FINAL REPORT

COMPARISON OF THE OPERATIONAL AND SAFETY CHARACTERISTICS OF THE SINGLE POINT URBAN AND DIAMOND INTERCHANGES

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16. Abstract

The purpose of this study was to evaluate and compare the safety and operational characteristics of the single point urban interchange (SPUI) and the diamond interchange (DI) and develop guidelines that identify traffic and/or geometric conditions that favor one type of interchange over the other.

State traffic engineers across the country were surveyed as to their experiences and opinions of the two types of interchanges in terms of operational performance and safety. Accident and operational data were also obtained for nine SPUIs and eight DIs. The interchange operations were studied using both field data and the computer simulation program TRAF-NETSIM. In addition, for each DI simulated, an SPUI counterpart was designed with the same geometric and traffic conditions for further comparison. No significant differences were found in the off-ramp, cross road, and overall interchange average delay. Ten volume scenarios were then developed and simulated for both interchanges at low- and high-volume conditions to analyze the effect of various traffic patterns on the relative operational performance of each interchange type.

The accident data for the SPUIs and DIs were compared according to severity, collision type, and location on the interchange. No significant differences were found between the severity distribution and rates of the two interchange types. However, the proportion of on-ramp and off-ramp accidents was greater at the SPUI, and the proportion of accidents occurring in the center of the signalized intersection was greater at the DI. The proportion of angle accidents was greater at DIs than at SPUIs, whereas the proportions of rear-end on-ramp, sideswipe, and fixed object accidents were greater at SPUIs. Vehicle conflicts at four interchanges in Virginia were also investigated and used along with the accident analysis results.

The operational results, safety analyses, literature review, and survey of state engineers were used to develop guidelines to aid traffic engineers in the selection and design of the appropriate interchange type.

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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

Historically, the most prevalent type of urban interchange has been the diamond interchange (DI). In recent years, however, to overcome the need for the additional right of way generally required for a DI and still respond to increased traffic demand, a new type of interchange has emerged: the single point urban interchange, or SPUI. The SPUI is similar to the DI, but it is controlled by a single set of traffic signals and provides for left turns from off-ramps to be completed in one movement. There is no consensus among traffic engineers as to the relative operational efficiency of the SPUI as compared with the DI. Also, the unfamiliar geometry of the SPUI and its large, uncontrolled conflict area have raised several concerns about the safety of motorists who travel through it.

The purpose of this study was to evaluate and compare the safety and operational characteristics of the SPUI and DI and develop guidelines that identify traffic and/or geometric conditions that favor one type of interchange over the other.

State traffic engineers across the country were surveyed as to their experiences and opinions of the two types of interchanges in terms of operational performance and safety. Accident and operational data were also obtained for nine SPUIs and eight DIs. The interchange operations were studied using both field data and the computer simulation program TRAF-NETSIM. In addition, for each DI simulated, an SPUI counterpart was designed with the same geometric and traffic conditions for further comparison. No significant differences were found in the off-ramp, cross road, and overall interchange average delay. Ten volume scenarios were then developed and simulated for both interchanges at low- and high-volume conditions to analyze the effect of various traffic patterns on the relative operational performance of each interchange type.

The accident data for the SPUIs and DIs were compared according to severity, collision type, and location on the interchange. No significant differences were found between the severity distribution and rates of the two interchange types. However, the proportion of on-ramp and off-ramp accidents was greater at the SPUI, and the proportion of accidents occurring in the center of the signalized intersection was greater at the DI. The proportion of angle accidents was greater at DIs than at SPUIs, whereas the proportions of rear-end on-ramp, sideswipe, and fixed object accidents were greater at SPUIs. Vehicle conflicts at four interchanges in Virginia were also investigated and used along with the accident analysis results.

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INTRODUCTION

Metropolitan areas in the United States are experiencing a steep increase in traffic growth and congestion on their urban freeways. Significant urban traffic growth on principal arterials, in particular, is causing severe congestion-related safety problems at major at-grade intersections (AGIs), thus producing the need for new, grade-separated intersections (interchanges). However, these grade-separated intersections require the acquisition of additional right of way, which is often a problem in urban areas. To add to these concerns, older urban freeway facilities have structural decay and are in need of rehabilitation, which must be made without adversely affecting the existing adjacent land use pattern. This, in turn, requires the selection of replacements for AGIs that minimize the impact to existing right of way.

In the past, the most prevalent type of urban interchange has been the diamond interchange (DI) (see Figure 1). In more recent years, however, to overcome the need for the significant additional right of way that is generally required for this type of interchange and still respond to the increased traffic demand, a new type of interchange has emerged called the single point urban interchange, or SPUI (see Figure 2). This grade-separated intersection is unique in that it contains one signalized intersection through which all four left-turn and through movements operate on the local road.

