FINAL REPORT

GUIDELINES FOR PRELIMINARY SELECTION OF THE OPTIMUM INTERCHANGE TYPE FOR A SPECIFIC LOCATION

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(The opinions, findings, and conclusions expressed in this
report are those of the authors and not necessarily those
of the sponsoring agencies)

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ABSTRACT

In Virginia, when new construction or major reconstruction is planned, the current practice is for a location and design engineer to select the interchange type for a given location. The engineer relies upon projected traffic data, right-of-way needs, environmental concerns, safety, and project costs to determine which interchange configuration will most efficiently serve the needs of a certain area.

The purpose of this study was to develop guidelines to aid designers in the preliminary selection of the optimum interchange type at a location. This study will provide engineers a starting point to begin their analyses. It is hoped that the development of these guidelines will result in reduced costs, improved levels of service, and increased uniformity.

A number of sources were used to develop the guidelines. A literature and a nationwide survey of state engineers helped determine current methods for interchange selection. These surveys also assisted in determining the relative advantages and disadvantages of the various interchange types. Also, 10 interchanges throughout Virginia were studied in order to find their operational and safety characteristics. Extensive computer simulations of the interchange types were performed in order to determine traffic characteristics that affected operations at the interchanges. Based on all of these sources, some general guidelines for preliminary interchange type selection were created.

EXECUTIVE SUMMARY

Introduction

The purpose of this study was to develop guidelines to aid designers in the selection of the optimum interchange type at a location. This study will give the engineers a starting point to begin their analyses. These guidelines will, it is hoped, reduce costs and improve levels of service. These guidelines could also result in improved interchange uniformity across the state, since these proposed guidelines will help standardize the interchange selection process. The guidelines could also help to reduce occurrences of under- or over-designed interchanges.

Methods

The methodology used in this study consisted of the following steps: 1) literature review; 2) field data collection; 3) data reduction; 4) analysis; and 5) guideline formulation.

The literature review was performed in order to synthesize the findings of earlier studies on interchange selection. Information on interchange type selection processes was reviewed, and the relative advantages and disadvantages of the various interchange types were explored.

The data collection phase of the methodology encompassed a number of sub-tasks. First, a nationwide survey was sent out to state engineers to determine current practices for interchange type selection and national opinions on the performance of the various interchange types. Operational and accident data were also collected at 10 interchanges in Virginia in order to get a sample of actual operating conditions in the state.

The data reduction step of the methodology involved converting the raw data obtained during the data collection task into a more usable form. Operational data were taken from traffic counters and video camera and evaluated, using the procedures in the *Highway Capacity Manual*. Models of existing conditions were developed and used to simulate the operations of each interchange studied.

During the analysis phase, the accident and operational data were examined to determine their significance. A series of CORSIM simulations were carried out to test the impact of different magnitudes of traffic and distributions of traffic to better compare the operational performance of the various interchange types. The accidents were analyzed to determine any safety trends at the interchanges. Finally, guidelines were developed by synthesizing the results of the survey, operational analysis, accident analysis, and literature review.

Findings

Survey Results

1. Diamonds are the most popular interchange nationwide for both urban and rural situations, followed by the partial cloverleaf.

2. Engineers ranked the SPUI as requiring the least right of way, followed next by the diamond, partial cloverleaf, trumpet, full cloverleaf, and directional.

3. Directional interchanges were seen as having the highest capacity, followed by the trumpet, SPUI, full cloverleaf, partial cloverleaf, and diamond.

4. Diamonds were ranked as having the lowest construction cost. Partial cloverleafs were next, followed by the trumpet, SPUI, full cloverleaf, and directional interchange.

5. Directional interchanges were ranked as having the greatest capability to handle left-turning movements, followed by trumpets, full cloverleafs, SPUIs, and partial cloverleafs. Diamonds were seen as having by far the greatest difficulty accommodating high, left-turn volumes
.

6. Most states responded that they did not have any kind of formal guidelines for interchange type selection. These states generally relied upon capacity studies to select interchange types. For some more rural states, interchange uniformity was a concern that greatly affected interchange type selection.

7. The states that indicated that they had existing interchange selection guidelines tended to possess very general ones. These guidelines generally outlined advantages and disadvantages of the various interchange types and listed other factors that engineers may want to consider when making selection decisions.

Accident Analysis

1. The statistical tests performed on the accident data reveal several trends in accidents at the interchanges. While the results of these tests are not conclusive due to the small sample size, they do indicate some differences in safety at the interchanges.

2. A smaller percentage of angle accidents occur at full cloverleafs (2%) than at partial cloverleafs (24%) and SPUIs (34%), probably due to the absence of turning movements at the full cloverleafs.

3. The SPUI had a larger percentage of sideswipe accidents (12%) than the diamond (7%) or partial cloverleaf (0%).

4. The full cloverleaf had a larger percentage of fixed object accidents (37%) than any other interchange type. This is primarily the result of run-off type of road accidents on loop ramps and in weaving areas.

5. The predominant collision locations for the various interchange types were:

Diamond: center of intersection (54.8%)
SPUI: cross road (50.8%)
Partial cloverleaf: crossroad (57.1%)
Full cloverleaf: weaving area (38.9%).

There seems to be no significant difference between the severity of accidents at the various interchange types. The tests showed that the partial cloverleaf had a lower accident rate than the SPUI for PDO accidents, but this result may have been influenced by the small sample size for these tests.

Conclusions

Based on the results of the study, several conclusions can be drawn regarding the selection of the various interchange types:

- While the literature review did not reveal any interchange type selection guidelines, it was useful for determining characteristics of each interchange type. The literature review aided in the identification of the advantages and disadvantages of the different interchange types.

- The survey of state engineers provided insight into how other states choose what type of interchange to build. The opinions expressed in the survey as to the relative merits of the various interchange types also helped confirm the information obtained from the literature review.

- While the small number of sites analyzed in the accident analysis limits the extent to which the results can be extended to all other sites, several findings were found to be relevant. First, full cloverleafs were found to have fewer angle accidents than SPUIs or partial cloverleafs and more fixed object accidents than all other types of interchanges. It was also determined that the SPUI had more sideswipe accidents than partial cloverleafs or diamond interchanges.

Several conclusions can be made based on the operational analysis of the volume scenarios and actual data:

- The diamond interchange operates at an acceptable LOS when the entering volume is at 1500 vph or less. In these cases, an unsignalized system can be used to minimize delay.

- The SPUI has a consistently lower delay than the diamond for all volume scenarios tested.

- The SPUI can operate at LOS D or better at entering volume of 5500 vph or less. The diamond can operate at LOS D or better until an entering volume of 4500 vph.

- Signalized delay is increased at the SPUI when the left turns off the ramps are unbalanced. There is also some indication that unbalanced mainline lefts also result in increased delays.

- Weaving areas are the critical interchange component for partial and full cloverleafs, in terms of LOS.

- Operations at weaving areas degrade to LOS E/F as the weaving volume approaches 1000 vph. This indicates that full cloverleafs and partial cloverleafs are not suitable for roads with large weaving volumes.

- Partial cloverleafs have a superior signalized LOS to the SPUI and diamond at all entering volumes, since large left-turning movements are handled by loop ramps.

Recommendations: Guidelines for Interchange Type Selection

Based on the information obtained in this study, it is possible to identify several factors that affect what type of interchange should be used in a given situation.

Right of Way Availability

The interchange type selection guidelines based on right-of-way issues were developed primarily from the literature review. The survey results helped to further validate the information found in the literature review, and also influenced the formulation of the guidelines. Based on these two sources, the following guidelines were developed:

1. When the right of way available is limited, SPUIs or diamonds are most appropriate since they can be built in a limited right of way.

2. In situations where the right of way is restricted in one or more quadrants, the partial cloverleaf should be considered.

3. Full cloverleafs require an extensive amount of right of way, due to the presence of the loop ramps. The amount of land required for the full cloverleaf increases significantly as the design speed for the loop ramp increases. Thus, full cloverleafs may not be suitable for application in urban areas or other situations where the amount of right of way available is limited.

4. Directional interchanges require the largest amount of right of way and are usually only justified for freeway to freeway connections.

Construction Cost

The construction cost guidelines were developed primarily from the literature review. The survey results helped to further validate the information found in the literature review, and also influenced the formulation of the guidelines. Based on these two sources, the following guidelines were developed:

1. Cost figures for interchanges are very site specific. Topography, land use, and environmental concerns can make identical interchange designs have very different final costs depending on the site.

2. Generally speaking, the diamond has the lowest cost of the interchange types, due to its small structure and limited amount of right of way required.

3. The cost of a SPUI is generally 10% to 20% higher than for a diamond, due to the large structure that must be constructed. This can result in a very large bridge span (mainline over cross road) or a butterfly-shaped structure (mainline under crossroad), which can cost considerably more than a conventional diamond interchange. While construction costs for the SPUI structure are somewhat greater than for diamond interchanges, this higher cost is mitigated somewhat by the reduced right of way costs for the SPUI, especially in urban areas.

4. Directional interchanges have the highest construction cost of all interchange types, due to the large structures involved and the extensive right of way they require, and they are generally justified only when high speeds and large capacities are needed.

Traffic and Operational Issues

Guidelines for interchange type selection based on operational issues were developed based on the literature review and the operational analysis. The guidelines based on the literature review are:

1. When arterial coordination is a major priority, the SPUI should be considered. The SPUI is easier to coordinate with other signals on an arterial route than a diamond, since it requires that only one signal be coordinated, rather than two.

2. Full cloverleafs without collector distributor roads should be used only when weaving volumes are small and right of way is not a concern, such as in rural areas.

The guidelines developed based on the operational analysis are:

1. The diamond interchange should be used when traffic volumes are very low (under 1500 vph peak hour entering volume). In these cases, signals usually are not warranted, and delays are very low with an unsignalized system.

2. In cases where volumes are between 1500 vph and 5500 vph, the SPUI should be used instead of the diamond. The diamond has consistently higher delays due to the two-intersection configuration of the interchange.

3. The delay at a SPUI increases significantly when the ramp left turns are unbalanced. There are also some indications that unbalanced mainline left turns may increase delay at the SPUI. Thus, proposed SPUI designs should be carefully analyzed when either of these conditions is present.

4. The partial cloverleaf provides greater capacity than the SPUI or the diamond when the peak entering volume is between 1500 and 2500 vph. The signalized delay at the partial cloverleaf is less than the SPUI and the diamond for all cases tested. All components of the partial cloverleaf performed at a higher LOS than the SPUI or diamond at 1500 and 2500 entering vph. Weaving operations are the critical component of high-volume, partial cloverleaf interchanges.

5. Weaving operations are critical at full cloverleafs and when provided at partial cloverleafs. The level of service of the weaving areas begins to decline as the number of weaving vehicles approaches 1000 vph. This indicates that full cloverleafs with collector-distributor roads, semi-directional interchanges, or directional interchanges should be used when weaving volumes approach 1000 vph. It also shows that partial cloverleafs should be designed without weaving areas when a condition like this occurs.

6. In suburban areas, volumes and traffic patterns can change dramatically in short periods of time. Delay at SPUIs and diamonds can change dramatically, depending on traffic distributions; therefore, signal timings must be optimized in these situations to minimize delays.

Other Issues

The remaining guidelines were developed principally from the literature review. The accident analysis did play some role in the development of guideline 1.

1. Loop ramps generally have a worse safety record than other ramp types and should generally be avoided where possible. Weaving areas have a poor safety record, especially when collector-distributor roads are not provided. Particular attention should be given to the design of weaving areas of cloverleaf interchanges, due to these safety concerns.

2. When two roads intersect at a large skew angle, use of the SPUI is not recommended. The skew angle will result in high construction costs for the SPUI and also result in reduced sight distances at the interchange.

3. Pedestrians are not easily accommodated by the SPUI without greatly increasing delay at the interchange. Diamond interchanges can accommodate high pedestrian volumes much better.

4. Full cloverleafs are the minimum facility that can be provided for two access-controlled facilities. However, the use of full cloverleafs for system interchanges is not recommended unless the weaving volumes are very low. Usually, directional interchanges provide better service for freeway-to-freeway connections.

5. Trumpets should be used when three intersecting legs are present.

6. When frontage roads are present, the diamond is preferred over the SPUI. A fourth phase would be required to handle the frontage roads at the SPUI, and this would significantly increase overall delay at the interchange.

7. Interchange uniformity should also be considered when making interchange type selections. Interchange uniformity along a route can aid drivers in identifying where they need to enter or exit and can help reduce driver confusion.

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INTRODUCTION

Increasing traffic congestion across the United States has resulted in many at-grade-intersections (AGIs) along major routes. These AGIs have become inadequate for the demand volume of traffic. Grade-separated interchanges offer improved traffic flow over AGIs, since some conflicting traffic flows are eliminated. While interchanges create better transitions between intersecting traffic streams, these interchanges cost more and require more right of way than AGIs. Thus, when a grade-separated interchange is called for, care must be taken that the type of interchange selected not only handles prevailing traffic well, but is also appropriate for the physical and traffic conditions at the individual location.

Since the first interchange was developed in 1928, grade separations have been used to improve traffic flow. With the development of the interstate highway system, the use of interchanges became more prevalent as engineers sought to improve flow on the nation's new highways. Engineers originally selected an interchange type based solely on the site's physical limitations and forecasted traffic volumes. During the 1970s and 1980s, an improved knowledge of traffic flow theory and better human factors research caused a rethinking of the interchange selection process. As a result, there was a realization that factors such as highway classification, traffic composition, design speed, access control, construction costs, right-of-way issues, and safety all needed to be considered in the selection process. Despite advances in interchange selection methods, there are still a number of interchanges nationwide that are either under- or over-designed.

In Virginia, when new construction or major reconstruction is planned, the current practice is for a location and design engineer to select the interchange type for a given location. The engineer relies upon projected traffic data, right-of-way needs and availability, environmental concerns, safety, and project costs to help determine which interchange configuration will most efficiently serve the requirements of the area. Engineering judgment is used to weigh these factors to determine which interchange type is warranted. In Virginia, no guidelines currently exist to help engineers select which type of interchange would be most appropriate in a given situation

PURPOSE AND SCOPE

The purpose of this study was to develop guidelines to aid designers in the selection of the optimum interchange type at a location. This study will give the engineers a starting point to begin their analyses. These guidelines will, it is hoped, reduce costs and improve levels of service. These guidelines could also result in improved interchange uniformity across the state, since these proposed guidelines will help standardize the interchange selection process. The guidelines could also help to reduce occurrences of under- or over-designed interchanges.

The scope of this study was limited to interchanges in Virginia. The types of interchanges investigated included diamonds, full cloverleafs, partial cloverleafs, and single-point urban interchanges (SPUIs). Directional and trumpet interchanges were dealt with in a less comprehensive manner, since their areas of application were better defined. Accident and operational characteristics of the interchange types were analyzed, and other factors that distinguished the interchange types from each other were also identified.

The specific objectives of this study were as follows:

1. To examine the literature and learn the results of past studies on interchange characteristics and interchange selection methods.

2. To survey state engineers to determine which states have established guidelines to help select interchange types, and to obtain engineers' opinions regarding the advantages and disadvantages of the various interchange types.

3. To examine accident characteristics of the various interchange types.

4. To identify significant differences between the operational characteristics of the different interchange types.

5. To identify geometric and traffic conditions influencing the safety and operations of the various interchange types.

6. To develop guidelines for selecting the optimum interchange type at a specific location.

METHODOLOGY

The methodology used in this study consisted of the following steps:

- literature review
- field data collection
- data reduction
- analysis
- guideline formulation.

The literature review was performed in order to synthesize the findings of earlier studies on interchange selection. Information on interchange type selection processes was reviewed, and the relative advantages and disadvantages of the various interchange types were explored.

The data collection phase of the methodology encompassed a number of sub-tasks. First, a nationwide survey was sent out to state engineers to determine current practices for interchange type selection and national opinions on the performance of the various interchange types. Operational and accident data were also collected at 10 interchanges in Virginia in order to get a sample of actual operating conditions in the state.

The data reduction step of the methodology involved converting the raw data obtained during the data collection task into a more usable form. Operational data were taken from traffic counters and video camera and evaluated, using the procedures in the *Highway Capacity Manual*. Models of existing conditions were developed and used to simulate the operations of each interchange studied.

During the analysis phase, the accident and operational data were examined to determine their significance. A series of CORSIM simulations were carried out to test the impact of different magnitudes of traffic and distributions of traffic to better compare the operational performance of the various interchange types. The accidents were analyzed to determine any safety trends at the interchanges. Finally, guidelines were developed by synthesizing the results of the survey, operational analysis, accident analysis, and literature review. A more detailed description of this methodology is included in this section of the report.

Literature Review

The first step in this study was to conduct a literature review on interchange type selection. A computerized search was performed using the Transportation Research Information Services (TRIS) database. A manual literature search was performed at the Virginia Transportation Research Council and University of Virginia libraries. Information on interchange characteristics, selection methods, and analysis methods were examined.

Interchange Definition

An interchange is defined by AASHTO as a system of interconnecting roadways in conjunction with one or more grade separations that provides for the movement of traffic between two or more roadways or highways on different levels.[1]

System and Service Interchanges

Interchanges can generally be separated into two categories: system interchanges and service interchanges. System interchanges connect freeways to other freeways and generally handle large traffic volumes operating at high speeds. System interchanges usually operate best when there are right-hand exits and one or more direct connectors. Weaving sections should be minimized on system interchanges due to the high volume present.[2] Service interchanges connect freeways and arterials to lesser facilities and generally serve lower volumes of traffic. Simple diamonds or partial cloverleafs are used mainly for service interchanges. These interchanges optimize freeway ramp movements and operations at the crossroad.[2]

Interchange Warrants

According to AASHTO's *Policy on the Geometric Design of Highways*, an interchange is justified when one of several warrants is satisfied. These warrants include:[1]

1. *Design Designation*. Example: If a highway has full access control, grade separations are required to maintain continuous traffic flow on the major road.

2. *Elimination of Bottlenecks or Spot Congestion*. Example: If insufficient capacity at an AGI causes excessive congestion, grade separation may be justified.

3. *Elimination of a Hazard*. Example: Grade separation reduces accidents significantly by eliminating some conflicting traffic flows.

4. *Site Topography*. Example: Grade separation may be more economical in mountainous terrain.

5. *Road User Benefits*. Example: Delay costs at an AGI are large enough to justify an interchange.

6. *Traffic Volume*. Example: Volumes are larger than an AGI can handle, such as when cross streets have very heavy traffic.

Interchange Types

Over the years, several grade-separated interchanges have been developed in order to facilitate traffic flow. Each interchange has specific advantages and disadvantages inherent in its design. Each of the six major interchange types will be reviewed below.

Diamond

Diamond interchanges are the simplest and most common type of interchange placed at the intersection of a major and minor facility, and are commonly used in both rural and urban settings. A diamond interchange consists of one-way diagonal ramps placed in each quadrant. A diagram of a diamond interchange is shown in Figure 1. All traffic can enter and leave the major road at relatively high speeds, but left turns take extra time. The diamond typically consists of two intersections with a coordinated three-phase signal control and tight-turning radii. Because of the two-intersection configuration, delays on the interior movements account for about 1/3 of the total delay in the diamond.[3] The capacity of the interchange is restricted by the capacity of the at-grade terminals of the ramp at the crossroad. Diamonds take a moderate amount of right of way and have a moderate capacity. Diamond interchanges are generally used at intersections with minor crossroads where traffic is not expected to greatly increase.[4]

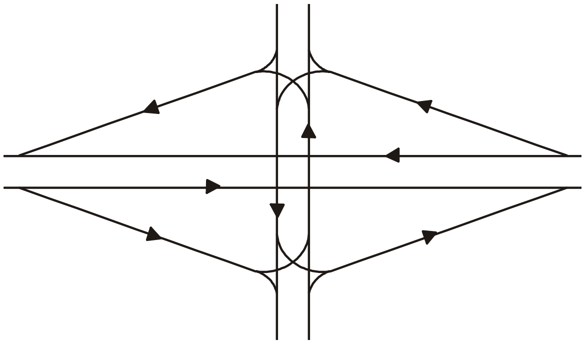

Figure 1. Typical Diamond Interchange

One advantage of the diamond interchange is that only a narrow right of way is required. The diamond is particularly appropriate to major-minor crossings where left turns onto the minor crossings are relatively low. Cost is typically low for a diamond interchange, with some interchanges costing as little as a few hundred thousand dollars.[5] They are 10-20% less expensive than SPUIs, on the average.[6] Diamonds have the additional advantages of high operating speeds and direct movements.

The diamond interchange has some drawbacks. Wrong-way entry onto the one-way ramps from the crossroad is possible, therefore adequate signing must be provided to help prevent this problem. Sufficient storage lanes must be provided. Additionally, any signals at the two intersections created by the diamond must be coordinated to maximize traffic flow through the crossroad.[1] Also, left turns are forced to cross the path of opposing left turns at two points in the interchange.[7] With diamond interchanges, conflicts can occur at the junction of ramps and crossroads. These conflicts can result in backups that reduce capacity and normal levels of service.[8]

Single-Point Urban Interchange (SPUI)

SPUIs are a relatively new design that were created to minimize the right of way required, making them particularly attractive for use in urban areas. The SPUI is similar to the diamond interchange, but it consists of only one signalized intersection. Left-turn radii are also flatter for SPUI turns than for left turns at diamond interchanges, allowing for higher speeds. A drawing of a SPUI is shown in Figure 2. Due to the ramp configuration and large left-turn radii, the signalized intersection at the SPUI is much larger than signalized intersections at diamond interchanges.

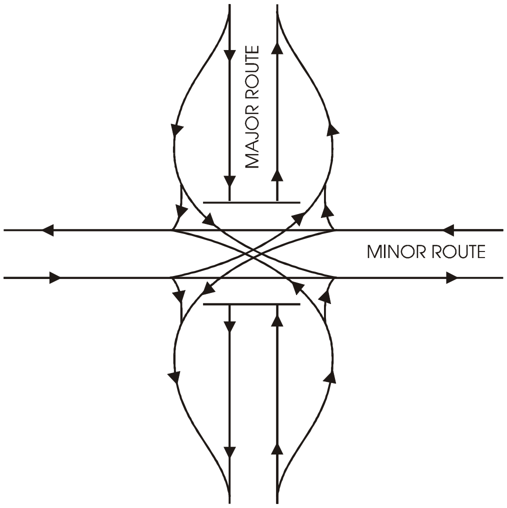

Figure 2. Typical SPUI

The SPUI design has several advantages. It can be constructed in a relatively confined right of way, which may result in significant design cost reductions. SPUIs also have the advantages of making arterial coordination easier due to their single signal design, and they can better serve high left-turn volumes.[9]

The SPUI design does have disadvantages, however. Although right-of-way costs are reduced, actual construction costs can be high. Overpass designs require a long, single span to go over the large intersection, and underpass designs result in a large, butterfly-shaped bridge. Both of these structures can potentially have a high cost. If the two roads intersect at a severe skew angle, the clearance and sight distances are both negatively affected. Pedestrians are also not easily accommodated by the SPUI, and the addition of a pedestrian phase would greatly degrade the operation of the SPUI. Clearance time is also a concern for the SPUI due to the large size of the intersection.[3] Since the SPUI is a relatively new design, there has been some concerns that driver unfamiliarity may result in accidents. Because of this problem, lane markings should be clear and should provide positive guidance for motorists. Some additional concerns about the SPUI that were found by a 14-state survey were: the signals were more difficult to mount, clearance intervals were long, the SPUI had less capacity than a partial cloverleaf, downstream intersections sometimes controlled flow, and left-turn storage was critical to the operation.[10]

Trumpet

The T-type trumpet interchange involves the intersection of two roads that meet in a "T" shape. The through traffic should be placed on a direct alignment, while the left-turning movement with the lower volume should travel on the loop ramp. Figure 3 shows an example of a typical trumpet interchange. Trumpets are used exclusively when three intersecting legs are present.

