), we shall use such information as a point of departure for our statements of feasibility for major interchanges and highlight the typical and promising techniques within each of the following control classifications: (1) ramp control, (2) main line control, and (3) corridor control.

Ramp Control

Closure

The two types of ramp control which are employed are metering and closure. Closure of the connecting roadways of a major interchange is obviously impossible. However, consideration has been given to selective closure of local access ramps in a major interchange. In response to the question of selective closure of local access ramps, 59% of the participants at the Design Workshop said that they thought this would be a very practical solution. The problems with this solution are both political and logistical. The political problem is one of public animosity due to denial of access to the freeway. Of note here is the fact that in some cases designs cannot get approved at the design stage public hearing unless local access is provided. To enhance public acceptance of selective closure, it would perhaps help if closures are implemented on a regularly scheduled basis (i.e., predictable for the potential local user) and used from the onset of operation of the facility. This, of course, assumes that the demand profiles are reasonably consistent over time, i.e., from one time of day to another and one day of the week to the other.

The logistics problem is that of physically closing the ramp each day -- unless, of course, some type of electro-mechanical device, e.g., pop-up rubber tube barriers, which could be remotely operated. The underlying cause of the logistics problem is that a physical barrier is needed because many drivers will not respond to a signed ramp closure. For example, Everall (1972) in reviewing a study of signed ramp closure, reports that the four ramps signed were running at 77% that of normal condition. A possible alternative to the actual physical closure may be the use of holographic "visual image barricades." While a feasibility study for such a concept has been proposed for wrong-way movement controls, the present state of the technology prohibits its use.

One type of "closure" control appropriate for two-lane major interchange connections was brought up at the Design Workshop and deserves mention here. In the situation where two two-lane roadways merge into a three-lane roadway, it was suggested that an improvement in flow could perhaps be achieved by closing one lane of either ramp to give the higher volume ramp the priority during certain periods of the day. Here again, of course, there is the problem of physical closure.

Finally, there is the obvious possibility of closing ramps in the near vicinity of the major interchange, i.e., upstream on-ramps could be closed to decrease the demand at the major interchange or downstream exit ramps could be closed to decrease the effects of a bad weaving situation which may be producing turbulence in the major interchange area. The latter example is a rather specialized situation and would be appropriate on very few occasions.

Metering

Another feasible modification of existing ramp control techniques would be to consider closure as the "zero" end of an adaptive metering scheme. We know, for example, that violations of the metering signal will increase when the service rate approximates 4 vehicles/minute. Thus, if the on-freeway demand increases to the point where the ramp(s) must be metered at this level, an integrated control would cause the physical closure to be activated, i.e., a "ramp closed" sign would flash on and after a suitable accommodation delay for vehicles in the process of entering, the pop-up cones would be activated (Pretty, 1972, discusses a variation on this integrated control for surface street signing). The diverted demand level could then be accommodated at an upstream or downstream ramp thus decreasing the likelihood that it would be closed on the basis of the low-criterion service rate.

Metering, either fixed or adaptive, is usually much more acceptable from the public's point of view. In its simplest form (fixed-cycle metering) standard 3-aspect or 2-aspect signals are regulated on one of several possible fixed-time bases to release entering vehicles. The release rate is chosen from historical calculations of the relationship between downstream capacity to upstream freeway demand and ramp volume. By contrast, traffic-responsive or adaptive control systems employ many different strategies and component configurations to regulate ramp flow on the basis of real-time mainstream traffic conditions. Principal among these are strategies which assess downstream demand-capacity ratios over the entire freeway (or shoulder-lane only) or upstream occupancy (usually in lane 2) on the one hand; and gap acceptance control modes on the other, and which on the basis of this data, attempt to project the lead ramp vehicle into an acceptable upstream gap. Systems which combine both features are used in Houston and in Dallas, i.e., demand-capacity conditions determine the overall metering rate for the ramp, however, the release of the lead ramp vehicle depends upon the availability of an acceptable upstream gap in the shoulder lane.

Two experimental installations display dynamic merging information to the ramp driver. Operating in a gap acceptance control mode, the "pacer" system uses a series of regularly spaced signal heads along the ramp to convey to the driver the "speed" of an available and acceptable gap. The driver's task is to pace his vehicle by keeping abreast of the illuminated signal. The "Green Band" system is similar in principle, i.e., the driver maintains his position relative to an illuminated moving green band, which, unlike the Pacer, provides additional information on the size, distance, headway and stability of the available gap.

Ramp Control Feasibility

The issue which currently plagues the designer is whether control systems can feasibly be included in the initial design. The answer, in the opinion of the experts, is complex. First of all, as mentioned previously, design engineers must change their philosophy that the implementation of control schemes on facilities of their creation represents a failure of design. It does not if the facility is designed to provide for the best possible geometric management of traffic within the available funds and right-of-way. If within these limitations the design capacity of the interchange could accommodate peak-demands over the life of the facility, it is doubtful that control schemes could significantly improve operations. The difficulty in demand forecasting, or, conversely, the inability to provide unlimited funds and rights-of-way for major interchange design (given an acceptable forecast) makes for a realization that eventually many designs will show operational shortcomings. The design may have been the very best available given the design parameters, but interacting relationship between design and use may contribute to its subsequent operational deficiency. (That is, good designs encourage more drivers to use the facility thereby increasing the overall demand, just as adding an extra lane of capacity to accommodate an excessive demand adds its own peculiar demand.)

Second, control schemes can best be employed to provide balance to the overall system. The overall system intended here is the upstream and downstream portions of the freeway system which influence operations in the vicinity of the major interchange or which are, in turn, influenced by the major interchange. To the extent that local access can be denied, the system will work more efficiently. Given the need for local approvals of interchange designs and political pressures, however, it is unlikely that local access can be eliminated. Where the latter condition exists, ramp controls can provide the required demand relief (sometimes, to be sure, at the expense of surface street operations; however, the freeways superiority in moving vehicles should justify temporary suboptimization).

Assuming a characteristic high design for major interchanges, it would seem that from the technological point of view, some ramp control techniques would be readily adaptable in their present state. Demand reductions, the immediate objective of ramp control, is effected regardless of the type of control exercised; however, traffic responsive systems have an advantage over fixed-cycle metering in that they can easily adjust to changing mainstream conditions. Integrated traffic responsive ramp control, where limits on local metering rates are established on the basis of the overall system demand/capacity ratio, leads to better utilization of the entire facility. Moreover, these limits can be individually increased or decreased in the event of unusual congestion-producing incidents.

