Operational Considerations for Systems of Interchanges

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Basic three-dimensional considerations in design include the composition of the elements of the highway and its effects on driver operation from a dynamic viewpoint. This discussion is an extension of basic three-dimensional design and covers interchange operational requirements, route considerations, and related signing. The features discussed are not as direct and are perhaps much more subtle than those that have to do with the geometrics of longitudinal and cross-sectional elements. Design considerations under this heading deal mostly with communicative aspects between the driver and the freeway and interchange complex in which the main thrust is to clarify, simplify, and facilitate driver operations. There are 13 operational and design criteria associated with freeway and interchange design. They are basic lanes, lane balance, applications of auxiliary lanes, route continuity, appropriate interchange form, no weaving within interchange on freeway, right exits and entrances only, single exit on freeway per interchange, exit in advance of crossroad, simplified signing, implementation of decision sight distance, freeway and exit ramp speed relationships, and ramp spacing. Although these operational and design criteria are discussed in various chapters of the 1990 AASHTO *Policy on Geometric Design of Highways and Streets*, the focus here is to clarify their application in freeway and interchange planning and design. Many of the concepts were first developed in the late 1950s and early 1960s, yet most were not incorporated in the AASHTO design policy until 1984—some 25 years after inception. The paper is intended for use as a practitioner's checklist of the 13 essential criteria during planning and designing a new freeway facility or considering operational and design improvements to an existing facility.

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The operational and design considerations discussed here have evolved as a result of the experience gained and research accomplished during the past 60 years since the first interchange and controlled-access facility was constructed. Much of this has been as a result of human factors research associated with driver characteristics and expectations related to highway geometrics and traffic control devices.

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Since it is the geometrics of the freeway and interchange system that dictates safe and efficient operations, an expanded definition of geometric design might be as follows: A dynamic facet of highway and traffic engineering, which, in its proper application, is a highly sophisticated and specialized discipline. It translates research and operational experience three-dimensionally into a physical highway plant, considering driver comfort and convenience, safety, and operational efficiency.

This expanded definition provides the purpose and gives direction to the designer. In following this definition there is the ability to look for new and better solutions in design of highways. These solutions should be tempered with results of operational experience, and the design should be approached from the viewpoint of all drivers—the stranger, the regular user, the angry, the harassed—who may be expected to use the facility as conceived by the designer. Should we not, then, provide a facility that allows the driver to perform tasks with a minimum of worry, indecision, and frustration?

If so, the driver should be able to see and know how to proceed along the highway. The task should be made so that it is easy to perform properly and difficult to perform improperly. However, should poor judgment be used or a mistake made, the highway should be "forgiving" and not exac too great a price for a moment's inattention or indecision The driver's attention should be drawn to what should be done and not to what should not be done. Transportation designers should simplify the driver's task and not complicate what already is complex for the driver operationally.

OPERATIONAL DESIGN FEATURES AND ROUTE CONSIDERATIONS

The research accomplished and experience gained in oper ating freeways has led to the establishment of operationa design criteria that are vital in effecting safe and efficien freeway operation consistent with the definition of geometri design presented previously. Although application of appro priate dimensions, longitudinal and cross-sectional, is critica in the planning and design process, of further consideratio are the system aspects and communicative features that ten to clarify and simplify operations through a uniformity i design that satisfies driver expectancy.

During the late 1950s and 1960s, a series of operation design criteria was formulated and documented (*1–4*). It wa not until the 1984 AASHTO design policy was published th most of these criteria actually became criteria. Many of th early articles and publications documenting these criteria were written by Jack Leisch. These publications were not referenced in either the 1984 or the 1990 AASHTO policies (*5*). The purpose of this paper is to recognize the Father of the criteria and to further clarify their importance in safe and efficient traffic operations.

The 13 criteria can be grouped into four concept categories:

- System criteria,
- Interchange considerations,
- Operational uniformity criteria, and
- Related or ancillary guidelines.

