CONFERENCE SESSION PAPERS: 1992 TRB ANNUAL MEETING

As an initial step to characterize the state-of-the-art in the interchange operations and help focus research, the Interchange Subcommittee hosted a Conference Session at the 1992 TRB Annual Meeting in Washington, D.C., titled "Interchange Operations on the Local Street Side." The four presenters covered a range of issues and concerns, briefly described as follows:

Dan Fambro (presenter) and Tom Urbanik of Texas Transportation Institute presented an overview paper on operational issues related to signalized interchanges. Though focused on diamond interchanges, issues of spillback, progression and levels of service were listed as pertinent to all interchange types.

Hobih Chen (presenter) of Viggen Corporation, plus Henry Lieu and Al Santiago of FHWA, provided an overview of various software packages that have been used to analyze interchange operations. Major packages discussed include HCS, SOAP, PASSER II and III, TRANSYT-7F, TEXAS, TRAF-NETSIM, and INTRAS.

Jim Lee of Lee Engineering presented a paper contrasting various techniques for evaluating diamond interchange operations from a planning perspective, starting with procedures first advocated 30 years ago. Not surprisingly, a variety of evaluation results occur in a sample application.

B. Kent Lall (presenter) of Portland State University, Jim Powell of Felsburg Holt & Ullevig and Michael Church of the California Department of Transportation (San Francisco) gave the results of a survey on interchanges and interchange operations from about one-half of the United States. Though a variety of responses came back, some common trends and themes emerged.

The discussion portion of the session involved the general audience in a discussion of future directions as well as perceived operational problems. The entire session along with the discussion portion was chaired by Jim Powell, chairman of the Interchange Subcommittee.

The papers presented represent the views and opinions of the authors, and have not been adapted as standards or procedures of the Interchange Subcommittee, or of the Committee on Highway Capacity and Quality of Service.

OVERVIEW OF SIGNALIZED INTERCHANGE OPERATIONS

Daniel B. Fambro and Thomas Urbanik II,
Texas A&M University

Introduction

The *Highway Capacity Manual* (HCM) (*1*) does not explicitly address analysis of signalized interchanges. In recognition of this shortcoming, the Transportation Research Board's Committee on Highway Capacity and Quality of Service established a subcommittee to consider the problem of analyzing the operation of signalized interchanges. This paper is intended to help identify the nature of the signalized interchange problem and begin formulating procedures for analysis.

There are a multitude of interchange configurations that could involve the use of signalized intersections. Generally speaking, the types of interchanges discussed in this paper would be those categorized by the American Association of State Highway and Transportation Officials in *A Policy on Geometric Design of Highway and Streets* (2) as service interchanges. These interchanges service the connection between freeways and arterial streets and include entrance and exit ramps connecting the freeway to an arterial street or parallel frontage road.

The interchanges discussed in this paper are represented by conventional two-level diamonds, split diamonds, three-level diamonds, and single-point urban (see Figure 1). Although these interchange forms are not all inclusive, they adequately illustrate the fundamental problems in analyzing signalized interchanges. It should be noted at this point that in addition to creating two closely spaced signalized intersections, these interchanges also create two intersections with higher percentages of turning traffic than typically occur at arterial street intersections.

The objective of this paper is to provide an overview of signalized interchange operations from both a technical and policy viewpoint. Specifically, this paper will discuss signalized interchange operational alternatives and issues, plus analysis and operational procedures. This paper, however, is not intended to provide answers to all signalized interchange questions. Rather, it is intended to identify a number of questions that need answers.