One behavioral caution should be noted for metering in a gap-acceptance control mode. Although we can demonstrate that drivers will tend to accept "smaller" gaps, our experience with such systems is limited. If we are truly interested in effective performance, we must design the gap acceptance logic to conform to the driver's decision rules for acceptance (Seguin et al., 1969 and Worrall et al., 1967) or alternatively educate the driver to rely on the system. It would seem that we have not yet progressed sufficiently along either path to the point where we might expect that the gap acceptance control mode would be superior to a demand/capacity traffic responsive mode based on upstream occupancy detection.

At the present state-of-the-art of adaptive ramp metering systems, it would not seem feasible to meter two-lane direct connecting roadways (ramps). However, there are sites in Detroit and Los Angeles where two-lane ramps are being time-metered. One of the problems in metering such facilities is that metering frequently requires a storage area and a directional interchange cannot provide such a storage area.

If then, we acknowledge: 1) that many major interchange designs will eventually be characterized by excessive demands, 2) that there is sufficient justification for suboptimizing on the major arteries inasmuch as the freeways have more capacity and can move traffic more efficiently than can frontage roads or arterial streets, and 3) that control systems can contribute significantly to reducing or eliminating congestion on these freeways; then, the inclusion of control systems in initial design would seem not only feasible but highly desirable. Additional reasons for the inclusion of ramp control in the initial design come from Athol via Moskowitz (1970) where the latter says:

> Patrick Athol has suggested that surveillance, should begin the day a freeway is opened to traffic, and ramp controls should be exerted before the demand has built up to the point where it exceeds capacity. In other words the actual flow on the freeway can be held to the design-hour volume if control is exerted early

> enough, and nobody will be diverted because traffic which is not allowed to enter the freeways has (historically) never entered the freeway anyway.

Moskowitz (1970) questions the validity of the historical non-use of the facility because the ramp control systems are insensitive to individual drivers (who diverted on any given day, may have been users since the opening day). He then supports the concept (although not the premises) by demonstrating through a hypothetical example that if controls are exerted early enough, delays will be imposed very gradually thus avoiding ". . . the shock that occurs if the ramp flow is reduced by several hundred VPH from one day to the next."

Main Line Control

Lane Distribution and Speed Control

While the immediate objective of ramp control is to relieve congestion by reducing access demand on the facility, the purpose of main line control is to regulate existing flow once access has been gained. This regulation is usually effected either by attempting to manipulate lane-specific demand via signing or lane closure, or by attempting to manipulate speed via signing. Main line control may be implemented to maximize throughput and efficiency under restricted capacity conditions produced by accidents, vehicle breakdowns, maintenance or construction, etc. Such control has also been effectively used to improve merging operations at major interchanges. Most of the operational experience with main line control via signing has been with overhead mounted variable message signs. For the lane closure controls the typical display employs an illuminated red "X" to indicate that a specific lane is closed, or a green arrow to show that the lane is open. The speed control signs usually display the desirable speed. The success with main line control has been highly variable; however, the problems associated with failures to achieve the goals are likely to be informational/behavioral rather than technological. From the technological, informational and behavioral standpoints, there is no reason why main line control would not be as feasible on a major interchange as it would on any other type of interchange since the main line features are the same for each type. However, the translation of the informational requirements into signing could well be different for an urban major interchange because of the greater number of guide signs which frequently must be used, i.e., the guide signs may compete for the drivers' attention. This, however, is a site specific problem and cannot be dealt with here. Since main line control should not vary much with the type of interchange, the results obtained in past research are largely relevant to major interchanges. Thus, the focus of this section will be to provide some indication of the results of such applications and to develop some thoughts as to how main line control might be made more effective.

Based upon a review of a number of main line freeway control and related informational studies, the following general criteria for the success of main line controls are suggested here and will be developed in more detail in the following paragraphs:

1. The desired response must be clearly communicated to the driver.
2. It must be communicated with enough lead time for him to respond.
3. The justification (i.e., congestion, accident, etc.) for the advised response should be provided.

4. The justification should be credible (e.g., in real time) and provide orientation to event (e.g., congestion, accident) which necessitates the desired response.
5. The relationship between the justifying situation and the response should be clear so that the advantage of responding in the specified manner is apparent, i.e., so that the driver wants to perform the response.

One final general consideration which deserves mention is that the dynamics of major interchange problems impose additional criteria on the feasibility of freeway control. The control should be automatic or at least remotely initiated. Manual placement of cones for lane closure does not provide the response time necessary for maximum effectiveness in a dynamic environment. Second, the fact that the major interchange is a critical node in a complex system suggests that it may be necessary to begin control further upstream of the interchange then would be required for a non-major interchange. Finally, while main line controls have been shown to be useful in a number of applications, they have generally been less consistently successful than ramp control in achieving their operational goals. For example, Wattleworth and Wallace (1968) found that motorists will not reduce their speed unless there is an apparent (visible) reason to do so. A similar observation was made by Brewer (1972) when he tried to exercise speed control through a maintenance area by forcing a weave. He found that during heavy construction activity, better than 50% of the drivers traveled below the posted limit through the weave area; however, under the same roadway conditions but in the absence of much activity, less than 20% complied with the limit. Wingerd (1968) demonstrated that posting minimum speed limits for each lane fails to decrease travel time or delay. As volumes approach capacity, drivers reduce their speeds to a range between 35 and 45 mph so that minimum speed signs have no effect. When operating at least than capacity, the signs result in more drivers moving left with an increase in passing on the right which was the exact opposite of the desired effect. As Wattleworth (1967) notes in his study of main line controls, the effectiveness of overhead control signals appears to be a function of the freeway demand. One plausible explanation for their lack of effectiveness might be that drivers perceive main line displays as "advisory" messages rather than as legally sanctioned controls. If no such ambiguity exists, we can only assume that drivers who violate these controls are willing to play the odds on being apprehended. Enforcement, however, cannot be regarded as the solution; and better methods must be found to appeal to the rational side of the driver's nature so that he can understand control messages and want to abide by them. In general terms, the results of studies such as these were verified by participants in the Design Workshop, who gave many examples of such experience from operational tests.

The studies by Dudek _et al_., (1971) and Heathington _et al_., (1971) focus not upon the effectiveness of the control system _per se_, but upon the information aspects of presenting control information to the driver. They have examined the kinds of information that drivers say they prefer. While there is certainly no assurance that drivers will act appropriately given information that conforms to their expressed preferences, the approach seems worthy of continued study if the effectiveness of main line control is to be maximized.