The categories will be discussed in detail in the following sections.

SYSTEM CRITERIA

When implemented, the system criteria, which include basic number of lanes, route continuity, lane balance, and application of auxiliary lanes, permit the freeway facility to operate in a sufficiently flexible mode to accommodate variations in volume and pattern of traffic. It is thus a design component to achieve a smoother flow of traffic to develop a more nearly uniform level of service, with improvement in driver comfort and convenience.

The first step toward determining the number of lanes required for flexibility in operation entails a capacity (level-of-service) analysis, predicated on normal peak hours, which are repeated daily during the morning (home-to-work) and the evening (work-to-home) periods; the capacity analysis is further extended to include any other known peaks, such as holiday or weekend concentration. This serves as a base on which appropriate number and arrangement of lanes are ultimately developed, with allowance for flexibility. The remaining steps in the process involve determination of the basic number of lanes, provision of lane balance, and application of special auxiliary lanes.

Basic Number of Lanes

Fundamental to establishing the number and arrangement of lanes on a freeway is the designation of the basic number of lanes. Consistency should be maintained in the number of lanes along an arterial facility. Thus, the basic number of lanes is defined as the minimum number of lanes designated and maintained over a significant length of the route, irrespective of changes in traffic volume and requirements for lane balance (Figure 1). In other words, it is a constant number of lanes assigned to a route, exclusive of auxiliary lanes. The number of lanes is predicated on the general volume of traffic over a substantial length of the facility. The volume considered here is the design hourly volume (normally representative of the morning or afternoon/evening weekday peak). Localized variations are ignored so that the volumes on individual segments between ramp terminals that are below the general level would theoretically have reserve capacity, whereas volumes on segments somewhat above the general level would be compensated for by the addition of auxiliary lanes introduced within these segments.

Required changes in the number of basic lanes are generally accomplished at major junctions (e.g., at freeway-to-freeway or system interchanges). In the case of an increase in basic lanes, the added lane is introduced via a 2-lane entering ramp at the system interchange. In the case of a decrease in basic lanes, the lane normally is not dropped at the ramp of the system interchange discharging the heavy volume, but via an exit at the following interchange. Another case in which the basic number of lanes may be reduced occurs when a series of exits, as in an outlying area of a city, causes the traffic load on the freeway to drop sufficiently to justify the smaller basic number of lanes. The selection of the basic number of lanes should be a matter of planning and design policy consistent with the overall system of freeways in a particular area.

Lane Balance and Auxiliary Lanes

Capacity analyses sometimes indicate abrupt changes in number of lanes at points of entrance or exit. Whereas such changes may be logical in terms of volume-capacity relations, they are not always appropriate in achieving smooth operating characteristics. To ensure efficient operation and to realize the indicated capacity potential where merging, diverging, and weaving take place, a certain balance of lanes must be maintained. Lane balance should comply with the relations shown in Figure 2.

The equations indicate that at exits the number of lanes approaching should be equal to one lane less than the combined number departing. At entrances, the combined number of lanes after the merge should either be equal to or one lane less than the total number of lanes approaching the merge. The principle of having an extra lane at the point of divergence (i.e., one more lane "going away") is a type of escape hatch, or a device that tends to flush traffic away from the point of divergence because of greater exit than approach capacity.

Since lane balance in effect produces lane drops on the freeway at certain exits, whereas basic lane arrangement

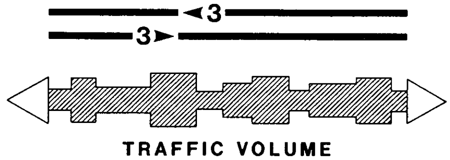

FIGURE 1 Basic number of lanes is maintained over a significant length of route.