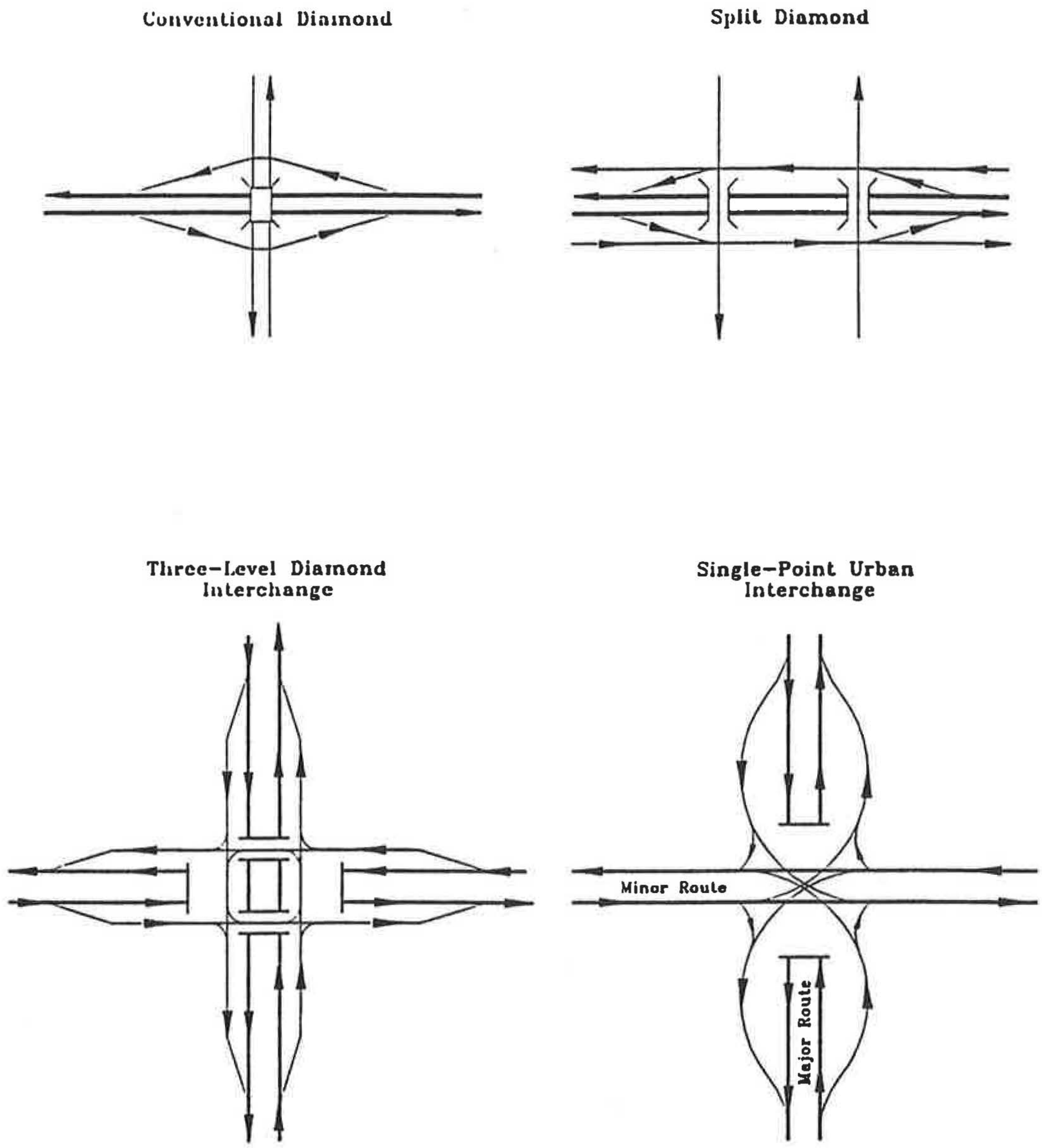

FIGURE 1 Common types of signalized interchanges.

Diamond Interchange Operations

Although there are many variations of signalized interchanges, the majority of them are full diamonds with or without frontage roads (*3*). Signal control at diamond interchanges has traditionally been provided by either a 3-phase pretimed signal sequence in which both off-ramp/frontage roads are released simultaneously (see Figure 2), or by two non-interconnected, full-actuated controllers with one controller at each intersection. The 4-phase, 2-overlap signal phase sequence (see Figure 2) developed by the Texas Transportation Institute in the late 1950's also has been used to increase interchange capacity and reduce operational problems and delay under certain circumstances (*4*). Current signal control at diamond interchanges are typically variations and/or combinations of these two basic phasing sequences using pretimed or actuated controllers.