The unfamiliar geometry and operation of the SPUI and its large, uncontrolled conflict area have raised several concerns about the safety of motorists who travel through it. Yet, the literature analyzing the safety of operational characteristics of SPUIs is limited. Because of this, engineers and researchers[1,2] have indicated a need for a more comprehensive analysis of the safety and operational issues associated with the unusual design and operation of the SPUI.

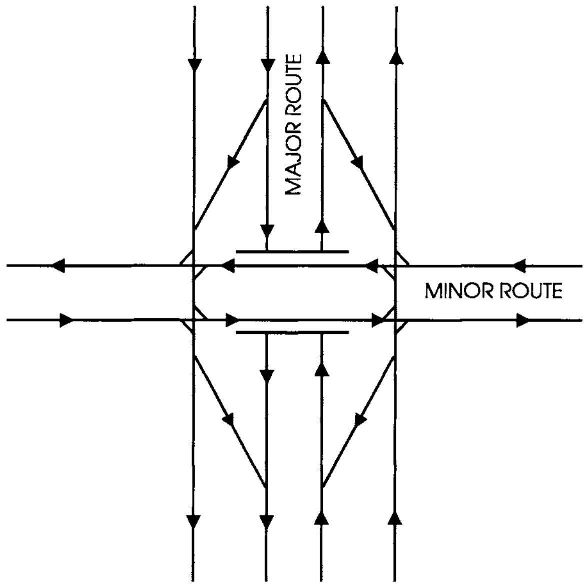


Figure 1. Typical Diamond Interchange

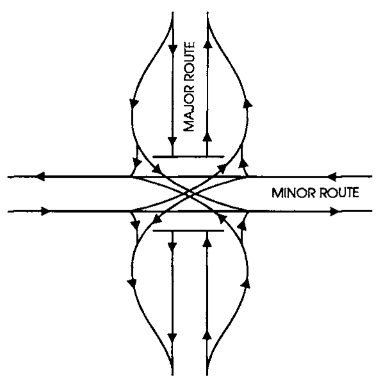


Figure 2. Typical Single Point Urban Interchange

The reason for the lack of safety investigations at SPUIs is largely because most attention has been focused on the SPUI's capacity, configuration, and traffic delay issues, since the SPUI was developed mainly for increasing capacity and easing traffic congestion. Among traffic engineers, however, there is no consensus concerning the relative operational efficiency of the SPUI as compared with the DI. Several comparative studies have conflicting results and conclusions about the operational performance of the two interchange types, but many agree that the selection of the appropriate interchange at a location depends on the specific traffic and physical characteristics at that location. The Virginia Transportation Research Council (VTRC), therefore, conducted a study to develop guidelines to aid transportation engineers in the selection of the more appropriate interchange for a specific urban location.

PURPOSE AND SCOPE

The purpose of this project was to evaluate and compare accident and operational characteristics of the SPUI and DI and develop guidelines that identify the traffic and/or geometric conditions that favor one type of interchange over the other.

The scope of this study was limited to interchanges in Virginia and those interchanges in other states for which the relevant data were available.

The objectives of this study were as follows:

1. Obtain from state engineers their experiences and opinions of SPUIs and DIs in terms of operational performance and safety.

2. Identify significant differences between the operational characteristics of the SPUI and DI.

3. Identify significant differences between the accident characteristics of the SPUI and DI.

4. Identify geometric and/or traffic conditions influencing the safety and operation of SPUIs and DIs.

5. Develop guidelines for selecting either the SPUI or DI at a specific location.

METHODOLOGY

Literature Review

The first step in this study was to conduct a literature survey regarding interchange design and operations in general, although emphasis was placed on the operation and design practices of the SPUI. A computerized search was performed through the Transportation Research Information Service (TRIS) data base, as well as a manual survey of the University of Virginia and VTRC libraries.

To develop the background needed for this project, the literature review was divided into four categories:

1. selection, operational, and safety characteristics of conventional interchanges

2. history, design, operations, and safety of SPUIs

3. analysis of comparative studies

4. conflicts as a safety measure.

The fourth category covered the procedures and practices for conducting conflict studies according to the Federal Highway Administration (FHWA). It also covered the relationship between accidents and conflicts, justifying the use of conflicts as a safety measure, as it is used in this study. The third category concentrated on research that compared the operational and safety characteristics of the SPUI and other interchange types. None of these studies used field data in their analysis. Instead, most used computer simulation and accident data.

Selection, Operational, and Safety Characteristics of Conventional Interchanges

Selection

According to AASHTO's *A Policy on Geometric Design of Highways and Streets,*[4] the *"Green Book,"* an *interchange* is defined as a system of interconnecting roadways in conjunction with one or more grade separations that provide for the movement of traffic between two or more highways on different levels. Its main function is to supply the driver with an efficient and safe method for changing route directions.[3] When intersecting through-traffic lanes are separated by grade, the best efficiency, safety, and capacity may be achieved. The selection of an appropriate interchange design type is influenced by factors such as highway classification, character and composition of traffic, design speed, and degree of access control.[4] Figure 3 shows the interchange types commonly used. Figure 4 shows a cloverleaf, a DI that has some of the features of the SPUI, and the SPUI.