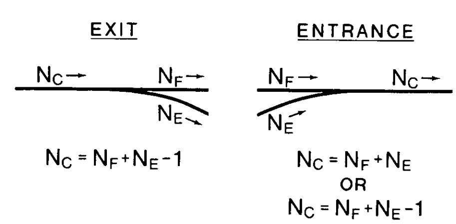

FIGURE 2 Lane balance (reduced lane changing).

maintains a constant number along the freeway, there appears to be a conflict between the two. This need not be so. The necessary requirements for maintaining both lane balance and basic lanes can be met by holding the basic number of lanes and then achieving lane balance by building on the basic number of lanes, that is, by adding auxiliary lanes or removing auxiliary lanes from the basic width of the traveled way. Thus, in no case would there be less than the basic number of lanes on the freeway.

To further illustrate the two situations, Figure 3 shows how lane balance and application of auxiliary lanes can be coordinated to produce desired arrangement. The two examples shown in Figure 3, Case A and Case B, demonstrate application of auxiliary lanes and establishment of lane balance to provide operational flexibility. Case A is to accommodate increases in entering and exiting traffic and resultant weaving between adjacent interchanges; Case B is to accommodate a volume increase over two or more interchanges requiring an auxiliary lane over a longer distance.

Any application of auxiliary lanes for the purpose described above must include consideration of an effective distance before the exit or beyond the entrance. Where interchanges are closely spaced and the auxiliary lane must be introduced at an entrance, the added lane should be carried to the exit of the following interchange or an added lane required for an exit should be extended back to the entrance of the previous interchange. An entrance followed by an exit frequently forms a weaving section, which requires the use of added width and certain minimum length (entrance to exit) to comply with capacity requirements for a weaving section. Here, an effective length of auxiliary lane on a full freeway should be of the order of 2,000 ft, preferably more, and should in no case be less than 1,500 ft. These controls govern where weaving capacity requirements alone may show lesser acceptable distances. On a facility serving as an adjunct to a freeway such as a collector-distributor road or a freeway distributor, a normal minimum length of auxiliary lane between an entrance and an exit is 1,000 ft.

Where interchanges are widely spaced, it might not be feasible or necessary to extend the auxiliary lane from one interchange to the next. In such cases, the auxiliary lane picked up at a two-lane entrance should be carried along the freeway for an effective distance beyond the merging point, or an auxiliary lane introduced on a two-lane exit should be carried along the freeway for an effective distance in advance of the exit and extended onto the ramp. Experience indicates that minimum distances of about 2,500 ft are needed to produce the necessary operational effect and to develop the full capacity of two-lane entrances and exits on high-type facilities.

Auxiliary lanes are essential to provide balanced and efficient operation. The objective is to add and remove auxiliary lanes on the freeway as required to account for localized increases and decreases in traffic volumes and to achieve a more uniform level of service. An auxiliary lane, however, has potential for trapping a driver at its termination point or where it is continued onto a ramp or turning roadway. Consequently, the driver should be made aware when traveling in or adjacent to an auxiliary lane. A special marking, contrasted with normal lane lines, and overhead signing should be provided for this purpose, and both should be compatible with the *Manual on Uniform Traffic Control Devices.*

The message conveyed by the marking becomes quite obvious to drivers. First, the basic lanes, those continuing through on the facility, are delineated, advising the through driver to stay to the left of the marking. Second, the marking informs the exiting driver to assume a position on the right of the marking. Third, it alerts the entering driver that it is necessary to cross over this marking to continue on the highway. The principle advanced here constitutes the means of providing the driver with prior information coupled with a visual indicator for positive guidance.

Route Continuity

Route continuity refers to the provision of a directional path along and throughout the length of a designated route. The designation pertains to a route number or to the name of a freeway.

Route continuity is an extension of operational uniformity coupled with the application of proper lane balance and the principle underlying the use of a basic number of lanes. Its attributes are of particular value to the unfamiliar driver who must rely on uniformity of design when presented with a choice of route. The uniformity associated with route continuity allows the driver approaching a bifurcation to be positioned properly across the lanes, followed by a confirmation received from route marking and directional signing.