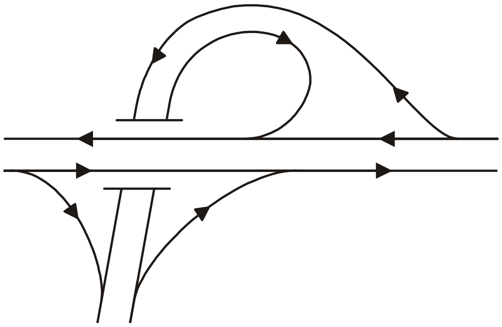

Figure 3. Typical Trumpet Interchange

Full Cloverleaf

Cloverleafs have several advantages over other forms of interchanges. Cloverleafs provide loop ramps for all left-turning movements. Figure 4 shows an example of a typical full cloverleaf interchange. Since left-turning movements are handled by loop ramps, cloverleafs avoid the safety problems that at-grade left turns create at diamond interchanges. Cloverleafs allow for a free flow of traffic in all directions, with no traffic control.[7] The cloverleaf interchange is the minimum design that can be used where two fully controlled access facilities cross, and turn at grade are prohibited. This makes cloverleafs a less expensive alternative to directional interchanges, which are described later in this report.

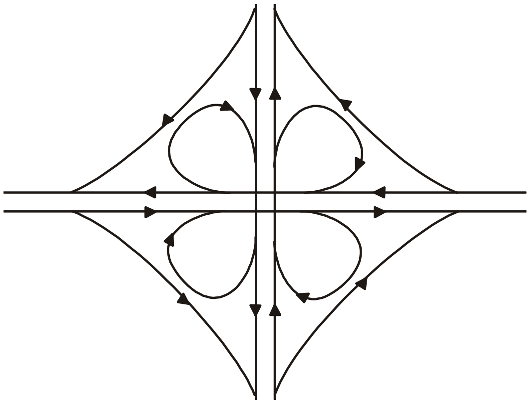

Figure 4. Typical Full Cloverleaf

There are several disadvantages to using the cloverleaf design. First, the use of loop ramps creates some concerns. Loop ramps consume a great deal of the right of way. As the design speed of the loop ramp increases, the amount of space required for the loop increases dramatically. Second, cloverleafs generate weaving maneuvers. This can cause safety concerns, particularly when only a short distance is available for weaving. When collector-distributor roads are not used, this is an even larger concern, since there will be weaving on the main line. It has been found that weaving can cause speed reductions and interference when the sum of the traffic on the two adjoining loops approaches 1000 vph (vehicles per hour).[1] According to AASHTO, when traffic exceed 1000 vph, collector distributor roads should be used to reduce the impact of the weaving maneuvers on mainline traffic. Levels of service in weaving areas also tends to be lower than the level of service for other interchange components.[8]

These drawbacks tend to make full cloverleafs less desirable in an urban environment. Because of the problems associated with weaving sections when large weaving and through volumes are present, collector distributor roads may need to be used, which require longer distances between loops. Large amounts of right of way are required to carry this out, and this is usually not cost-effective in an urban environment.[2] Because of this drawback, cloverleafs have been found to be most appropriate for applications in rural areas with low turning movements.[4]

Partial Cloverleaf

The partial cloverleaf interchange is similar to a full cloverleaf, except that loop ramps are present in three quadrants or less. An example of a two-quadrant partial cloverleaf can be seen in Figure 5. Partial cloverleafs are generally used where the right of way is not available in a quadrant or when the traffic making a particular movement is much smaller when compared to other movements. The operation of partial cloverleafs has been studied less than full cloverleafs, however, the conventional wisdom is to arrange the ramps to provide the least impediment to left turns.[8] With partial cloverleafs, the ramps should be laid out so that the entrances and exits cause the least amount of disruption to traffic flow on the major road. Specifically, if through volumes on the major road are much larger than the volumes on the minor road, major turning movements should be accommodated by right-turn entrances and exits.[1] Partial cloverleafs are primarily used in locations where access needs, right of way, and street network configurations control the interchange configuration. Partial cloverleafs suffer from many of the same disadvantages as the full cloverleaf with regards to loop ramps and weaving areas.

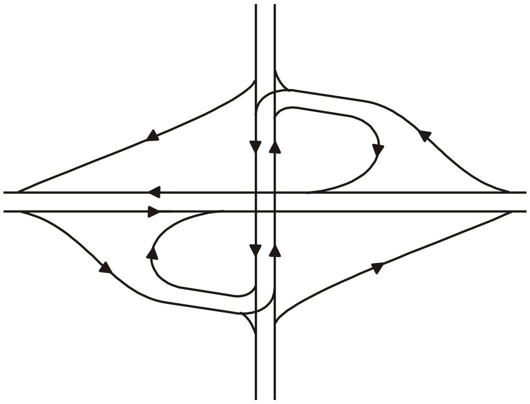

Figure 5. Typical Partial Cloverleaf

Directional

Directional interchanges offer the highest capacity of any type of interchange, but at the highest cost. In fact, some directional interchanges have cost as much as $100 million.[5] There are several advantages to using directional interchanges. Travel distance is reduced, speed and capacity are increased, weaving is eliminated, and driver confusion created by driving in loops is reduced. All of these advantages make the directional interchange the preferred type of interchange to use for system connections over the cloverleaf. Directional interchanges are not usually justified, however, due to their extremely high cost of construction and their considerable right-of-way requirements.

There are two main types of directional interchanges: direct connection and directional. A direct connection is a one-way road that does not greatly deviate for the intended direction of travel. Directional interchanges can be further separated into fully directional interchanges and semi-directional interchanges. A fully directional interchange uses direct connections for all major left-turn movements. A possible design for a fully directional interchange can be seen in Figure 6. A semi-directional interchange uses one or more direct connectors and one or more loops.

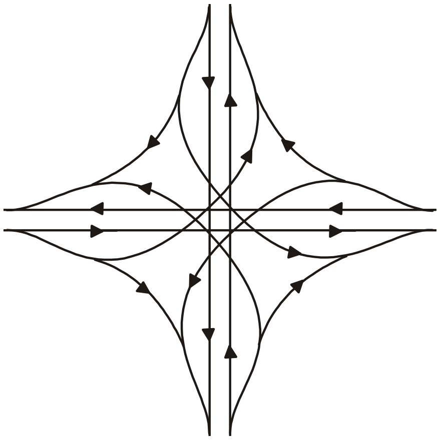

Figure 6. Typical Fully Directional Interchange

Summary of Interchange Type Characteristics

The literature review has revealed several key characteristics of the six major interchange types. Table 1 summarizes the relative capacity, right of way, and cost characteristics of the diamond, SPUIs, partial cloverleafs, full cloverleafs, trumpets, and directional interchanges.

Accidents and Safety

Safety at an interchange is generally superior to an AGI, since conflicting turning movements are eliminated through the use of grade separations. Several studies have assessed where the risk of crash involvement is greatest at an interchange. These studies have shown that the ramps and acceleration and deceleration lanes are the principal locations where accidents occur.

Table 1. Summary of Interchange Characteristics

Interchange Type	Right of Way Required	Capacity	Cost	Notes
Diamond	Low	Low	Low	Simplest interchange
SPUI	Low	Moderate	Low-Moderate	Designed for urban use, problems accommodating pedestrians
Partial Cloverleaf	Moderate	Moderate	Moderate	Loops should be arranged to serve largest left turning movements
Full Cloverleaf	High	Moderate	High	Weaving areas are safety and capacity concerns
Trumpet	Moderate-High	Moderate	Moderate-High	Should be used when 3 legs are present
Directional	Very High	High	Very High	Preferred interchange for freeway to freeway connections

Ramps

Off ramps have the highest accident rates, since vehicles enter curves at high speeds and the capacity at ramp terminals is frequently deficient. Loop ramps of trumpet interchanges, loop ramps of cloverleaf interchanges without collector-distributor roads, and left-side ramps have consistently higher accident rates than other ramp types.[11] All left-hand entrances and exits were also found to have poor accident records[11] Ramps of diamond interchanges tend to have the lowest accident rate.[12]

Several design recommendations have been made to improve safety on interchange ramps. First, interchange ramps should have flat horizontal curves and avoid using the maximum curvature. Sharp curves at the ends of ramps and sudden changes from straight alignment should be avoided. Collector-distributor (C-D) roads should be used when a high volume interchange is being designed. This can have a very important impact on cloverleaf ramps, since cloverleaf ramps with no C-D roads have higher accident rates than those with C-D roads.[12]

Acceleration/Deceleration Lanes

The length of acceleration and deceleration lanes has also been found to have a major impact on safety at interchanges. The shorter these lanes are, the higher is the probability of accidents. Urban interchanges have much higher accident rates than rural interchanges (214 accidents/100 million vehicles vs. 109 accidents/100 million vehicles). This may be partially due to inadequate acceleration lanes in urban areas due to the limited right of way.[12] Safety is increased if acceleration lanes are at least 243.8 m (800 ft), deceleration lanes are at least 274.3 m (900 ft), and weaving sections are at least 243.8 m (800 ft).[12] A comprehensive study of safety, operation, and capacity at 50 interchanges in New Jersey validated these length figures. This study found that the greatest benefit in terms of accident reduction occurred when deceleration lanes were more than 243.8 m (800 ft) in length. However, even a short deceleration lane could have reduced the number of accidents significantly.[11] Acceleration lanes less than 274.3 m (900 ft) in length generally had poor accident records because some drivers stop or slow down before entering the roadway.[11] Through traffic was also more willing to yield to merging traffic if long acceleration lanes were present. These long acceleration lanes tended to create smoother operating conditions and increase capacity.[11]

Interchange Type Selection

Interchange type selection is the primary and most important step in the design of an interchange.[4] Since interchange selection is often based on experience and engineering judgment, it can be a time-consuming and expensive process.[13]

Due to site-specific characteristics, adapting a general, ideal design is not always feasible. While it is possible to give a general indication of the preliminary interchange type to examine for given characteristics, specific conditions at the site must be examined. Some of the factors that must be investigated include: topography, land use, traffic volumes, population densities, real estate values, and availability of financing.[14]

The interchange selection process should examine a variety of factors. The type of interchange selected depends on factors such as highway classification, character and composition of traffic, design speed, and degree of access control. Interchanges must be selected based on prevailing conditions at an individual site.

There is a great deal of resistance to adopting an evaluation methodology for interchange design and location. Designers are cautious about using design aids to assist in the planning of something as large and complex as an interchange. Even if an evaluation strategy is presented as an aid and not as a decision-making device, designers are reluctant to use it. Experience of the designer is the most important factor in generating alternate design configurations. The person who handles this portion of the design process should have a great deal of training in highway design and traffic operations. Interchange designers need to be thoroughly trained and knowledgeable of the social and environmental issues.[13] Public attitudes, costs, and available resources also need to be considered when generating these alternate designs. The generation process is not a “cookbook” procedure that can be performed by an inexperienced individual with a set of instructions. It requires a designer who is knowledgeable about the design process.

Interchange Selection Methods

Cost/benefit and economic analysis have been used occasionally to determine interchange configuration. However, economic analysis tends to be used less frequently because design decisions are becoming more and more detailed. Many designers have little interest in using an economic analysis to select design details, since they feel that economic analyses provide an unnecessary and impractical constraint.[15] States generally do not use an economic analysis in selecting interchange types, however, they do evaluate costs when choosing individual interchange elements such as ramps and speed change lanes.[13] This is done because it is not feasible to estimate all of the costs and benefits of constructing an interchange, but it is relatively easy to quantify the benefits of a specific interchange element. Several alternatives to economic analysis selection methods have been proposed.

Wattleworth and Ingram

Wattleworth and Ingram[16] developed a procedure for comparing alternate systems. This procedure took into consideration both the costs of the configuration as well as its effectiveness. Each configuration was evaluated, based on peak-hour capacity. A linear programming model was used to establish peak-hour capacity for each alternative. This model assumed two things: that the volume to capacity ratio is ≤ 1.0 and that traffic is distributed among all possible movements.

This model found that the maximum peak hour for the entering volume of traffic for this configuration adequately handled traffic before the interchange became congested This model also identified the critical element in the interchange that limited capacity. Based on the results of the model, new design configurations were selected that would provide an increased capacity on the identified critical elements. By using this process, each interchange modeled had a higher capacity than the previous one. The 24-hour capacity was then plotted against the cost of the alternative in order to find the options that yielded the highest capacity at the lowest cost.

While Wattleworth and Ingram’s paper provided some insight into a possible interchange analysis method, there were some deficiencies. First, the paper was published in 1972. While the linear program model presented in the paper was probably adequate at that time, computing technology and modeling techniques have improved tremendously since its publication. The linear programming model assumed that the interchange benefits were linear, but in actuality they were inherently non-linear. For example, small increases in traffic volumes can result in large increases in delay. Thus, the linear programming model represents a simplification of reality that will most likely produce less accurate results than modern models. Finally, this paper used only two criteria--cost and capacity--for interchange type selection. The optimal interchange type can be influenced by a number of factors beyond cost and capacity.

Mullinazzi and Satterly

Mullinazzi and Satterly[17] proposed a methodology to select an interchange configuration for a specific site. This procedure consisted of the following steps:

1. Determine whether a system or service interchange required. If a system interchange needed, ramp terminals must be free-flowing for quick transfer. Service interchanges may have free-flowing or controlled-ramp terminals.

2. Identify the number of legs required.

3. Determine if the location has any limiting constraints, such as land use, frontage roads, or obstructions.

4. Is the design problem simple or complicated? Simple design problems involve choosing between one or two alternatives. An example of a simple design problem would be choosing interchange configurations in rural areas with level terrain. Complicated design problems involve choosing between more than 2 alternatives, such as choosing a design configuration for an urban interchange.

Once these basic questions were answered, alternate configurations were evaluated based on several criteria. These included:

1. Operational and design factors

    - level of service
    - safety
    - uniformity
    - flexibility
    - number and length of weaving sections
    - travel time.

2. Community impact factors

    - number of acres of right of way required
    - number of families relocated
    - number of tax dollars removed
    - number of local streets closed
    - effect on public lands, such as schools, historic places, wetlands
    - access to adjacent property.

3. Miscellaneous

    - radius of curvature
    - ramp grades
    - topography
    - soil conditions
    - interchange spacing
    - design speed
    - traffic composition
    - operating costs.

Initial costs were developed for each alternative design. Next, an effectiveness profile was developed using a point-weighting scheme. A point value was assigned for each criteria. The alternative with the highest number of points that satisfied certain minimum criteria was chosen as the best type. The variables examined included both market and non-market variables.

While this methodology does a good job of identifying factors that need to be analyzed, there are some drawbacks to using this procedure for interchange type selection. First, the quality of the solution is dependent upon the factors that are included in the analysis. If a critical factor is not included, the results of the analysis may not be optimal. Second, the point values assigned to the criteria can be somewhat arbitrary. This may introduce a measure of bias, depending upon the analyst's personal preferences.

Smith and Garber

Smith and Garber[9] developed some selection guidelines that applied specifically to SPUIs and Diamonds. They conducted an exhaustive study of the safety and operational characteristics of these two interchange types and came to several conclusions. Their study was not an attempt to develop an evaluation methodology so much as an attempt to create “rules of thumb,” which could be applied when an engineer was trying to choose between a SPUI and a diamond interchange.

They found that the lack of a full, right-turn lane on the off ramps significantly affected ramp delay, especially at diamonds. When cross road throughs and lefts were unbalanced and the higher through volume opposed the higher left-turn volume, the delay at the SPUI sometimes increased by up to 30%. Increase in delay at the diamond increases more dramatically than at the SPUI as approach volume increases. Accident rates were not significantly different, although the proportion of accidents that occurred in the center of the interchange was greater for the diamond than for the SPUI. These findings led Garber and Smith to develop the following selection guidelines for when the two interchanges are being compared:

1. Diamonds should be used over SPUIs when pedestrian volumes are present. Delay at the SPUI increases greatly when the signal phasing is changed to accommodate pedestrians.

2. When frontage roads are present, diamonds are better than SPUIs. In this case, SPUIs must add an additional fourth phase to accommodate the frontage road, increasing the interchange delay greatly.

3. Diamonds should be used when there is a large skew angle between roadway alignments. When a large skew angle exists, the SPUI requires a much larger structure, and sight distance is greatly reduced.

4. When cross-road left turns become significant, the SPUI is preferred. The SPUI is superior because the cross roads permit left-turn phasing.

5. SPUI is better when the distribution of traffic to and from the major road is of greater significance and the diamond is more efficient when arterial throughs are of greater significance.

Practices in Other States

Several methods have been used to help in the selection and design of various interchanges. In Hawaii, Indiana, Virginia, and Wisconsin the AASHTO *Policy on Geometric Design of Highways and Streets* (commonly referred to as the Green Book) is used as a design data source. Indiana also requires a level of service (LOS) B for new rural interchanges, and a LOS C for new urban interchanges, regardless of configuration. Montana tries to use diamonds consistently, especially in rural areas, regardless of the level of service this creates. Missouri determines the optimum interchange configuration through a capacity analysis. Wyoming avoids using cloverleafs, since they have had low levels of service in main line weaving areas.[8]

Computer Modeling and Simulation of Interchanges

Computer software used to simulate traffic flow can play an important role in modeling interchanges. The criteria used to select software for this project were ability and credibility. This meant that the software must have had both the ability to model certain interchange types and it also must have been able to produce results that reflected real world conditions to an acceptable degree of accuracy.[3]

Freeway simulations can generally be separated into two general classifications: microscopic and macroscopic. Microscopic models simulate vehicles based on car-following and lane-changing theory. Vehicles arrive based on a statistical distribution and are advanced using constant-time steps. Microscopic models require a great deal of computing power, and execution of the simulation can be time-consuming. Macroscopic models are based on relationships developed through research on freeway capacity and traffic flow. Individual vehicles are not tracked. Rather, simulation takes place at a platoon level. Computing requirements are much less demanding for macroscopic models than for microscopic models. Macroscopic models do not have the ability to evaluate geometric and operational improvements as well as microscopic models, but they do present a better option for analyzing long sections of freeway.[18]

Since interchanges are composed of interconnecting freeway and surface streets, the current practice is to evaluate each component separately, i.e., freeway models for freeway sections and surface street models for the cross road. Chen et al., published the results of a questionnaire that was sent to the TRB Freeway Operations Committee and the Interchange Subcommittee of the TRB Highway Capacity and Quality of Service Committee.[19] Each person on the Committee was asked to name the computer models they used for interchange analysis, and any other tools that they have used for interchange analysis. The most popular models were TRANSYT, HCS, PASSER, and NETSIM. The respondents noted that these models were used to conduct analysis on:

- capacity
- interchange type
- intersection spacing
- progression
- queue analysis

- signal timing
- spillback
- ramp metering
- weaving

In order to simulate an interchange properly, a simulation model should be able to accurately model several features. These include:

- *Weaving*: Weaving occurs when on-ramp vehicles try to merge into mainline traffic or when freeway vehicles move to the off-ramps. For cloverleafs and directionals, weaving occurs on the crossroad. Weaving can significantly affect capacity and safety on the crossroad.
- *Closely Spaced Intersections*: This is needed for diamond interchanges and other situations where closely spaced, coordinated systems exist.
- *Spillback*: Spillback can disrupt traffic flows, degrade performance, and create congestion at the interchange.
- *Ramp metering.*

Since this survey was conducted, the FHWA has released CORSIM, which integrates the freeway modeling abilities of FRESIM with the local road modeling capabilities of TRAF-NETSIM. This allows for holistic modeling of the interchanges with local roads and freeways. While CORSIM does allow the user to model the traffic operations at an interchange, CORSIM cannot evaluate such factors as sight distance, right of way required, or construction costs. Care should be taken with any computer model results. The output should be examined for validity, and not immediately accepted at face value.

Need for Further Research

While previous studies have defined methodologies for interchange type selection or produced guidelines for the use of certain interchange types, research on interchange type selection is still needed. In particular, guidelines that address all interchange types are required. These guidelines will help engineers choose a specific type for a given location, thereby increasing interchange uniformity in the state. Much of the literature written on interchange selection was published in the 1970's, and the methodologies used at that time relied on what are now outdated technologies for interchange analysis. The microscopic traffic simulation models of today offer an opportunity for better analysis of interchange types, potentially making selection decisions more accurate. The traffic simulations should offer an objective comparison between the interchange types. By simulating all interchange types with microscopic traffic simulation models, some guidelines that will aid engineers in interchange type selection should be produced.

Data Collection

The data collection phase consisted of the following tasks:

- a nationwide survey
- site identification for field data collection
- field data collection
- obtaining accident data.

Nationwide Survey

Surveys were sent out to state engineers across the United States to determine which states are currently using guidelines to assist in interchange type selection. This survey also helped to ascertain opinions on operational, safety, and cost issues involved in the selection of interchange types. This information was used to identify factors that affect traffic operations at different interchange types.

First, engineers concerned with interchange location and design for each state were contacted. They were informed of the purpose of the study and asked to participate. It was expected that by informing the engineers before they received the survey, a higher response rate would be obtained.

The questions on the survey dealt with the following topics:

- whether guidelines are used in the state
- if guidelines are in use, for which types of interchanges are they available, and how were they developed
- the approximate percentage of each interchange type in use in the state
- the predominant interchange type used in urban and rural areas of the state

- the predominant interchange type used for service and system interchanges

- opinions on the relative performance of various interchange types in areas such as safety, cost, land use, right of way, capacity, etc.

A sample of the interchange survey can be found in Appendix A.

Data Collection Site Identification

The selection of study sites was a very important step in the data collection for this project. The sites selected needed to represent a good cross section of interchange types in Virginia. The layout of the interchanges also had to be such that it was feasible to collect data. The shoulders had to be sufficiently wide to allow the data collection team to work safely. This was sometimes difficult to achieve, especially in urban areas.

