Some Aspects of Reverse-Flow Freeway Design

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Designers are reaching a point where they can no longer hope to accommodate projected traffic demands with conventional freeway designs. The problems of not enough freeway capacity and not enough merging capacity are aggravated by severe unbalances of flow during peak hours.

When the directional distribution of traffic on a multilane highway is greatly out of balance during peak hours, the capacity of a given section can be appreciably increased by devoting more than half of the lanes to the predominant direction of flow. This principle of reverse-flow operation is grudgingly being applied to freeway design with limited success.

This paper is a generalization of the reverse-flow freeway concept in that it suggests some interchange designs which enable ingress and egress directly to and from the at-grade street system rather than the outside freeway roadways. In addition to preserving the increased capacity of the reversible freeway lanes, this innovation should double or triple the merging capacity at certain interchanges.

A step-by-step procedure for utilizing this new type of reverse-flow facility is explained. The geometrics of the proposed interchanges are discussed in detail, complete with a plan-profile, typical section, and proposed signalization phasing plan.

•BETWEEN the invention of the wheel and the invention of the automobile, the primary concern of road builders was "getting the road user out of the mud." Only the structural aspects of design were considered. With the 1920's came the concept of traffic engineering providing gradual curves, smooth highway surface, flat grades, and route markers. This proportioning of the visible elements of the road we still call "geometric design." The third phase of road history is the present period of making the road fit the environment. Land use, the natural setting, social conditions and human psychology are some of its concerns. Its application might be called "functional design." Thus, structural design is related to vehicular load, geometric design to vehicle capabilities and driver requirements, and functional design to the demands of traffic and travel.

THE SYSTEM CONCEPT

Designing for traffic movement and circulation about a city implies a twofold purpose: the direct and natural connection between two or more points, and clear direction for those traversing the roadways. The freeway system is the most promising instrument for achieving this purpose. The difference between a freeway system and a collection of streets is the assurance, in the case of the former, that traffic movement has been optimized in some sense or according to some criteria.

The distinguishing feature of any system is that, although its performance depends on all its components, it transcends that of any one such that its performance cannot be

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determined by the analysis of the individual components alone. The freeway system may be broken down into at least six components: the express lanes, the entrance ramps, the exit ramps, the frontage roads, the cross streets, and the interchanges. The components must be analyzed in turn. The analysis will reveal important characteristics that must be considered in producing a satisfactory design. Classical systems are described in terms of a set of variables, commonly called parameters, by means of which the system performance is described. In a freeway system the number of lanes of traffic, the number of on-ramps, the number of off-ramps, and the number of lanes per ramp are design parameters.

After deciding the value of a particular parameter, it is important to know its effect on the operation of that component and what effect it has on the overall system design. Thus, it might seem that an entrance ramp component should have two lanes. However, it is well known that a two-lane entrance ramp is not compatible with the freeway express lanes unless an express lane is added so that the number of lanes downstream of the ramp is one more than the number upstream.

There is growing sentiment that the trouble with freeways lies in the fact that there are too many interchanges causing weaving and increased traffic interaction. True, if there were not as many interchanges, freeway operation would be improved. However, eliminating interchanges means that a freeway driver must either go several blocks past his street and then double back or exit long before he would like to. On the other hand, a driver desiring to use a freeway with fewer interchanges has a much longer trip on the surface streets before he can enter the freeway. In both cases, this adds up to increased time and distance in traffic, making the elimination of interchanges doubtful as a creative solution.

Where one has the choice of supplying too little of something (too little space between interchanges) or too much (too much space resulting in longer surface street trips), by using a two-parameter analysis it is conceptually simple to find an optimum. In practice, however, what we end up with in this case is what the system engineer calls "suboptimization" rather than optimization. This principle of suboptimization states that optimization of each subsystem independently will not in general lead to a system optimum and, more strongly, that improvement of a particular subsystem may actually worsen the overall system (1). It remains to be shown that interchange spacing is only one aspect of the problem by simply introducing other system components or manifestations of the freeway system design problem.

Because the directional distribution of traffic during peak hours is greatly out of balance, the capacity of a given pavement width can be greatly increased by devoting more than half the lanes to the predominant direction of traffic. This would be particularly effective on radial freeways in large cities carrying heavy volumes toward the CBD in the morning and outward in the evening.

This type of operation has been used rather effectively to provide traffic relief on existing major arterials and bridges. For example, a six-lane facility may be operated with four lanes in one direction and two lanes in the other to fit an unbalanced traffic flow. Since the facility is operated with three lanes in each direction during the off-peak, traffic control is accomplished by (a) signing, (b) cones between and (c) traffic signals over the convertible lanes.

As pointed out in the AASHO Redbook (2), this principle, though theoretically applicable to expressways, is complicated by the median. Under some arrangements traffic on the left of the median is isolated from all exits for some distance and the anticipated operation would not be compatible with freeway, or even expressway-type, operation.

The heart of the matter lies in the complexity of a freeway system. The freeway designer must avoid the dangers of suboptimization—in this case dealing with the problem of interchange spacing and reversible express lanes separately. What follows in the form of a typical freeway design illustration is an attempt to give the reader a feeling for the point of view which distinguishes creative freeway system design from classical geometric design.