McCausland (1972) noted that positive closure of freeway lanes via the manual placement of traffic cones, such as in the Loutzenheiser and Henderson (1972) study of the I-10 and I-610 interchange, would not be an acceptable solution for a recurring problem unless something akin to the remotely operated "pop-up barrier" technology were adapted to the main line lanes. Despite the public acceptance for this type of control (over a two-week test period) McCausland (1972) believes that it should not be employed without advance warning information geared to day-to-day variations in traffic conditions.

To the extent that the logic of lane control (as well as other) systems can be designed for compatibility with the driver's perferred behaviors, system failures will be minimized. Under certain conditions drivers will elect to intentionally disregard command functions because they lack a visual verification of the need for the indicated control. It must be quite simply that driver's do not believe the system. The rationale for such skepticism probably originates with the countless number of experiences which each driver has been confronted with, which attempt to control his behavior with little or no apparent justification. How many times, for example, does a driver wait for the green light at a signalized intersection in the small hours of the morning when the visibility in all directions is unlimited and the crossing traffic non-existent? How many times is a driver advised of a maximum safe speed (that was calculated on the basis of vehicle handling and suspension packages of the 30's, 40's and 50's) on horizontal curves that he can easily and safely exceed sometimes by an order of magnitude above the posted limit? Further examples are speed limits on sections of empty multi-lane freeways, flashing school speed-limit signs operating on Sundays and holidays, etc., etc. In short, it is little wonder that drivers bring their cynical attitudes to bear on freeway control systems. The translation of this attitude into a behavioral rule seems to follow the adage, "Burn me once, shame on you; burn me twice, shame on me." In the absence of immediate tangible evidence which verifies the need for control, drivers are going to behave according to their preferences, and they will subject any regulatory system to tests of credibility. To the extent that a verification factor can be designed into a real-time control display, system effectiveness will be enhanced.

To illustrate this "system test" or "driver verification factor," we have borrowed a collection of ideas from the discussions held during the Workshop, and from the literature and practice (highway and other) and applied them to the alternate routing of the freeway driver to avoid a downstream bottleneck. We borrow, for example, the concept of the advisory sign "congestion ahead"; the shape and context of diagrammatic signs; segment analysis from flow theory; matrix displays from changeable message signs; centralized computer control; and, finally, "you are here" location maps from department stores and office buildings. The key ingredient, strange as it may seem, is the last element, since it provides the wherewithal for the driver to assess immediately the accuracy and utility of the message displayed. Let us now consider how the systems credibility might be established, using a worst case situation, i.e., route diversion as opposed to the more simply accomplished lane or speed change.

In our illustrative situation, let us suppose that we wish to reduce upstream demand and encourage the driver(s) to take an alternate route (frontage road or arterial street) to avoid downstream congestion. We can accomplish this by informing the driver of the congested condition while he still has an opportunity to re-route, i.e., prior to an exit terminal. Only instead of simply telling him that there is congestion ahead, let's show him via signing where it is in relation to him (within limits, say 3 to 5 miles ahead).

Much of what we configure, with the exception of the verification factor, does not differ a great deal from display technology already in use. Fundamentally, we employ a simple schematic sign of the next 3 to 5 miles of freeway and the immediately adjacent frontage road or the first and second arterial streets which parallel the freeway. We break up the freeway and the sign into corresponding segments which do not have to be of uniform size. While it may be appropriate to employ segments of uniform length on the freeway itself (perhaps 1/2 mile in length), shorter segments might be used to represent an entrance ramp or exit ramp segment. Sensors, installed in each segment of interest would feed the data to a centralized computer which would evaluate the data in terms of the level of service currently provided in each segment. Real-time information would be fed back to each display sign. Within each sign segment the method of display would be through an arrangement of "bulb's" superimposed on the back of the through travel lanes and exit terminals (and if desired, a singular row for) frontage roads, etc.). Most likely color could be used to convey the "flow conditions" to the driver. Under a color mode, we would, of course, attend to the cultural bias and employ green for free flow, yellow for moderate congestion, and red for stop-and-go heavy congestion. Flashing red would indicate the presence and location of an unusual incident like an accident, maintenance operation, vehicle breakdown, or law enforcement operation.

Everything thus far exists in one form or another at one place or another. The verification feature to be added consists of feeding back real-time level-of-service information to the driver who is in the process of reading the sign by informing him of conditions in the segment in which he and the sign are located. Thus, he need only observe conditions in his immediate vicinity and compare these conditions to the indicated display (the bottom, or "you are here" segment of the sign) to establish to some degree the credibility of that information and, consequently, information concerning downstream conditions.

It should be noted that the particular contribution in this discussion is to implore engineers to provide verification information to the driver if real-time displays are to be considered for freeway control. While we do not as a rule subscribe to misleading drivers and risking a failure on a "system test" by the drivers, we should note that conservative display strategies could be employed (in the computer software) to indicate in the event of downstream congestion, that conditions in the "you are here" segment are better than he observes them to be. That is, if he is, in fact, in a condition yellow -- moderate congestion condition -- let the sign indicate that this condition is considered green-free flow. Thus, we may be able to shift the driver's perceptual scale of level-of-service with the result that he interprets the situation thus, "If they consider these traffic conditions green what am I in for when I get to that yellow or red segment -- better get off here."

While the ideas presented here do not immediately appear as being relevant to statements of feasibility, they were presented because it is felt that lane control is feasible within the current state-of-the-art and that it can be a powerful tool for preventing or solving congestion problems if the considerations provided here are factored into the design of such systems.

Reversable Lanes

Other prevalent forms of main line control are Lane Reversibility and Lane Exclusivity. The objective of the former is to compensate for a serious imbalance in the directional distribution of traffic during the peak hour. The reversible lane solution, in short, is to devote more than half of a given pavement width to the predominant direction of flow. It should be noted that where other control procedures manipulate the demand for a given capacity, reversible lane control manipulates capacity to accommodate the demand, and it does so in an economical fashion (i.e., with minimal or no requirement for additional right-of-way).