The selection of an appropriate type of interchange, particularly in urban areas, requires careful consideration of prevailing conditions. For example, a cloverleaf interchange is the minimum design that can be used at the crossing of two fully controlled access facilities or where left turns at grade are prohibited.[4] Partial cloverleaf designs are appropriate where rights of way are not available in any number of quadrants and when a particular movement or movements in the interchange are disproportionate to any of the others. DIs are the simplest and most common type of interchange at the intersection of a major and minor facility. However, the capacity of the interchange is restricted by the capacity of the at-grade terminals of the ramps at the cross road.

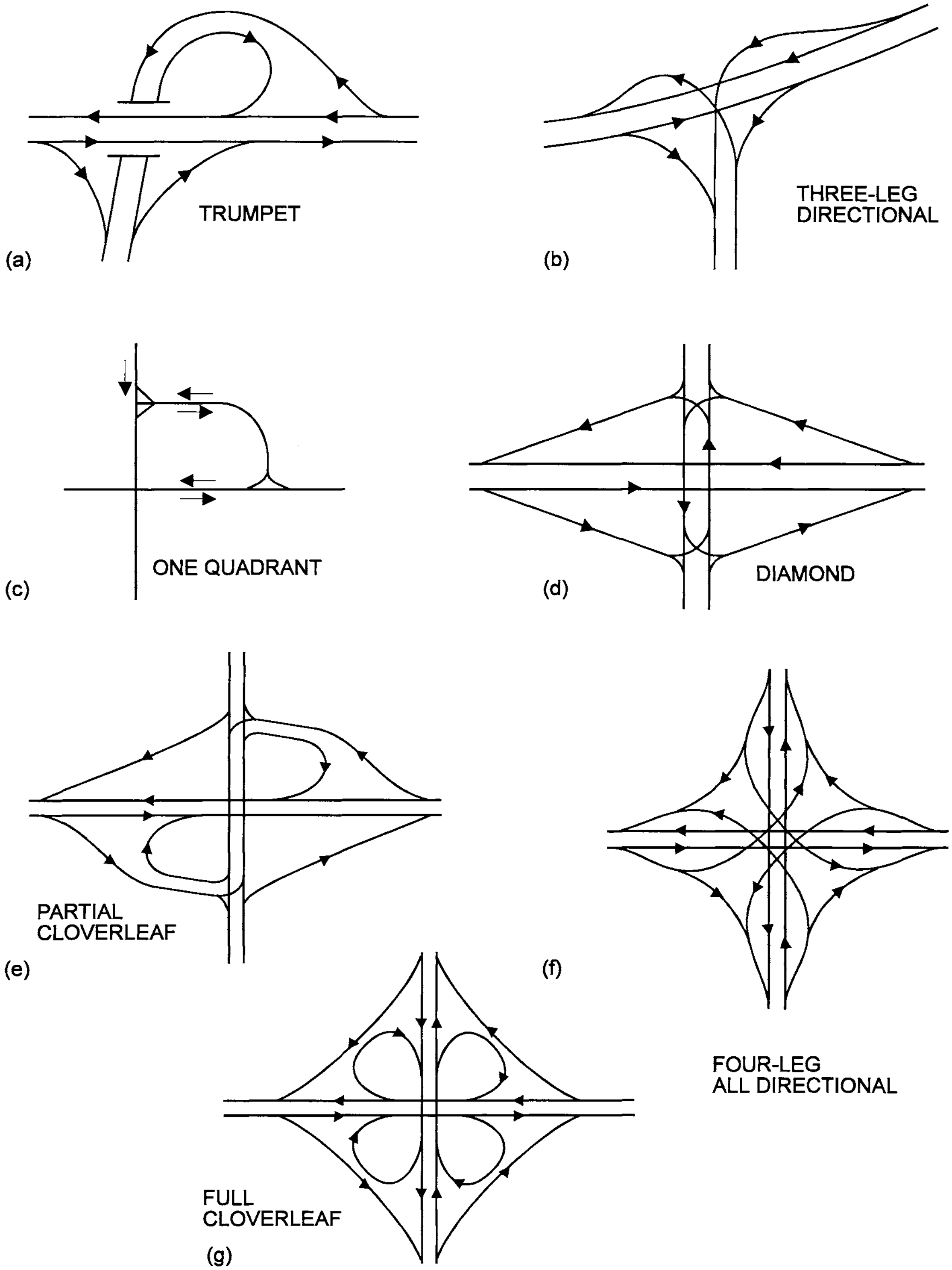
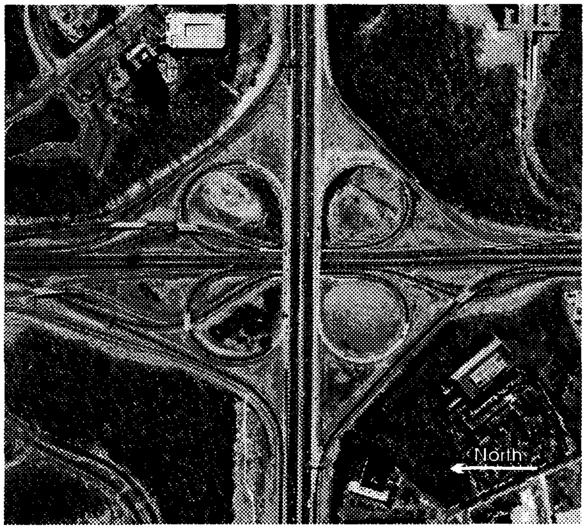
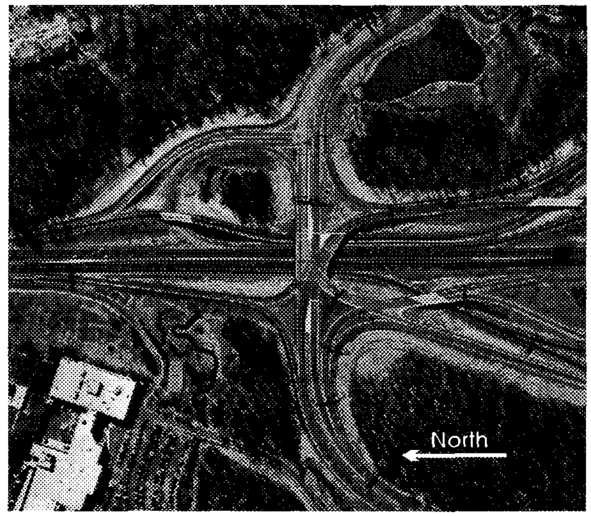