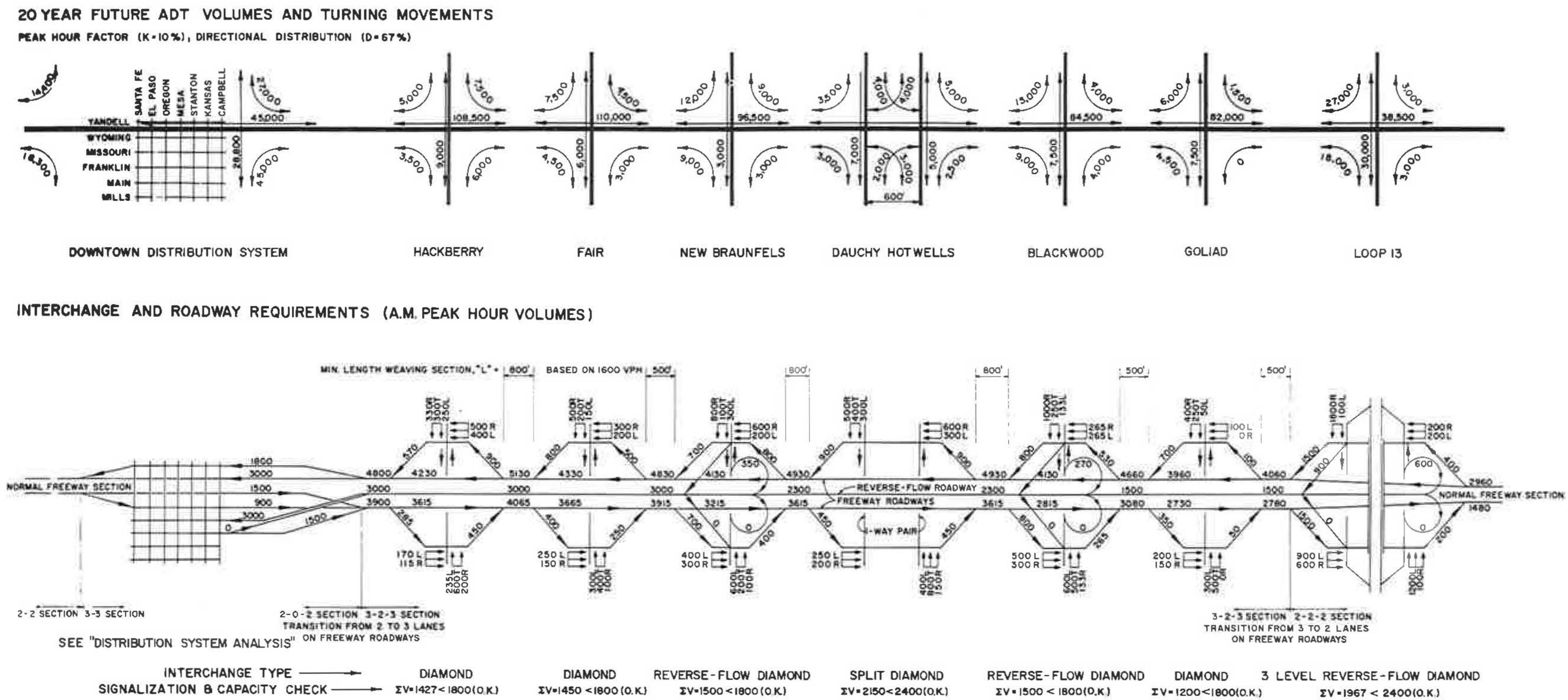

Figure 1. Reverse-flow freeway schematic.

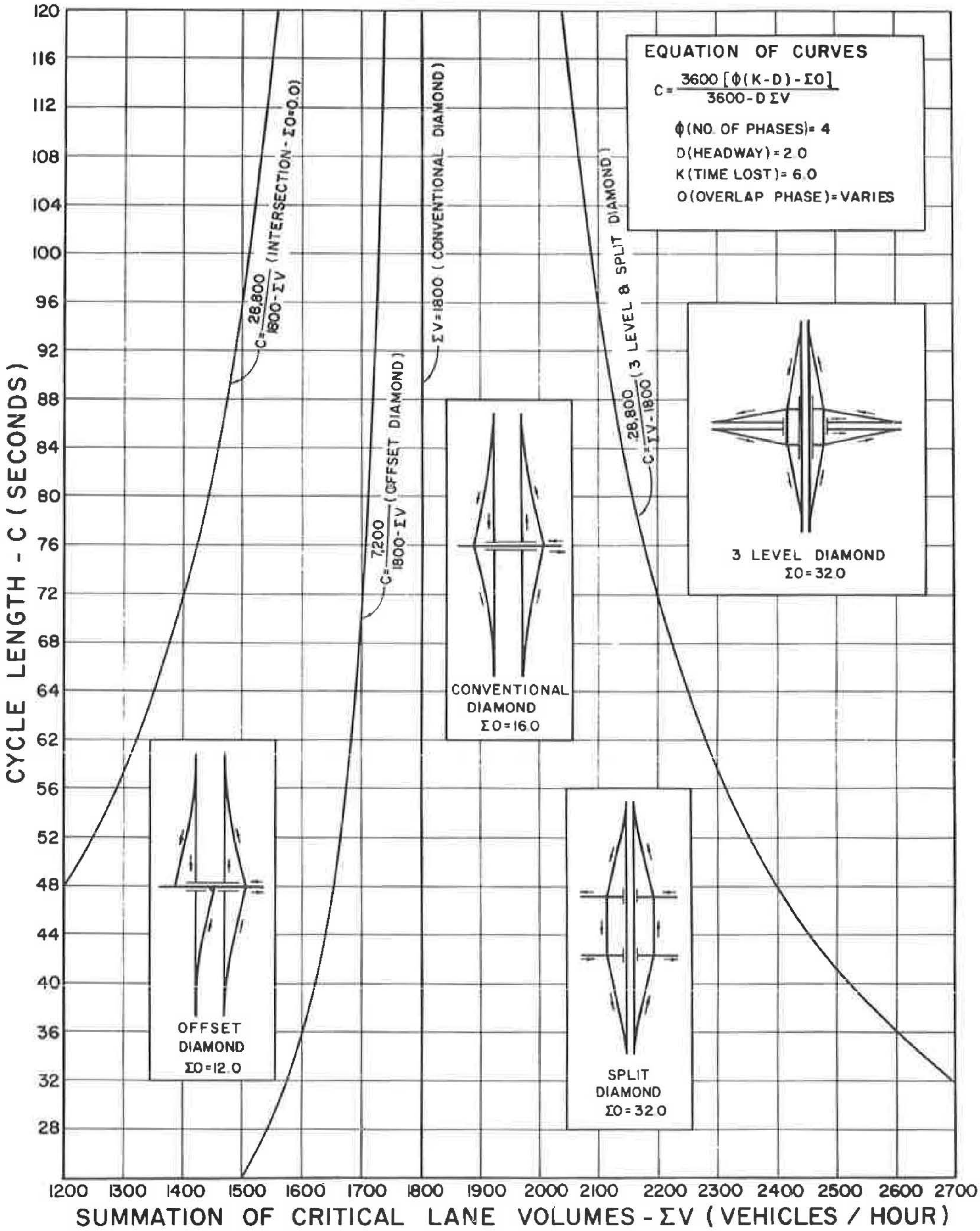

Figure 2. Design curves for 4 phase facilities.