Data were collected for one diamond, three full cloverleafs, and three partial cloverleafs. Existing data for two SPUIs and one diamond were also obtained. These interchanges came from both urban and rural environments. Traffic flow on the interchanges varied a great deal. Data for a total of 10 interchanges in Virginia were obtained. The interchanges studied were:

1. I-664 and Aberdeen Rd., Hampton, Diamond (D-1)

2. US 19 and SR 654, Lebanon, Diamond (D-2)

3. I-81 and US 60, Lexington, Partial Cloverleaf (2 quadrant) (PC-1)

4. I-64 and US 29, Charlottesville, Partial Cloverleaf (3 quadrant) (PC-2)

5. I-81 and US 11, Greenville, Partial Cloverleaf (1 quadrant) (PC-3)

6. I-81 and US 33, Harrisonburg, Full Cloverleaf (FC-1)

7. I-664 and SR 135, Suffolk, Full Cloverleaf (FC-2)

8. I-664 and SR 337, Chesapeake, Full Cloverleaf (FC-3)

9. Hampton Roads Center Parkway and Magruder Blvd., Hampton, SPUI (SP-1)

10. Arlington Blvd. and Gallows Rd., Fairfax, SPUI (SP-2).

The abbreviation in parentheses will be used throughout this report to refer to each specific interchange. Directional and trumpet interchanges were not explicitly considered, since the conditions for their use are already well defined in the literature.

Field Data Collection

Preliminary Visit

After the sites were identified, a preliminary visit was made to each site in order to determine the feasibility of collecting data there. The width of the shoulders and the traffic conditions were observed in order to determine if it would be safe to collect data at the site. Photographs were taken of the interchanges, and adjacent land uses were noted.

During the preliminary visit, a sketch of the intersection was drawn. The number of lanes, lane usage, ramp details, channelization, and speed limits were all recorded. A number of geometric measurements were also collected. These included:

- lane widths
- turn-pocket lengths
- distance to adjacent intersections
- length of tapered sections of ramps
- ramp and cross-road grades
- locations of stop and yield signs and traffic signals.

At signalized ramps, traffic signal information was also collected. The data compiled included cycle length, phase length, interval length, and phasing sequence. Since some sites used an actuated system, twenty to thirty signal timings were collected to find an average length for each interval.

Video cameras were used to collect delay data at the signalized and unsignalized intersections studied. During the preliminary visit, camera locations were identified so that each camera would be able to accurately capture all of the needed data.

Data Collection

Data collection procedures varied according to what type of interchange was being studied. One camera was used to record each turning movement that experienced delay. These cameras were set up to record for three hours during the morning peak period and three hours during the afternoon peak period. The cameras were carefully placed so that they recorded all vehicles from the end of the queue up to the intersection stop bar so that accurate delay measurements and turning movement counts could be obtained. The number and placement of the cameras varied according to the interchange configuration. Delay data were collected in this way for the diamond, SPUI, and partial cloverleaf interchanges.

Electronic traffic counters were used to collect speed and traffic count data when it was required. Diamond Phoenix traffic counters were used. The Phoenix counters could collect speed, vehicle classification, and headway data simultaneously. Data were collected in this manner at the full cloverleafs and partial cloverleafs for at least 72 hours. The counters were placed on all ramps and on the mainline in order to collect the needed speed and volume data.

Accident Data

After the data at the study sites had been collected, police accident reports (FR-300s) for the study sites for the three years prior to when data were collected were obtained. Reports were obtained for all accidents within 45.7 m (150 ft) of the interchange and on all of the on- and off-ramps. Information on the following was extracted for each accident report:

- traffic control
- weather and road surface condition
- time of day
- accident type (e.g., sideswipe, rear-end)
- severity (i.e., property damage, injury, fatality)
- vehicle maneuver
- points of impact on vehicle.

The location of the accident was also noted. The location of the collision was defined as the location where the accident initially occurred. Identifying the precise accident location was very important, since a difference of less than 15.2 m (50 ft) could change how the accident location was classified.

This information was used to analyze any possible safety problems associated with the interchange. The average daily traffic (ADT) for each interchange was found by taking 72-hour counts at the interchange during data collection. VDOT traffic data were then used to determine the growth rate in traffic at the interchange over the past three years so that the count data could be regressed. These ADTs were used to calculate accident rates for each interchange per 100 million vehicles entering the intersection, using the following formula:

$$Accident \quad rate = \frac{(A_1 + A_2 + A_3) * 100{,}000.000}{365 * (ADT_1 + ADT_2 + ADT_3)}$$

Where: Accident Rate = Accident rate per 100 million entering vehicles

A_N = Number of accidents in year N

ADT_N = Average daily traffic in year N.

Data Reduction

Data reduction procedures varied according to the type of data collected. Videotaped delay data were viewed, and turning movement volumes were recorded at 15-minute intervals, and the peak hour was determined. Delays were also determined using the *Highway Capacity Manual* (HCM) procedures described below. For traffic counter data, the peak hour was determined as well as the average speed during the peak hour.

Each interchange was then evaluated using the LOS procedures in the HCM (see Table 2 for level of service criteria). Every interchange was composed of several different components, which were each examined to determine the operational characteristics of the interchange as a whole. The components present at each interchange were:

Diamond : Signalized intersection, unsignalized intersection

SPUI: Signalized intersection, unsignalized intersection

Partial cloverleaf: Signalized intersection, unsignalized intersection, weaving areas, ramps and ramp junctions

Full cloverleaf: Ramps and ramp junctions, weaving areas.

Table 2. Signalized Intersection Level of Service Criteria[20]

Level of Service	Stopped Delay (s/veh)
A	≤ 5.0
B	>5.0 and ≤ 15.0
C	>15.0 and≤ 25.0
D	>25.0 and ≤ 40.0
E	>40.0 and≤ 60.0
F	≥ 60.0

The HCM evaluated each of these components using a different measure of effectiveness (MOE), so it was not possible to directly compare the different components to each other. Thus, each component was evaluated separately using their unique measure of effectiveness, and compared with each other using the qualitative LOS letter. A description of the HCM procedures for evaluating LOS for each component is described below. The qualitative explanation of the different levels of service can be found in Appendix B. It should be noted that levels of service were evaluated using the criteria supplied in the 1994 HCM. These criteria will change in the next edition of the HCM, but the new information was not available at the time of this study.

Although the MOEs were different for each component, it is reasonable to use the qualitative LOS explanation to compare the various interchange components, because they are all somewhat related. In all cases, poor levels of service corresponded to increased travel time through the interchange. For example, signalized and unsignalized intersections directly measure the delay incurred by a driver. For at-ramp and ramp junctions, density was the primary MOE. As density increases in the area of the ramp junction, speeds declined and travel time increased. Likewise, weaving and non-weaving speeds were measured at weaving areas. Poor levels of service indicated a decline in weaving/non-weaving speeds and a corresponding increase in perceived travel time. The LOS delay criteria for unsignalized intersections are shown in Table 3. Table 4 shows the density and speed MOEs for ramp and ramp junctions. Table 5 shows the LOS criteria for weaving and non-weaving areas.

Table 3. Unsignalized Intersection Level of Service Criteria[20]

Level of Service	Average Total Delay (s/veh)
A	≤ 5
B	> 5 and ≤ 10
C	> 10 and ≤ 0
D	> 20 and ≤ 30
E	> 30 and ≤ 45
F	≥ 45

Table 4. Ramp and Ramp Junction Level of Service Criteria[20]

Level of Service	Maximum Density (Primary MOE) (veh/km/ln, [veh/mi/ln])	Minimum Speed (Secondary MOE) (KPH/[MPH])
A	6.2, [10]	93.3, [58]
B	12.4, [20]	90.1, [56]
C	17.4, [28]	83.7, [52]
D	21.7, [35]	74.0, [46]
E	> 21.7, [35]	67.6, [42]
F	Demand flow exceeds table limits	Demand flow exceeds table limits

Table 5. Weaving Area Level of Service Criteria [20]

Level of Service	Minimum Average Weaving Speed (KPH, [MPH])	Minimum Average Non-Weaving Speed (KPH, [MPH])
A	88.5, [55]	96.6, [60]
B	80.5, [50]	86.9, [54]
C	72.4, [45]	77.2, [48]
D	64.4, [40]	67.6, [42]
E	56.3, [35]	56.3, [35]
F	< 56.3, [35]	< 56.3, [35]

Computer Simulation

The computer program CORSIM was used to simulate the traffic operations of the interchanges studied. This program was selected, since it is a microscopic model that has the ability to model the movements of individual cars. Factors such as driver aggressiveness, start-up lost times, and headways can all be changed in order to calibrate the simulation to accurately model the driving behavior at a specific site. CORSIM also has the ability to integrate freeway and surface street networks, which is an important asset when modeling interchanges. By simulating the interchanges, the program produced data on the average delay per vehicle, speeds, and density. In order to create a model of the interchange, several pieces of data were needed. These included:

- geometry of the interchange
- channelization of traffic
- traffic control
- traffic volumes

- traffic composition
- turning movements
- free-flow speeds.

In CORSIM, the roadway system is represented as a link-node diagram. Links represent sections of roadway and nodes represent points where geometric or traffic characteristics change. Samples of link-node diagrams created for the interchange simulations in this project can be found in Appendix C. The output of the model contains information for each link including:

- average speed
- average and maximum queues
- delay
- density.

Using the output from CORSIM, it is possible to determine the level of service for the interchange components by using the delay, speed, and density information.

After the networks were created, the models were calibrated to ensure that they accurately represented actual field conditions. The field speed and delay data were compared to the CORSIM output to learn if there was a good correlation between the data sets. Factors such as driver aggressiveness, car-following sensitivity, percent of drivers changing lanes for merging vehicles, and startup lost time were varied until the CORSIM models closely simulated the actual field conditions.

Analysis

Accident Characteristics

The accident data extracted from the police accident reports were used to compare the safety of the different types of interchanges. Hypothesis testing using the t-test was performed to compare the accident rates at the different interchanges. The following null hypotheses were formulated:

H_0 = The total accident rates on all interchanges were equal.

H_0 = The fatal accident rates on all interchanges were equal.

H_0 = The injury accident rates on all interchanges were equal.

The proportionality test was used to test the following null hypothesis:

H_0 = The proportional distribution by collision type was the same at all interchange types.

The results of this analysis should indicate how accident characteristics differ between interchange types.

The collision location distribution was also examined. No statistical tests were performed on the collision location data because all interchange types did not possess the same locations. For example, there was no attempt to compare accidents at weaving areas on a full cloverleaf to any location on a diamond interchange.

Operational Comparisons

After the models were calibrated, simulations were created with CORSIM for all of the interchanges studied. Existing traffic volumes, geometrics, and traffic-control characteristics were used to accurately simulate existing conditions at the interchanges. Each existing interchange was then replaced by each of the other types of interchanges and then simulated. The results of these simulations helped to gain insight into the relative performance of the interchange types. For example, a diamond interchange was redesigned as a SPUI, full cloverleaf, and partial cloverleaf. The same traffic volumes were applied to all of the redesigned interchanges, and the same lane configurations were used. For these redesigned interchanges, signal timings were optimized using the Highway Capacity Software to find the minimum overall delay. When the interchange was redesigned as another configuration, the guidelines outlined in AASHTO's *Policy on the Geometric Design of Highways* were followed. These simulations helped to show differences in the operational capabilities of the different interchanges.

While these analyses provided some insight into the relative operation of the different interchange types, it was necessary to develop further interchange scenarios in order to gain a better picture of how the interchanges operate. In order to do this, 10 interchange volume scenarios were developed. The 10 volume scenarios developed used the following traffic distributions:

- **A & B** Equal through volumes and equal mainline left-turn volumes
- **C & D** Unbalanced mainline left-turn volumes and unbalanced through volumes where the heavier through volume opposes the heavier left-turn volume.
- **E & F** Unbalanced mainline left-turn volumes and unbalanced through volumes where the heavier through volume opposes the lighter left-turn volume.
- **G & H** Balanced mainline left-turns and unbalanced through volumes.
- **I & J** Unbalanced mainline left-turn volumes and balanced through volumes.

The first volume scenario in each pair had balanced left turns off of the ramps, and the second volume scenario had unbalanced left turns. These were tested on the interchange at 4 different entering volumes: 1500 vph, 2500 vph, 4500 vph, and 6500 vph. The volumes were increased proportionately between each scenario so that the relative percentages of vehicles making each movement remained constant. A copy of the volume scenarios used can be found in Appendix D. It should be noted that the terms “balanced” and “unbalanced” will be used in the following sections to describe the relationships between left turns on both the minor route and on the off-ramps. “Balanced” means that the turning movements are equal in both cases. When referring to ramp left turns, “unbalanced” refers to unequal left turns where the southbound left turn is twice the magnitude of the northbound left turn. When referring to minor route left turns, “unbalanced” means that the larger turning movement is 2.5 times the smaller movement. While these general terms are used throughout this report, they are intended to refer to these specific ratios only.

The same network was used to test all volume scenarios for a particular interchange type. Since the geometric characteristics remained constant, the effects of the different volume scenarios on traffic operations at each interchange type was easier to discern than with the field data.

Guideline Development

Guideline formulation was influenced by several analyses. First, the safety and operational analysis of the field sites highlighted differences in the performance of the different interchange types. The literature review also provided insight into the relative advantages and disadvantages of the various interchange types. Finally, the survey results served to highlight the findings and opinions of other state agencies. The synthesis of all of the results created a more comprehensive view of the relative performance of the interchange types.

RESULTS

The results of the study can be broken down into three parts. Each section will be examined separately. They are:

- interchange surveys
- accident analysis
- operational analysis.

Results of Interchange Surveys

A nationwide survey was sent out in September 1996 to all 50 states and the District of Columbia. A second round of surveys was sent in January 1997 to give non-respondents a second opportunity to return the survey. A total of 36 states responded, yielding a response rate of a little over 70%.

Interchange Types in Use

Each state was asked to give the approximate percentage of each type of interchange in use in their state. The pie graphs shown in Figures 7 and in Figures 9 through 12 are intended to show the average selection processes nationwide. All states are given equal weight--California is viewed the same as Rhode Island. Figure 7 shows the average distribution across the country. The pie chart shows that diamonds are the type of interchange most commonly used. The “other” category accounts for tight diamond interchanges (TDIs) as well as interchange configurations that are unique to certain states, such as Missouri’s folded diamond interchange. Figure 8 shows a diagram of a folded diamond interchange, which has elements of a partial cloverleaf and a diamond. Conventional diamond interchanges and TDIs are generally distinguished by the spacing between intersections. This is approximately 70-106.7 m (200-350 ft) for the TDI and 182.9 m (600 ft) for the diamond.

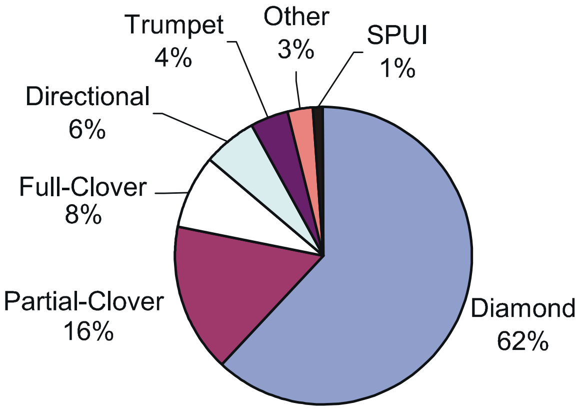

Figure 7. Nationwide Interchange Type Percentages From Survey

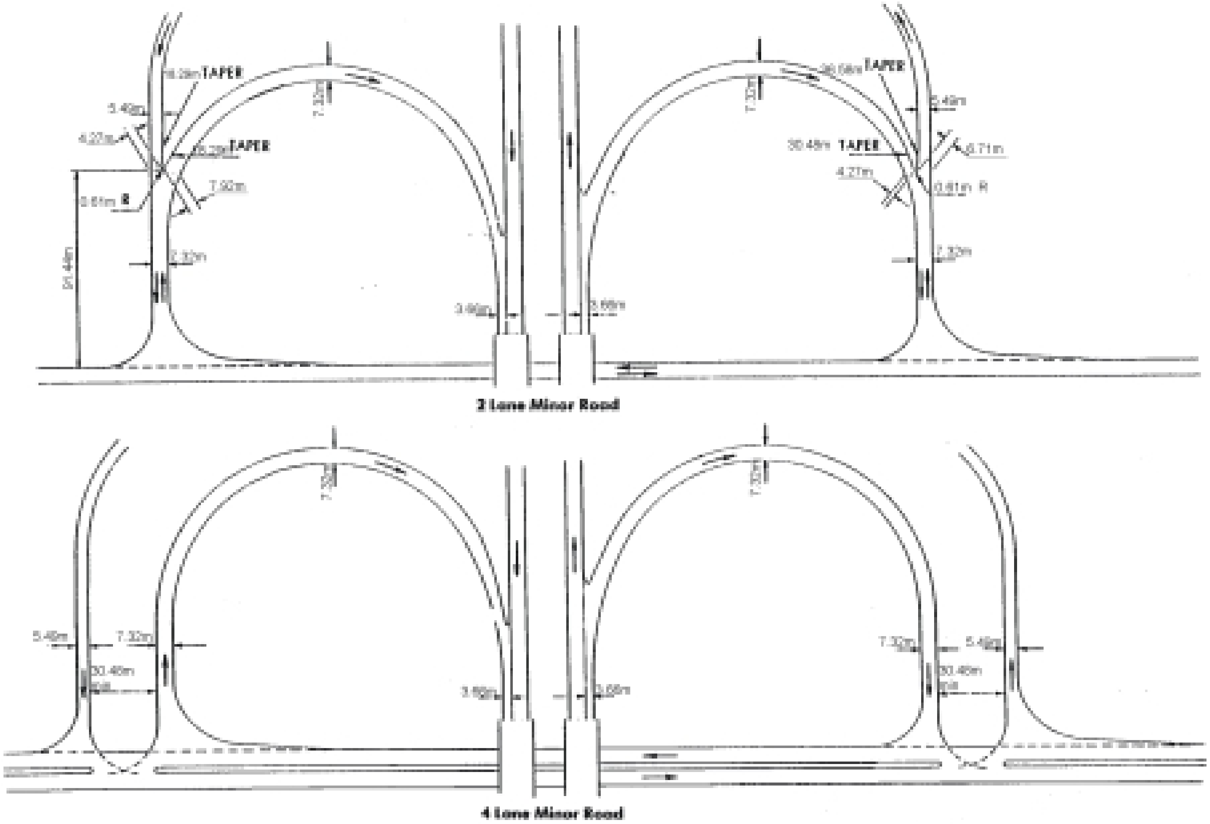

Figure 8. Missouri Folded Diamond Interchange

The next question on the survey asked which single interchange type was used most frequently in urban and rural areas of each state. Diamonds were the most common interchange type used in both rural and urban situations. The distributions can be seen in the Figures 9 and 10.

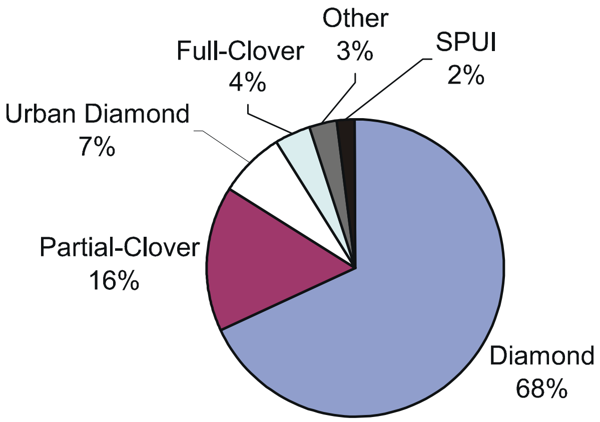

Figure 9. Primary Urban Interchange Type

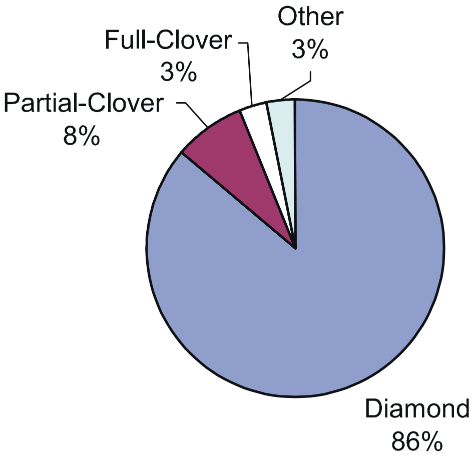

Figure 10. Primary Rural Interchange Type

Engineers then identified which single interchange types were most commonly used for system interchanges and for service interchanges. Directionals were cited as the most common system interchange, and diamonds were the most common service interchange. Figures 11 and 12 show these distributions.

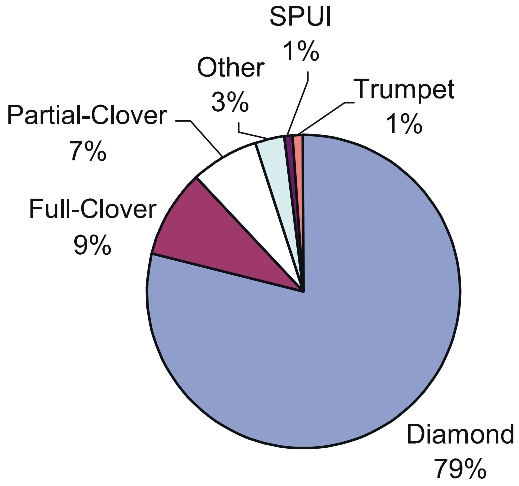

Figure 11. Primary Service Interchange by Type

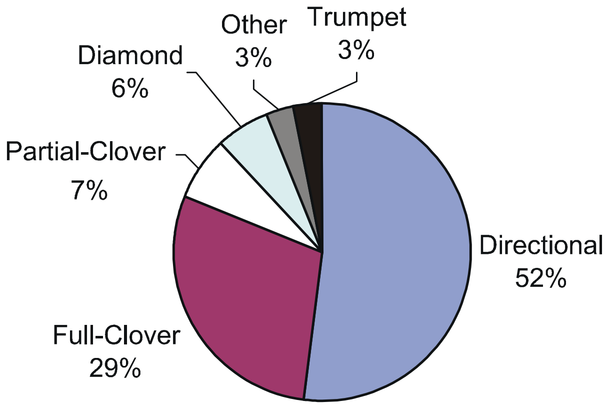

Figure 12. Primary System Interchange by Type

Interchange Rankings

The state engineers were asked to rank their reasons for selecting a certain interchange type over other interchange types. Each interchange type was ranked from 1 to 5, with 1 being the worst and 5 being the best for several selection criteria. The numbers were then averaged together to find an average nationwide ranking for the selection factors.

First, state engineers were asked to rank each interchange type with regard to its use in situations where the right of way available was restricted. SPUIs were seen as being the best for this situation, followed by diamonds. Directionals and full cloverleafs were seen as the worst. Figure 13 shows the relative rankings.