Figure 3. Interchange Types





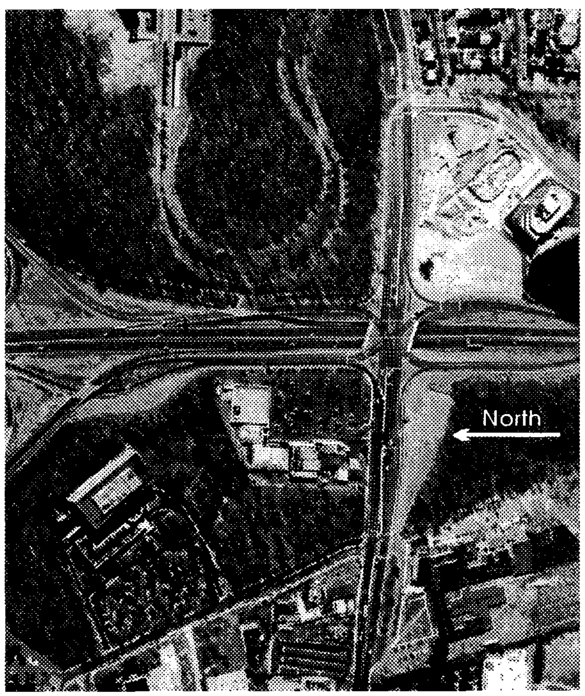


Figure 4. ***Top left:*** **A cloverleaf at the intersection of Route 250 and Gallows Road.** ***Top right:*** **A diamond interchange with directional ramps.** ***Bottom center:*** **A single point interchange.**

When high volumes of through and turning movements on the cross road exist, the DI is generally not chosen for design, unless signalization is used.[4] These guidelines, although general, are the only ones readily available for transportation planners and traffic engineers.

Operational Characteristics

Interchanges are generally adaptable to all types of traffic. When a high percentage of heavy vehicles exists, the provision of an interchange becomes particularly desirable, as stops and deceleration for trucks are avoided, thus increasing the capacity of the intersecting roadways.

Through traffic on the major road has no difficulty or delays at grade separations, except where approach grades are long and steep and the percentage of heavy vehicles is high. The interchange ramps have no serious effect on the through traffic except where the capacity is inadequate or the merging lanes are not long enough. Turning traffic, however, has a more significant effect on operation and is accommodated to varying degrees. Where turning movements are light, a one- or two-quadrant ramp design may suffice. For heavy volumes of through traffic and any volume of turning traffic, an interchange design with a ramp for every turning movement is better suited, assuming the ramps and terminals are designed with adequate capacity. Right-turning movements generally follow simple, direct, or nearly direct paths, with little driver confusion.[4]

Except on major freeways, interchanges are usually designed only where crossing and turning traffic cannot be accommodated by a less costly AGI. The major benefits at interchanges that include the reduction of delays, stops, and accidents more than compensate for any minor driver confusion that may be created at complicated interchanges.[4]