TABLE 1

FREEWAY CAPACITY WITH CONFIDENCE LIMITS

Peak 5-Min Flow (VPH)	Approx. Probabilities of Various Types of Flow in Peak 5-Min			Freeway Design Service Volume (Total Hourly Vol./Lane) for Metropolitan Area Population of:			
	Stable	Unstable	Forced	100,000	500,000	1,000,000	5,000,000
1500	1.00	0.00	0.00	1100	1200	1300	1300
1600	0.98	0.02	0.00	1200	1300	1300	1400
1700	0.85	0.15	0.00	1300	1400	1400	1500
1800	0.50	0.48	0.02	1400	1500	1500	1600
1900	0.15	0.69	0.16	1500	1600	1600	1700
2000	0.03	0.47	0.50	1500	1600	1700	1800

REVERSE-FLOW FREEWAY SCHEMATICS

The location of a highway and its design elements—though influenced to some degree by topography, physical features, and land use of the area traversed—should reflect anticipated traffic patterns and travel desires. Average daily traffic volumes and turning movements along a hypothetical route—presumably provided by the Planning Survey Division of the State Highway Department—are shown in Figure 1. Design hourly volumes for the peak periods are obtained by multiplying the ADT volumes by a 10 percent "K" factor (ratio of peak hour to daily traffic) and a 67 percent "D" factor (distribution of peak freeway traffic by direction). The high traffic volumes, urban nature of the route location, and economic considerations suggest a design speed of 70 mph as a basis for controlling all the design elements toward achieving an efficient balanced level of service.

The full control of access feature of freeways automatically requires grade separations for intersecting streets, and interchanges where turning movements are to be provided for. Interchanges may be classified according to the number of legs, as direct or indirect, and as signalized or unsignalized. The three principal types are, of course, the cloverleaf, the directional, and the diamond interchange. The capacities of fully directional and cloverleaf interchanges are essentially determined by the capacities of their ramps. Diamond interchanges are always signalized in urban areas and their capacities are therefore dependent upon the individual intersections or the coordinated system of intersections. Diamond interchange capacity curves are illustrated in Figure 2 (3).

Though not generally appreciated, it is important that the interchange requirements for the freeway schematics be determined before the freeway main lane requirements are investigated, because the number of ramps depends on the choice of interchange. Thus, a cloverleaf interchange and a directional interchange may have one or two entrance ramps and one or two exit ramps in each direction, whereas diamond interchanges have one entrance and one exit ramp in each direction. If the interchange is to be signalized, a capacity check is made to see if the planned facilities will handle the traffic with reasonable cycle lengths. Should a facility be apparently under-designed, additional approach lanes may be added or a higher type interchange be substituted in its place. For example, if a conventional diamond will not work a three-level diamond should be tried.

The next step is the determination of the number of main lanes based on an analysis of (a) the estimated peak hour demand and (b) the service volume value chosen as the design capacity. The freeway design service volumes in Table 1 enable the designer to judge what level of service can be expected for a given service volume based on the probability of obtaining various types of flow conditions during the peak 5-minute period (4). For this example, the population of the metropolitan area in the design year is taken to be in the 1,000,000 range. Thus, based on a possible capacity of 2000 vph per lane, Table 1 tells us that a freeway design service volume of 1700 would give a rate of flow of 2000 vph during the peak 5-minute period.