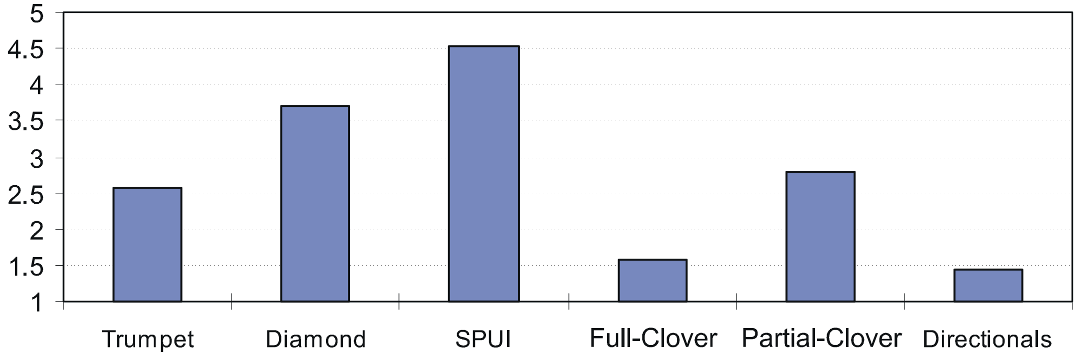

Figure 13. Rankings When Right of Way Availability Is Limited

The next question asked the states to rank the interchange types based on their ability to improve traffic carrying capacity. Responses indicated that directionals have the highest potential to increase capacity, while diamonds have the least. Figure 14 shows these results.

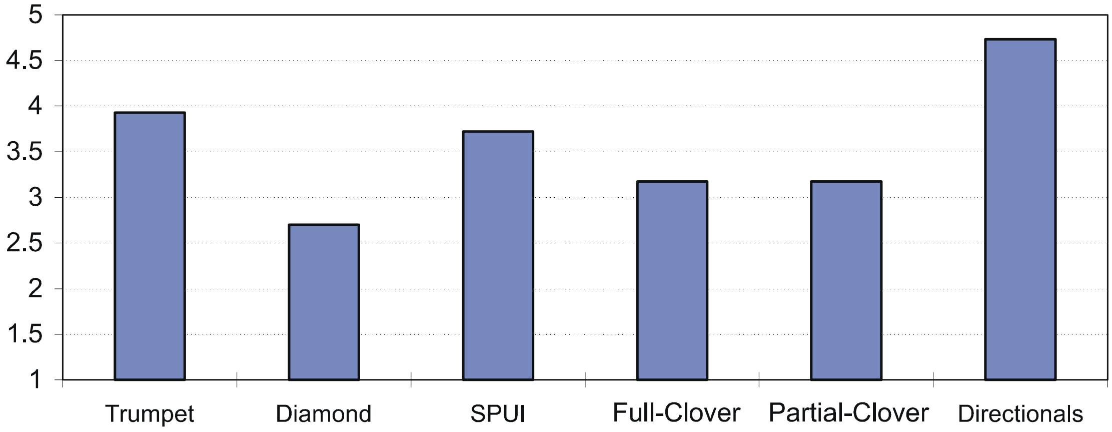

Figure 14. Ability To Increase Traffic Carrying Capacity Rankings

Respondents were also asked to rank each interchange type in terms of construction cost. Diamonds interchanges were seen as by far the least expensive, while directional interchanges were seen as the most expensive. Figure 15 shows the relative rankings.

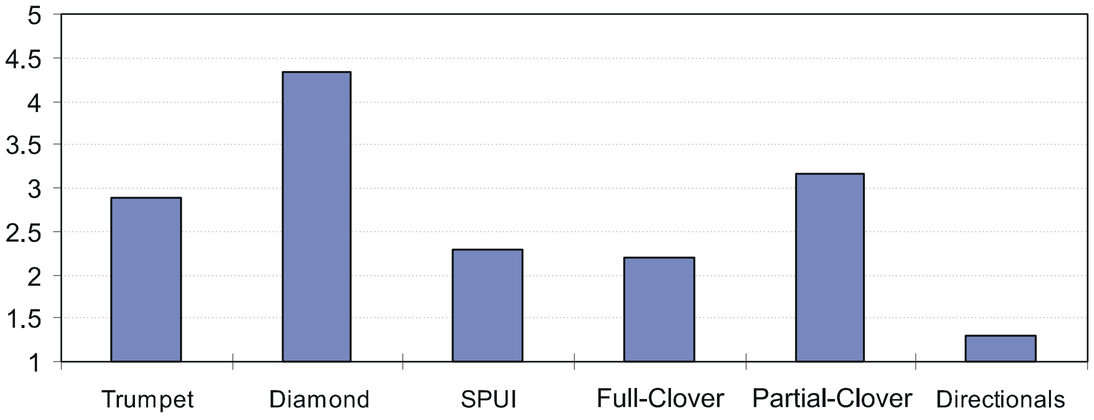

Figure 15. Construction Cost Rankings

Next, each interchange type was ranked according to its ability to accommodate high left-turn volumes. Directionals were seen as handling high left-turn volumes the best, and diamonds were seen as handling them the worst (see Figure 16).

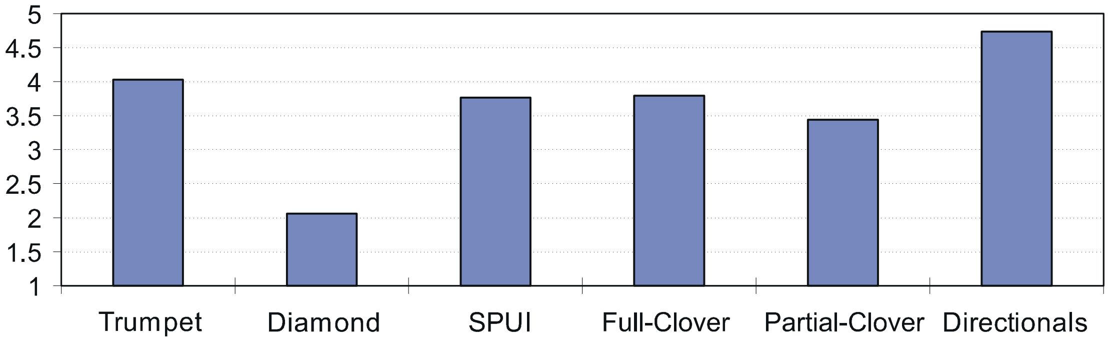

Figure 16. Ability To Accommodate High Left Turning Movement Rankings

Each survey participant was also asked to rank interchange types according to their safety performance. The rankings for all interchange types were fairly close to one another, with trumpet and directionals being ranked the safest. The safety rankings can be found in Figure 17.

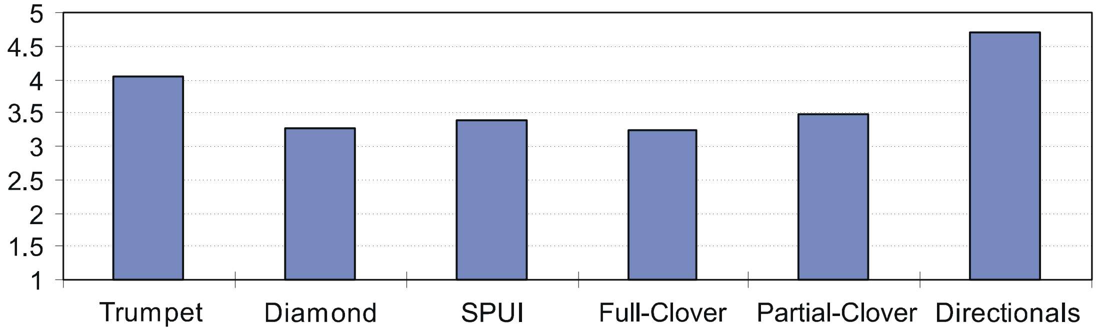

Figure 17. Safety Rankings

Interchange types were also ranked by how easy and inexpensive they were to maintain. Diamonds were ranked as the easiest and most inexpensive to maintain, while directionals were ranked as the most expensive and difficult to maintain (see Figure 18).

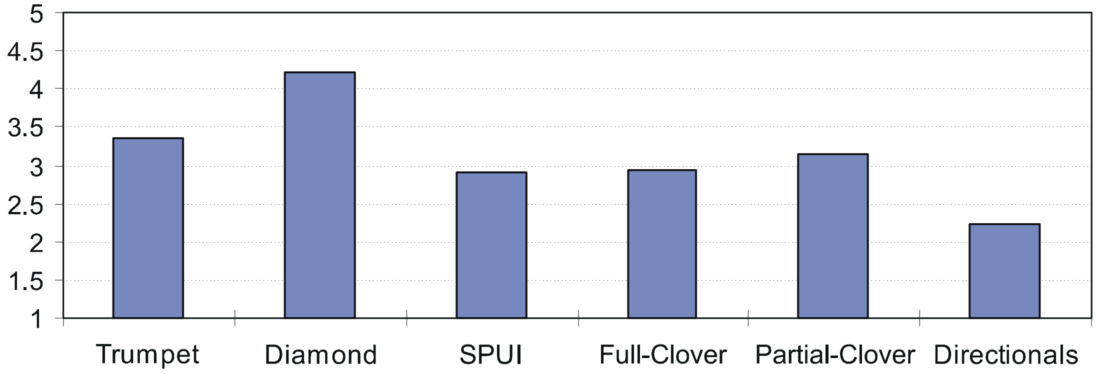

Figure 18. Ease And Cost Of Maintenance Rankings

Finally, each interchange type was ranked according to its ability to provide good access to surrounding land uses. Diamonds and SPUIs were seen as providing the best access, while directionals were seen as providing the worst access (see Figure 19).

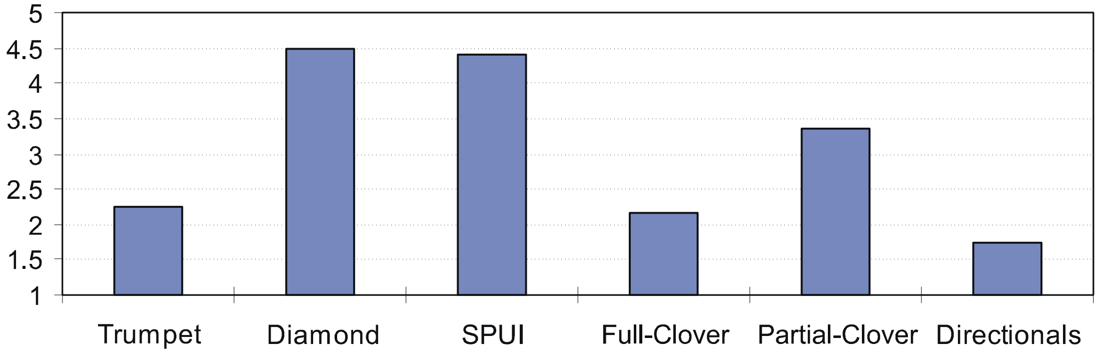

Figure 19. Ability To Provide Access To Surrounding Land Use Rankings

Comparison of Survey Results to Findings of Literature Review

The survey responses generally reinforced the findings of the literature review. While the responses showed trends, engineers ranked the interchanges according to their own personal preferences. For example, some respondents ranked the diamond ahead of the SPUI when the right of way is limited, although the overall mean of the rankings indicated that SPUIs were superior. While the individual rankings given by the state engineers for the various criteria could vary significantly, the overall average rank and most common ranks generally coincided with the findings of the literature review. For example, the state engineers recognized that:

1. SPUIs and diamonds are the most appropriate when the right of way is limited.

2. Directional interchanges have the highest capacity.

3. Diamond interchanges are the least expensive configuration, while directional interchanges are by far the most expensive.

4. Diamond interchanges have the greatest difficulty accommodating large left-turning movements.

States with No Guidelines

The majority of the states (78%) responding to the survey indicated that they did not have any formal interchange selection guidelines. These states used a variety of studies to determine which interchange type should be selected for a given location. A primary concern of many rural states, such as North Dakota and Kansas, was interchange uniformity. These states sought to create uniform interchanges throughout the state in an effort to improve driver familiarity, and thereby increase safety. The result of these efforts was usually a high percentage of diamond interchanges. Maryland, Michigan, and North Carolina noted that they relied upon capacity studies and other engineering studies to select an interchange type. These studies examined traffic patterns, weaving distances, capacity, cost, and the right of way required.

States with Interchange Selection Guidelines

Of the 36 responding states, only 8 (California, Indiana, Illinois, Louisiana, Missouri, New York, South Carolina, and Wisconsin) stated that they have guidelines that aid in the selection of an interchange for a particular location. Most of the interchange selection guidelines obtained are quite general. They offered general advice on the advantages and disadvantages of each interchange type, but provided no indication as to which was best for a particular situation.

Several states provided general guidelines for when an interchange was warranted. California’s guidelines stated that an interchange may be warranted when the main road is part of an expressway, when the installation of an interchange would improve safety or remove bottlenecks, and when topography dictated that an interchange would be used. Indiana’s warrants included all of these, but also stated that an interchange may be warranted whenever an at-grade intersection was operating at a poor level of service. In general, these warrants follow those presented in the AASHTO Green Book.

The states surveyed indicated that guidelines were developed using a variety of sources. Illinois and California based their guidelines on the AASHTO Green Book, the experiences of designers, and current research. Most states said that the guidelines were created in order to aid designers in the selection of an interchange type, although Illinois noted that its guidelines would also help increase interchange uniformity throughout the state.

States have found that the selection of the optimal interchange type must consider a variety of factors. Factors that California examined when selecting an interchange type included speed, traffic volume, traffic composition, number of intersecting legs, topography, amount of available right of way, impact on local planning, interchange spacing, community and environmental impact, and cost. In addition to all of these factors, Illinois conducted a road user benefit analysis to find out the economic benefits of constructing the interchange. However, a highway user benefit cannot be the sole reason for constructing an interchange. Indiana also considered route continuity, level of service of each interchange element, operational characteristics, driver expectancy, geometric design, potential for staged construction, and potential growth of surrounding area. For the most part, the factors considered were listed, but no policies were given as to when to use a certain interchange type.

The guidelines from other states consisted primarily of a description of each interchange type taken almost straight from the AASHTO Green Book and a list of factors for designers to consider. While most states' guidelines simply listed factors to consider and descriptions of interchange types, South Carolina took its guidelines a little bit further. South Carolina engineers produced a table that recommended a preliminary interchange type based on the interchange location, type of intersecting facility, and total interchange traffic (see Table 6).

Table 6. South Carolina DOT Preliminary Interchange Selection Table

Interchange Location	Type of Intersecting Facility	Total Interchanging Traffic (VPD)	Recommended Interchange Type (Preliminary)
Rural	Freeway	Light < 15000 AADT	Cloverleaf
		Moderate 15000 to 25000 AADT	Cloverleaf with C-D roads, semi-directional
		Heavy > 25000 AADT	Semi-directional, full directional
	Primary or Other Major Highway	Light < 15000 AADT	Diamond
		Moderate 15000 to 25000 AADT	Partial cloverleaf, cloverleaf, trumpet
		Heavy > 25000 AADT	Cloverleaf with C-D roads, semi-directional
	Local Road	Light < 10000 AADT	Diamond
		Moderate 10000 to 20000 AADT	Trumpet to cloverleaf
		Heavy - N/A	N/A
Urban	Freeway	Light – N/A	N/A
		Moderate 20000 to 35000 AADT	Cloverleaf with C-D roads, semi-directional
		Heavy > 35000 AADT	Semi-directional, full directional
	Primary or Other Major Highway	Light < 20000 AADT	Diamond, split diamond
		Moderate 20000 to 35000 AADT	Urban diamond, partial cloverleaf, full cloverleaf
		Heavy > 35000 AADT	Cloverleaf with C-D roads, semi-directional
	Local Road or Minor Street	Light < 15000 AADT	Diamond, split diamond
		Moderate 15000 to 30000 AADT	Urban diamond, partial cloverleaf
		Heavy > 30000 AADT	Cloverleaf with C-D roads

Accident Analysis Results

Accident data for the 2 diamond interchanges, 2 SPUIs, 3 partial cloverleafs, and 3 full cloverleafs studied were obtained and analyzed. Accidents were classified according to severity, collision location, and collision type. Summary tables for the 4 interchange types can be found in Appendix E.

Statistical tests were performed on the accident data using the t-test and proportionality test. It should be noted that due to the limited number of data points, the results of the statistical tests should not be given undue emphasis. The small number of data points may skew statistical results based on the accident data collected at the particular sites used. The statistics and graphical data presented are intended to show possible trends in crashes at each interchange type, not to show strong correlations between factors. More data points would be required to make any definitive assertions as to the relative safety advantages and disadvantages of each interchange type.

Severity

The t-test was used to examine differences between accident severity at the four interchange types. Since only 1 of the 178 accidents studied involved fatalities, statistical analysis was limited to examining overall injury and property damage only at the (PDO) accident rates.

Figure 20 shows the severity distribution for each of the four interchange types as a percentage of the total number of accidents occurring at that interchange type. The percentage of accidents at each severity level was very similar for all interchange types.

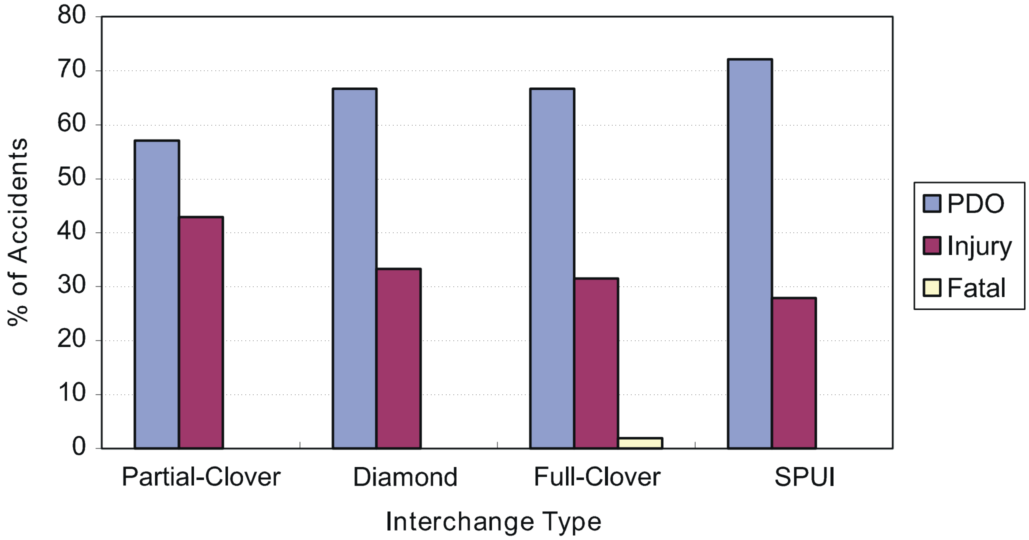

Figure 20. Accident Severity Distribution

The means of the accident rates for each severity level were tested using the t-test. The accident rate for each interchange type was compared to each other interchange type at $\alpha=0.05$. The following null hypotheses were formulated for the t-tests:

H_0: The overall accident rates were not significantly different among the interchange types

H_0: The injury accident rates were not significantly different among the interchange types

H_0: The PDO accident rates were not significantly different among the interchange types

The statistical tests show that there were no significant differences between the severity rates in nearly all cases. The only exception was the tests comparing the PDO and overall accident rates between SPUIs and partial cloverleafs, which showed that the partial cloverleafs had a significantly lower PDO and overall accident rate than SPUIs. It was possible, however, that this result was not representative of all SPUIs and partial cloverleafs due to the limited number of data points used. The results of the statistical tests can be found in Table 7.

Table 7. Results of Statistical Tests on Severity

Type 1	**Type 2**	**Accident Rate Tested**	**t**	**t_α**	**Result**
Partial Cloverleaf vs.	Diamond	Overall	0.05	2.35	Do not reject H_o
		Injury	0.69	2.35	Do not reject H_o
		PDO	-0.44	2.35	Do not reject H_o
	Full Cloverleaf	Overall	-0.55	2.13	Do not reject H_o
		Injury	-0.21	2.13	Do not reject H_o
		PDO	-0.60	2.13	Do not reject H_o
	SPUI	Overall	-2.44	2.35	Reject H_o, $\mu_{P\text{-}clo} < \mu_{SPUI}$
		Injury	0.33	2.35	Do not reject H_o
		PDO	-2.39	2.35	Reject H_o, $\mu_{P\text{-}clo} < \mu_{SPUI}$
Diamond vs.	Full Cloverleaf	Overall	-0.43	2.35	Do not reject H_o
		Injury	-0.80	2.35	Do not reject H_o
		PDO	-0.23	2.35	Do not reject H_o
	SPUI	Overall	-0.70	2.92	Do not reject H_o
		Injury	-0.53	2.92	Do not reject H_o
		PDO	-0.74	2.92	Do not reject H_o
Full Cloverleaf vs.	SPUI	Overall	-0.10	2.35	Do not reject H_o
		Injury	0.56	2.35	Do not reject H_o
		PDO	-0.27	2.35	Do not reject H_o

While fatalities were not explicitly analyzed due to the limited number of data points, it should be noted that any larger scale study of interchange accidents should consider fatalities. Fatal accidents have significant consequences in terms of lives lost and economic impact. The National Safety Council[21] published figures estimating the cost of the accidents types as:

- PDO: $6,000/accident
- injury: $32,200/accident
- fatality: $790,000/accident.

Based on these figures, the total economic impact of the accidents studied showed that the economic impact of the lone fatality was significant. The single fatality accounted for approximately 24% of the total economic impact of the accidents studied (see Table 8).

Table 8. Economic Impact of Accidents Studied

Interchange Type	Number Studied	PDO	Injury	Fatality	Total
Diamond	2	28	14	0	42
SPUI	2	44	17	0	61
Full Cloverleaf	3	36	17	1	54
Partial Cloverleaf	3	12	9	0	21
Total	10	120	57	1	178
Cost	10	$720,000	$1,835,400	$790,000	$3,345,400
% of Total Cost		21.5%	54.9%	23.6%	100%

Collision Type

The accident data were then broken down by collision type. The collision classifications used were: rear-end, angle, sideswipe, fixed object, and backed-into. Figure 21 shows the accident distribution by collision type for the four interchange types. This graph gives an indication as to the types of collisions that were most prevalent at the interchanges. Very few angle collisions occurred at the full cloverleafs because the full cloverleafs do not require turning movements that conflict with oncoming traffic. Likewise, there was a much higher percentage of fixed object accidents at full cloverleafs due to run-off road accidents on the loop ramps.