In the process of keeping the driver on line, particularly in and around metropolitan areas, interchange configuration

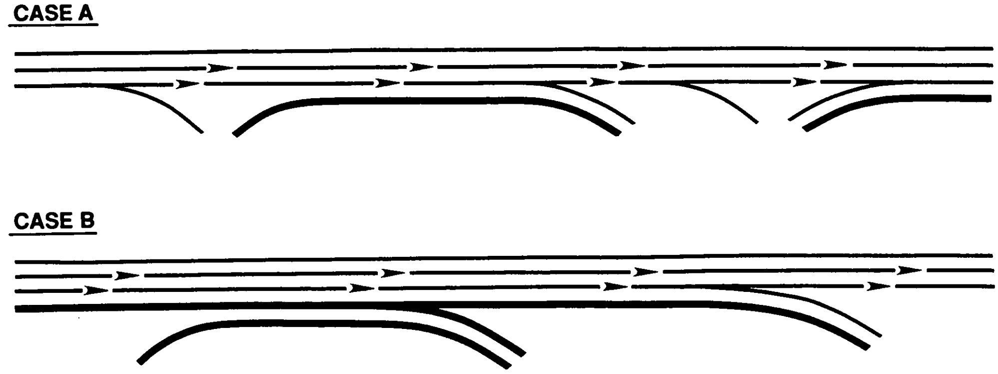

FIGURE 3 Auxiliary lane application.

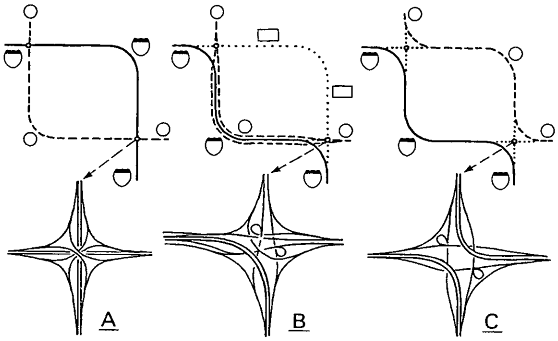

FIGURE 4 Route continuity.

must not necessarily favor the heavier movement at the point of bifurcation. It is the through facility (the designated route) that should always maintain its directional character. However, any predominant movement separating from the freeway should form a well-aligned exit on the right, equivalent operationally to the through movement.

Figure 4 shows the principle of route continuity as applied to a series of route configurations. It is important that the driver who wants to remain on route stays to the left and the driver who wants to leave or exit the route moves to the right and exits right.

INTERCHANGE CONSIDERATIONS

Two criteria are associated with interchanges: implementation of appropriate interchange form and no weaving within the nterchange on the mainline of the freeway. The first relates o the correct interchange form and details of its design geometrics for the conditions at the location. The second relates o internal operations of the interchange to minimize vehicle conflicts and to facilitate safe and efficient operations.

ppropriate Interchange Form

he appropriate interchange form at any particular location s dictated by a variety of considerations, which may include he following:

- Classification of intersecting facilities,
- Volume and pattern of existing and future traffic,
- Physical constraints and right-of-way considerations,
- Environmental requirements,
- Local access and circulation considerations,
- Construction and maintenance costs, and
- Road user costs.

The interchange selection process can be greatly simplified hrough an understanding of the general characteristics of the arious interchange forms. These general characteristics inude capacity, safety, operations, right-of-way requirements, nd construction costs. At any one interchange, there are erhaps only two or three forms that may fit the conditions equired characteristics). The appropriate interchange form(s) n initially be selected for further study based on the type r classification of the facility with which the freeway will