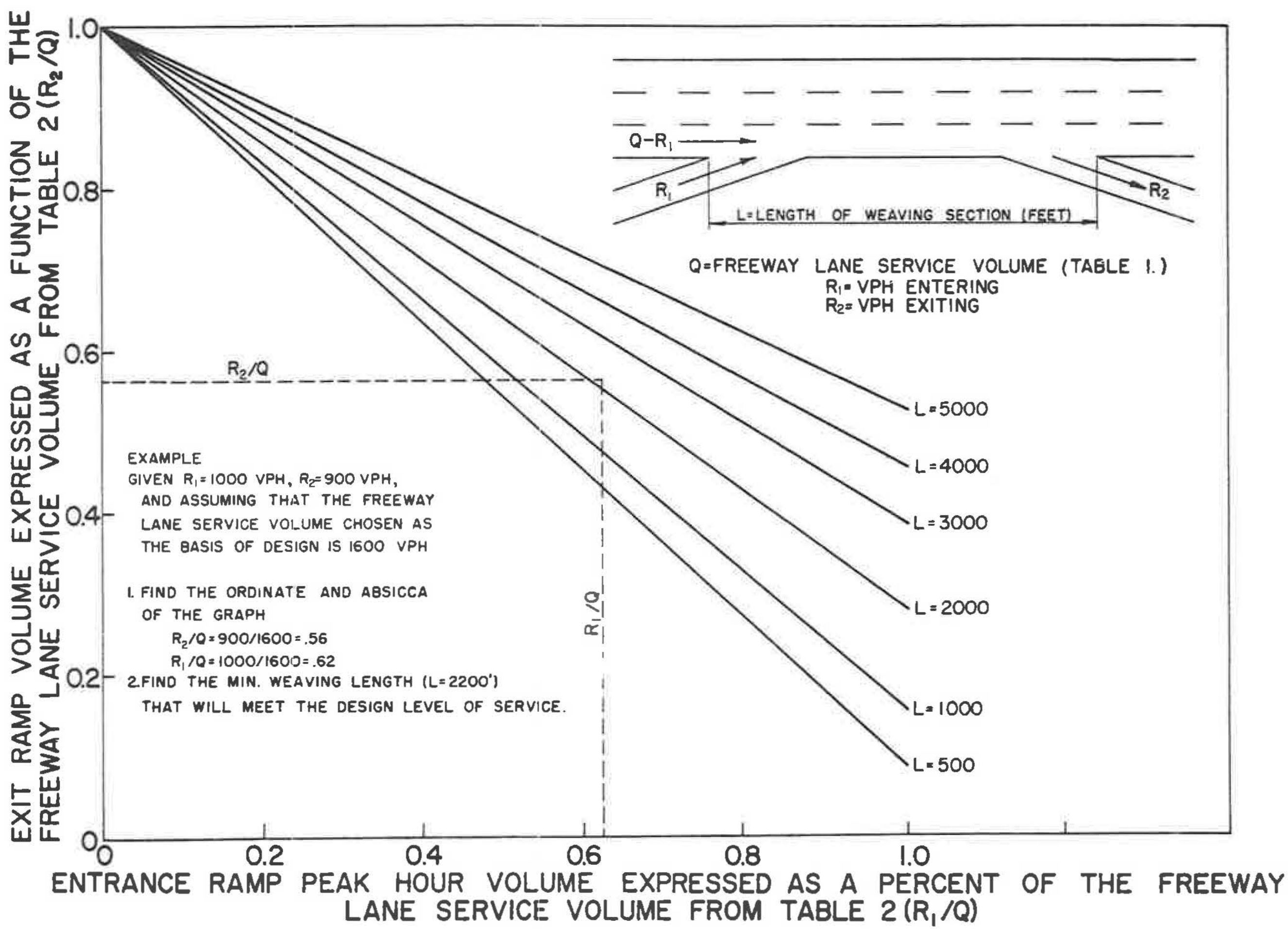

Figure 3. Determination of minimum length of weaving section to meet the design level of service.

The last step involves a check of operating conditions at critical locations to insure that the designated level of service is met at every point on the freeway. Critical sections include merging and weaving sections where the merging capacity is defined as the service volume chosen in the previous step from Table 1 (in this case 1700 vph). Figure 3 provides the basis for determining if weaving sections on the freeway meet the designated level of service (4).

The DHV traffic volumes and turning movements from Figure 1 show that seven locations have turning movements which warrant interchanges. The problem in deciding on an interchange type is providing for the efficient movement of high ramp volumes onto the freeway. Such conventional devices as the use of two-lane entrance ramps or two separate entrance ramps per interchange to accommodate high turning movements do not really solve the problem since all vehicles are still forced to merge onto a single outside freeway lane. Rather than solutions, more often than not, these tactics are no more than exercises in "pencil whipping."

Of equal concern is the high number of freeway lanes needed to handle the assigned volumes. Efficiency of operation is at its peak with three freeway lanes in one direction and drops off rapidly as four lanes of traffic, or five, in each direction are contemplated. Yet, such are the requirements in the hypothetical case illustrated in Figure 1 if a conventional freeway section is to be used.

As indicated previously, freeways with a separate third roadway for reverse-flow operation are feasible where peak-hour traffic volume requires an eight-lane or wider facility and traffic by directions is substantially unbalanced. Although AASHO (2) limits its discussion of the applicability of this concept to depressed freeways, there seems to be no reason why it could not be applied to elevated facilities. Reverse-flow sections of three-two-three lanes and three-three-three lanes would be theoretically equivalent in capacity during peak hours to 10- and 12-lane facilities, respectively.

AASHO further limits the reverse-flow freeway concept to situations where the traffic using the reverse-flow roadway is destined for a distant point without intermediate ingress or egress. This seems to be an unnecessary—even unrealistic—restriction, as shall be shown.

The schematic layout in Figure 1 includes the relative locations and types of interchanges. The choice of interchange in each case is based on capacity limitations and operational considerations. Thus, for the three low-demand interchanges, a diamond interchange with a critical lane capacity of 1800 vph (see Fig. 2) could be used since the summations of critical lane volumes are 1427 vph and 1450 for the two interchanges closet to the CBD and 1200 for the next to the last interchange. The 600-ft spacing between the two cross streets in the center of the schematics suggests that they be utilized as one-way pairs and a split-diamond be constructed for their turning movements. The summation of critical lane volumes for this interchange, 2150 vph, is less than 2400 vph, the capacity of the split-diamond (Fig. 2).

For the two interchanges on either side of the split-diamond, a capacity check of the turning movements shows that a conventional diamond suffices at both locations. The decision to use a reverse-flow diamond in each case is based on the high entrance ramp volumes of 1400 vph and 1500 vph respectively. The utilization of two ramps on the center reverse-flow dual roadway spreads each of these volumes over three entrance ramps. This is illustrated even more dramatically for the last interchange, a three-level reverse-flow diamond, in which the total volume desiring to enter the freeway equals 3000 vph. Using a conventional freeway section this would be impossible; however, it can be accomplished if the ramp movements are interchanged with the center reverse-flow dual roadway as well as the outside freeway roadways.

It is seen in Figure 1 that utilization of the reverse-flow dual roadway also solves the problem of reducing the number of freeway lanes. Traditionally, access to the center roadway is provided by crossover lanes connecting with the outside roadways. However, provision of entrance and exit ramps directly to the center roadway from the intersecting cross street seems desirable from the point of view of reducing ramp volumes by increasing the number of ramps without increasing the weaving volumes on the outside freeway lanes. Distances between weaving exit and entrance ramps shown in Figure 1 are minimums obtained by entering Figure 3 with the appropriate ramp volumes (based on a design service volume of 1600 vph).