Safety Characteristics

At intersections, minimizing the crossing and turning conflicts is critical in providing a reasonable degree of safety. Regardless of design or traffic control, AGIs always have a potential for vehicle-contact accidents. By separating grades of intersecting highways, however, one can significantly decrease accidents caused by crossing and turning movements. Depending on the type of interchange used, left turns may be avoided or confined to the minor road. Right-turning traffic can be accommodated on high-design ramps that sustain operation approaching that of free flow. Also, conflicts caused by crossing and turning traffic are virtually eliminated or minimized, providing the maximum degree of safety.[4]

History, Design, Operations, and Safety of the SPUI

Historic Features

The simplest and most common type of interchange is the DI, found in both urban and rural settings. It is the DI design that eventually led to the design of the SPUI, also commonly called the single signal interchange, single point urban DI, or simply the urban interchange. This innovation in interchange design is relatively new and is not yet recognized by AASHTO in the *Green Book,* although an inclusion for the SPUI was written in 1993 and will appear in the next publication.[5]

The date of the original debut of the SPUI is a point of controversy. The proposed AASHTO inclusion indicates the earliest construction date being in the early 1970s.[5] Two articles from *Public Works*[6,7] agreed, stating that the first location was in Clearwater, Florida, and that it was given several awards as being "the first major breakthrough in highway design in more than 20 years." The articles also credited the development of the SPUI to Greiner Engineering Inc., a firm claiming to have first applied this "innovative solution." The *Urban Interchange,*[8] a publication released by Greiner, introduced their concept, simply describing it as "a DI with left turns inverted." They also stressed the urban compatibility of the SPUI as being a significant feature of the design, since it requires minimal right of way. Although these design concepts were presented by Greiner in 1970, the discussion of this date was met with disagreement by several engineers in "Letters to the Editor" in subsequent issues of *Public Works,*[9,10] noting a similar conceptual design and construction in Illinois in the mid-60s, and another in Palo Alto, California, in 1960. Although the founder of the concept is in question, it is clear that Greiner was the apparent industry leader in spreading the word about the SPUI to the profession and across the country.[11]

Design and Operational Features

AASHTO now recognizes the SPUI as an innovative design, noting several advantages. First and most beneficial in urban settings in particular, the interchange can be constructed in a relatively confined right of way, potentially resulting in significant design cost reductions. In addition, operationally, the interchange provides for left-turning movements in a way that eliminates a major source of traffic conflict. This inverted left turn reduces the phasing systems from four to three, increasing the overall efficiency of the intersection. Also, left-turn curve radii are significantly flatter at SPUIs than at conventional intersections, allowing these movements to occur at higher speeds. These operational improvements result in greater capacity than that found at a conventional tight DI (TDI).[5]

The primary disadvantage of SPUIs as indicated by AASHTO is the high construction cost associated with the bridge. Overpass designs require long single-span bridges to span the vast intersection beneath, and the bridge needed for the underpass design tends to be wide and butterfly shaped, *both* resulting in high-cost structures. A second potential problem of the SPUI design is the length and geometry of the left-turn vehicle wheel path through the intersection, creating a need for positive guidance. The presence of severe skew angles between the two roadway alignments also adversely affects SPUIs as it increases the clearance distances and affects sight distance as well. Last, pedestrian movements through SPUIs require careful consideration, since the addition of a pedestrian phase would significantly decrease the overall interchange efficiency.[5]

Design Features. There are many uncertainties about the design and operations of the SPUI, and many conflicting results have been noted in a variety of studies; yet many SPUIs are still being planned or proposed for construction.[11,12] Some authors believe the SPUI to be an ideal solution to congested intersection problems,[6,13] whereas others believe the design has certain limitations.[14,15] Published statistics indicate that approximately 40 SPUIs are in operation in the United States and a similar number are under construction or consideration.[16]

The SPUI is often described as another form of the grade-separated two-level DI; it is different from a typical DI in that all left-turn and through movements operate under a single signalized intersection. This high-speed single signal operation of the left turns influences the geometry of the intersection, as the SPUI uses large left-turning radii from 45.72 to 91.44 m (150 to 300 ft) to supply adequate visibility and overall efficient operations for left turns.[11] Because of this geometric feature, the bridge design requires careful consideration for both overpass and underpass configurations (recent statistics indicate that approximately 44 percent of the SPUIs in operation are of the overpass type).[12] In no other interchange design are the bridge details so interrelated to the geometric and traffic control device features.