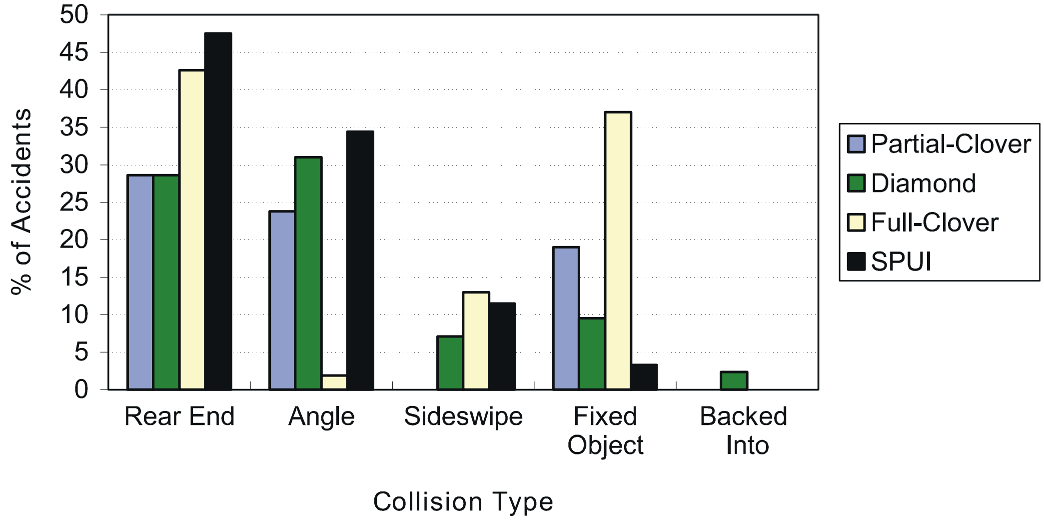

Figure 21. Collision Type Distribution

Proportionality tests were performed to examine the difference between the proportion of collision types at the various interchanges. The tests were performed at $\alpha = 0.05$ and used the following null hypotheses.

H_o: The proportion of rear-end accidents was the same for all interchange types.

H_o: The proportion of angle collisions was the same for all interchange types.

H_o: The proportion of sideswipes was the same for all interchange types.

H_o: The proportion of fixed object accidents was the same for all interchange types.

H_o: The proportion of backed-into accidents was the same for all interchange types.

The results of the tests can be found in Tables 9-13. The statistical analyses indicated several things:

1. There was no significant difference in the percentage of rear-end collisions at the four interchanges.

2. Full cloverleafs had a significantly smaller percentage of angle collisions than SPUIs or partial cloverleafs. This was probably attributed to the absence of left-turn movements that conflicted with oncoming traffic at full cloverleafs.

3. SPUIs had a significantly larger percentage of sideswipe accidents than partial cloverleafs and diamond interchanges.

4. Full cloverleafs had a statistically larger percentage of fixed object crashes than the other interchange types. These fixed object crashes were typically the result of a run-off-the-road type accident on the loop ramps.

5. No significant difference existed among the four interchange types for backed-into accidents.

Table 9. Rear End Collision Results

	Type 2	Z	Z_{crit}	Result
Diamond	Partial Cloverleaf	0.64	1.64	Do not reject H_o
	SPUI	0.44	1.64	Do not reject H_o
	Full Cloverleaf	1.04	1.64	Do not reject H_o
SPUI	Full Cloverleaf	1.54	1.64	Do not reject H_o
	Partial Cloverleaf	0.53	1.64	Do not reject H_o
Full Cloverleaf	Partial Cloverleaf	-0.60	1.64	Do not reject H_o

Table 10. Angle Collision Results

Type 1	Type 2	Z	Z_{crit}	Result
Diamond	Partial Cloverleaf	-0.12	1.64	Do not reject H_o
	SPUI	-1.12	1.64	Do not reject H_o
	Full Cloverleaf	0.93	1.64	Do not reject H_o
SPUI	Full Cloverleaf	23.3	1.64	Reject H_o, $p_{SPUI} > P_{FCLO}$
	Partial Cloverleaf	1.61	1.64	Do not reject H_o
Full Cloverleaf	Partial Cloverleaf	-1.78	1.64	Reject H_o, $p_{FCLO} < p_{PCLO}$

Table 11. Sideswipe Results

Type 1	Type 2	Z	Z_{crit}	Result
Diamond	Partial Cloverleaf	1.00	1.64	Do not reject H_o
	SPUI	-1.84	1.64	Reject H_o, $p_{DMD} < p_{SPUI}$
	Full Cloverleaf	-0.35	1.64	Do not reject H_o
SPUI	Full Cloverleaf	0.89	1.64	Do not reject H_o
	Partial Cloverleaf	3.99	1.64	Reject H_o, $p_{SPUI} > p_{PCLO}$
Full Cloverleaf	Partial Cloverleaf	1.00	1.64	Do not reject H_o

Table 12. Fixed Object Accident Results

Type 1	Type 2	Z	Z_{crit}	Result
Diamond	Partial Cloverleaf SPUI Full Cloverleaf	-0.89 -0.34 -2.52	1.64 1.64 1.64	Do not reject H_o Do not reject H_o Reject H_o, $p_{DMD} < P_{FCLO}$
SPUI	Full Cloverleaf Partial Cloverleaf	-2.63 -1.15	1.64 1.64	Reject H_o, $p_{SPUI} < P_{FCLO}$ Do not reject H_o
Full Cloverleaf	Partial Cloverleaf	2.02	1.64	Reject H_o, $p_{FCLO} > p_{PCLO}$

Table 13. Backed Into Accident Results

Type 1	Type 2	Z	Z_{crit}	Result
Diamond	Partial Cloverleaf SPUI Full Cloverleaf	0.98 0.98 0.98	1.64 1.64 1.64	Do not reject H_o Do not reject H_o Do not reject H_o
SPUI	Full Cloverleaf Partial Cloverleaf	0 0	1.64 1.64	Do not reject H_o Do not reject H_o
Full Cloverleaf	Partial Cloverleaf	0	1.64	Do not reject H_o

Collision Location

Each accident was also classified according to where it took place. The general classifications used were: on-ramp, off-ramp, cross-road, weaving area, and center-of-intersection. Obviously, not all of these classifications were used for each interchange, since certain geometric features may not be present. For example, full cloverleaf interchanges did not have any intersections, and diamonds and SPUIs did not possess weaving areas. Since the interchange components were not always analogous, no statistical analysis was performed on the data. Instead, the analysis of collision location was performed in a more qualitative way.

Figure 22 gives an indication of the relative percentages of accidents that occurred at each location for each interchange type. Nearly all of the collisions at full cloverleafs tended to occur on the ramps and the weaving areas. The prevalence of accidents in these locations may be influenced by the geometrics of the loop ramps. Over 50% of the accidents for partial cloverleafs occurred on the crossroad. SPUIs also experienced a large proportion of accidents on the crossroad. Diamond interchanges experienced over 50% of their collisions at the intersections of the ramp terminal and the major road, where conflicting traffic flows intersected.

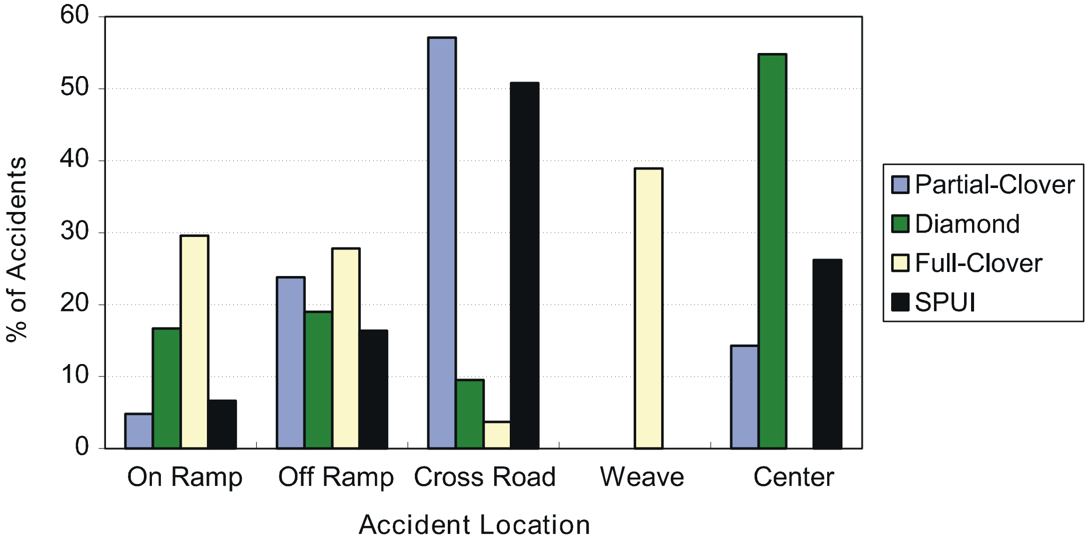

Figure 22. Accident Location Distribution

Operational Comparison

Field Data Simulations and Model Calibration

The interchanges studied in the field were each simulated using CORSIM. CORSIM produced data on delay, speed, and density, which was used to evaluate the performance of each interchange under the existing traffic and geometric conditions. The existing traffic flows present at the interchanges studied are shown in Table 14. The total peak hour volumes (PHV) varied greatly, ranging from 666 to 6623.

Table 14. Volume Characteristics of Field Data Sites

Interchange	NB		SB		EB			WB			PHV
	L	R	L	R	L	T	R	L	T	R	
D-1	140	195	189	71	77	587	189	276	588	127	2439
D-2	62	16	19	85	201	73	122	18	55	15	666
PC-1	56	61	159	71	69	331	66	41	252	158	1264
PC-2	202	246	354	57	29	176	107	625	704	735	3235
PC-3	9	35	164	103	25	167	67	14	240	18	842
FC-1	176	384	209	102	96	715	281	312	364	269	2908
FC-2	31	57	308	18	15	94	78	146	75	193	1015
FC-3	191	529	359	62	62	244	113	342	314	358	2574
SP-1	253	217	41	87	43	881	114	105	683	26	2450
SP-2	806	373	326	806	923	1257	136	500	742	754	6623

Since each interchange type is composed of different components, the analyses performed varied with interchange type. The analyses performed for each interchange type were:

1. *Diamond*: Signalized delay, unsignalized delay (according to existing conditions).

2. *SPUI*: Signalized delay, unsignalized delay.

3. *Partial Cloverleaf*: Weaving (where appropriate), signalized delay (where appropriate), unsignalized delay, ramp and ramp junction density.

4. *Full Cloverleaf*: Weaving, ramp, and ramp-junction density.

It should be noted that these analyses were performed for the interchange as a whole. This can have a significant impact on the data. For example, since diamond interchanges have two at-grade intersections at the junctions of the ramp with the minor road, the delay experienced by vehicles traveling through the interchange was actually the sum of the delays at the two intersections. An average value was then found for each component for the entire interchange by taking a weighted average.

The results of the analysis of current conditions can be found in Table 15. Due to the limited number of sites, no trends can be identified in the data. Thus, it was necessary to simulate each interchange as the other three interchange types in order to get a better idea of how the different interchange types perform relative to one another.

Table 15. Level of Service of Field Data Sites

Interchange	Signalized		Unsignalized		On/Off Ramps		Weave (Weaving/ Non-weaving)	
	Delay (s/veh)	LOS	Delay (s/veh)	LOS	Density (veh/km/ln, [veh/mi/ln])	LOS	Speed (kph, [mph])	LOS
D-1	20.4	C	3.8	A	-	-	-	-
D-2	-	-	2.8	A	-	-	-	-
PC-1	-	-	5.1	B	2.3, [3.7]	A	-	-
PC-2	-	-	9.2	B	7.0, [11.2]	B	61.2/69.2 [38/43]	E/D
PC-3	-	-	5.4	B	1.2, [2.0]	A	-	-
FC-1	-	-	-	-	8.8, [14.2]	B	76.9/88.2 [47.8/54.8]	C/B
FC-2	-	-	-	-	2.4, [3.8]	A	85.3/93.0 [53.0/57.8]	B/B
FC-3	-	-	-	-	6.5, [10.4]	B	74.7/84.0 [46.4/52.2]	C/C
SP-1	18.8	C	4.0	A	-	-	-	-
SP-2	61.4	F	8.0	B	-	-	-	-

The CORSIM model generally needed only minor adjustments in order to simulate existing conditions. Merging/diverging movements, signalized delay, and unsignalized delay were usually modeled relatively accurately. CORSIM did have difficulty modeling the unsignalized delay at the very low-volume interchanges, usually underestimating the delay. In these cases, start-up lost times were increased to compensate for this. CORSIM also had some difficulty modeling the weaving areas. Entrance/exit signs had to be placed near the midpoint of the weaving area in order to prevent vehicles from entering the freeway immediately or leaving at the last moment. There also were problems with the weaving vehicles missing their exits, particularly as volumes increased. In these cases, the percent of vehicles yielding to lane-changing vehicles was also increased to help counteract this problem.

Interchange Redesign and Simulation

In this phase, each interchange was redesigned as each of the other interchange types. Signal timings were optimized, and good geometric design principles were used in creating the simulations for the new interchange types. This was done in order to learn how the interchange types performed relative to one another under the existing traffic conditions at the location.

There were some difficulties with maintaining the calibration of the model as interchanges were redesigned. When diamonds were converted to SPUIs, or vice versa, the factors changed for calibration were identical. In these cases, the diamond and SPUIs could be assumed to operate similarly. When the simulations required changing from a FRESIM to a NETSIM model (e.g., diamond being converted to a full cloverleaf), the calibration factors could not be carried over. In these cases, the factors changed to calibrate the NETSIM models were not the same as the factors calibrated in the FRESIM models. For these situations, an existing site of the proper type of interchange whose traffic characteristics were similar to the one to be modeled was identified. The calibration values used for this existing site were applied to the new interchange model.

The results of these analyses can be found in Table 16. One conclusion that can be made is that diamond interchanges operate very well when the entering volumes are low (under 1500 vph). In these cases, an unsignalized diamond can be used and a very high level of operations can be maintained.

It is difficult to make other conclusions based on the interchanges' performance due to site-specific characteristics. Only two of the sites had entering volumes above 3000 vph, and geometric characteristics varied widely. For example, some sites had deficient weave/merge areas. Whether right turns were signalized or unsignalized varied from site to site.

Table 16. Operational Results of Interchange Redesign

Site	**Designed as**	**Signalized**		Unsignalized		**On/Off Ramps**		**Weave (Weaving/ Non-weaving)**	
		Delay (s/veh)	**LOS**	**Delay (s/veh)**	**LOS**	**Density (veh/km/ln, [veh/mi/ln])**	**LOS**	**Speed (kph, [mph])**	**LOS**
D-1	Diamond	40.9	E	3.8	A	-	-	-	-
	SPUI	25.9	D	4.0	A	-	-	-	-
	P-Clo	16.5	C	-	-	6.4, [10.3]	B	-	-
	F-Clo	-	-	-	-	5.4, [8.7]	A	77.1/90.1 [47.9/56.0]	C/B
D-2	Diamond	-	-	3.0	A	-	-	-	-
	SPUI	16.1	C	3.1	A	-	-	-	-
	P-Clo	-	-	6.3	B	2.3, [3.7]	A	-	-
	F-Clo	-	-	-	-	1.8, [2.9]	A	93.8/99.6 [58.3/61.9]	A/A
PC-1	P-Clo	-	-	5.1	B	2.3, [3.7]	A	-	-
	Diamond	-	-	6.6	B	-	-	-	-
	SPUI	14.8	B	1.2	A	-	-	-	-
	F-Clo	-	-	-	-	2.7, [4.3]	A	86.6/97.5 [53.8/60.6]	B/A
PC-2	P-Clo	-	-	9.2	B	7.0, [11.2]	B	61.2/69.2 [38/43]	E/D
	Diamond	86.2	F	-	-	-	-	-	-
	SPUI	28.3	D	5.6	B	-	-	-	-
	F-Clo	-	-	-	-	9.3, [14.9]	B	68.9/77.1 [42.8/47.9]	D/D
PC-3	P-Clo	-	-	5.4	B	1.2, [2.0]	A	-	-
	Diamond	-	-	6.1	B	-	-	-	-
	SPUI	13.9	B	1.7	A	-	-	-	-
	F-Clo	-	-	-	-	1.9, [3.0]	A	90.3/99.0 [56.1/61.5]	A/A
FC-1	F-Clo	-	-	-	-	8.8, [14.2]	B	76.9/88.2 [47.8/54.8]	C/B
	Diamond	21.6	C	-	-	-	-	-	-
	SPUI	20.9	C	2.2	A	-	-	-	-
	P-Clo	8.0	B	-	-	6.3, [10.2]	B	-	-
FC-2	F-Clo	-	-	-	-	2.4, [3.8]	A	85.3/93.0 [53.0/57.8]	B/B
	Diamond	-	-	5.8	B	-	-	-	-
	SPUI	17.1	C	0.6	A	-	-	-	-
	P-Clo	-	-	5.4	B	2.2, [3.5]	A	-	-
FC-3	F-Clo	-	-	-	-	6.5, [10.4]	B	74.7/84.0 [46.4/52.2]	C/C
	Diamond	31.3	D	-	-	-	-	-	-
	SPUI	18.5	C	2.3	A	-	-	-	-
	P-Clo	-	-	6.8	B	5.2, [8.3]	A	66.0/77.2 [41/48]	D/C
SP-1	SPUI	18.8	C	4.0	A	-	-	-	-
	Diamond	17.1	C	3.8	A	-	-	-	-
	P-Clo	-	-	9.7	B	7.0, [11.2]	B	-	-
	F-Clo	-	-	-	-	6.0, [9.6]	A	77.6/93.8 [48.2/58.3]	C/B
SP-2	SPUI	61.4	F	8.0	B	-	-	-	-
	Diamond	61.0	F	-	-	-	-	-	-
	P-Clo	133.1	F	-	-	14.5, [23.3]	C	49.9/62.8 [31.0/39.0]	F/E
	F-Clo	-	-	-	-	15.3, [24.6]	C	52.6/67.1 [32.7/41.7]	F/E

Note: P-Clo = partial clover. F-Clo = full clover.

Volume Scenario Simulations

In order to make a better comparison between the interchange types, it was necessary to simulate a variety of volume scenarios on the same interchange network so that geometric conditions could be held constant. These simulations were loosely based on the conditions at the actual field data sites and should serve to highlight traffic conditions that affect the operations at each interchange type. The volume scenarios used can be found in Appendix D. These scenarios were developed to test how the various interchange types reacted to (1) different entering volumes and (2) different traffic distributions with a constant volume. The results of these simulations are dealt with below.

SPUI Simulations

The network used to simulate the SPUI had unsignalized right turns from the ramps and unsignalized rights from the minor route onto the ramps. This was done because Smith and Garber found in their research that the provision of unsignalized right turns on the ramps of SPUIs and diamonds decreased overall delays significantly. The same road network was used in all simulations to provide a consistent basis for comparison. Signal timings were optimized, based on the traffic at the interchange. In addition to the four entering volumes applied to all of the interchanges, a 5500 vph entering vehicle volume case was used at the SPUI in order to fill in gaps in the delay graphs.

The graph of the unsignalized delay for the right-hand turns at the SPUI can be found in Figure 23. For entering volumes of 5500 vph or less, the unsignalized delay is LOS C or better, with most volume scenarios operating at LOS A or B. For the 6500 vph case, the unsignalized delay begins to vary dramatically as congested conditions begin to occur on the mainline. For this case, small changes in vehicle distributions can result in substantial changes in delay. It should be noted that throughout this report, the data points presented are connected with lines in order to better compare values. The data points presented are discrete and the lines connecting the data points should not be assumed to represent trends. In other words, a volume scenario with characteristics half way between A and B cannot be assumed to have a value at a point halfway between the A and B on the line connecting the two.

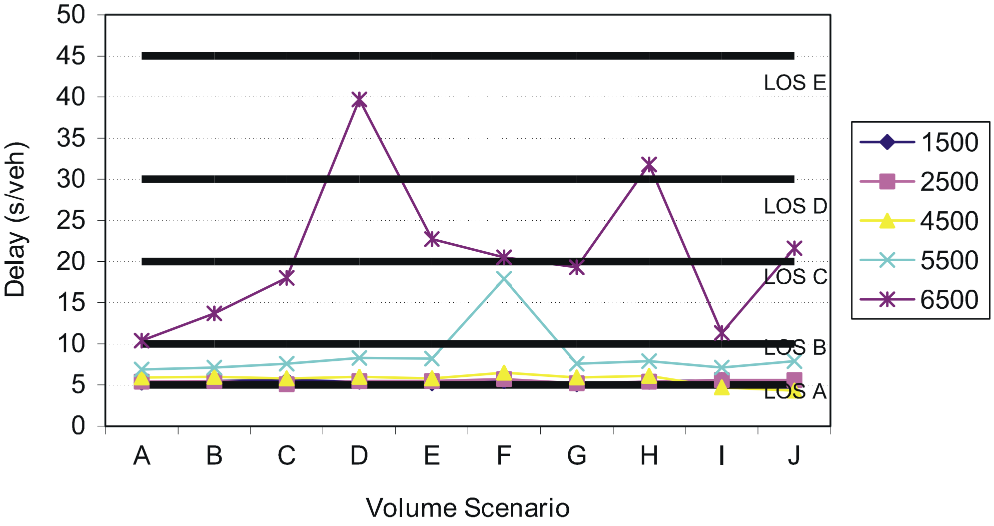

Figure 23. Average Unsignalized Delay for Right Turning Movements at SPUI

Figure 24 shows the average signalized delay at the SPUI. Signalized delay is LOS D or better when the entering volume is 5500 vph or less. As the entering volume increases, differences in delay for the various volume scenarios became more dramatic. Volume scenario A (Equal throughs, ramp lefts, and mainline lefts) consistently had lower average delay than the other scenarios, especially in the high-volume cases. Volume scenarios C, D, E, F, and H also represent peaks in the delay at the interchange. This seem to indicate that the SPUI perform worse when there are unbalanced mainline left turns. The graph also shows that when the left turn-offs on the ramps are unbalanced, the delay is always higher than the corresponding scenario where the ramp left turns are balanced. From this graph, it would appear that the distribution of volumes at the SPUI can have a significant impact on delay at the SPUI.

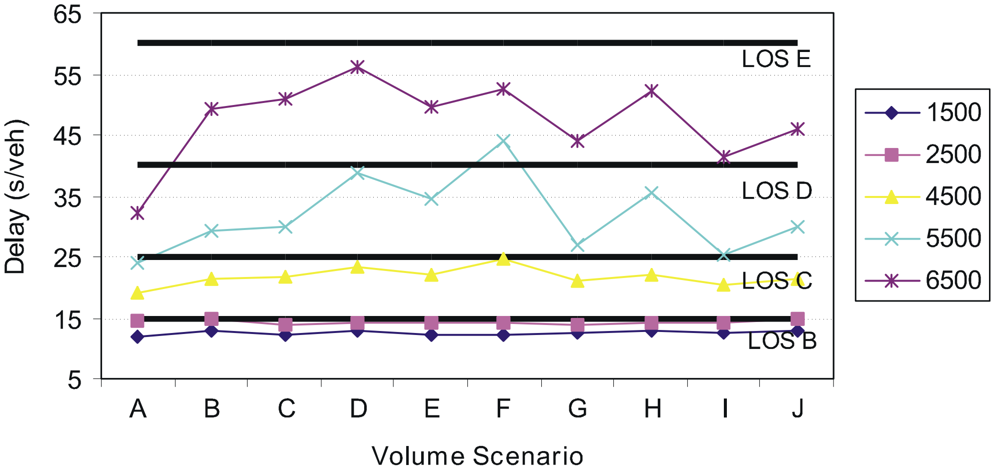

Figure 24. Average Signalized Delay at SPUI

Diamond Interchange Simulations

The diamond interchange network used also had unsignalized right turns. Signal timings were optimized, based on the volumes at the interchange. The road geometry was held constant for all the simulations.