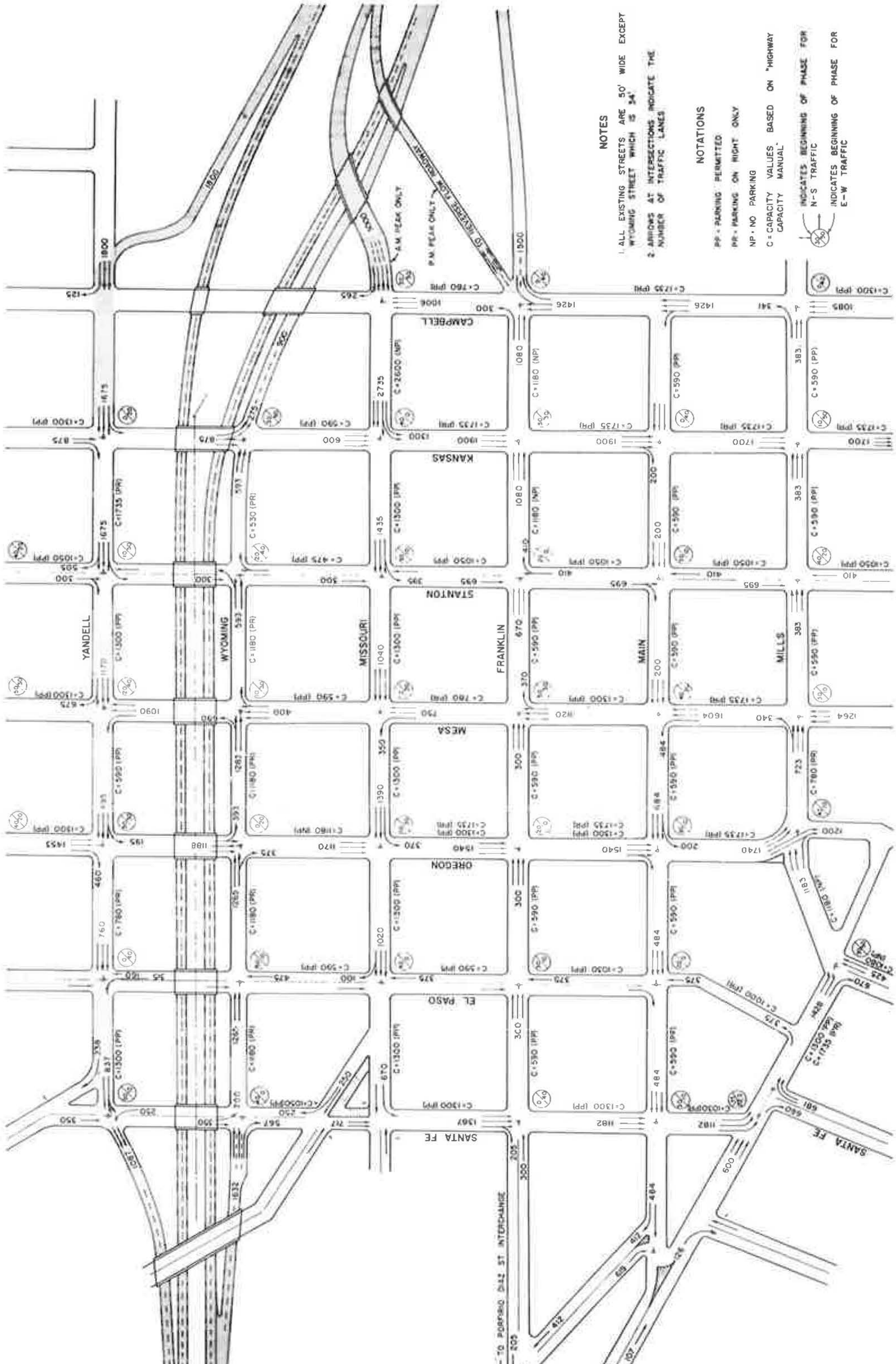

Figure 4. Distribution system analysis.

Essentially the reverse-flow diamond type interchanges are a combination of two interchanges, a partial cloverleaf on the reverse-flow center roadway and a diamond on the outside freeway roadways. It should be emphasized 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. In fact, the freeway ramps form the diamond part of the interchange, much as they would in the conventional design.

Uniformity of pattern and its effect on operation of interchanges should always be considered. A dissimilar arrangement of exits and entrances between successive interchanges causes confusion, decelerations, shock waves, and forced weaving. It is seen in Figure 1 that the driver on the outside roadways is faced with the familar exit-entrance pattern of the conventional diamond, whereas on the center reverse-flow dual roadway the cloverleaf continuity is preserved throughout.

DOWNTOWN DISTRIBUTION SYSTEM

The daily pattern of arrivals and dispersals in the central business district is one of the most involved problems confronting designers today. All the transportation systems—the subway, the surface transit system, the pedestrian, and of course the automobile—must enter the central business district at the same time.

Probably the most critical point in the urban freeway system is where the facility crosses the central business district. The problem is one of providing the freeway with the ability to discharge and collect traffic in a relatively short distance. Leisch (5) has documented many diagrammatic schemes using lateral and parallel distributors, emphasizing that some form of distribution system is essential in conjunction with urban freeway development to serve downtown areas properly.

It must be realized that a new freeway skirting the downtown area may completely alter the existing circulation pattern, and severely tax the capacities of the downtown streets. In order to prevent this, the entire problem must be attacked on a total system basis rather than by a piecemeal approach. Thus, the downtown distribution system should include the freeway, the interchanging ramps, the entire network of feeder streets in the downtown area affected by the freeway, and the downtown signalization system. Although these components may be analyzed separately, initially, the usual tests of system compatibility must be satisfied.

Figure 4 illustrates an analysis of the downtown distribution system for the hypothetical conditions established in Figure 1. The "existing" street system consisted of two-way operation except for the one-way pair consisting of Kansas and Campbell Streets with Kansas northbound and Campbell southbound. The shaded area defines the proposed freeway system. Numbers on the streets are peak hourly volumes based on the future design year.

Taking the components of the distribution system one by one, we consider first the freeway itself. An important characteristic of freeways is that they are big and have the same power as any big topographical feature such as a hill or a river to create geographical, and in consequence social, divisions. Therefore, the decision was made to depress the freeway lanes below the existing street level, and thus not to create a physical or psychological barrier to the development of the CBD for this rapidly growing city.

A single freeway intersecting a downtown area is often served by several closely spaced interchanges. However, because the heavy peak hour freeway volumes terminiating in the business district (4800 from the east and 1632 from the west each morning) are so great and the streets so closely spaced, in this case a solution was approached using another arrangement. A freeway exit ramp is to be brought into the network from the east connecting to Yandell with the number of freeway lanes from the east to be reduced from three to two to facilitate discharging this 1800 vph volume. A single two-lane exit ramp is deemed sufficient to handle the morning peak traffic from the west; this exit ramp joins the downtown network at Wyoming Street. Thus, the proposed freeway consists of a six-lane facility on either side of the CBD with four through lanes and two lanes dropped and added to improve the discharging and collecting of traffic (Fig. 4).