Most design applications of the reversible lane concept place the dual roadway in the median with the outer freeways operating in a normal unidirectional fashion. The AASHO* reversible concept restricts the use of the reverse-flow freeway to express traffic by denying intermediate access points. The Kennedy Expressway in Chicago has an 8-1/2 mile two-lane reversible of this type in the median. In contrast to the express-reversible, some dual roadways like the Seattle facility (8 miles of Interstate 5) provide several interchange points along its route. A major criticism of this latter type is that access to the center roadway is provided by crossover lanes connecting with the outside roadways which, in effect, increases the weaving volumes on the outside lanes. Drew (1968) overcomes this problem via a design which provides entrance and exit ramps directly to the center roadway from the intersecting cross streets. Drew's reverse-flow diamond interchange is really a combination of two interchanges, a partial cloverleaf on the reverse-flow center roadway and a diamond on the outside freeway roadways. He notes that because the loops of the cloverleaf operate off the center dual roadway in the center of the right-of-way instead of off the freeway lanes, only slightly more right-of-way is required than would be required for a conventional diamond interchange. The freeway ramps from the diamond part of the interchange are much as they would be in the conventional design; hence, users of the outside roadway are provided with the familiar exit-entrance pattern of the conventional diamond, whereas on the center reverse flow roadway, the cloverleaf continuity is preserved throughout.

A relatively unique system designed for the Aston Expressway in England (left hand drive) (Wall and Burr, 1972) is the "tidal flow system" which provides a very flexible system of lane control since the undivided carriageway is seven lanes wide. Normally four lanes carry the peak direction flow and three lanes the non-peak direction flows. The so-called tidal lane is surfaced with a red asphalt for contrast with the black asphalt on the other lanes.

Maintenance operations, accidents or other unusual incidents are easily handled by the system's capability to reverse any combination of the center three lanes as needed. The changeable message displays on the signal gantry indicate for a given direction lanes open to traffic by white arrows and those closed to traffic by red "X"'s. Advisory speed limits and destination information (route and place names) can be provided for each lane open to traffic. The electronic direction signing system has been extended to include control of all points of access to the expressway, and by the use of "secret" signs (visible only when illuminated) the road can be automatically closed and vehicles diverted on to the most suitable alternative route.

Under normal operation the tidal lane will have its flow reversed every 12 hours using the following computer/TV-monitored, police controller sequence:

> At the controller's instigation, the last gantry in the tidal length will first have the vertical arrow over lane 4 (the center lane) changed to a divert left arrow, and 20 seconds later a red cross. Ten seconds after the start, the penultimate gantry will switch from vertical arrow to divert left arrow, and 20 seconds later to a red cross. In this way; the tidal lane will be progressively swept clear in an upstream direction, so that at the end of the progression, red crosses will be displayed on both sides of all gantries over the centerlane. Once the police controller has examined the tidal lane on the TV system to ensure that it has cleared and no traffic remains in it, white vertical arrows will replace the red crosses simultaneously on the reverse side of every gantry over the centerlane, and four lanes will then be available for the other traffic stream. In the event of a blockage occurring, e.g., a vehicle breakdown, then the tidal lane will remain closed until the obstacle has been removed.

While reversible lane control is not a method which would have widespread application because of the conditions under which it is appropriate, it was discussed here because it involves lane control concepts and because there is the definite requirements to design the geometrics related to such control into the system, i.e., this is not a control method which could,in most cases,be used remedially. Thus, where control is considered in the design stage, it is a method which should perhaps be included in overall consideration of the control strategies which could be employed -- if, of course, directional imbalance is anticipated.

Exclusive Lanes

Lane exclusivity refers to the reservation of one or more lanes for a particular class of vehicles, viz. buses and multi-occupant passenger vehicles. Indirectly, through maximizing the passenger travel and reducing travel time per passenger, a reserved bus (or bus plus multi-occupant vehicle) lane should reduce the demand on the facility. This is accomplished theoretically, through encouraging occupants of single passenger vehicles to join car pools or ride the bus.

Nowhere does the choice of a criterion impact more on the assessment of feasibility than it does when one considers whether the provision of exclusive bus lanes would enhance major interchange operations. Certainly, we must acknowledge the advantages of the reserved bus lane in terms of passenger miles traveled. Hodgkins (1964), for example, in postulating a lower-volume limit of 200 buses/hr. points out that the reserved lane could move approximately 10,000 people/hr. in contrast to the less than 8000 people/hr. that would be accommodated on the two adjacent lanes. Drew, in commenting on the underutilization of the reserved lane, attends to volume in terms of vehicles/hr. when he states that no practical bus frequency can provide enough demand to fill a freeway lane. Martin (1970), in evaluating the greater peak hour bus concentration in California, viz. the Bay Bridge, concludes that an exclusive bus lane is not feasible because the increased delay to automobile users far exceeds the savings to the bus passengers. It is extremely doubtful, however, whether the inherent disadvantage of underutilized capacity of a bus-only lane will permit any generalized use of this control technique. More recent efforts have attempted to recovery some of the lost capacity by including multi-occupant vehicles in the exclusive lanes. This type of preferential treatment was mathematically modeled by Sparks and May (1971) under some rather severely limiting assumptions; however, the authors felt that the "priority-lane" treatments studied showed promise and pointed to the need for parallel field research to further the development of the models. A follow-up study by Capelle et al. (1972) indicated that the exclusive lane for bus and car pool usage was determined to be basically sound during commuting hours; however, they noted that the success of the reserved lane concept depends largely on a voluntary compliance on the part of every driver since enforcement is extremely difficult.