Figure 25 shows the unsignalized right-turn delay at the diamond interchanges. Right turns are operating at LOS A/B for the cases with 4500 entering vph or less. The 6500 vph case varies from LOS C/D. Again, there is a great deal of variability in the unsignalized LOS as the volume increases to 6500 vph.

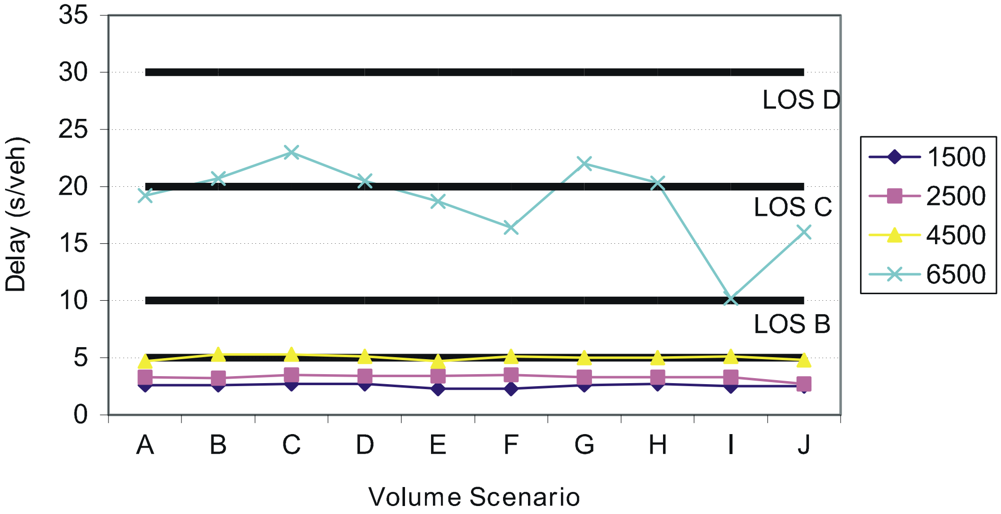

Figure 25. Average Unsignalized Delay for Diamond Right Turning Movements

The diamond interchange signalized delay is shown in Figure 26. The interchange is operating at LOS D or better for the cases where the entering volume is 4500 vph or less. At 6500 vph, the interchange is operating at LOS E/F. The diamond interchange produce higher delays than the SPUI for all of the volume scenarios studied. This is probably due primarily to the two-intersection configuration of the diamond vs. the one intersection of the SPUI.

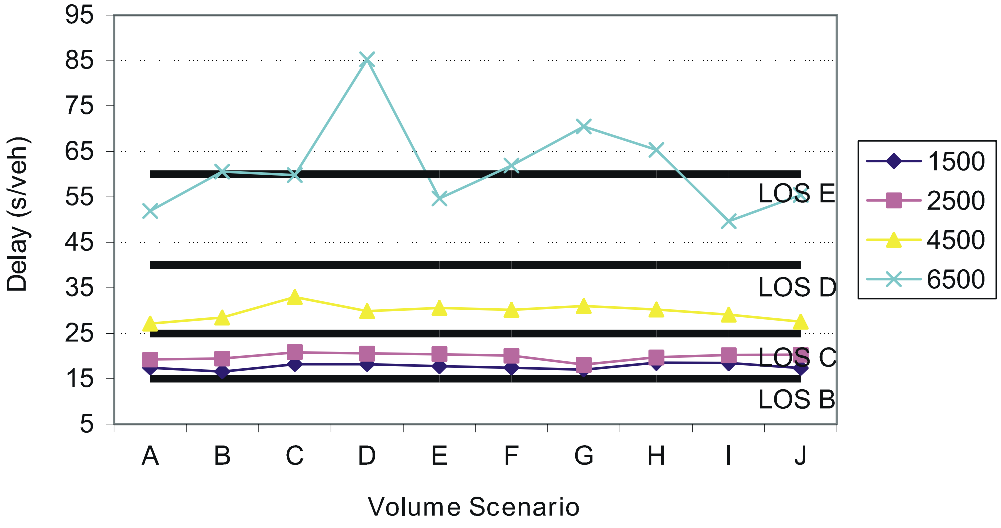

Figure 26. Average Signalized Delay for Entire Diamond Interchange

Full Cloverleaf Simulations

The full cloverleaf simulations were all conducted on the same network. The geometric layout was kept constant; only the volume scenarios were changed.

A weighted average of the densities was found for all of the ramps at the interchange. Figure 27 shows the densities in the influence of the ramp junctions. The ramps are operating at an average LOS of C or better for all of the entering volumes. Peaks in average density occur at volume scenarios E, F, G, and H for all of the volumes. While the LOS is acceptable in all cases, it seem that when throughs are unbalanced and minor route left turns are either balanced or opposed by a lower through volume, the ramp densities increase slightly.

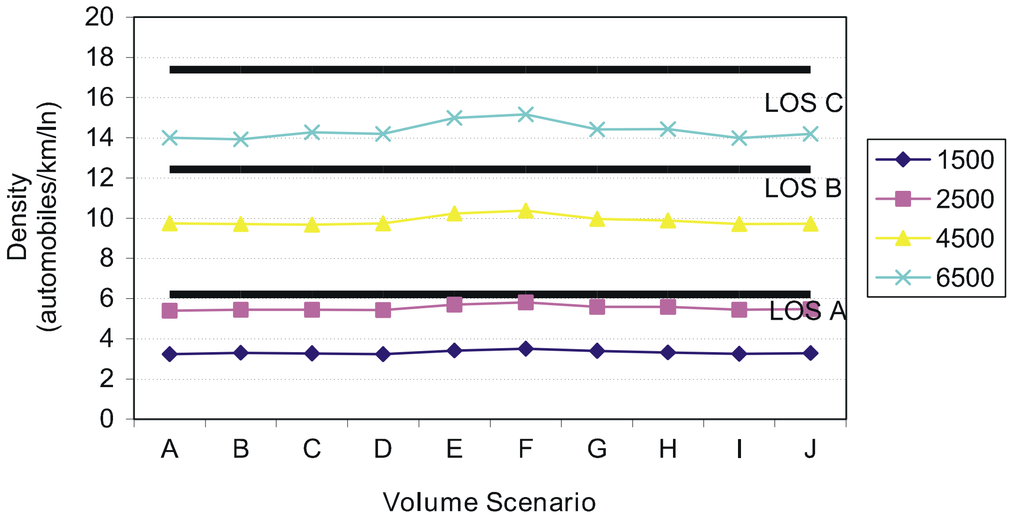

Figure 27. Average Ramp Junction Density for Full Cloverleaf

Next, the weaving areas were analyzed. The analysis of weaving areas was broken down further into the analysis of the speeds of weaving vehicles and non-weaving vehicles. These speeds were separated by viewing the interchange network in the TRAFVU component of CORSIM and manually clicking on weaving and non-weaving vehicles. Figure 28 shows the average non-weaving speeds at the weave area for the various volume scenarios. The non-weaving vehicles are operating at LOS D or better for entering volumes of 4500 vph, or less.

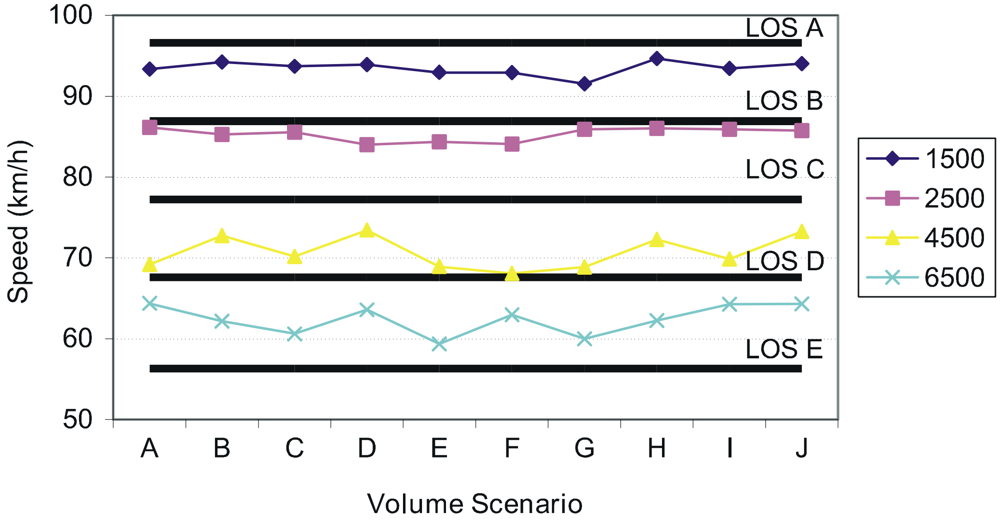

Figure 28. Average Non-Weaving Speeds at Full Cloverleaf Weaving Areas

Average weaving speeds for the full cloverleaf are shown in Figure 29. The weaving speeds are somewhat lower than the non-weaving speeds. At 4500 entering vehicles and higher, the weaving vehicles are operating at LOS E/F. It should be noted that the AASHTO Green Book states that weaving operations begin to degrade when the number of weaving vehicles approached 1000 vph. For the 4500 vph case, the average number of weaving vehicles is 855, and at 6500 vph it is 1235 vph. This confirms the AASHTO guidelines. Weaving speeds at the full cloverleaf are much more dependent on the magnitude of the entering volume than on how that volume is distributed. This is shown in Figure 29, as the variations among the volume scenarios are relatively minor for each entering volume tested.

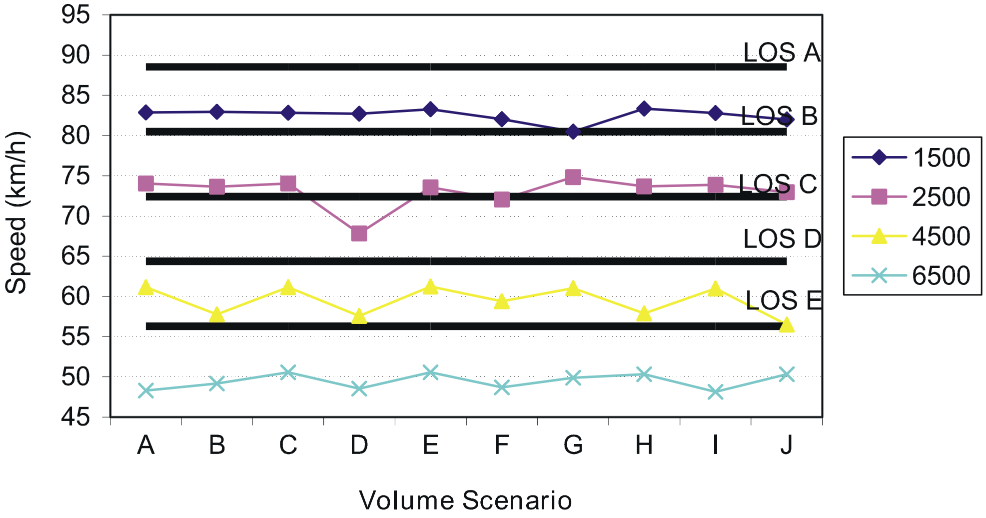

Figure 29. Average Weaving Speeds at Full Cloverleafs

Partial Cloverleaf Simulations

Due to the number of possible ramp variations in a partial cloverleaf, the design of the partial cloverleafs was more difficult. The configurations used in these simulations differed somewhat as entering volumes and volume scenarios changed. First, the number of loop ramps provided (and their configurations) changed as the entering volumes increased. One loop ramp was provided for the 1500 vph case, 2 for the 2500 vph case, and 3 for the 4500 vph and 6500 vph cases. The number of loop ramps provided was based on the literature, and the number of loop ramps provided at the actual partial cloverleafs studied in the field. Loop ramps were provided for the left-turning movements that had the highest volumes, so that the least impediment would be provided to the largest-left turning movements. Interchange configurations were uniform within each volume case, with the exception of the 2500 vph case. In that case, the loops were in opposite quadrants for scenarios A, B, C, E, G, H, and I. For scenarios D, F, and J, the volume scenarios required that the loop ramps be placed side by side so as to create a weaving area in order to accommodate the highest left-turn movements. The network used for these cases can be found in Appendix C.

The traffic control used also changed as the volumes increased. For the 1500 vph and most of the 2500 vph cases, signalized controls were provided at both of the ramp junctions (nodes 4 and 7 in Appendix C). When the third loop was added or when the weave was provided in the 2500 vph case, only one intersection was controlled by a signal (Node 4) since a left-turn conflict point had been eliminated due to the provision of a loop for the eastbound left turns.

The signalized delay experienced at the partial cloverleaf can be found in the Figure 30. The signalized delay experienced was generally LOS B or C. The signalized delay was much lower than the SPUI or diamond, since the largest left turning movements were handled by loop ramps. There was a large reduction in the average signalized delay between the 2500 vph case and the 4500 vph case, since this was the point where the interchange went from two signalized intersections to one, thus reducing the delay. Volume scenarios D, F, and J had the lowest delays for the 1500 vph, 2500 vph, and 6500 vph cases. This was due to the low number of mainline left turns handled by the signalized control in these cases.

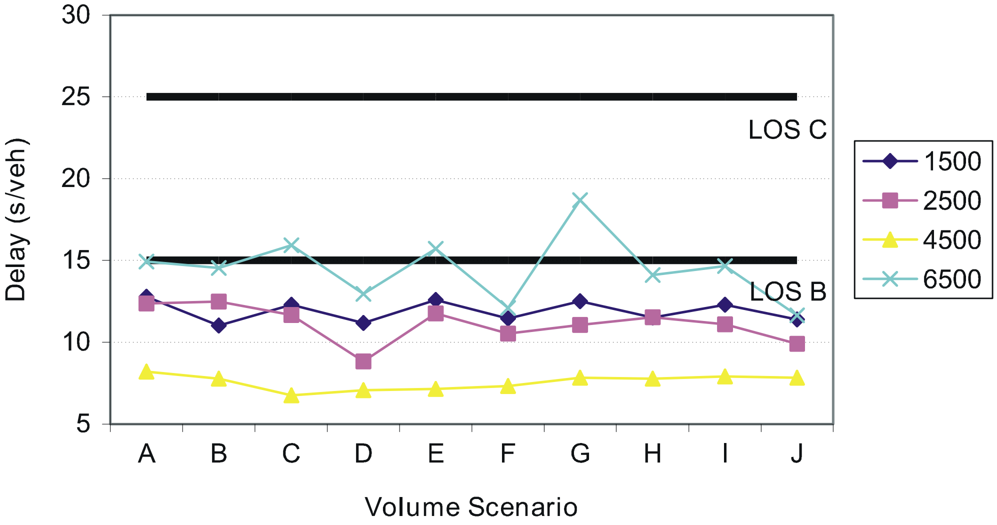

Figure 30. Average Signalized Delay at Partial Cloverleafs

The graph of the ramp densities can be found in Figure 31. Ramp densities generally increased as the entering volume increased, but all ramp junctions were operating at LOS C or better. With the higher entering volumes, scenarios E and F represented the low points and scenarios G and H represented the peaks. While there was variation within the graph, all LOSs were within acceptable ranges.

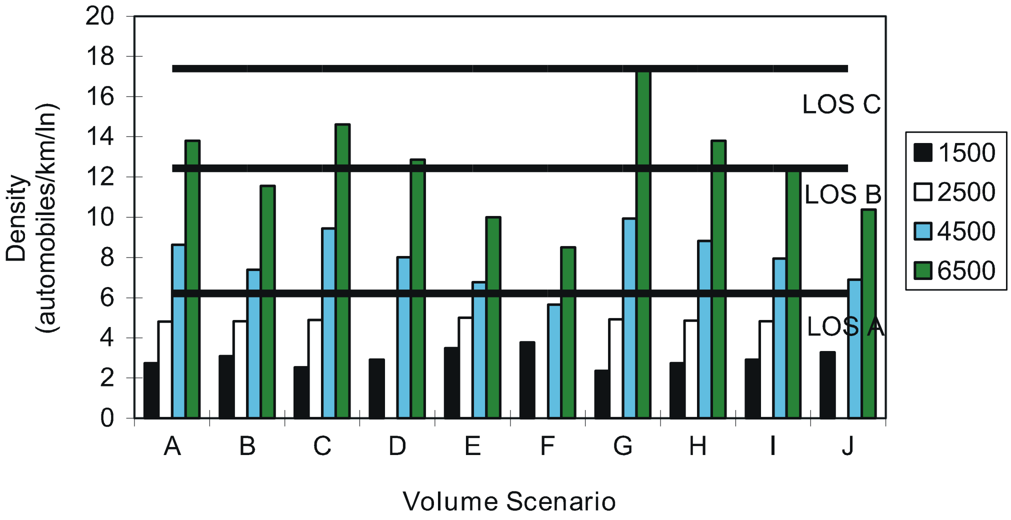

Figure 31. Average Density at Partial Cloversleaf Ramp Junctions

The non-weaving speeds for the partial cloverleaf configurations with a weaving area are shown in Figure 32. As indicated earlier, weaving areas existed for scenarios D, F, and J. The speeds for the 2500 vph and 4500 vph cases were generally LOS D. The LOS for the 6500 vph case were LOS E. Speeds peak for the 4500 vph and 6500 vph case at scenario G, where there was the lowest number of weaving vehicles and the smallest through volume. The non-weaving speeds were comparable to the full cloverleaf non-weaving speeds.

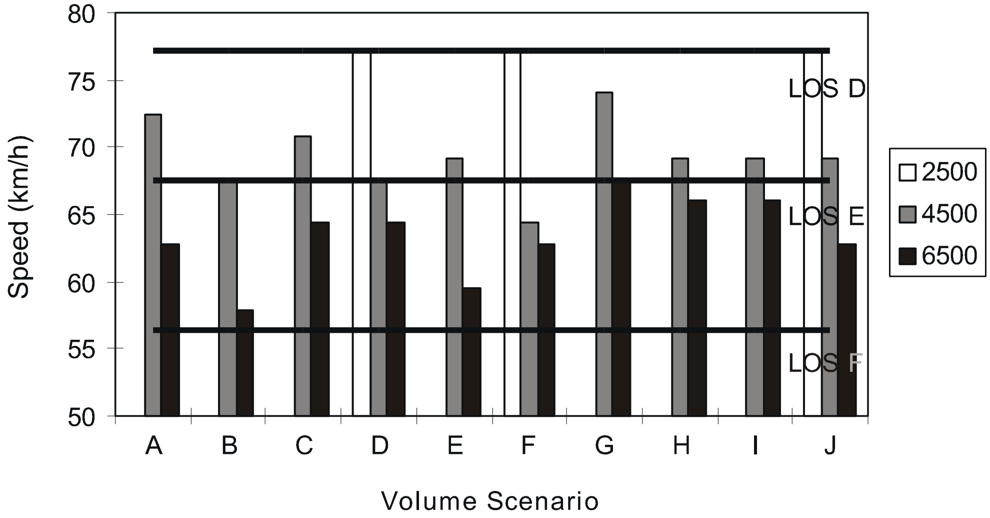

Figure 32. Average Non-Weaving Speeds at Partial Cloverleaf Weaving Areas

The weaving speeds for the partial cloverleafs are shown in the Figure 33. The 2500 vph case had weaving speeds in the LOS D range. All other cases were operating at LOS E/F.

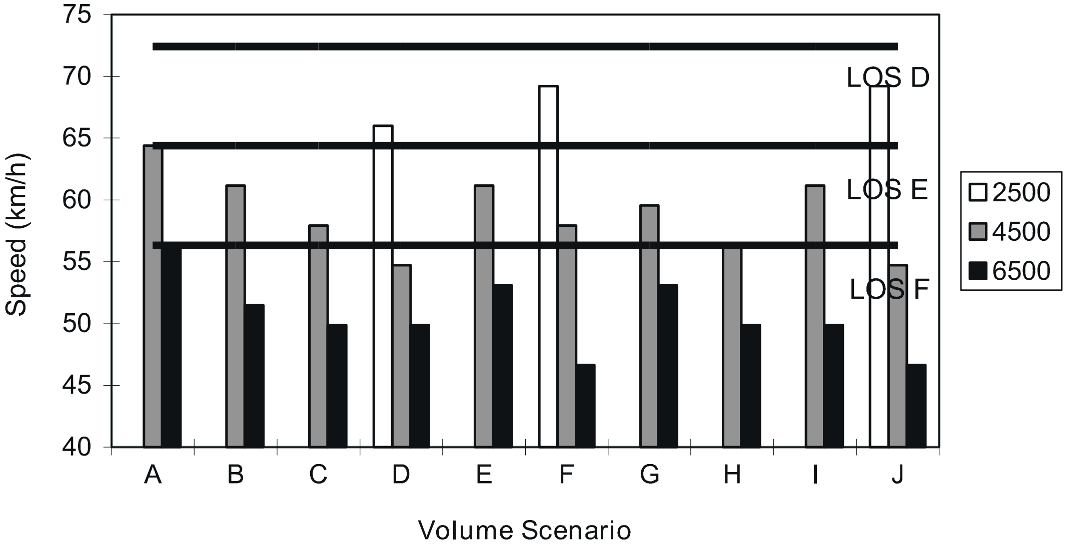

Figure 33. Average Weaving Speeds at Partial Cloverleaf Weaving Areas

Statistical Analysis of Volume Scenario Data

While the graphs presented earlier seem to show some trends, statistical tests were performed to determine if the differences in the data were statistically significant. The Friedman's F_r test for randomized block design was chosen for these analyses for several reasons. The F_r test is a non-parametric test, meaning it does not rely on any underlying assumptions on the distribution of the data. It also allows for blocking of data in order to take into account various factors. In the F_r test, the data are ranked numerically from first to last within each block and then tested to see if the null hypothesis is accepted or rejected. An example of this process can be found in the next section.

Entering Volume

The first test was done to determine if the entering volume had a statistically significant impact on the average signalized delay at a SPUI. The following null hypothesis was formed:

H_o = The distribution of delays was the same for all entering volumes.