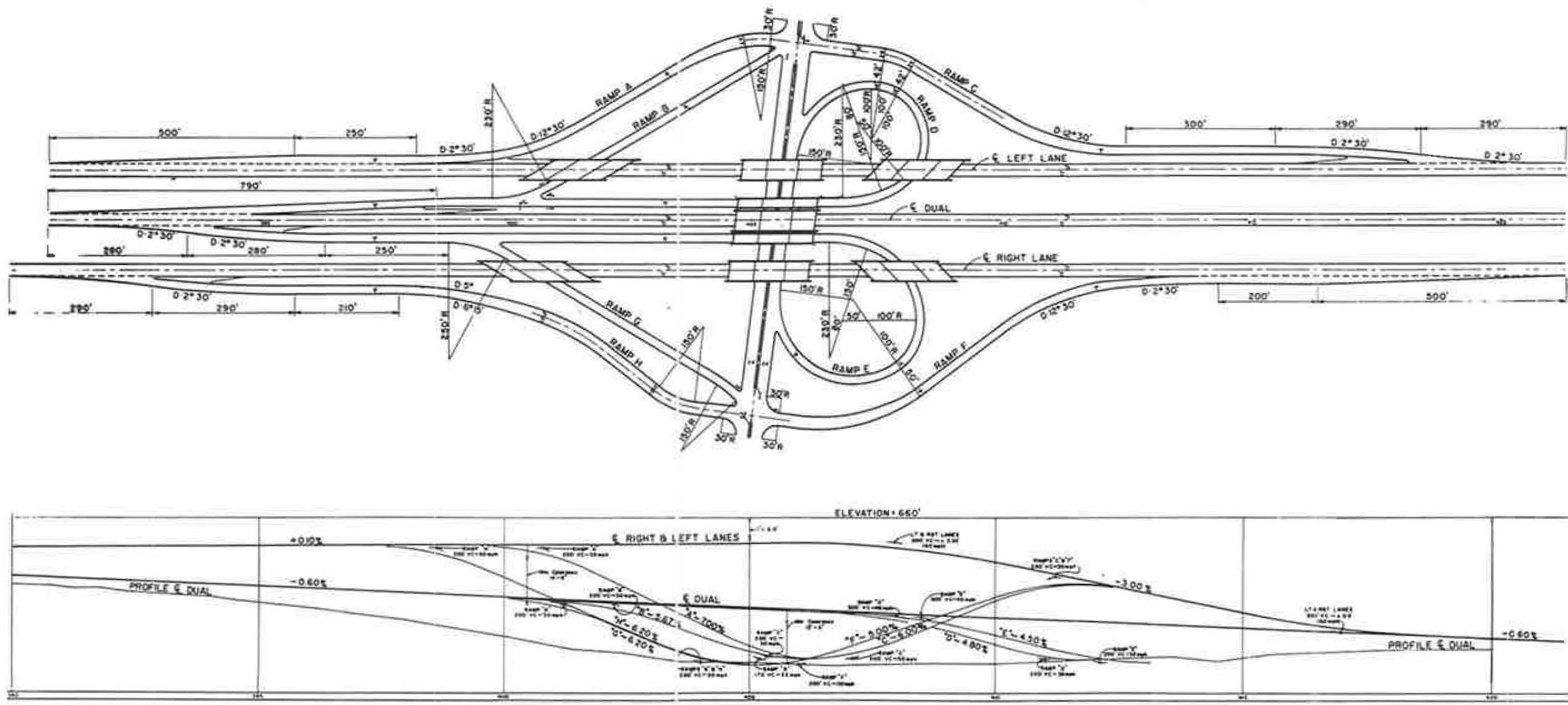

Figure 5. Geometrics of reverse-flow diamond interchange.

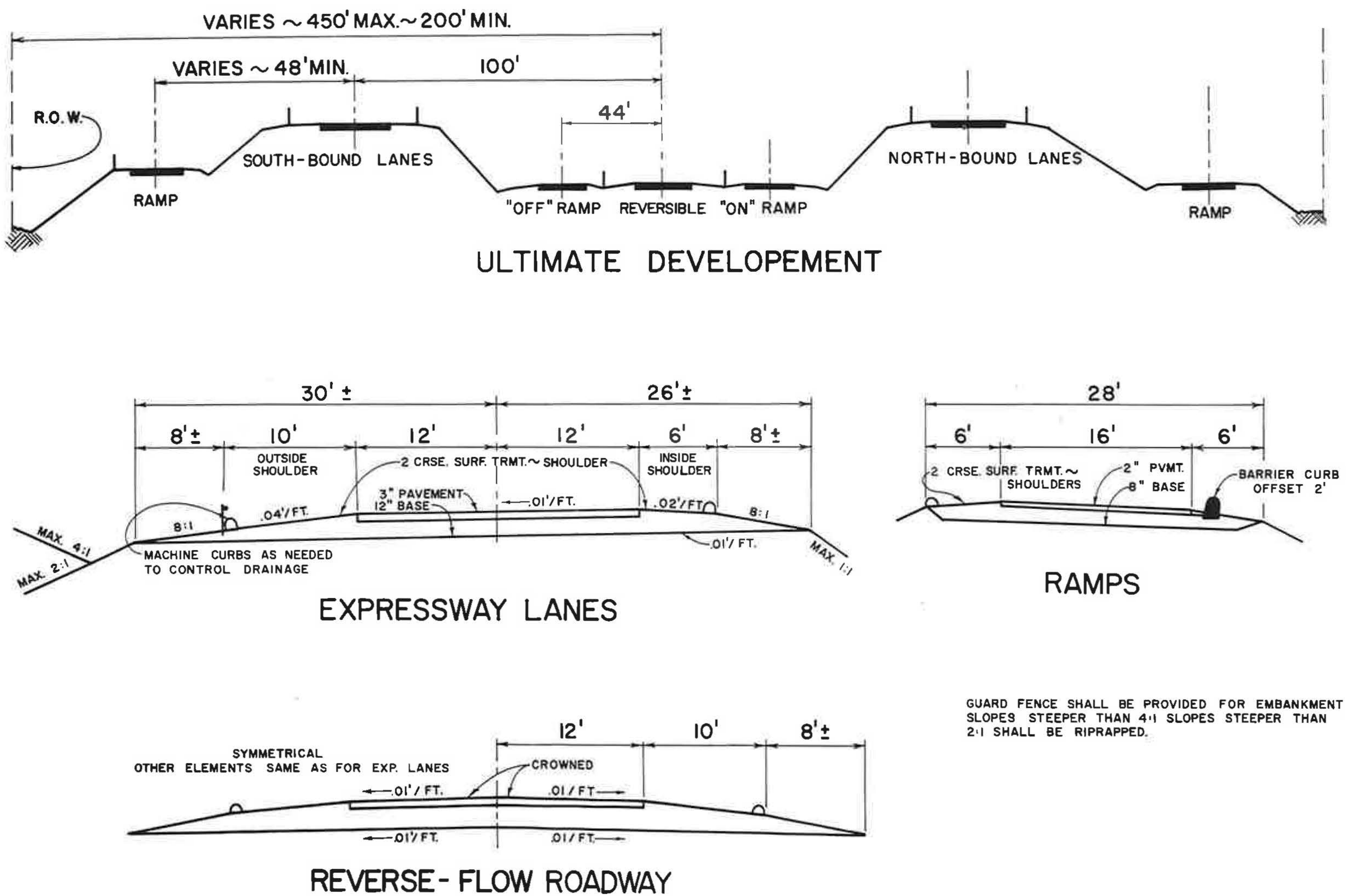

Figure 6. Typical sections.