Pretimed controllers are appropriate where a limited number of traffic patterns are found that repeat themselves on a daily basis. These controllers can be easily interconnected with adjacent signalized, controlled intersections. The basic phasing can be modified through changes in the split and offset if two pretimed controllers are used at the interchange (one at each cross street intersection) (*5*). Actuated controllers are

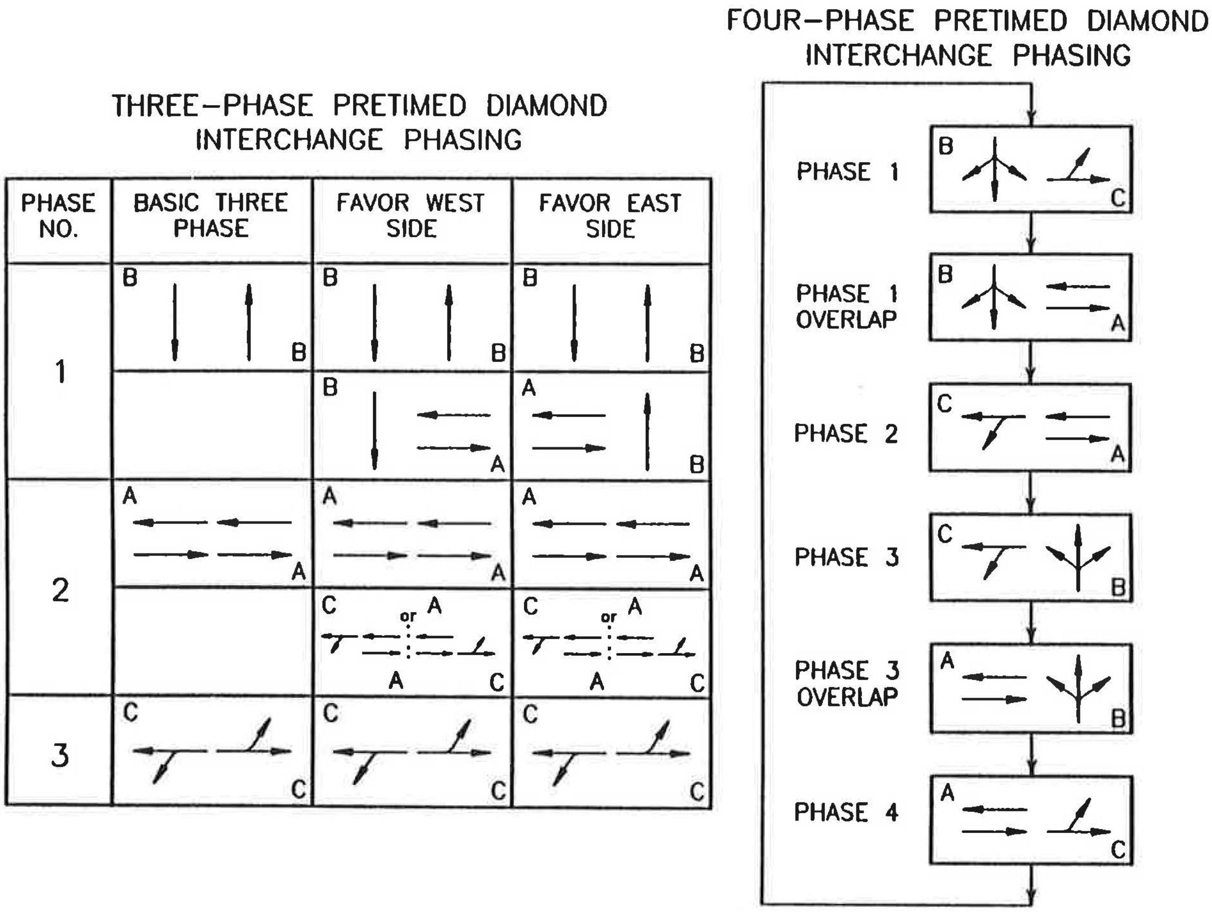

FIGURE 2 Common types of pretimed diamond interchange signal phasing.