In general, while the feasibility of the exclusive lane is determined by the characteristics of the specific freeway, physical alterations may not be required to implement reserved-lane operation, so there would appear to be no real technological barriers. One of the major obstacles to exclusive bus lanes is the requirement and cost to provide the associated exclusive ramps. Otherwise, operational problems are usually produced. For example, if the median lanes are used for the exclusive lanes, the bus must weave thru a number of traffic lanes in order to enter and/or exit the exclusive lanes. The cost effectiveness of providing exclusive ramps is still in question since some studies, referred to by Workshop participants, have indicated that buses do not significantly decrease the number of vehicles on the highway. As an example of the ramp costs for exclusive lanes, it was pointed out at the Workshop that a seven million dollar exclusive bus lane project would have an extra one million dollars added if they provide for exclusive bus ramps. Another aspect of the exclusive bus lane problem on which there is disagreement among the experts is whether the median lane or the right lane should be used. As mentioned, the use of the median lane requires additional ramps. The problems with the use of the right lane is that it interferes with other exiting traffic in that you have to permit other traffic to use that lane for exiting. If the exclusive service would be such that all of the buses entered at one interchange and got off at the next, this would not produce a major problem. However, in many cases the bus lanes are not used for local service but rather are express service lanes from the CBD to the outskirts. Perhaps the biggest obstacle to the potential operation of improvements which the exclusive lane offers is the voluntary violations. As Cappelle notes, however, this may be overcome by a good positive public relations program. It was reported by the New York representative at the Workshop that the use of signs to prohibit cars from using exclusive bus lanes is not effective unless a high volume of buses is using that lane. However, California has reported that drivers will obey such signs. It would appear that there might be regional differences in compliance -- although the experience is not yet sufficient to verify such a conclusion. To the extent that the "exclusive" operation can be an integral part of new designs, i.e., before commuters lane-usage patterns become relatively fixed, the problem of driver conformance would be lessened and perhaps an increase in bus ridership would even be increased. However, since the facility must be built and operated in order to generate the ridership (and the possible consequent reduction in private vehicle use), the "gamble" is obvious. Another form of priority-treatment that deserves mention is the provision for exclusive or reserved right lane for buses on two-lane entrance ramps. Traffic is metered in the left lane and the bus is permitted to bypass the ramp queue. This system has been successfully implemented in Texas and on both the Harbor and Hollywood Freeways in California (Gillis, 1970).

In summary, there are still a large number of unresolved questions regarding both the design and the cost-effectiveness of exclusive bus lanes. Further, the inclusion of a major interchange into an overall system using such control poses even more severe restraints than a non-major interchange in that the speeds are typically higher and the volumes are greater. Thus, for example, the problem of bus weaving for entry and exit become more severe. While we would have to conclude that such inclusion is possible, a great deal more must be known about both the design and operation of exclusive lanes before any determination of practicality and cost-effectiveness can be made.

Corridor Control

Corridor Control, the conceptual epitome of adaptive control schemes is still too far in its infancy to render any accurate judgments as to the feasibility of including major interchange design in an overall corridor control scheme. However, there is no reason to believe that such a system used to distribute traffic over an entire system could not have a facilitative effect upon a major interchange -- particularly an urban interchange where alternate routes are usually available. Conceptually a corridor consists of a freeway(s), frontage roads and some undefined portion of the arterial street network which parallels the freeway. The objective of corridor control is to optimize flow over the entire corridor system.

Because of its brief history little exists in the way of hard research data on "corridor" operations. One of the earlier studies, performed by Wattleworth (1967) on the Lodge Freeway, evaluated the effects of ramp metering on freeway operations and about 50 miles of arterial streets. The net effect was an overall reduction in "corridor" travel time at little expense to the arterial street system. This early corridor work was characterized by active manipulation via ramp controls and passive observation of the arterial street system (as well as the freeway).

In this and subsequent work, however, it was recognized that unused capacity detected in the arterial street system and/or on a downstream portion of the freeway (beyond a bottleneck) was of little utility unless information concerning its existence could be conveyed to the driver. If information on traffic conditions within the corridor were available to the driver at or before choice points, he would be in a better position to elect an alternate route. The use of driver communications to minimize travel time within the corridor is accomplished by directing some traffic off the freeway to alternate routes that have available capacity and by directing some approaching traffic that would normally use the freeway to alternate arterial routes. A scheme for the real-time integration of ramp metering and diversionary signs located at choice points was proposed by Pretty (1972). Basically, his approach is to detect excessive queue lengths on controlled ramps (metered on basis of downstream capacity) and signal via sign-state changes at each choice point the quickest route to the next choice point or downstream ramp. The successful use of corridor control to reduce demand on a major interchange rests primarily in the degree to which the excessive demand on the major interchange is generated by local access ramps and/or ramps in the immediate upstream vicinity of the interchange.

APPENDIX M

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Reference	Interchange Configuration	Interchange Classification	Interchange Design	Interchange Structures	Entrance Ramps	Exit Ramps	Weaving Areas	Lane Drops	Delineation & Signing	Accidents	Traffic Operations	Land & Environment	Control Systems
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ITE (1968). Two-Lane Entrance Ramps -- An ITE Informational Report. Report of Committee 5F(63), Dept. 5, Technical Council, Institute of Traffic Engineers. (April)	X				X						X		
JENKINS, I. (1969). *Balanced Freeway Design.* Paper presented at Kansas Highway Engineering Conference. (March)	X							X					
JOHNSON, R. & Newman, L. (1968). "East Los Angeles Interchange Operation Study." *Highway Research Record* 244, 27-46.								X	X		X		

	Interchange Configuration	Interchange Classification	Interchange Design	Interchange Structures	Entrance Ramps	Exit Ramps	Weaving Areas	Lane Drops	Delineation & Signing	Accidents	Traffic Operations	Land & Environment	Control Systems
JOUZY, N. & MICHAEL, M. (1963). "Use and Design of Acceleration and Deceleration Lanes in Indiana." Highway Research Record 9, 25-51.				X	X						X		
KELLER, H. (1971). "Analysis of Detection and Service Systems on Freeways." Accident Analysis & Prevention, 3, 149-192.			X							X			
KOCHANOWSKI, R. (1963). "Banksville Weaving Area Study." Traffic Engineering, 33 (8), 11+. (May)							X				X		
KUHN, H. (1969). "Planning Implications of Urban and Rural Freeway Interchanges." Journal of the Urban Planning and Development Division, 95 (VPI), 81-92. (April).												X	
LANGSNER, G. (1959). Accident Experience at Ramps -- Exits and Entrance -- Preceding and Beyond Interchange Structures. Presented at the Regional Meeting, AASHO Committee on Design. Denver (Sept.)			X		X	X				X			
LEFEVE, B. et al. (1961). "Panel Discussion on Interchanges and Their Problems." Assoc. of Highway Officials of the North Atlantic States Proceedings, 37th Ann. Convention, 96-120. (March)			X										
LEISCH, J. E. (1959a). "Adaptability of Interchanges to Interstate Highways." ASCE Transactions, 124, 588-613.		X	X				X				X		