Although most SPUIs do not have frontage roads, a few do. Some studies[15,17] have concluded that the presence of frontage roads significantly degrades the performance of the interchange, due to the need for an additional phase to provide for the frontage road through movement. This, in turn, leads to additional lost time and delay. Severe skew angles between the two roadway alignments also have an adverse effect at SPUIs as they increase clearance distances and negatively affect sight distance.[5] Also, a skew often results in a smaller left-turn radius path and a more acute angle of entry with the intersecting roadway. Very severe skew angles may increase the bridge length and extend the distance between stop bars on the local street. AASHTO recommends exercising extreme care in planning SPUIs when the angle between the intersecting roadways approaches 30 degrees.[5]

Operational Features. The typical signal sequence for SPUIs consists of three basic phases, plus any necessary overlap, as shown in Figure 5. This scheme is used at all SPUIs, except those with continuous, one-way frontage roads. When continuous frontage roads exist, a fourth phase is added (see Figure 6). The additional phase generally follows Phase 3 and is similar in operation to the major road through phase at a typical AGI.[17] Because of the unique left-turn operation, the actuated signal controller allows the overlapping of either cross road left-turn

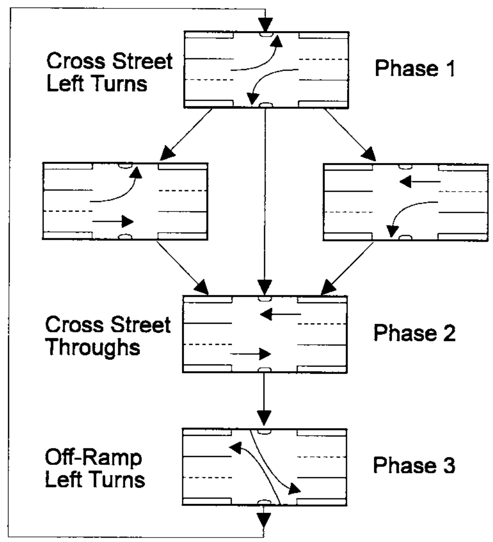


Figure 5. Typical SPUI Three-Phase Sequence

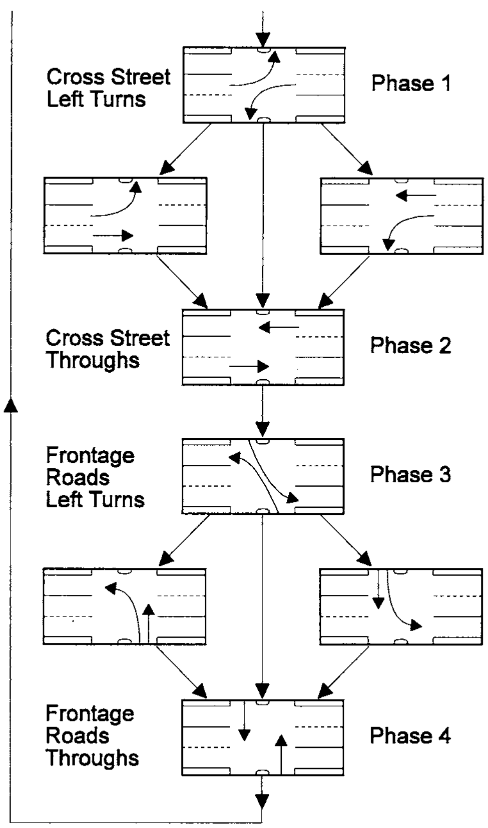


Figure 6. Typical SPUI Four-Phase Sequence

movement with its adjacent through movement, depending on observed traffic demands. This capability improves the SPUI's efficiency when demand is unbalanced by allowing the controller to distribute cycle time appropriately on a cycle-by-cycle basis.

The timing of the clearance interval (yellow plus all-red) at SPUIs commands special attention due to the interchange's large size and lengthy travel paths. Typically, all-red intervals for SPUIs range from 1.0 to 10.0 sec per phase.[14] This is quite large compared with conventional intersection interval lengths of 1.0 to 2.5 sec per phase.[17]

Attempts have been made to study the headway characteristics and evaluate saturation flow rates and lost times at SPUIs. Poppe et al. investigated saturation flow rates for the through and left-turn movements at various SPUIs and startup and clearance lost times.[2] Some arguments presented questioned whether the SPUI configuration affected saturation flow rates because of its large left-turn radii and whether the long clearance interval required to cross the expansive land area increased the lost time per phase. To examine this, headways were measured in relation to signal head indication changes.

Based on the data collected, it was determined that 2,000 passenger cars per hour of green per lane (pcphgpl) is an acceptable saturation flow rate base value for the through *and* left-turn movements at the SPUI. The large radius causes the left-turn movement to operate similarly to a through movement in a capacity sense. The data also showed that even higher saturation flow rates may be suitable for left-turn movements with a radius greater than 91.44 m (300 ft).[2]

Startup lost times did not vary significantly by type of movement and generally fell between 1.5 and 2.0 seconds per phase. The clearance lost time, however, was closely related to the length of the clearance interval, generally 2.5 to 3.0 sec less per phase than the clearance interval time for the phase.