appropriate where a large number of traffic patterns are required and these patters vary greatly on a daily basis. Because they are not easily interconnected with adjacent traffic signals, the primary usage of actuated controllers is at isolated diamond interchanges. When operating the 4-phase, 2-overlap signal phase sequence in an actuated mode, multipoint detection and detector switching logic on the ramp/frontage road is necessary to promote full utilization of the overlap phases and minimize the lost time associated with these phases (*6*).

The California Department of Transportation has developed a diamond interchange software program for the Model 170 controller unit which can provide either 3- or 4-phase actuated control strategies (*7*). Two standard NEMA full-actuated controller units also can be used to provide both 3- and 4-phase operation. The Texas Diamond Controller uses one NEMA full-actuated controller unit to provide both 3- and 4-phase operation at the same interchange (*8*). The change from one phasing operation to the other is made by a time clock or by external traffic responsive logic.

Split, offset, and cycle length determinations are additional considerations at a diamond interchange. The two intersections at the interchange can either be timed separately to minimize intersection delay (i.e., 3-phase control) or timed together to maximize interchange progression and thus minimize queue storage between the two intersections (i.e., 4-phase control). Neither method is universally better than the other (*9*) and each will probably result in different optimal cycle lengths (*6*). Left-turn lane requirements and type of protection (i.e., protected, protected/permitted, permitted) also must be considered. Recognizing this myriad of alternatives, the question arises: How do transportation engineers determine which strategy is most appropriate at any given signalized interchange?

Operational Issues

There are a number of operational issues that must be addressed in the analysis of a signalized interchange. First, traffic patterns at signalized interchanges are different from those at signalized intersections because of the higher percentage of turning movements at interchanges. Second, an analysis procedure for signalized interchanges must be flexible for a planning analysis and detailed for an operational analysis. Third, queue spillback considerations are extremely important at signalized interchanges because of the short spacing between intersections and the limited capacity for queue storage on some entrance and exit ramps. Fourth, the close proximity of adjacent intersections and/or access points may create weaving problems in the interchange area. In addition to operational issues with signalized interchanges, institutional issues between the freeway operator (usually the state) and the arterial operator (usually the city) may create problems in coordinating interchange operations. Each of these issues is discussed in the following sections.

Traffic Patterns

Because through traffic on one of the major roadways is grade separated, the primary movements at the two intersections of the interchange are left and right turns. This pattern is different from the pattern at signalized intersections where through movements tend to dominate. In fact, turning movement volumes and/or percentages at signalized interchanges often are two to four times greater than at signalized intersections.

In addition to higher turning movement volumes, the turning patterns change over time. For example, heavy left-turns during the morning peak at one of the intersections often result in heavy right-turns during the afternoon peak at the other intersection. This change means that in the morning peak multiple left-turn lanes may be needed at one of the intersections, but at other times of the day, additional through-right lanes may be needed. Unless the lane assignments can be changed by time of day, the turning lanes necessary to handle the peak traffic are under utilized during most of the day.

Planning versus Operations

As a result of the many signalized interchange forms, phasing alternatives, and changing traffic patterns, operational analysis procedures must be detailed and complex. Planning procedures, however, must be simple and allow flexibility because of the sensitivity to traffic patterns and the large number of unknowns at the planning stage.

Queue Spillback

Because of the limited distance between the two signalized intersections at an interchange, queue spillback potential between the two signals is especially critical. If the conditions (signal timing and intersection spacing) are such that the queue backs into the upstream signal, gridlock will occur. When this situation occurs, the ramp/frontage road signals may be green, but vehicles can not use the intersection because the interchange is blocked by stopped vehicles.