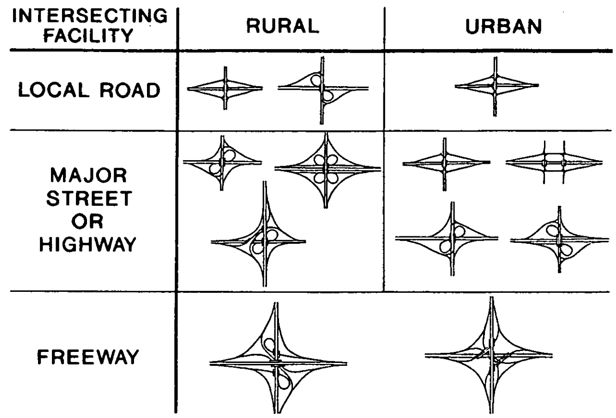

FIGURE 5 Adaptability of interchanges.

interchange. The matrix in Figure 5 associates basic interchange forms with type of interchanging facility in urban and rural areas. This is based on general operational, capacity, and right-of-way characteristics associated with the urban or rural location and facility type. It is only intended as a guide in beginning the interchange selection process.

Geometric variations of the basic forms that may be appropriate are not shown in Figure 5. An example may be in an urban area where a major or arterial street interchanges with the freeway. Other diamond interchange variations may be appropriate (e.g., three-level diamond, single point urban diamond, or compressed diamond). Figure 5 shows basic forms only and is intended as a guide.

No Weaving Within Interchange

Interchange forms as cloverleafs and some partial cloverleafs (loops in adjacent quadrants) result in weaving operations in the interchange. Such interchanges exhibit high accident experience and poor operational characteristics that usually affect not only entering and exiting traffic but mainline flow as well. To avoid such problems, collector-distributor roads can be added or the interchange can be converted to another form.

Figure 6 shows in concept the example solutions suggested here. In this case, a cloverleaf is modified or converted to

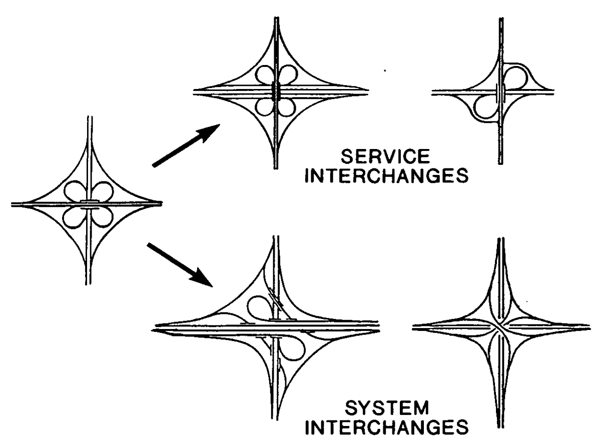

FIGURE 6 No interchange weaving.

other forms, depending on whether the interchange is a system interchange (freeway to freeway) or a service interchange (freeway to street).

OPERATION UNIFORMITY CRITERIA

When implemented, operation uniformity criteria produce a uniformity of operation along the freeway by facilitating and simplifying the driver's task, which results in more efficient operations.

Right Exits and Entrances

Much has been written about this criterion. It only needs to be emphasized here that right exits and entrances only should exist on a designated freeway route. This satisfies driver expectancy and keeps slow-moving vehicles from left lanes and avoids weaving across all lanes of the freeway. It should be noted that the accident rate at left-side ramps is twice that at right-side ramps.

Single Exit Per Interchange in Advance of Crossroad

This criterion is a critical one in simplifying the driver's task by providing only one decision point on the freeway and giving the driver a view of the exit ramp well in advance. Operational Uniformity can thus be achieved by implementing the previous criterion. Use of these criteria produces a uniform arrangement of exits and entrances along a freeway, providing for a uniform pattern of directional signing and allowing drivers to exit in a consistent manner at all interchanges, as shown in Figure 7.

The two freeway and interchange systems shown in the figure produce different operational characteristics, although the basic forms of the interchanges are identical. In the upper facility, a difficult or confusing pattern of exits is shown. Each interchange produces different operational characteristics along the freeway. Some interchanges result in two exits, some one exit. One interchange has one exit beyond the crossroad hidden from the driver's view, and the cloverleaf has not only two exits with one beyond the crossroad but a weaving section between the entering and exit loop ramps.