The two-lane reverse-flow dual roadway divides itself at the CBD into two two-lane branches—one for the inbound flow in the morning peak and the other to receive the outbound flow in the afternoon peak. The inbound branch is increased to four approach lanes at the Missouri Street signalized connection to the downtown network. The reverse-flow roadway connection for the afternoon peak is initiated at Franklin Street as is the connection to the outbound freeway roadway.

The existing streets of Yandell and Wyoming which parallel the freeway are to be designated one-way frontage roads. Kansas and Campbell Streets are to be reversed to make them compatible with the freeway ramp components. The northern part of Santa Fe Street is made two-way to facilitate loading the westbound entrance ramp since this made it possible to feed the ramp during the entire signal cycle. At the transition from two-way to one-way, it is proposed to channelize Santa Fe Street as shown in Figure 4.

Considering the CBD network component of the distribution system, all streets are assumed to remain at their existing widths (50 ft except for 34 ft for Wyoming Street). Arrows at intersection approaches indicate the number of traffic lanes needed based on a lane capacity of 1000 vehicles per hour of green. Where ramps terminate at downtown streets, it is assumed that all traffic signals installed are to be made a part of the existing downtown PR signal control system. For the purpose of this analysis a two-phase (2:1 split), 60-second cycle with offsets set for 20-mph progression is used. A peak hour factor of 10 percent and a 67:33 directional distribution are assumed. Based on these assumptions, downtown peak hour parking would be virtually unrestricted.

In addition, values recommended by the Highway Capacity Manual are shown for each downtown block, as an alternate form of capacity analysis. Based on these values, some parking restrictions would be necessary during the peak hour as indicated by the designation PR for "parking on right only" and NP for "no parking."

In conclusion, a complete analysis of the downtown distribution system including the freeway components, feeder streets, downtown network, and traffic signal components seems to suggest that the proposed geometrics fulfill two important objectives, i.e., providing a freeway route close enough to the CBD to maintain its integrity, yet far enough away to reduce congestion.

GEOMETRICS OF THE REVERSE-FLOW INTERCHANGE

Having established the types of interchanges and the number of lanes, it remains to dimension the roadways. A plan-profile for a reverse-flow interchange is illustrated in Figure 5. The typical section for this type of system design is shown in Figure 6.

Provision for future widening has been made on the inside of the express-lanes; no provision was made on the dual throughout the limits of interchanges. However, the 100 ft center to center between the expressways and the reverse-flow roadway allow plenty of latitude. It should be added that 200 ft between opposing roadways should eliminate glare from high beams at night, since the operating hours for the dual would normally be during the daylight hours for most seasons of the year.

Back slopes for ditches in cut sections would be 4:1. Embankment slopes should vary with the heights of fill, from 8:1 for fills 5 ft or less to 1:1 in extreme cases between the express-lanes and the dual at interchanges. Fills in this area may be as high as 35 ft which is about the break-even point between a 1:1 embankment or structures. Slopes steeper than 2:1 shall be riprapped and guardrails shall be provided for embankment slopes steeper than 4:1.

Horizontal clearances shall conform to the shoulder line for the expressways and dual for grade separation structures—both overpass and underpass. Vertical clearances shall be a minimum of 17 ft over the dual and expressway, and 14 ft 6 in. over ramps (preferably 17 ft also). Clearances over city cross streets shall be 12 ft 6 in.

The results of comprehensive ramp studies isolated the vital elements of good entrance ramp design as the angle of entry formed by the intersection of the entrance ramp approach and freeway lanes, the visibility relationship between ramp traffic and freeway traffic, and the delineation of the ramp nose and acceleration lane. Thus, if