Queue spillback, however, is not confined to a between-signal problem. Queues can back up on an exit ramp and block the freeway's main lane if demand exceeds capacity at the exit ramp terminal. Queues also can back up on an entrance ramp and block the intersection if the demand exceeds the capacity at the entrance ramp terminal. In both cases, the potential for queue spillback must be carefully evaluated and take into account the potential consequences on adjacent facilities.

Weaving Areas

Traffic entering or exiting the freeway can create weaving problems on the arterial street or frontage road. If lengths between the interchange and adjacent signalized intersection on the arterial are not adequate, vehicles turning right from the ramp/frontage intersection and desiring to turn left at the next intersection on the arterial must weave across several lanes of arterial traffic. If intersection spacings are short or traffic volumes are heavy, weaving demands may contribute to congestion problems on the arterial.

Likewise, at interchanges with one-way frontage roads parallel to the freeway, traffic exiting the freeway to turn right at the frontage road arterial street intersection must weave across two or three lanes of frontage road traffic. If these distances are short, traffic volumes are heavy, or driveways are located within the weaving segment, operational problems may occur on the frontage road.

Institutional Issues

Different agencies are responsible for operating the signalized interchange and the adjacent signalized intersections (i.e., ramp/frontage road signals are typically controlled by the state and adjacent arterial signals are typically controlled by the local governments). This differing responsibility can cause problems due to different equipment, operational strategies, and traffic control objectives. For example, the state may be concerned with favoring vehicles exiting the freeway and not having them stop within the interchange. If so, they would adopt an operational strategy to accomplish this objective. The local government, on the other hand, may be concerned with progression along the arterial street and would desire to implement an operational strategy favoring through vehicles on the arterial and not having them stop at the interchange.

Analysis Issues and Procedures

The differences between the single-point urban and the other interchange forms highlight some of the difficulty in performing analyses of operational and geometric alternatives. The analysis of the single point urban using HCM procedures is relatively straightforward except for the selections of appropriate values for factors such as clearance interval and saturation flow rates. The selection of these factors is primarily a problem of limited field data reported in the literature. When it is necessary to compare a single-point urban to a conventional diamond, however, a variety of problems related to an equitable comparison using Chapter 9 of the HCM develop. The conventional diamond, which has two signals, requires separate analysis of each signal. However, the operational performance of the two signals cannot be considered in isolation. It is, therefore, necessary to consider the appropriateness of the HCM procedures to undertake a comparative analysis.

The HCM has two procedures that could be applied to signalized interchanges. The most basic analysis would be performed utilizing the signalized intersection procedures of Chapter 9 of the HCM. The only procedures for analyzing the system interaction of signals is using either the progression adjustment factors or the arterial analysis procedures of Chapter 11 of the HCM. The Chapter 11 procedures, however, are explicitly restricted to conditions with typical arterial street turning volumes. The limitations to signalized interchange analysis of the Chapter 9 procedures, including the progression adjustment factors, will be discussed later in this paper.

Qualitative Measures

Capacity and level of service are the basic components of an intersection operational analysis. The basic procedures are widely recognized. Capacity is reflected in the volume to capacity ratio (v/c ratio) and level of service is reflected in stopped delay. The primary measure of system effectiveness is the platoon ratio or the proportion of the volume arriving on green which reflects the quality of progression and the characteristics of the platoon.

Several important issues should be considered in the signalized interchange analysis. Two issues that need consideration and that are not explicitly a part of the current procedures are queue spillback and pedestrian effects. As mentioned previously, closely spaced intersections are subject to effects of downstream intersection spillback. Vehicular minimum timing requirements may not be sufficient to accommodate pedestrian minimum timing requirements. An additional issue is lost time, which include start-up losses, clearance time requirements, and phasing considerations. Each of these issues will also be discussed briefly.

Capacity Analysis Tools

The most fundamental consideration in interchange analysis is the capacity of the various lane groups and the geometry of the intersections. For simplicity, it is assumed that saturation flows are known or can be determined. The effective green time is variable; therefore, it is necessary to determine the appropriate value. Start-up and clearance values can be determined, although there is some question as to the appropriate values for single-point urban interchanges. A more difficult question involves the appropriate phase length and offset necessary for satisfactory system performance. This issue is especially important at signalized interchanges where turning movements are high.