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LEISCH, J. E. (1963). "Designing Operational Flexibility into Urban Freeways." ITE Proceedings, 209-237	X	X					X						
LEISCH, J. (1972). "Determination of Interchange Types on Freeway Facilities: Systems Engineering Approach." Traffic Engineering, 42 (8), 16-24. (May).	X												
LEISCH, J. (1971). The Development and Use of Simplified Ramp Capacity Charts. Paper, Dept. of Civil Engineering, Northwestern University.			X								X		
LEISCH, J. (1971). "Intersectional Aspects, Route Considerations, and Related Signing." Dynamic Design for Safety Seminar, Dallas, Texas. (Oct.).	X		X					X	X				
LEISCH, J. E. (1965). "Lane Determination Techniques for Freeway Facilities." Canadian Good Roads Association Proceedings.									X				
LEISCH, J. E. (1959b). "Spacing of Interchanges on Freeways in Urban Areas." Journal of the Highway Division, Proceedings of ASCE, 85 (NW4), 61-75. (Dec.)	X						X						
LEISCH, J. E., & Associates (1971). Alinement. Highway Users Federation for Safety and Mobility Series, Traffic Control & Roadway Elements -- Their Relationships to Highway Safety/ Revised, Chapter 12.									X	X			

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LEONG, H. (1970). "Effect of Kerbed Median Strips on Accident Rates on Urban Roads." Australian Road Research Proceedings, 5, Paper No. 666, Part 3, 338-364.									X	X			
LEOPOLD, L. et al. (1971). "A Procedure for Evaluating Environmental Impact." Geological Survey Circular 645, U.S. Geological Survey.												X	
LOUTZENHEISER, D. (1963). "New Concepts for Urban Freeway Interchanges." ASCE Proceedings, 128, Part IV, 332-346.	X	X	X										
LOUTZENHEISER, R. C. & HENDERSON, D. M. (1972). "Reducing Imbalance of Intersecting Freeways by On-Freeway Control." Highway Research Record 388.			X					X					X
LUNDY, R. (1967). "The Effect of Ramp Type and Geometry on Accidents." Highway Research Record 163, 80-119.	X	X		X						X			
MANHEIM, M. (1970). "Decision Theories in Transportation Planning." Highway Research Board Special Report 108, 17-26.			X										
MANHEIM, M. & Hall, F. (1968). "Abstract Representation of Goals." P-67-24, Department of Civil Engineering, M.I.T. (January).			X										

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MARINO, R. (1970). First Interim Report -- Freeway Inventory Geometric Bottleneck Congestion. California Division of Highways.											X		
MARTIN, D. B. (1970). "Feasibility of an Exclusive Lane for Buses on the San Francisco-Oakland Bay Bridge." Highway Research Record 303.											X		
MASON, J. & MOORE, C. (1970). Location Criteria for Highway and School Planners - Part B - Theoretical and Methodological Framework. HPR Report No. 45-B, Alabama Highway Research Group, University of Alabama. (Aug.)			X									X	
MAY, A. & JAMES, J. (1972). "Cost-Effectiveness Evaluation of Freeway Design Alternatives." Interim Report 3-1, ITTE. (Dec.).												X	
MCCAUSLAND, W. R. (1972). "Freeway Control and Information Systems." Research Report 139-13F, Texas Transportation Institute, Texas A&M University, College Station, Texas.									X		X		X
McDERMOTT, J. M. (1967). "Operational Effects of Automatic Ramp Control on Network Traffic." Highway Research Record 202.											X		X

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McIVOR, G. (1970). "Geometric Design Standards for High Speed Freeways and Freeway Interchanges." 1970 World Survey of Current Research and Development on Roads and Road Transport, International Road Federation, Washington, D.C., 551-555. (Dec.)			X										
MENCKHOFF, G. (1971). "Reevaluation of Urban Freeway System" Traffic Engineering, 41 (5), 15-21. (Feb.)											X	X	
MILLER, J., III. (1969) "Assessing Alternative Transportation Systems." RM-5865-DOT, The Rand Corporation. (April).			X										
MINE, M. & MIMURA, T. (1969). "Highway Merging Problem with Acceleration Area." Transportation Science, 3 (3), 205-213. (Aug.)			X		X								
MOORE, R. (1968). Some Human Factors Affecting the Design of Vehicles and Roads. Paper 5 of the Vehicle and Road Design for Safety Symposium. (July)			X										
MOSKOWITZ, K. & JORGENSON, R. & ASSOCIATES. (1970). "Analysis and Projection of Research on Traffic Surveillance, Communication, and Control." NCHRP Program Report 84, Highway Research Board.											X		X
MOSKOWITZ, K. & NEWMAN, L. (1963). "Notes on Freeway Capacity." Highway Research Record 27, 44-68.	X						X						

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MULINAZZI, T. E. & MICHAEL, H. L. (1967). "Correlation of Design Characteristics and Operational Controls with Accident Rates on Urban Arterials." Proceedings of the 53rd Annual Road School, Purdue Univ., Bulletin No. 128, LI (5), 150-173. (Sept.)										X			
MULLINS, B. & KEESE, C. (1961). Freeway Traffic Accident Analysis and Safety Study. Presented at the HRB 40th Annual Meeting										X			
MUNJAL, P. K. (1970). "A Simple Off-Ramp Traffic Model." Highway Research Record 334, 48-61.			X			X							
MUNJAL, P. & PIPES, L. (1971). "Propagation of On-Ramp Density Perturbations on Unidirectional Two and Three-Lane Freeways." Transportation Research, 5 (4), 241-254. (Dec.)			X								X		
MUNJAL, P. et al. (1971). "Analysis and Validation of Lane-Drop Effects on Multi-Lane Freeways." Transportation Research, 5 (4), 257-266. (Dec.).			X					X			X		
NCHRP (1972). Interactive Graphic Roadway Design System, NCHRP Project 20-8.			X										
NEVE, J. P. (1962). "A Scorecard for Interchanges." Traffic Engineering, 32 (12), 22+ (Sept.)			X							X	X		
NEWMAN, L. (1963). "Traffic Operation at Two Interchanges in California." Highway Research Record 27, 14-43.							X				X		