Bonneson also studied headway and lost time characteristics at SPUIs by using analysis techniques and regression models to recognize significant effects and calibrate predictive models of minimum discharge headway and startup lost time. The results of the study indicated that the minimum discharge headways of the SPUI's two left-turn movements (off-ramp and cross road) were significantly lower than the numbers typically used for protected left-turn movements under ideal conditions.[18] The left-turn movement headways varied with turn path radii: the larger radii resulted in minimum headways about 0.12 sec shorter than those for AGI left-turn paths. In addition, the headways for through movements at SPUIs were longer than those at AGIs. The through movement headways were longer than those of the left-turn movements, contrary to conventional trends at AGIs.[18]

In summary, the models used in that study predicted minimum discharge headways that were commonly lower and startup lost times that were higher than those calculated by conventional methods.[11]

Safety Features

Most attention has been focused on the SPUI's capacity, configuration, and traffic delay issues since the concept of the SPUI design was developed mainly for increasing capacity and easing traffic congestion. Because of this, the availability of reports and analyses of safety at SPUIs is limited.[1] Poppe et al. indicated a need for a comprehensive study of potential safety problems associated with the operation and design of the interchange. This recommendation was based on the observations of a number of traffic violations and conflicts associated with road-user confusion.[2]

Cheng investigated the safety issues of SPUIs by analyzing Utah's SPUI accident experience.[1] The objectives of that research were twofold: (1) to determine if there were any predominant factors involved in accidents at three SPUIs, and (2) to compare the SPUIs with compressed DIs to determine the operational safety of the two interchange types. The report concluded that driver unfamiliarity with the new design was not a major factor in accident occurrence in the interchange area, although traffic engineers did report complaints of confusion at SPUIs just after they were opened to traffic. Other factors such as severity, weather, road surface, lighting, older driver population, pedestrian, and trucks also did not present any major problems. Last, evidence suggested that the predominant accident type at SPUIs was rear-end accidents on the off-ramp. This conclusion was supported by data from another study by Bonneson, who also recommended a more in-depth safety study, augmented by traffic conflict studies to supplement the sparse accident history at SPUIs.[14]

Messer et al. also observed conflicts and examined accident data at SPUIs.[11] A frequent conflict was between the clearing and entering vehicles of successive phases, due to the extended use of the yellow interval by the clearing vehicles. In most cases, the all-red interval was shorter than the actual time taken to clear the intersection. This conflict was most often observed between the clearing off-ramp and entering cross road left-turn movements. Another frequent conflict was between off-ramp right-turning and cross road through traffic. The off-ramp right-turn maneuver was even more complicated when the nearest downstream intersection was relatively close to the off-ramp right-turn entrance point on the cross road. The last frequently erratic maneuver involved left-turning drivers on the cross road who turned from the through lane instead of the left-turn bay. Other unusual maneuvers were also noted but did not occur as frequently.

Messer et al. also investigated accident data at five SPUIs, which indicated some variability among sites (characteristic of the random nature of accidents). The examination also determined that the SPUI design does not lead to a higher number of accidents as compared with a typical AGI. Last, a close examination of left-turn accident data did not indicate that a safety problem existed.[11]

Comparative Studies

Among traffic engineers, there is no consensus concerning the relative operational efficiency and safety of the SPUI as compared with the DI. Through this review, it was found that several journal publications have been written about the SPUI that make general statements regarding this comparison. Many contain no supporting analysis or provide only a partial description of methodologies used. Also, some studies presented conflicting opinions about the operational performance and safety of the two interchange types.

In the following sections, various aspects and comparisons of operations and safety at SPUIs and DIs are reviewed. The results and conclusions of several studies are presented, leading the authors to one conclusion on which many of them agree: the selection of an appropriate interchange form is very site specific and the responsibility of the traffic engineer becomes most evident here.[15]

Delay, Capacity, and Level of Service

In terms of comparative efficiency, the main differences in the operations of the SPUI and DI can be attributed to their distinctively different lane geometry and signal phasing schemes. These factors have led several engineers to draw conclusions as to the relative operations of the two interchanges. For instance, an article in the April 1989 *Public Works* noted that the large radius of the inverted left-turn lanes allows for faster and simultaneous movements from opposing directions while eliminating one signal phase in the sequence. From this it was concluded that the SPUI delivers 30 to 50 percent higher efficiency.[7] Brown and Walters reinforced this opinion, also stating that the SPUI can provide 10 to 50 percent more capacity, depending on the balance of the off-ramp left-turn volumes and relative minor street volumes.[13]

A common belief among designers is that the necessity of only three phases (in the absence of frontage roads) at SPUIs allows for greater capacity of the interchange. Leisch et al., however, found that the efficiencies gained by using the three-phase system were lost when more than one of the four left-turning movements necessitated double turn lanes and when the cross street required more than two through lanes in each direction.[15] Both of these geometric conditions can be found at the majority of SPUI locations across the country.[11]

Two of the more extensive comparative research studies on operational efficiency are summarized in detail in the following sections. As one can see, the conclusions drawn by the authors differ to a great extent.