Several computer models are available to analyze arterial streets and intersections. Simulation models offer the capability to evaluate alternative phasing patterns to minimize delay. The *Highway Capacity Manual* software (*10*) can be used for relatively quick analyses at specific locations or along arterial streets. The *Highway Capacity Manual* software uses a macroscopic, deterministic, off-line approach to evaluate traffic flow. The HCM procedures are useful in analyzing specific highway features. As traffic flow approaches capacity at a number of locations on a highway system, however, it is necessary to evaluate the roadways as a system. PASSER II-90 (*11*) is capable of analyzing isolated intersections as well as a series of signalized intersections. PASSER III-88 (*12*) is designed for diamond interchange analyses (i.e., two closely spaced intersections). NETSIM and TRANSYT-7F (*13*) also are capable of evaluating the operations along a series of intersections. Each model has unique qualities. Other computer models for intersection/interchange analysis also exist but are less widely used.

The previous summary of models was intended to indicate the range of alternatives that exist to the current HCM procedures. The development of computer models resulted in part from the recognition that sufficient green time on an approach does not necessarily translate into good operations. Stated another way, it is possible to optimize capacity at an individual intersection yet have an undesirable level of service or even a non-functional operation due to the inability of traffic to move due to spillback of the downstream queues. Capacity estimates must reflect realistic conditions, however no such measure of effectiveness exists in the HCM.

Level of Service

Intersection level of service is currently based on stopped delay. Delay is estimated from an equation having two terms: uniform delay and incremental delay. The uniform delay term assumes uniform arrivals while the incremental delay term accounts for random arrivals and cycle failures. A progression adjustment factor is used to account for platoons caused by upstream signal timing. Fambro, et al. discuss the progression factor considerations in the *Effects of the Quality of Traffic Signal Progression on Delay* (*14*). It is obvious that progression considerations affect delay at closely spaced intersections and should be taken into consideration when estimating delay.

For example, the timing plan for a typical conventional diamond interchange operating at high flow rates is likely to provide progression not only for the arterial movements but also for the ramp traffic turning through the interchange. Arrival patterns for these interior movements are platooned and delays caused by vehicles stopping within the interchange are likely to be minimal under a well designed phasing plan and unacceptable under a poorly designed phasing plan. The arrivals at the downstream signal are not likely to be random regardless of the origin of the traffic.

A further complication is the use of delay per vehicle as the measure of effectiveness when an analysis is performed for more than one intersection. Problems in comparing two alternatives exist even if two interchanges have equal numbers of vehicles, equal roadway lengths, and equal total delays. If the two interchanges have similar characteristics except that one has one signal and the other has two signals, the interchange with two signals will likely have less delay per vehicle. This discrepancy occurs because vehicles passing through more than one signal will be counted as two separate vehicles and the delay per vehicle is reduced because of the greater number of vehicles. Accounting for the total number of individual vehicles is only one issue when considering comparisons between alternatives with different numbers of signals. It should be noted that counting vehicles only once in a system of several intersections, however, does change the significance of the delay per vehicle criterion.

Queue Spillback

A fundamental assumption of most analyses is the nonexistence of spillback from downstream intersections. If the queue from a downstream intersection blocks a movement from an upstream intersection, effectively no capacity exists. This effect is pronounced especially in closely spaced (less than 600 feet between intersections) conventional diamond interchanges. Special timing plans are necessary to operate closely spaced diamond interchanges that are near capacity. These special phasing plans consider system effects of the two closely spaced intersections. The timing plans differ from those that would be implemented considering each intersection in isolation. The PASSER III computer model was developed explicitly to address this problem for diamond interchanges by constructing queue profiles for each of the internal movements.