Table 17 shows the table developed to rank the signalized delay at the SPUI for the different entering volumes. Using the data in that table, the F_r statistic can be calculated using the following equation:

$$F_r = \frac{12}{bk(k+1)} \sum R_j^2 - 3b(k+1)$$

Table 17. F_r Analysis for Effect of Entering Volume on SPUI Signalized Delay

Volume Scenario	Delay (s)									
	1500 vph	**Rank**	**2500 vph**	**Rank**	**4500 vph**	**Rank**	**5500 vph**	**Rank**	**6500 vph**	**Rank**
A	12.0	1	14.6	2	19.1	3	24.1	4	32.2	5
B	12.8	1	14.8	2	21.5	3	29.3	4	49.1	5
C	12.2	1	14	2	21.8	3	29.9	4	50.8	5
D	12.9	1	14.2	2	23.4	3	38.7	4	56.0	5
E	12.1	1	14.3	2	21.9	3	34.6	4	49.6	5
F	12.3	1	14.3	2	24.7	3	44.1	4	52.7	5
G	12.5	1	13.7	2	21.1	3	27.1	4	43.9	5
H	12.9	1	14.3	2	22.2	3	35.6	4	52.1	5
I	12.6	1	14.3	2	20.4	3	25.4	4	41.3	5
J	12.9	1	14.8	2	21.4	3	29.9	4	46.1	5
	R_1=	**10**	**R_2=**	**20**	**R_3=**	**30**	**R_4=**	**40**	**R_5=**	**50**

Where: b = number of blocks

k = number of treatments

R_j = ranked sum of jth treatment where the rank if each measurement is computed relative to its position within it own block.

The F_r statistic has approximately a χ^2 distribution with k-1 degrees of freedom. In this case, F_r=40.0, which is greater than $\chi^2_{(0.05,\,4)} = 9.49$. Thus, the null hypothesis is rejected, indicating that there was a significant difference in the signalized delays produced by the various entering volumes. Based on this result, it can be assumed that significant differences existed between the entering volume scenarios for all of the other MOEs tested, since the data all exhibited similar characteristics. Specifically, as the volume increased, levels of service consistently declined.

Volume Scenarios

The component with the lowest LOS for each interchange type was tested using the F_r test in order to determine if the different volume scenarios resulted in statistically significant differences in each MOE. The following null hypotheses were formed for these tests:

H_o = The distribution of partial cloverleaf weaving speeds was the same for all volume scenarios.

H_o = The distribution of full cloverleaf weaving speeds was the same for all volume scenarios.

H_o = The distribution of diamond signalized delays was the same for all volume scenarios.

H_o = The distribution of SPUI signalized delays was the same for all volume scenarios.

Analysis for each component was performed using the methodology presented earlier. The results of these tests are shown in Table 18.

Table 18. Results of Volume Scenario Statistics

Interchange	**MOE tested**	**F_r**	**$\chi^2_{(0.05,\,9)}$**	**Result**
Partial Cloverleaf	Weaving Speeds	14.84	16.92	Do not reject H_o
Full Cloverleaf	Weaving Speeds	14.73	16.92	Do not reject H_o
Diamond	Signalized Delay	14.29	16.92	Do not reject H_o
SPUI	Signalized Delay	20.51	16.92	Reject H_o

These results indicate that there is no statistically significant difference in the MOEs between the volume scenarios for the critical components of the partial cloverleaf, full cloverleaf, and diamond. While the differences in the volume scenarios were not found to be statistically significant in these cases, the trends shown in the graphs could provide some indication of characteristics that affect the operations of these interchange types.

In the case of the SPUI, it was found that the different volume scenarios did create significant differences in the amount of delay experienced by the vehicles at the interchange. The graph of the signalized delay at the SPUI showed that the scenarios where the interchange left turns are balanced (A, C, E, G, and I) were consistently lower than their counterparts when the left turns were unbalanced (B, D, F, H, and J) (see Figure 23). Another set of statistical tests was performed comparing scenarios A, C, E, G, and I (balanced ramp left turns) to each other and comparing scenarios B, D, F, H, and J (unbalanced left turns) to each other. The null hypotheses used in these analyses were:

H_o: The distribution of the signalized delays was not significantly different in the scenarios where the left-turning ramp movements were balanced.

H_o: The distribution of the signalized delays was not significantly different in the scenarios where the left-turning ramp movements were unbalanced.

The results of these tests are shown in Table 19.

Table 19. Results of SPUI Signalized Delay Volume Scenario Statistics

Case	$\mathbf{F_r}$	$\chi^2_{(0.05,4)}$	**Result**
Balanced ramp lefts	5.32	9.49	Do not reject H_o
Unbalanced ramp lefts	2.72	9.49	Do not reject H_o

When the data points are grouped by whether the ramp left turns are balanced or unbalanced, no significant differences were found within the two groups. These two statistical results, combined with the results shown in Figure 24, imply that the scenarios where ramp left turns were unbalanced are significantly different from the scenarios where ramp left turns are balanced. Examination of the data indicates that the scenarios with unbalanced ramp left turns experience significantly higher delays than when ramp left turns are balanced.

Summary of Volume Scenario Statistical Analyses

Figures 23 through 33 show the graphical implications of the statistical findings. First, Figures 24, 26, 29, and 33 all show the decline in LOS of the critical element of each interchange as the magnitude of the entering volume increases. In all of these cases, the smaller entering volumes operated at a higher LOS than the larger entering volumes. The statistics shown earlier verify that these trends are significant.

Comparison with Other Studies

This study confirmed the results of several past studies. The accident analysis identified the center of the intersection at the diamond and the weaving area at the full cloverleaf as areas where safety is a concern at those respective interchanges. This finding is in agreement with the literature.

The operational analysis also served to validate some findings from past studies. The results of the weaving area analysis verified that weaving operations degrade as the number of weaving vehicles approached 1000 vph, as AASHTO stated. This study also served to validate some of the results of Garber and Smith. Garber and Smith's simulations of traffic operations at diamonds and SPUIs also found that diamond delay is higher than SPUI delay at high volumes. In their high volume scenarios, Garber and Smith also showed that unbalanced ramp left turns experienced higher delays than their counterparts where left turns were balanced.

Summary of Findings

Literature Review

Diamond Interchanges

1. The capacity of diamond interchanges is restricted by the AGIs with the crossroad.

2. Right-of-way requirements for the diamond are less than for all other interchange types (except for the SPUI).

3. The diamond interchange has the lowest construction cost of all interchange types.

4. Due to the limited capacity of the interchange, the diamond should be used only when traffic is not expected to increase greatly.

SPUIs

1. Right-of-way requirements are the least of all interchange types.

2. Construction costs are, in general, 10% to 20% higher than for diamond interchanges.

3. SPUIs provide easier arterial coordination than diamonds due to the one-signal configuration of SPUIs.

4. When two roads intersect at a large skew angle, construction costs and clearance distances increase significantly.

5. Pedestrians are not easily accommodated by the SPUI. The provision of a pedestrian phase greatly increases delay.

6. When frontage roads are present, delay is greatly increased, due to the requirement for a fourth phase.

Partial Cloverleafs

1. Partial cloverleafs are used primarily when the right of way is not available in one or more quadrants or some turning movements are much less than others.

2. Loops should be arranged so as to provide the least impediment to left turns. This means arranging the loop ramps so that major left-turning movements can be accomplished with right-hand exits.

3. Accidents on cloverleaf loop ramps are much higher than on other ramp types.

Full Cloverleafs

1. Full cloverleafs are the minimum facility that can be provided for two fully accessed controlled facilities.

2. The right of way required for a full cloverleaf is extensive. The right of way required increases rapidly as the design speed of the loop ramp increases.

3. The weaving sections present on a full cloverleaf create a number of concerns, especially when collector-distributor roads are not used. Safety is a major concern, especially when inadequate space is provided for weaving maneuvers. As the number of weaving vehicles approaches 1000 vph, significant speed reductions and interference result. In these cases, collector-distributor roads should be used.

4. Cloverleafs tend to be better suited to application in rural areas with low-turning volumes, due to weaving and right-of-way concerns.

5. Cloverleaf loop ramps have consistently higher accident rates than other ramp types, and accident rates for full cloverleafs without collector-distributor roads are higher than those with collector-distributor roads.

Trumpets

1. Trumpets are used when there are three intersecting legs at the interchange. The left-turning movement with the lowest volume should be carried by the loop ramp.

2. Trumpet loop ramps have higher accident rates than other ramp types.

Directional Interchanges

1. Directional interchanges offer the highest capacity and can move traffic at the highest speeds. They are the preferred interchange for freeway-to-freeway connections.

2. Directional interchanges have the highest cost of any interchange type, due to their large structures.

3. Directional interchanges require the most right of way of any interchange type.

Survey Results

8. Diamonds are the most popular interchange nationwide for both urban and rural situations, followed by the partial cloverleaf.

9. Engineers ranked the SPUI as requiring the least right of way, followed next by the diamond, partial cloverleaf, trumpet, full cloverleaf, and directional.

10. Directional interchanges were seen as having the highest capacity, followed by the trumpet, SPUI, full cloverleaf, partial cloverleaf, and diamond.

11. Diamonds were ranked as having the lowest construction cost. Partial cloverleafs were next, followed by the trumpet, SPUI, full cloverleaf, and directional interchange.

12. Directional interchanges were ranked as having the greatest capability to handle left-turning movements, followed by trumpets, full cloverleafs, SPUIs, and partial cloverleafs. Diamonds were seen as having by far the greatest difficulty accommodating high, left-turn volumes.

13. Most states responded that they did not have any kind of formal guidelines for interchange type selection. These states generally relied upon capacity studies to select interchange types. For some more rural states, interchange uniformity was a concern that greatly affected interchange type selection.

14. The states that indicated that they had existing interchange selection guidelines tended to possess very general ones. These guidelines generally outlined advantages and disadvantages of the various interchange types and listed other factors that engineers may want to consider when making selection decisions.

Accident Analysis

6. The statistical tests performed on the accident data reveal several trends in accidents at the interchanges. While the results of these tests are not conclusive due to the small sample size, they do indicate some differences in safety at the interchanges.

7. A smaller percentage of angle accidents occur at full cloverleafs (2%) than at partial cloverleafs (24%) and SPUIs (34%), probably due to the absence of turning movements at the full cloverleafs.

8. The SPUI had a larger percentage of sideswipe accidents (12%) than the diamond (7%) or partial cloverleaf (0%).

9. The full cloverleaf had a larger percentage of fixed object accidents (37%) than any other interchange type. This is primarily the result of run-off type of road accidents on loop ramps and in weaving areas.

10. The predominant collision locations for the various interchange types were:

    Diamond: center of intersection (54.8%)
    SPUI: cross road (50.8%)
    Partial cloverleaf: cross road (57.1%)
    Full cloverleaf: weaving area (38.9%).

11. There seems to be no significant difference between the severity of accidents at the various interchange types. The tests showed that the partial cloverleaf had a lower accident rate than the SPUI for PDO accidents, but this result may have been influenced by the small sample size for these tests.

Operational Analysis

1. Simulation results indicate that diamond interchanges operate at a very high level of service when traffic volumes are under 1500 entering vph. In these cases, unsignalized control can be used without any negative operational effects.

2. The SPUI operates at LOS D or better when the entering volume is 5500 vph or less.

3. Statistical analyses showed that the SPUI experiences more delay when the left turning movements off of the ramp are unbalanced than when they are balanced.

4. The graph of SPUI signalized delay shows that the delay peaks when there are unbalanced mainline left turns. Although the statistical analyses did not show these volume scenarios to be significantly higher than the other volume scenarios, this represents a trend in the operations of the SPUI.

5. The diamond interchange operates at a LOS D when the entering volume reaches 4500 vph. The statistical analyses did not reveal any significant differences in the delay at the interchange, depending on the volume scenario applied.

6. The diamond consistently experienced higher levels of delay than the SPUI, most likely due to the presence of two signal controllers at the diamond versus one at the SPUI.

7. Weaving speeds at the full cloverleaf declined to LOS E when the volume entering the interchange reached 4500 vph. At this point, the number of weaving vehicles averaged 855 vph. AASHTO stated that weaving operations begin to deteriorate due to increased turbulence when the weaving volume approaches 1000 vph. These results support that guideline.

8. Partial cloverleaf signalized delays are significantly less than at diamonds or SPUIs for all entering volumes. This is due to the fact that large left-turning movements are serviced by ramps, and do not factor into the phasing systems at the signalized intersections.

9. When weaving sections are present at partial cloverleafs, their operations begin to degrade when the entering volume reaches 4500 vph, much like the full cloverleaf.

10. For full and partial cloverleafs, the minimum weaving speeds occur at the scenario when the volume that is weaving and the through volume are both at a maximum.

CONCLUSIONS

Based on these results, several conclusions can be drawn regarding the selection of the various interchange types:

- The literature review aided in the identification of the advantages and disadvantages of the different interchange types.

- The survey of state engineers provided insight into how other states choose what type of interchange to build. The opinions expressed in the survey as to the relative merits of the various interchange types also helped confirm the information obtained from the literature review.

- While the small number of sites analyzed in the accident analysis limits the extent to which the results can be extended to all other sites, several findings were found to be relevant. First, full cloverleafs were found to have fewer angle accidents than SPUIs or partial cloverleafs and more fixed object accidents than all other types of interchanges. It was also determined that the SPUI had more sideswipe accidents than partial cloverleafs or diamond interchanges.

Several conclusions can be made based on the operational analysis of the volume scenarios and actual data:

- The diamond interchange operates at an acceptable LOS when the entering volume is at 1500 vph or less. In these cases, an unsignalized system can be used to minimize delay.

- The SPUI has a consistently lower delay than the diamond for all volume scenarios tested.

- The SPUI can operate at LOS D or better at entering volume of 5500 vph or less. The diamond can operate at LOS D or better until an entering volume of 4500 vph.

- Signalized delay is increased at the SPUI when the left turns off the ramps are unbalanced. There is also some indication that unbalanced mainline lefts also result in increased delays.

- Weaving areas are the critical interchange component for partial and full cloverleafs, in terms of LOS.

- Operations at weaving areas degrade to LOS E/F as the weaving volume approaches 1000 vph. This indicates that full cloverleafs and partial cloverleafs are not suitable for roads with large weaving volumes.

- Partial cloverleafs have a superior signalized LOS to the SPUI and diamond at all enteringvolumes, since large left-turning movements are handled by loop ramps.

GUIDELINES FOR INTERCHANGE TYPE SELECTION

Based on the information obtained in this study, it is possible to identify several factors that affect what type of interchange should be used in a given situation.

Right of Way Availability

The interchange type selection guidelines based on right-of-way issues were developed primarily from the literature review. The survey results helped to further validate the information found in the literature review, and also influenced the formulation of the guidelines. Based on these two sources, the following guidelines were developed:

5. When the right of way available is limited, SPUIs or diamonds are most appropriate since they can be built in a limited right of way.

6. In situations where the right of way is restricted in one or more quadrants, the partial cloverleaf should be considered.

7. Full cloverleafs require an extensive amount of right of way, due to the presence of the loop ramps. The amount of land required for the full cloverleaf increases significantly as the design speed for the loop ramp increases. Thus, full cloverleafs may not be suitable for application in urban areas or other situations where the amount of right of way available is limited.

8. Directional interchanges require the largest amount of right of way and are usually only justified for freeway to freeway connections.

Construction Cost

The construction cost guidelines were developed primarily from the literature review. The survey results helped to further validate the information found in the literature review, and also influenced the formulation of the guidelines. Based on these two sources, the following guidelines were developed:

5. Cost figures for interchanges are very site specific. Topography, land use, and environmental concerns can make identical interchange designs have very different final costs depending on the site.

6. Generally speaking, the diamond has the lowest cost of the interchange types, due to its small structure and limited amount of right of way required.

7. The cost of a SPUI is generally 10% to 20% higher than for a diamond, due to the large structure that must be constructed. This can result in a very large bridge span (mainline over cross road) or a butterfly-shaped structure (mainline under crossroad), which can cost considerably more than a conventional diamond interchange. While construction costs for the SPUI structure are somewhat greater than for diamond interchanges, this higher cost is mitigated somewhat by the reduced right of way costs for the SPUI, especially in urban areas.

8. Directional interchanges have the highest construction cost of all interchange types, due to the large structures involved and the extensive right of way they require, and they are generally justified only when high speeds and large capacities are needed.

Traffic and Operational Issues

Guidelines for interchange type selection based on operational issues were developed based on the literature review and the operational analysis. The guidelines based on the literature review are:

3. When arterial coordination is a major priority, the SPUI should be considered. The SPUI is easier to coordinate with other signals on an arterial route than a diamond, since it requires that only one signal be coordinated, rather than two.

4. Full cloverleafs without collector distributor roads should be used only when weaving volumes are small and right of way is not a concern, such as in rural areas.

The guidelines developed based on the operational analysis are:

3. The diamond interchange should be used when traffic volumes are very low (under 1500 vph peak hour entering volume). In these cases, signals usually are not warranted, and delays are very low with an unsignalized system.

4. In cases where volumes are between 1500 vph and 5500 vph, the SPUI should be used instead of the diamond. The diamond has consistently higher delays due to the two-intersection configuration of the interchange.

7. The delay at a SPUI increases significantly when the ramp left turns are unbalanced. There are also some indications that unbalanced mainline left turns may increase delay at the SPUI. Thus, proposed SPUI designs should be carefully analyzed when either of these conditions are present.

8. The partial cloverleaf provides greater capacity than the SPUI or the diamond when the peak entering volume is between 1500 and 2500 vph. The signalized delay at the partial cloverleaf is less than the SPUI and the diamond for all cases tested. All components of the partial cloverleaf performed at a higher LOS than the SPUI or diamond at 1500 and 2500 entering vph. Weaving operations are the critical component of high-volume, partial cloverleaf interchanges.

9. Weaving operations are critical at full cloverleafs and when provided at partial cloverleafs. The level of service of the weaving areas begins to decline as the number of weaving vehicles approaches 1000 vph. This indicates that full cloverleafs with collector-distributor roads, semi-directional interchanges, or directional interchanges should be used when weaving volumes approach 1000 vph. It also shows that partial cloverleafs should be designed without weaving areas when a condition like this occurs.

10. In suburban areas, volumes and traffic patterns can change dramatically in short periods of time. Delay at SPUIs and diamonds can change dramatically, depending on traffic distributions; therefore, signal timings must be optimized in these situations to minimize delays.

Other Issues

The remaining guidelines were developed principally from the literature review. The accident analysis did play some role in the development of guideline 1.

4. Loop ramps generally have a worse safety record than other ramp types and should generally be avoided where possible. Weaving areas have a poor safety record, especially when collector-distributor roads are not provided. Particular attention should be given to the design of weaving areas of cloverleaf interchanges, due to these safety concerns.

5. When two roads intersect at a large skew angle, use of the SPUI is not recommended. The skew angle will result in high construction costs for the SPUI and also result in reduced sight distances at the interchange.

6. Pedestrians are not easily accommodated by the SPUI without greatly increasing delay at the interchange. Diamond interchanges can accommodate high pedestrian volumes much better.

8. Full cloverleafs are the minimum facility that can be provided for two access-controlled facilities. However, the use of full cloverleafs for system interchanges is not recommended unless the weaving volumes are very low. Usually, directional interchanges provide better service for freeway-to-freeway connections.

9. Trumpets should be used when three intersecting legs are present.

10. When frontage roads are present, the diamond is preferred over the SPUI. A fourth phase would be required to handle the frontage roads at the SPUI, and this would significantly increase overall delay at the interchange.

11. Interchange uniformity should also be considered when making interchange type selections. Interchange uniformity along a route can aid drivers in identifying where they need to enter or exit and can help reduce driver confusion.

Flow Diagram Summary of Results

In order to better summarize the guidelines presented here, two flow diagrams were developed. Figure 34 shows the flow diagram for interchange type selection for system (freeway to freeway) interchanges. Figure 35 is the flow diagram for service (freeway to lesser facility) interchanges. Figures 34 and 35 were developed primarily from the operational analysis, survey results, and literature review, with the accident analysis playing a less influential role. These flow diagrams should not be used for final interchange type selection. The flow charts incorporate information from the literature review, surveys, and data analysis. They do not contain a number of factors that are very important in the selection of the optimum interchange type, such as topography, community impact, cost, and environmental concerns. These characteristics tend to be very site specific, and must be examined based on the particular conditions at the site. The flow charts presented here are intended to help engineers choose a starting interchange type with which to begin their analysis.