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NEWMAN, L.; DUNNET, A. M.; & MEIS, G. J. (1970). "An Evaluation of Ramp Control on the Harbor Freeway in Los Angeles." Highway Research Record 303.											X		X
NOBLE, C. (1971). "Highway Design and Construction Related to Traffic Operations and Safety." Traffic Quarterly, 25 (4), 533-549. (Oct.)					X	X	X	X	X	X		X	X
NORTHWESTERN UNIVERSITY. (1969). "The Suitability of Left-Hand Entrance and Exit Ramps for Freeways and Expressways." Final Report, Ill. Cooperative Highway Research Project IHR-61. (June.)			X		X	X			X	X		X	
OECD RESEARCH GROUP (1971). Road Research: Electronic Aids for Freeway Operation (April).											X		X
OFFICE OF HIGHWAY SAFETY (1964). "Exit Ramps Wrong-Way Traffic Problem for U.S." Traffic Engineering, 35 (1), 24-27, 56. (Oct.)			X			X							
O'FLAHERTY, C. A. & COOMBE, R. D. (1971). "Speeds on Level Rural Roads: A Multivariate Approach." Traffic Engineering and Control, 13 (3), 108-111. (July)			X										
OPPENLANDER, J. C. & DAWSON, R. F. (1970). Interchanges. Highway Users Federation for Safety and Mobility Series, Traffic Control & Roadway Elements --Their Relationship to Highway Safety/Revised, Chapter 9.	X			X	X	X				X			

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ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT (1970), Driver Behaviour. Report by an OECD Research Group, Paris. (June)										X			
ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT (1971). Electronic Aids for Freeway Operation. Report by an OECD Research Group, Paris. (April)													X
PFEFER, R. C. (1968). "Two-Lane Entrance Ramps." Traffic Engineering, 39 (2), 18-23. (Nov.)			X		X		X		X				
PIGNATARO, L. et al. (1972). Weaving Area Operations Study: Analysis and Recommendations. Submitted for Presentation at HRB 51st Annual Meeting.							X						
PINNELL, C. (1960). "Driver Requirements in Freeway Entrance Ramp Design." Traffic Engineering, 31 (3), 11+. (Dec.)			X		X						X		
PINNELL, C. (1961). "Freeway Entrance Ramp Design." ITE Proceedings, 31st Meeting, 132-141.	X		X		X					X	X		
PINNELL, C. & BUHR, J. (1966a). "Urban Interchange Design as Related to Traffic Operation -- Part I -- Diamond Interchanges." Traffic Engineering, 36 (6), 20-50. (March)	X	X											

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PINNELL, C. & BUHR, J. (1966b). "Urban Interchange Design as Related to Traffic Operation -- Part II -- Cloverleaf and Directional Interchanges." Traffic Engineering, 36 (7), 51-56. (April)	X	X									X		
PINNELL, C. & KEESE, C. (1963). "Traffic Behavior and Freeway Ramp Design." ASCE Transactions, 128 (Part IV), 1-26.	X				X	X				X	X		
PINNELL, C. et al. (1967). "Evaluation of Entrance Ramp Control on a Six-Mile Freeway Section." Highway Research Record 157, 22-70.					X						X		X
POULIQUEN, L. (1970). "Risk Analysis in Project Appraisal." World Bank Staff Occasional Paper Number 11, International Bank for Reconstruction and Development.													
PRETTY, R. L. (1972). "Control of a Freeway System by Means of Ramp Metering and Information Signs." Highway Research Record 388.									X				X
RAPUANO, M. et al. (1968). The Freeway in the City. A Report to the Secretary, USDOT, by the Urban Advisors to FHWA. (May).	X		X	X								X	
ROTH, W. (1970). "Interchange Ramp Color Delineation and Marking Study." Highway Research Record 325, 36-50.					X	X			X		X		

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ROTH, W. & DEROSE, F. (1966). "Interchange Ramp Color Delineation and Marking Study." Highway Research Record 105, 113-125.					X	X			X		X		
SATTERLY, G. & BERRY, D. (1967). "Spacing of Interchanges and Grade Separations on Urban Freeways." Highway Research Record 172, 54-93	X		X										
SAVAGE, G.; COOK, J.; PLAYFAIR, C.; & TECTOR, J. (1971). "3-D Dynamic Modeling." Proceedings of the Kentucky Workshop on Computer Applications to Environmental Design, University of Kentucky, Lexington, 137-143.			X										
SCHAEFER, W. (1971). "Developing an Effective Freeway Traffic Management System." Highway Research Record 368, 37-39.			X										X
SCHAEFER, B. & WEST, J. (1970). Developing an Effective Freeway Traffic Management System for Los Angeles. Report presented to AASHO Committee Joint Session, Communication and Electronics Committee, Traffic Committee, Houston, Texas. (Nov.)													X
SCHNELLE, K. (1967). Case Analysis and Business Problem Solving. McGraw Hill, New York, N.Y.			X										
SEGUIN, E. L.; CARTER, R. G.; HURST, P.M.; TAYLOR, J. I.; HOSTETTER, R. S.; & KING, R. B. (1969). "Interim Report on the Effects of Environmental Conditions on Driver On-Ramp Merging Behavior." Report 413511-41-1, HRB-Singer, State College, Pa.										X			X

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SIMONFFY, Z. (1968). "The Two-Level No-Weave Interchange." Surveyor, 132 (3979), 43-44. (Sept.)	X	X					X						
SMITH, F., Jr. (1963). An Analysis to Determine Correlations of Freeway Traffic Accidents with Specific Design Features Master's Thesis, Texas A&M.	X		X							X			
SMITH, W. (1971). "Rational Location of a Highway Corridor: A Probabilistic Approach." Highway Research Record 348, 42-60.			X									X	
SPARKS, G & MAY, A. (1971). "A Mathematical Model for Evaluating Priority Lane Operations on Freeways." Highway Research Record 363, 27-42.											X		
STEIN, M. (1969). "Highway Interchange Area Development -- Some Recent Findings." Public Roads, 35 (11) 241-250. (Dec.)												X	
STEINBERG, E. (1971). "Benefit-Cost Analysis and the Location of Urban Highways." Highway Research Record 348, 35-41.												X	
STEPHENS, B. W. (1971). "Some Principles for Communicating with Drivers through the Use of Variable Message Displays." Highway Research Board Special Report 129.									X				
SURTI, V. H. & GERVAIS, E. F. (1967). "Peak Period Comfort and Service Evaluation of an Urban Freeway and an Alternate Surface Street." Highway Research Record 157.											X		