Pedestrian Effects

Pedestrian flows may be minor, resulting in analysts ignoring their effects on operations. If pedestrian minimum timings exceed vehicle minimum timings, however, some consideration of pedestrian effects is warranted. Clearly, the level of service at an interchange is a function of pedestrian phasing and flows. The process of analysis is, however, complicated by the lack of guidance on how to consider such effects. This paper does not provide any guidance on how to conduct an analysis explicitly dealing with pedestrians, although this problem is clearly an area that merits further attention.

Operational Analysis Procedures

The most common method of analysis is based on the 1985 HCM procedures. This type of analysis is focused primarily on level of service based on stopped delay per vehicle. The procedure is limited obviously by the previously discussed issues. It is inappropriate to analyze individual intersections in isolation. The development of accurate progression adjustment factors could deal with some of the interaction issues as related to platoon dispersion. It would still be necessary, however, to address queue spillback potential.

An alternative to the HCM procedures is the use of computer models. A number of computer models were described earlier including PASSER III, which will be discussed only to further illustrate some of the issues and considerations. PASSER III is based largely on the delay equation in the HCM, however, it does use a delay offset analysis to address the effect of progression on the interior movements of a diamond interchange. Although PASSER III and other computer models are subject to some of the same problems as the HCM procedures, they do offer some improvements over an isolated intersection analysis. The advantages include measures of effectiveness in addition to stopped delay per vehicle, and the use of optimization to obtain the best feasible operations.

PASSER III, for example, is designed to find solutions that provide acceptable operations under the specific conditions of a conventional diamond. It does so partly through the incorporation of additional measures of effectiveness in the level of service analysis (i.e., three measures of effectiveness—average stopped delay, volume-to-capacity ratio, and storage ratio—are used to assess the interchange performance). Table 1 illustrates the measures of effectiveness and level of service threshold criteria used by PASSER III.

PASSER III also calculates level of service based on the total number of individual vehicles passing through the interchange.

Although PASSER III can address some of the identified problems, it is a special-purpose tool geared only to conventional diamond interchanges. It cannot, for example, evaluate a three-level diamond. TRANSYT-7F is a more flexible tool but does not explicitly address all spillback issues of the conventional diamond. It does, however, identify in the output the approaches with potential queue spillback problems. TRANSYT-7F also does not individually identify vehicles, so delay per vehicle is partly a function of the number of intersections.

Recommendations

The most critical issue in interchange analysis is an awareness by the user community of the limitations in the current *Highway Capacity Manual* procedures when applied to system problems such as signalized interchanges. Computer models offer the potential to reduce the number of problems associated with more complex analyses because they are generally more powerful tools than manual techniques. Additional measures of effectiveness such as volume to capacity and storage ratios, however, are needed to make the best use of these computer models. Furthermore, one should not assume that more sophistication eliminates all problems. Delay per vehicle is but one example where erroneous conclusions can be drawn if inappropriate comparisons are made between alternative interchange configurations.

Some recommendations can be made concerning the need for additional measures of effectiveness for signalized interchange analysis, as well as limitations in the measures of effectiveness currently being used. An analysis of closely spaced intersections (less than 600 foot spacing) should be based on three measures of effectiveness applied in the following order: storage ratio, volume-to-capacity ratio, and vehicular delay. If a level of service F condition (which needs to be defined for storage ratio) is calculated for either storage ratio or volume-to-capacity ratio for any movement and/or phase, no further calculations are made and the overall interchange level of service is reported as level of service F. If storage ratio and volume-to-capacity ratio for all movements and/or phases are acceptable, then vehicular delay can be used to determine overall interchange level of service.

Average stopped delay per vehicle should be limited in its application to a single intersection unless the number of individual vehicles in the interchange is known. That is, comparison between interchange alternatives with different numbers of intersections cannot be made fairly unless the number of individual vehicles in the interchange is known. Therefore, system or total interchange delay is a more appropriate measure of effectiveness when comparing interchange alternatives.

References

1. *Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 1985.

2. *A Policy on Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 1990.

3. "Signal Control Strategies for Signalized Diamond Interchanges." Report No. FHWA/IP-80-5. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation, December 1980.