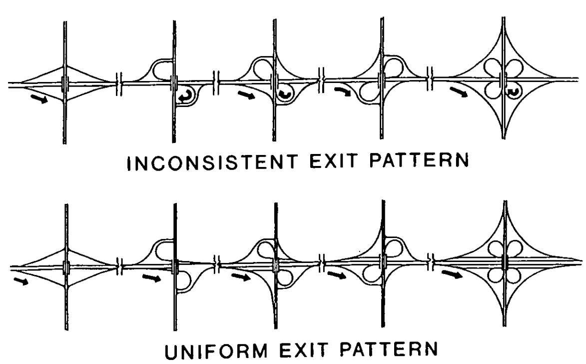

FIGURE 7 Operational uniformity.

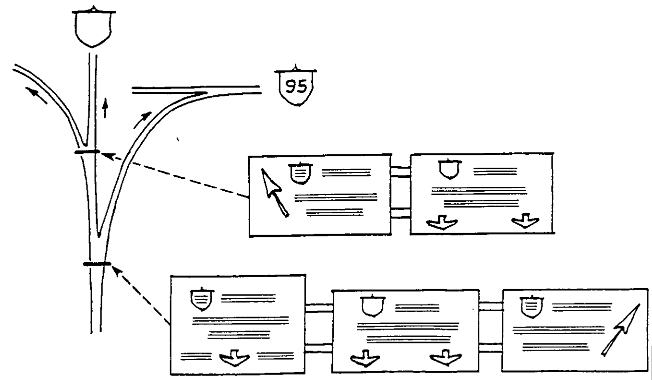

FIGURE 8 Complex signing.

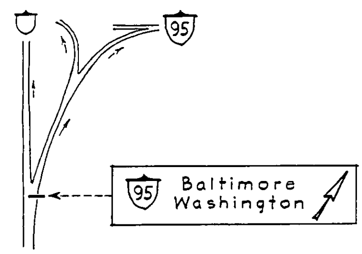

FIGURE 9 Simplified signing.

The facility in the lower portion of the figure with simila interchange forms has a uniform pattern of exits from th freeway. With geometric adjustments, each interchange ha a single right exit in advance of the crossroad. This unifor pattern of exits also produces uniformity in signing along th freeway, further simplifying the driver's task.

Simplified Signing

This operational uniformity criterion is a result of the previou criteria. To demonstrate how signing can be simplified, tw examples are shown in Figures 8 and 9. Figure 8 shows a interchange with two exits—one right and one left. The re quired sign panels and message units are shown to provid the information necessary to the driver to successfully ne gotiate the interchange. This can be compared with the singl right exit design in advance of the crossroad portrayed i Figure 9. In this case, only one sign panel with four messag units is necessary at the exit from the freeway—one decisio point and no confusion. Once the driver exits and is operatin at a lower speed, the ramp splits, in this case to go east o west. Supplemental signing at the ramp bifurcation would b provided to guide the driver to the desired destination.

ANCILLARY GUIDELINES

For lack of better term, the last three criteria are categoriz as ancillary criteria. They are decision sight distance, freew and ramp speed relationships, and ramp sequencing or spaci requirements.

Decision Sight Distance

This element or criterion in freeway design and operations relates to the distance at which a driver can perceive a decision point along the freeway. In most cases, these decision points are exits or lane drops. Major bridges and tunnels should also be considered because they may require significant driver adjustment to changing conditions. The criteria for determining decision sight distance are defined in Figure 10. The AASHTO policy clarifies the definition and longitudinal dimensions for various facilities and circumstances. The distances indicated in the figure for freeways with design speeds of 60 or 70 mph are within the range of values in the AASHTO policy. These distances of design speed are those necessary for the driver to perceive the decision point, react, and perform the appropriate maneuver.