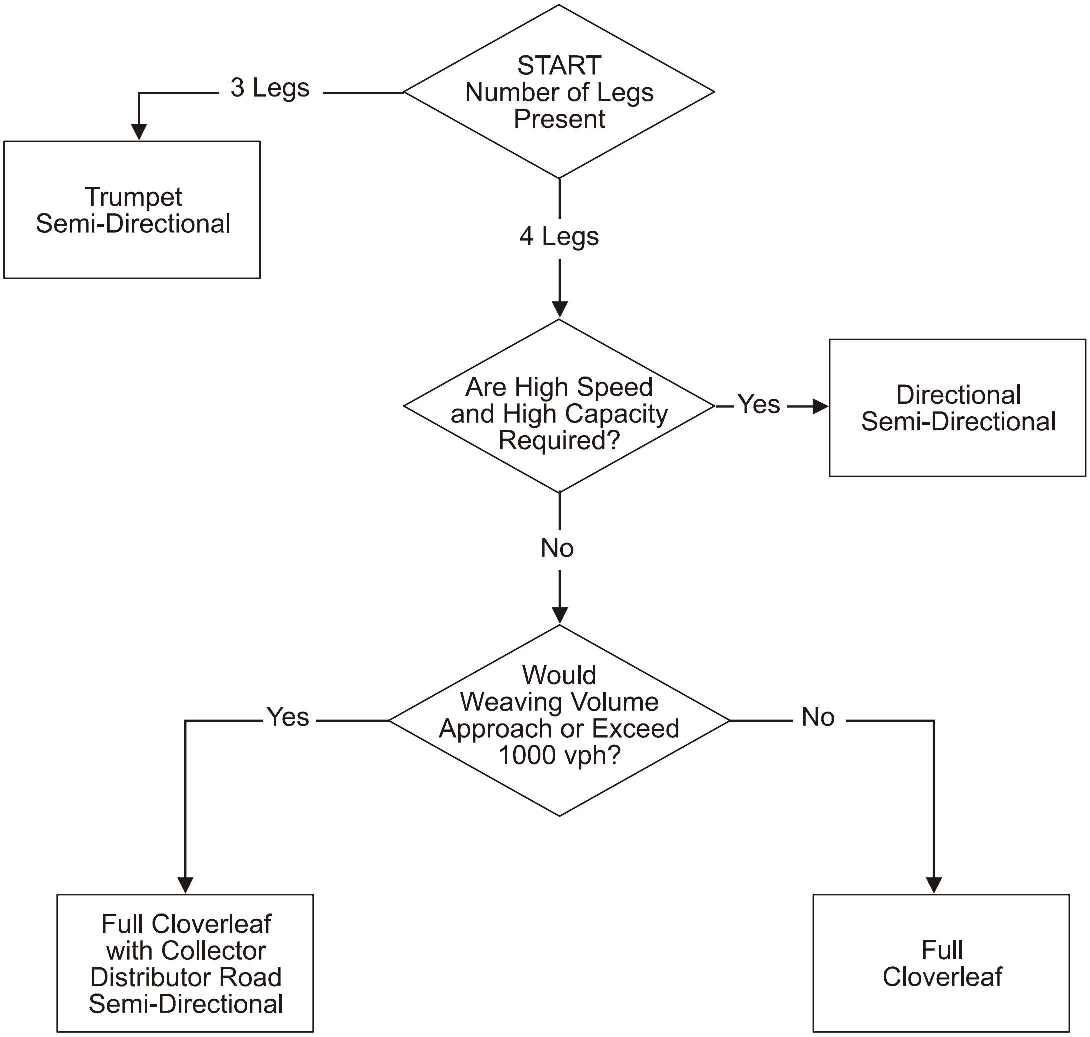

Figure 34. Flow Chart for Preliminary Selection of System Interchanges (Freeway to Freeway)

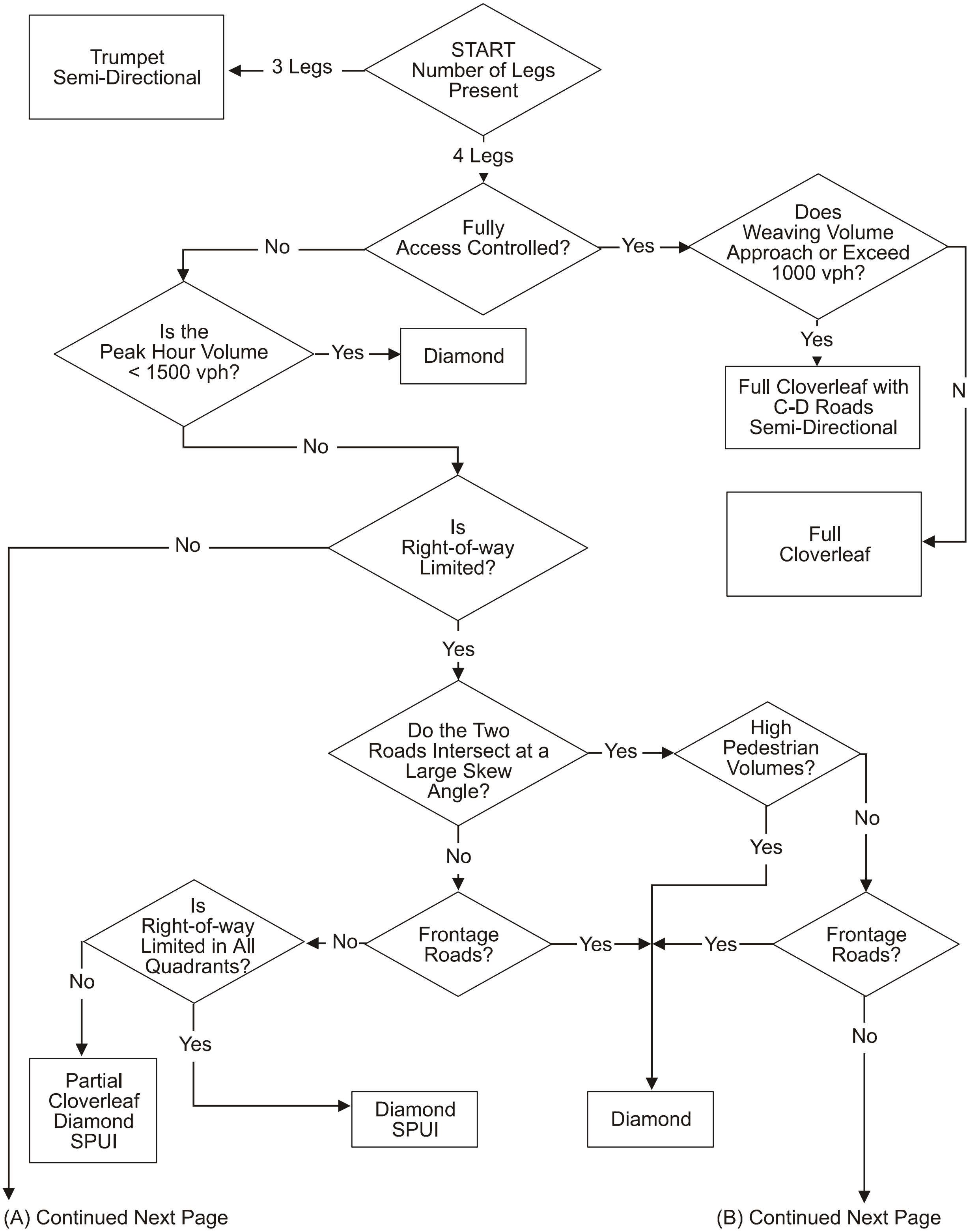

Figure 35. Service Interchanges (Major Road to Lesser Facility)

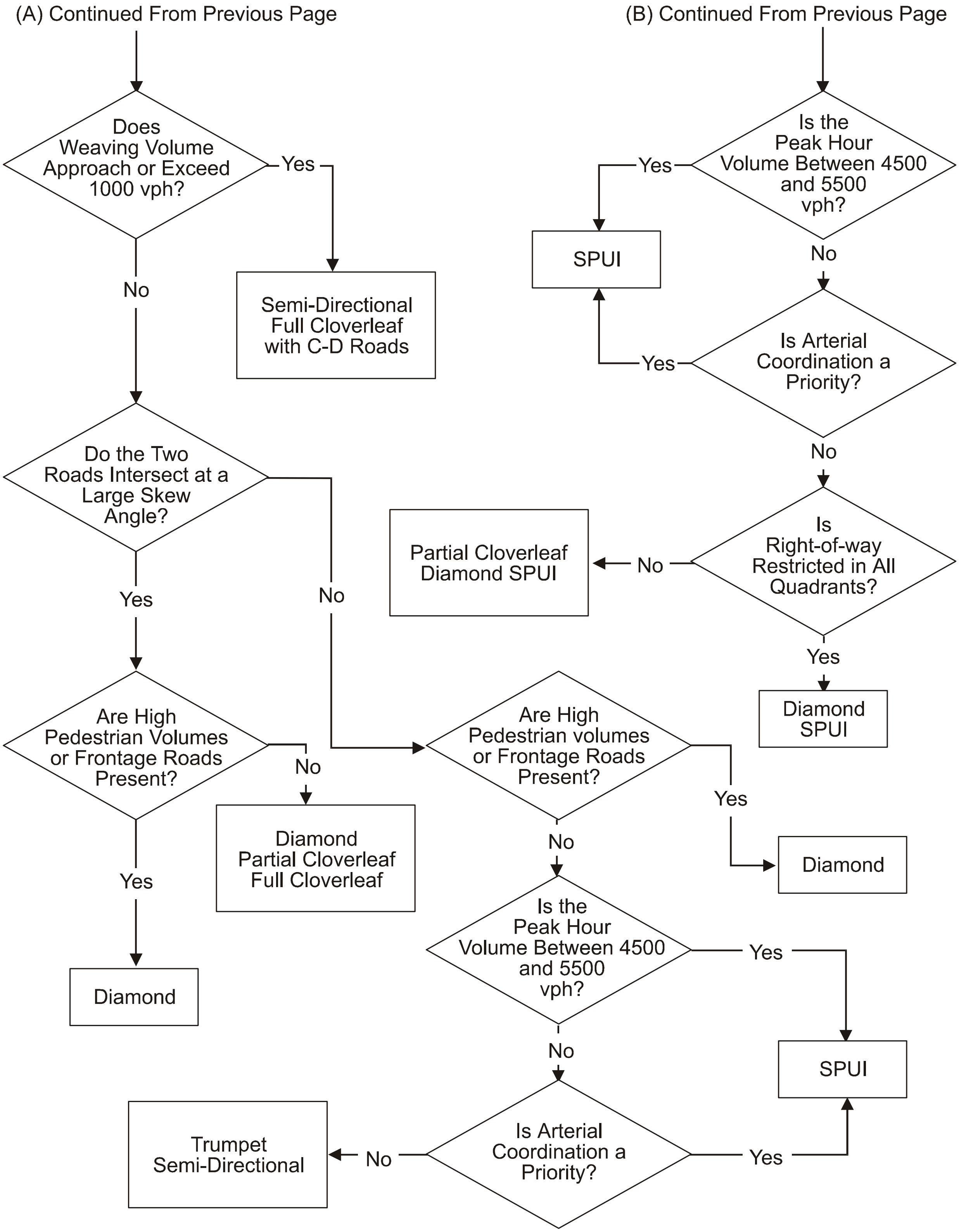

Figure 35. Service Interchanges (Major Road to Lesser Facility) (Continued)

Closing Remarks

It should be noted that the conclusions and guidelines produced by this study represent a starting point for engineers involved in interchange type selection. The operational results presented show trends with respect to entering volumes and volume distributions, but they are specific to the volumes used. Traditional capacity studies should still be performed using projected volumes for the individual site. The results presented in this report represent a starting point with which to begin analysis and should not be construed as absolute recommendations. Every site is different and may very well require a solution that is different from what is presented here.

It should also be noted that a number of other factors to be considered in interchange type selection are not explicitly dealt with by this study. Soil conditions, environmental concerns, and a number of other factors can tremendously influence the type of interchange selected. These factors can vary so much from site to site that the engineers must rely upon their judgment as how best to incorporate these issues into the interchange selection process.

RECOMMENDATIONS FOR FURTHER STUDY

This study identified and analyzed several factors that must be considered when choosing an interchange type for a location. However, there are several areas where further study is warranted:

1. While this study presented some qualitative cost data, a detailed cost analysis of the various interchange types could aid in interchange type selection decisions. Cost can play an important role in selection decisions. Cost statistics for various interchange components, as well as the effect of topography, surrounding land use, etc., on interchange costs could be invaluable in helping to make selection decisions in a more informed manner.

2. Currently, no method exists with which to compare interchange types directly to each other. It is difficult to make comparisons relating signalized systems to weaving areas because there is no measure of effectiveness that is common to both. A possible area of research would investigate how to better compare interchange types so that decisions based on operations can more easily be made.

3. While this study gave some indication of accident trends at the interchange types, the data used in this study were rather limited, and may contain some biases based on the individual site data used. A more comprehensive accident analysis of the various interchange types should be conducted to determine any safety advantages and disadvantages related to the interchange types.

4. The operational data indicated the deficiency of using weaving areas when volumes are very high (such as in urban areas). However, this study did not investigate the use of collector-distributor roads in these situations. An operational study should be conducted to see what effect C-D roads have on weaving operations and also when C-D roads cease to be effective.

5. In this study the volume to capacity (v/c) ratio was not held constant between the various interchange types simulated. This was because the capacity is calculated in a different manner for the various components studied. For example, at a signalized intersection the green phase to cycle length ratio (g/C) plays an important role in determining the capacity of a particular movement. On the other hand, weaving movements use freeway capacity determinations and do not include g/C in the calculations. Another study could be conducted with constant v/c ratios to compare the various interchange types when they are operating at the same v/c.

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Appendix A

NATIONWIDE INTERCHANGE SURVEY QUESTIONNAIRE

NATIONWIDE INTERCHANGE SURVEY QUESTIONNAIRE

1. Does your state have any guidelines for the selection of a particular type of interchange? (Circle one)

   YES NO

2. If your answer to question 1 is YES, check the ☐ for each type of interchange you have guidelines available.

   ☐ Trumpet
   ☐ Diamond
   ☐ SPUI
   ☐ Full Cloverleaf
   ☐ Partial Cloverleaf
   ☐ Directionals
   ☐ Other (Specify) ____

3. If your answer to question 1 was YES, why were these guidelines developed and how were they developed?

____

____

____

____

____

4. If your answer to question 1 is YES, could a copy of these guidelines be made available for use in this study?

   YES NO

5. Check the box next to the types of interchanges that are currently in operation in you state. Also indicate the approximate percentage of all interchanges in you state that are of each type in the parentheses.

   ☐ Trumpet ( )
   ☐ Diamond ( )
   ☐ SPUI ( )
   ☐ Full Cloverleaf ( )
   ☐ Partial Cloverleaf ( )
   ☐ Directional ( )

Others (specify type and approximate number in operation)
____

6. What is the predominant interchange type used in rural areas of your state?

7. What is the predominant interchange type used in urban areas of your state?

8. Typically, what interchange type(s) do you use for:

   System Interchanges: ____

   Service Interchanges: ____

   (System interchanges connect freeways to other freeways. Service interchanges connect freeways to lesser facilities.)

9. Do you have any traffic and/or accident data available for the different types of interchanges that are currently in operation in your state?

Diamond	YES	NO
SPUI	YES	NO
Full Cloverleaf	YES	NO
Partial Cloverleaf	YES	NO

10. If the answer to question 8 is YES, can these data be made available for use in this study?

    YES NO

Rate your reasons for selecting one interchange type over other types of interchanges on a scale of 1 to 5 (5 being excellent and 1 being poor).

Reason	Trumpet	Diamond	SPUI	Full Cloverleaf	Partial Cloverleaf	Directional	Other
Restricted right of way							
Efficient signal phasing to obtain minimum delay							
Expected to increase traffic carrying capacity							
Signalization at only one major intersection simplifies coordination on the arterial							
Low construction cost							
Can accommodate high left-turn volumes							
Existence of excessive large truck operations involving left turns							
Expected to relieve congestion							
Safer alternative design							
Easy and/or inexpensive to maintain							
Easier access to surrounding land use							

11. Additional Comments

NAME: ____

STATE: ____

TELEPHONE NUMBER: ____

Thank you very much for your time.

Please return to:

Nicholas J. Garber
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

Questions, call Mike Fontaine at (804) 293-1997

Appendix B

LEVEL OF SERVICE DESCRIPTIONS

LEVEL OF SERVICE DESCRIPTIONS

Note that these descriptions were taken from the 1994 HCM. A new edition of the HCM is due for release, but it was not available when this study was written.

Signalized Intersections

LOS A: Very low delays are present (< 5.0 sec per vehicle). Extremely favorable progression is present and most vehicles arrive during the green phase. Many vehicles do not stop at all, and low cycle lengths are often present.

LOS B: Delay is greater than for LOS A (between 5 and 15 sec per vehicle). Progression is good and cycle lengths are short.

LOS C: Delay is between 15 and 25 sec per vehicle. Progression is fair, cycle lengths are longer, and individual cycle failures begin to appear. The number of vehicles that are stopping is significant, although many still pass through the intersection without stopping.

LOS D: Delay is between 25 and 40 sec per vehicle. Congestion becomes noticeable, and longer delays result from a combination of unfavorable progression, long cycle lengths, and high v/c ratios. Cycle failures are noticeable, and the proportion of vehicles not stopping declines.

LOS E: Delay increases to between 40 and 60 sec per vehicle. These high delays are usually due to a combination of poor progression, long cycle lengths, and high v/c ratios. Cycle failures are frequent.

LOS F: Delay is in excess of 60 sec per vehicle. The LOS occurs when arrival flow rates exceed the capacity of the intersection. Poor progression and long cycle lengths contribute to these high delays.

Unsignalized Intersections

The LOS is defined as the time from when a vehicle stops at the end of a queue until when it leaves the stop bar. The table presented within the report shows describes the delay measures used to differentiate between the LOSs.

Ramps and Ramp Junctions

LOS A: Operations are unrestricted. Density is low enough to allow merging and diverging without disrupting through vehicles. No noticeable turbulence exists in the ramp influence area and speeds remain close to those on the basic freeway sections.

LOS B: Minimal levels of turbulence exits, and merging and diverging maneuvers become noticeable to through drivers. Speeds of drivers in the influence area decline slightly.

LOS C: Turbulence at merge/diverge areas becomes noticeable, resulting in a decline in the average speed in the ramp influence area. Mainline and ramp vehicles have to adjust speed to make merge/diverge movements, but driving conditions are still relatively comfortable.

LOS D: Turbulence levels become intrusive and all vehicles must slow to handle merge/diverge movements. Some ramp queues may form on heavily used on ramps, but freeway operations remain stable.

LOS E: Conditions are approaching capacity. Speeds reduce to low 40's and turbulence become intrusive to all vehicles in the influence area. Small changes in demand or disruption in the traffic stream can cause both ramp and freeway queues to form.

LOS F: Breakdown or unstable operations exist. Demand flows exceed discharge capacity of downstream freeway. Queues form on the freeway and on ramps.

Weaves

While the HCM does not explicitly describe the conditions that exist for each LOS at a weaving section, it does note that the LOS descriptions for weave areas are the same as those for basic freeway sections.

LOS A: Free flow exists and no interference occurs from other vehicles.

LOS B: Free flow speeds are generally sustained, but density increases. There is some restriction in the ability to enter or leave the traffic stream, but drivers do not find it difficult to make such maneuvers.

LOS C: Speeds are near free flow speeds, but the ability to maneuver is noticeable restricted. Lane changes require greater driver vigilance.

LOS D: Speeds decline and freedom to maneuver is further limited. Drivers experience reduced physical/psychological comfort.

LOS E: Operations are volatile and there are virtually no gaps. Lane changes and merging can result in disturbances to the traffic stream. Minor incidents can result in immediate and extensive queue buildup.

LOS F: Operation is under breakdown conditions and uniform flow cannot be maintained. At weaving areas, the number of vehicles arriving is less than the number discharged.

Appendix D

VOLUME SCENARIOS

Table D-1

Case 1: 1500 Entering vph

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
A	180	60	180	60	105	330	75	105	330	75
B	120	60	240	60	105	330	75	105	330	75
C	180	60	180	60	150	240	60	60	420	90
D	120	60	240	60	150	240	60	60	420	90
E	180	60	180	60	150	420	90	60	240	60
F	120	60	240	60	150	420	90	60	240	60
G	180	60	180	60	105	240	60	105	420	90
H	120	60	240	60	105	240	60	105	420	90
I	180	60	180	60	150	330	75	60	330	75
J	120	60	240	60	150	330	75	60	330	75

Table D-2

Case 2: 2500 Entering vph

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
A	300	100	300	100	175	550	125	175	550	125
B	200	100	400	100	175	550	125	175	550	125
C	300	100	300	100	250	400	100	100	700	150
D	200	100	400	100	250	400	100	100	700	150
E	300	100	300	100	250	700	150	100	400	100
F	200	100	400	100	250	700	150	100	400	100
G	300	100	300	100	175	400	100	175	700	150
H	200	100	400	100	175	400	100	175	700	150
I	300	100	300	100	250	550	125	100	550	125
J	200	100	400	100	250	550	125	100	550	125

Table D-3

Case 3: 4500 Entering vph

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
A	540	180	540	180	315	990	225	315	990	225
B	360	180	720	180	315	990	225	315	990	225
C	540	180	540	180	450	720	180	180	1260	270
D	360	180	720	180	450	720	180	180	1260	270
E	540	180	540	180	450	1260	270	180	720	180
F	360	180	720	180	450	1260	270	180	720	180
G	540	180	540	180	315	720	180	315	1260	270
H	360	180	720	180	315	720	180	315	1260	270
I	540	180	540	180	450	990	225	180	990	225
J	360	180	720	180	450	990	225	180	990	225

Table D-4

Case 4: 5500 Entering vph (SPUI Only)

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
A	660	220	660	220	385	1210	275	385	1210	275
B	440	220	880	220	385	1210	275	385	1210	275
C	660	220	660	220	550	880	220	220	1540	330
D	440	220	880	220	550	880	220	220	1540	330
E	660	220	660	220	550	1540	330	220	880	220
F	440	220	880	220	550	1540	330	220	880	220
G	660	220	660	220	385	880	220	385	1540	330
H	440	220	880	220	385	880	220	385	1540	330
I	660	220	660	220	550	1210	275	220	1210	275
J	440	220	880	220	550	1210	275	220	1210	275

Table D-5

Case 5: 6500 Entering vph

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
A	780	260	780	260	455	1430	325	455	1430	325
B	520	260	1040	260	455	1430	325	455	1430	325
C	780	260	780	260	650	1040	260	260	1820	390
D	520	260	1040	260	650	1040	260	260	1820	390
E	780	260	780	260	650	1820	390	260	1040	260
F	520	260	1040	260	650	1820	390	260	1040	260
G	780	260	780	260	455	1040	260	455	1820	390
H	520	260	1040	260	455	1040	260	455	1820	390
I	780	260	780	260	650	1430	325	260	1430	325
J	520	260	1040	260	650	1430	325	260	1430	325

Appendix E

ACCIDENT DATA SUMMARIES FOR FIELD DATA SITES

Table E-1

Accident Data Summary for Diamond Interchanges

		D-1	D-2	Total	%
Severity	**PDO**	27	1	28	66.7
	Injury	14	0	14	33.3
	Fatal	0	0	0	0
Collision Type	**Rear End**	11	1	12	28.6
	Angle	13	0	13	31.0
	Sideswipe	3	0	3	7.1
	Fixed Object	4	0	4	9.5
	Backed Into	1	0	1	2.4
	Other	9	0	9	21.4
Collision Location	**On Ramp**	6	1	7	16.7
	Off Ramp	8	0	8	19.0
	Center	23	0	23	54.8
	Crossroad	4	0	4	9.5

Table E-2

Accident Data Summary for SPUIs

		SP-1	SP-2	Total	%
Severity	**PDO**	21	23	44	72.1
	Injury	6	11	17	27.9
	Fatal	0	0	0	0.0
Collision Type	**Rear End**	13	16	29	47.5
	Angle	9	12	21	34.4
	Sideswipe	4	3	7	11.5
	Fixed Object	0	2	2	3.3
	Backed Into	0	0	0	0.0
	Other	1	1	2	3.3
Collision Location	**On Ramp**	2	2	4	6.6
	Off Ramp	2	8	10	16.4
	Center	10	6	16	26.2
	Crossroad	13	18	31	50.8

Table E-3

Accident Data Summary for Full Cloverleaf Interchanges

		FC-1	FC-2	FC-3	Total	%
Severity	**PDO**	29	1	6	36	66.7
	Injury	11	2	4	17	31.5
	Fatal	0	0	1	1	1.9
Collision Type	**Rear End**	22	0	1	23	42.6
	Angle	1	0	0	1	1.9
	Sideswipe	7	0	0	7	13.0
	Fixed Object	8	3	9	20	37.0
	Backed Into	0	0	0	0	0
	Other	2	0	1	3	5.6
Collision Location	**On Ramp**	8	2	6	16	29.6
	Off Ramp	11	1	3	15	27.8
	Weaving Area	19	0	2	21	38.9
	Crossroad	2	0	0	2	3.7

Table E-4

Accident Data Summary for Partial Cloverleaf Interchanges

		PC-1	PC-2	PC-3	Total	%
Severity	**PDO**	4	6	2	12	57.1
	Injury	5	3	1	9	42.9
	Fatal	0	0	0	0	0
Collision Type	**Rear End**	0	4	2	6	28.6
	Angle	3	2	0	5	23.8
	Sideswipe	0	0	0	0	0
	Fixed Object	3	1	0	4	19.0
	Backed Into	0	0	0	0	0
	Other	3	2	1	6	28.6
Collision Location	**On Ramp**	0	1	0	1	4.8
	Off Ramp	2	2	1	5	23.8
	Center	2	0	1	3	14.3
	Crossroad	5	6	1	12	57.1