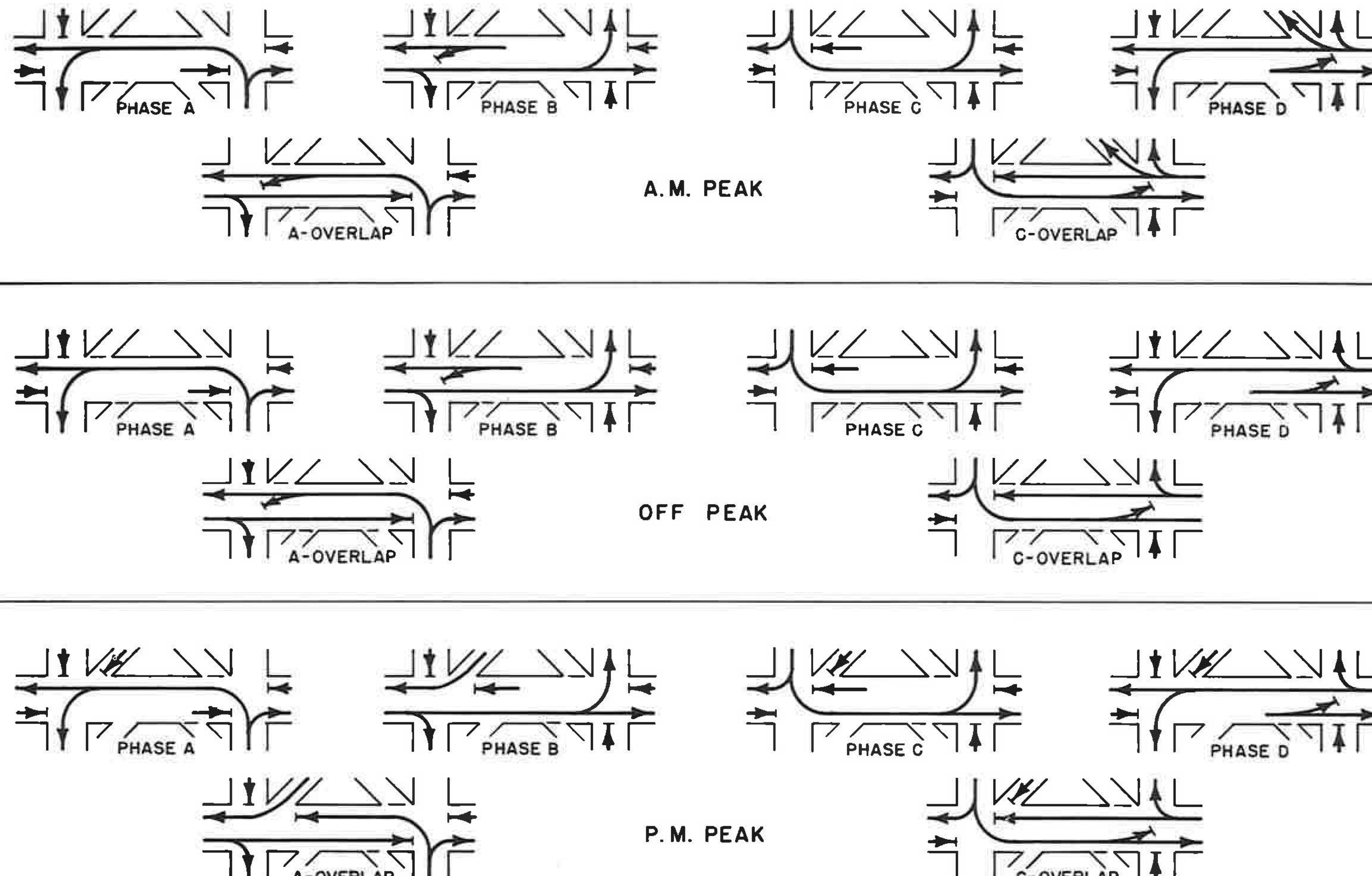

Figure 7. Phasing for reverse-flow diamond interchange.

desired usage of the speed change lane is to be realized, it is necessary to align the driver along the acceleration lane. This is best accomplished by providing a flat-angle approach.

Since the efficiency of the entrance depends to a large extent on an early gap evaluation, preferably some 250 ft before the nose, grade profiles on the ramp should not limit sight below this distance. Thus, in the geometrics extreme care has been taken in locating ramp VPI (vertical points of intersection) to comply with this concept.

Consideration of exit ramp operation also indicates a need for the correlation of traffic behavior with the elements of good exit ramp design. Specifically, the design should provide a natural exit path which can be negotiated at the average running speed of the freeway, adequate sight distance unrestricted by profile limitations, and again, proper delineation. The main feature is the provision for the deceleration of the vehicle off the freeway lanes or adjacent lanes (referred to as deceleration lanes). These concepts are put into practice in the geometrics by utilizing a relatively flat 2° 30' reverse curve at the point of departure from the freeway, a long deceleration tangent parallel to the expressway, and then proper alignment to the ramp terminal.

For both entrance and exit ramps there should be a definite relationship between the design speed and the running speeds at each end of the ramp. Guide values for ramp design speeds in relation to the highway design speed take on less significance because of the geometrics proposed in the previous discussion, i.e., the concept of speed adjustment off the freeway. The terminals for the ramps forming the diamond intercept the cross street at approximately right angles, and since the intersection is signalized, terminal speeds can be relatively lower.

For loops, as shown off the reverse-flow roadway, desirable values of design speed generally do not apply, since they would require large areas and excessive travel times. Changes in radii are accomplished with multiple compound curves which effected a safe, practical reduction and acceleration in speeds by controlling the lengths of arc to the ratio of successive radii.

Operation of the reverse-flow interchange (Fig. 5) would necessarily be aided by signing both on the reverse-flow dual roadway and at the cross street. Ramps B and D would only be used in the morning peak and ramps G and E only in the afternoon peak. Phasing for a reverse-flow diamond interchange such as illustrated in Figure 5 is shown in Figure 7.

SUMMARY

To increase freeway capacity and reduce congestion during rush hours, several cities have developed a system of reversible lanes (6). Interstate 70 in St. Louis includes two reversible lanes for a six-mile section, from downtown to the northwest edge of the city. This section of the freeway is three lanes in each direction, with two center lanes reversible for morning and evening rush-hour traffic.

In Chicago, the Kennedy Expressway out of the CBD provides six miles of reversible roadway, from the junction with Edens Expressway to the north edge of the Loop. Eight lanes of freeway, four in each direction, flank the two reversible center lanes, which are open only to inbound traffic during the morning peak hours and only to outgoing evening traffic, and eliminate all access and egress except at the ends.

Use of the reversibles in St. Louis and Chicago provides extra lanes of traffic in one direction in the peak period, thus affording economical solutions since little additional right-of-way was necessary in excess of that needed for a conventional freeway. Whereas these facilities have provided practical solutions to the directional distribution phenomenon, the restrictions on access and egress compromise utilization of the reverse-flow roadway. The reverse-flow interchanges described in this article offer a means of increasing utilization of the center roadway as well as improving operation of the outside freeway roadways by reducing weaving volumes.

The reverse-flow freeway offers a very versatile planning tool. A freeway is not built specifically for some date 20 years in the future; it must go to work the first day and serve efficiently all through its expected life. Traffic projections and designs must be made on partial or incomplete systems if desirable service is to be obtained in the years before the whole system is completed.

Looking ahead to 1975, Seattle found that it could best satisfy its anticipated traffic volume requirements with a four-lane reversible roadway, integrated with the 16.5 mile eight-lane Seattle Freeway. Downtown, the freeway expands from eight lanes to twelve; the center four reversible for morning and evening peak-hour demands. The outer freeway lanes will be utilized while the reversible roadway is under construction.

Two general techniques of stage construction—the completion of a highway section to something less than the ultimate planned improvement but to a stage where it can be used for traffic operation—can be utilized in a reversible freeway system. In one method, the route can be progressively constructed by sections; first from the CBD to some intermediate point, etc. In the second method, a first-stage improvement can be made consisting of the construction of the outside roadways, the construction of the reverse-flow center roadway to bring it up to the ultimate design being made later.

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