4. Woods, D.L., "Limitations of Phase Overlap Signalization for Two-Level Diamond Interchanges." *Traffic Engineering.* Vol. 39, No. 12 September 1969, pp.38-41.

5. Guyton, J.W., Yarbrough, J.W., and Arey, T.M. "Control Strategies for Signalized Diamond Interchanges." Report No. FHWA/TS-78-206. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation, April 1978.

TABLE 1 PASSER III LEVEL OF SERVICE CRITERIA FOR OPERATIONAL MEASURES OF EFFECTIVENESS AT SIGNALIZED DIAMOND INTERCHANGES

Measures of Effectiveness	Level-of-Service					
	A	B	C	D	E	F
Volume-to-Capacity Ratio[a]	<.60	<.70	<.80	<.85	<1.0	>1.0
Average Vehicular Delay[b]	<6.5	<19.5	<32.5	<52.0	<78.0	>78.0
Interior Storage Ratio[c]	<.05	<.10	<.30	<.50	<.80	>.80

[a] "Guide for Designing and Operating Signalized Intersections in Texas."
[b] Total delay (1.3 times stopped delay).
[c] Average queue length per cycle (veh) divided by the available queue storage (veh).

6. Messer C.J. and Chang, M.S. "Traffic Operations of Basic Traffic Actuated Control Systems at Diamond Interchanges." Transportation Research Record 1114. Washington, D.C.: Transportation Research Board, National Academy of Sciences, 1988, pp. 54-62.

7. "Diamond Interchange Program User's Manual." Report No. FHWA/IP-80-4. Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation, December 1980.

8. Haenel, H.E., Kosik, A.H., and Marsden, B.G. "Innovative Uses of Traffic Responsive Control in Texas." Proceedings of the 1983 Engineering Foundation Conference on "Traffic Monitoring and Control Systems." Henniker, New Hampshire, July 1983, pp 95–112.

9. Messer, C.J., Fambro, D.B., and Richards, S.H. "Optimization of Pretimed Signalized Diamond Interchanges." Transportation Research Record 644. Washington, D.C.: Transportation Research Board, National Academy of Sciences, 1977, pp 78-84.

10. *Traffic Software Integrated System User's Manual 2.0.* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1989.

11. Chang, E.C.P. and C.J. Messer. "Arterial Signal Timing Optimization Using PASSER II-90 - Program User's Manual." TTI Report No. 467-3F, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1990.

12. Fambro, D.B., N.A. Chaudhary, C.J. Messer, and R.U. Garza. "A Report on the User's Manual for the Microcomputer Version of PASSER III-88." TTI Report No. 478-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1988.

13. *TRANSYT-7F User's Manual.* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1988.

14. Fambro, D.B., E.C.P. Chang, and C.J. Messer. "Effects of the Quality of Traffic Signal Progression on Delay." NCHRP Report No. 339, National Research Council, Transportation Research Board, Washington, D.C., September 1991.

INTERCHANGE OPERATIONS: SOFTWARE EVALUATION TECHNIQUES IN USE

Hobih Chen, Viggen Corporation; Henry Lieu and Alberto Santiago, FHWA

Introduction

Serving as the interface point between two intersecting facilities (freeway/freeway, freeway/arterial, or arterial/arterial), an interchange provides an environment that allows vehicles to perform weaving and merging maneuvers safely and smoothly when they move from one facility to another. Since the weaving/merging activities cause disturbance to the traffic flow, a poorly designed and/or operated interchange can easily become a traffic bottleneck. In spite of its importance, interchange planning and operational analysis have received much less attention than other components of the freeway system, judging from the methodologies and analysis models available. The formation of the Interchange Subcommittee under the Transportation Research Board Committee on Highway Capacity and Quality of Service is a first step in the right direction to address this issue and recognize the need for developing methodologies and modelling tools for analyzing the unique operating and performance characteristics of interchanges.

The objective of this paper is to review the existing software evaluation techniques for interchange operations analysis, to identify unique issues related to interchanges and their immediate operating