Freeway and Exit Ramp Speed Relationships

This criterion refers to the distance required for the driver to decelerate the vehicle from the speed of the freeway to the speed of the controlling curve of the ramp (Figure 11). The dimensions indicated are from the physical gore of the exit ramp to the beginning of the controlling curve of the ramp. The assumption is that the vehicle is travelling at approximately the speed of the freeway at the gore and decelerates at a comfortable rate to the ramp curve (the dimensions have been rounded). Although the roadway element of length L in the figure is shown as a tangent, it may be a flat curve, a series of transition curves, or a spiral.

The purpose of providing this distance is not only for safe vehicle deceleration and operation but also to eliminate the need for drivers to decelerate on the freeway to safely negotiate the exit. This encourages more uniform speeds on the freeway and thus safer operation.

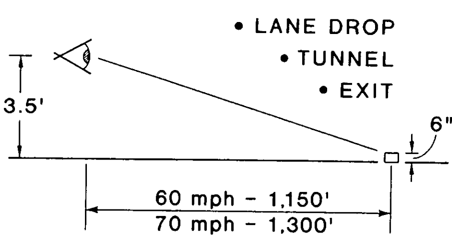

FIGURE 10 Decision sight distance.

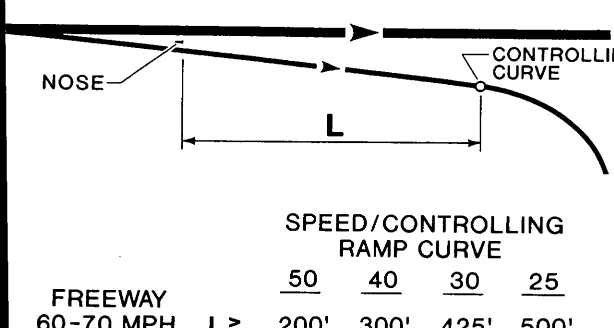

FIGURE 11 Freeway and exit ramp speed relationship.

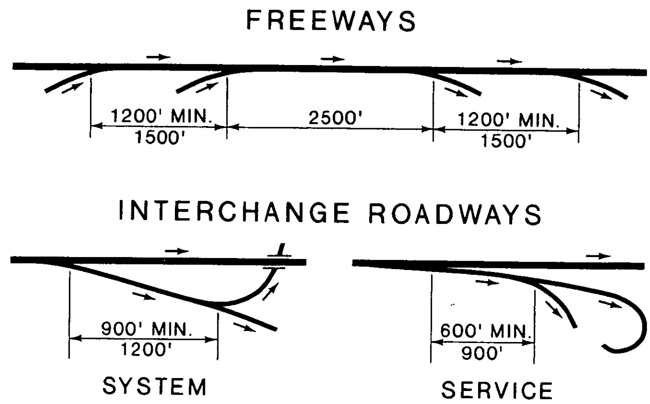

FIGURE 12 Ramp spacing.

Ramp Sequence

Dimensions for sequencing of ramps are described in the AASHTO policy on the basis of design requirements and, to an extent, capacity relationships. Some of the dimensions for successive exits or entrance, entrance followed by an exit, and ramp exits for system and service interchanges are shown in Figure 12. These dimensions, which are based on experience, have proved to be appropriate not only to accommodate ramp exit or entrance geometric criteria but also to take into account driver operational needs in spreading conflict or decision points. This also results in smoother freeway operations with more uniform operating speeds.

SUMMARY

Although the operational and design criteria discussed in this paper are discussed in various chapters of the 1990 AASHTO policy (*5*), the intention here is to clarify their application in freeway and interchange planning and design. Many of the concepts were first developed in the late 1950s and early 1960s, yet most were not incorporated in the AASHTO design policy until 1984—some 25 years after inception. This paper is also intended as a practitioner's checklist of the 13 essential criteria for planning and designing a new freeway facility or considering operational and design improvements to an existing facility.

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