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TAKEBE, K. (1969). "Theoretical Analysis of Interchange Composition." Transportation Engineering Journal. Proceedings of the American Society of Civil Engineers, 95, (TE 3), 483-503 (August)		X											
TASHIIAN, Z. & CHARLES, S. (1971). Weaving Safety Study. Final Report. Prepared for California Division of Highways, Contract No. RTA 13945-13742. (May)							X						
TAYLOR, J. et al. (1972). "Roadway Delineation Systems." NCHRP Report 130.					X	X			X				
TAYLOR, J. & MCGEE, H. (1973). "Improving Traffic Operations and Safety at Exit Gore Areas." NCHRP Report 145.						X		X			X		
THARP, K. & HARR, M. (1965). "A Quantitative Evaluation of the Geometric Aspects of Highways." Highway Research Record 83, 29-44.			X										
THIEL, F. (1965). "Highway Interchange Area Development" Highway Research Record 96, 24-42.			X									X	
TIPTON, W. & PINNELL, C. (1967). "An Investigation of Factors Affecting the Design Location of Freeway Ramps." Highway Research Record 152, 1-35.	X										X		
TOKYO EXPRESSWAY PUBLIC CORPORATION (1964). "On the Edobashi Interchange." Annual Report of Roads, Japan Road Association 64-67			X									X	

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TOKYO EXPRESSWAY PUBLIC CORP. (1970). TOKYO EXPRESSWAY 1970.	X			X						X		X	
TRACEY, F. (1970). "Highway Design for Safety in Virginia." Highway Safety Conference Proceedings, HS-009 301, 17-27.				X									
TURNER, A. & MILES, R. (1971). "The GCARS System: A Computer-Assisted Method of Regional Route Location." Highway Research Record 348, 1-15.			X									X	
UNDERWOOD, R. (1970). "Some Aspects of the Design of Rural Freeway Interchanges." Proceedings, S(1), Fifth Conference of the Australian Road Research Board, 92-119.	X				X	X				X		X	
USDOT/FHWA. (Undated). Driver Expectancy Checklist. Report based on "Diagnostic Studies of Highway Visual Communication Systems," TTI.			X										
US DOT/FHWA (1968+). A Handbook of Highway Safety Design and Operating Practices. U.S. Government Printing Office, Washington, D.C. Basic Handbook plus periodic supplements								X		X			
US DOT (1967). Highway Safety Program Standards. U.S. Dept. of Transportation Pamphlet, 20-21 (June)										X			
US DOT/FHWA (1971). Manual on Uniform Traffic Control Devices. U.S. Government Printing Office, Washington, D.C.									X				

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WAINWRIGHT, W. & JAIN, R. (1972). Techniques of Ramp Control. C. E. 72-47, University of Connecticut.													X
WALKER, L. (1972). "Automated Road Design." Automation Systems for Highway Organizations, Highway Research Board Special Report 128, 28-35.			X										X
WALKER, R. (1970). "Geometric Design Related to Traffic Safety." Highway Safety Conference Proceedings, HS-009 301, 11-16.			X										
WALL, J. & BURR, M. (1972). "Aston Expressway Signing and Signalling System." Traffic Engineering and Control, 14 (8), 370-375+. (Dec.).									X		X		X
WASHINGTON CENTER FOR METROPOLITAN STUDIES (1970). Comprehensive Planning for Metropolitan Development. Prepared for Urban Mass Transportation Administration, US DOT, DOT-UT-33.												X	
WATTLEWORTH, J. (1965). "Estimation of Demand at Freeway Bottlenecks. "Traffic Engineering, 35 (5), 21-26. (Feb.)			X										
WATTLEWORTH, J. (1967). "Peak Period Analysis and Control of a Freeway System." Highway Research Record 157, 1-10.			X										X
WATTLEWORTH, J. (1971). "Accomplishments in Freeway Operations in the United States." Highway Research Record 368, 26-32.			X										X

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WATTLEWORTH, J. & INGRAM, J. (1972). "Cost-Effectiveness Technique for Analysis of Alternative Interchange Design Configurations." Highway Research Record 390, 27-35.	X		X									X	
WATTLEWORTH, J. A. & WALLACE, C. E. (1968). "Evaluation of Operational Effects of an 'On-Freeway' Control System." Highway Research Record 244.											X		X
WATTLEWORTH, J. A.; ARCHAMBAULT, C.; WALLACE, C. E.; & CARVELL, J. D. (1967). "The Development of Techniques for the Analysis of Operation of Major Interchanges." Texas Transportation Institute, Texas A&M University, College Station, Texas.											X		
WATTLEWORTH, J. et al. (1967). "Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging." Highway Research Record 208, 79-114.	X				X						X		
WEBB, G. & ISREAL, R. (1954). "Freeway Ramps - Proper Spacing Important in Preventing Accidents." California Highways and Public Works, 34, 14-16. (Sept. - Oct.)	X									X			
WEINBERG, M. & THARP, K. (1969). "Application of Vehicle Operating Characteristics of Geometric Design and Traffic Operations." NCHRP Report 68.											X		
WEISS, G. (1969). "The Single Lane Merging Problem with Mixed Cars and Trucks." Transportation Research, 3, 195-199.			X										

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WINGERD, N. C. (1963). "Minimum Speed Limits on Freeways." Highway Research Record 244.											X		
WOODIE, W.; AHLBORN, G.; & MAY, A. (1969). "A Computer Program for Weaving Capacity." Traffic Engineering, 39 (4), 12-17. (Jan.)			X				X						
WOODS, D. (1971). "The Driver and the Road." Transportation Engineering Journal, 97 (TE4), 609-617. (Nov.).											X		
WORRALL, R. & BULLEN, A. (1970). "An Empirical Analysis of Lane Changing on Multilane Highways." Highway Research Record 303, 30-43.			X				X				X		
WORRALL, R.; BULLEN, A.; & GUR, Y. (1970). "An Elementary Stochastic Model of Lane-Changing on a Multilane Highway." Highway Research Record 308, 1-12.			X				X				X		
WORRALL, R., et al. (1965). "Study of Operational Characteristics of Left-Hand Entrance and Exit Ramps on Urban Freeways." Highway Research Record 99, 244-273.	X										X		
WORRALL, R. et al. (1966). "Merging Behavior at Freeway Entrance Ramps: Some Elementary Empirical Considerations." Highway Research Record 157, 77-107.					X	X	X				X		
YATES, J. (1970). "Relationship Between Curvature and Accident Experience on Loop and Outer Connection Ramps." Highway Research Record 312, 64-75.	X									X			

YATES, J. & BEATTY, R. (1970). "Relationship Between Lighting and Accident Experience Between Interchanges." Highway Research Record 312, 85-92.

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	Interchange Classification
X	Interchange Design
	Interchange Structures
	Entrance Ramps
	Exit Ramps
	Weaving Areas
	Lane Drops
	Delineation & Signing
X	Accidents
	Traffic Operations
	Land & Environment
	Control Systems