Comparison of Two Diamond Interchange Forms in Urban Areas[15]

In this study, the authors compared several aspects of the SPUI and DI. The operational comparison is of particular interest, as they took five real world traffic scenarios and analyzed them for each interchange type using the computer model TRANSYT-7F. This model optimized them for each interchange type using the computer model TRANSYT-7F. This model optimized signal timings and operational characteristics and provided measures of effectiveness for comparison purposes.

The results of their analysis showed that in four of the five scenarios, the compressed DI was more efficient than the SPUI. They also noted that in all four cases, the volumes consisted of heavy through traffic and heavy unbalanced left turns. (This is consistent with the opinions of Brown and Walters discussed previously.) In the one case where the SPUI was more efficient, all left turns were heavy and the through traffic was light. Overall, the authors reached the following conclusions:

- The compressed DI is more efficient than the single-point DI for most traffic volume/pattern situations.

- Cycle length requirements are usually significantly shorter for the compressed DI, resulting in potentially shorter queues.

- The compressed DI can accommodate a greater variability of traffic patterns.

Their analysis suggested that applications are limited for the SPUI and that, in general, the compressed DI is less costly, has similar right-of-way requirements, and is more efficient.

Operational Comparison of the Single Point Urban and Tight Diamond Interchanges[19]

This study was performed primarily in response to the many conflicting statements from research that were accompanied by incomplete documentation regarding methodologies and assumptions. Fowler realized upon reviewing these studies that the critical element of an SPUI-TDI comparison was the traffic volumes used in the analysis. For this reason, different traffic scenarios were first examined, using a spreadsheet, for both the SPUI and TDI for a quick v/c comparison. From this initial analysis, Fowler discovered exactly which variations in traffic volume characteristics had significant effects on the relative capacities of the TDI and SPUI. The following results were found as to the traffic volume characteristics and performance of the TDI with respect to the SPUI:

- As the directional split of the cross street through volumes increases, the performance of the TDI improves.

- As the volume of the cross street left turn opposing the heavy through movement increases, the performance of the TDI improves.

- As the off-ramp left turns become more imbalanced, the performance of the TDI improves.

However, it was determined that for an interchange location to receive more capacity from a TDI than an SPUI, the traffic volumes would likely need to display all *three* characteristics.

For a more detailed analysis, 12 traffic volume scenarios were developed and input into TRANSYT-7F for v/c and delay comparisons. Under most traffic volume conditions, the SPUI provided greater capacity than the TDI, and even when the TDI operated at a lower v/c ratio, the SPUI operation still resulted in a lower average delay. Last, Fowler also illustrated that, relative to the SPUI, the capacity of the TDI is more sensitive to variations in traffic volumes.

Saturation Flow Rate and Lost Time Comparisons

As discussed previously, Poppe conducted a study in 1990 that measured saturation flow rate, startup lost time, and clearance lost time at SPUIs. In response to this, Hook and Upchurch collected similar data at DIs to compare these parameters with those found at the SPUIs.[20] The results indicated no significant difference for saturation flow rates for through movements and cross road left turns between the two interchange forms. However, SPUIs had significantly higher saturation flow rates for the off-ramp left-turn movements. The difference can be explained by analyzing the interchange geometry. At both types of interchanges, the cross road left-turn movement must turn through 90 degrees to reach the on-ramp. The off-ramp left-turn situation is quite different, however: the ramp at a typical diamond is nearly perpendicular to the cross road, whereas the ramp at an SPUI is at a large skew to the intersection, as it is *inverted.* The angle through which these off-ramp left turns must pass is much less at the SPUI.

There was no significant difference in startup lost time between the interchange forms. However, there was a significant difference in the clearance lost time for both left-turn movements between the SPUI and the DI. The clearance lost time at SPUIs was higher due to the much longer clearance intervals. Finally, there was no significant difference in the through movement clearance lost time.

Safety Comparison

Various conflicting opinions also exist as to the relative safety of the SPUI and DI. Leisch et al. believed the potential for increased accidents is present at SPUIs because of the large, uncontrolled open pavement area and the opposing left turns.[15] Another paper, however, stated that the radii of the SPUI's turning lanes made it safer than the DI by eliminating the need for conflicting left-turn movements across opposing traffic lanes.[7]

The availability of accident analysis research between these two interchange forms is minimal. This is due, in a large part, to the fact that more research attention has been focused on the SPUI's operational characteristics since it was developed primarily for increasing capacity and alleviating congestion in urban interchange areas.[1] Also, because SPUIs are a relatively new design concept, no substantial accident data base exists.

Safety issues of SPUIs were investigated by Cheng (discussed previously in this review).[1] One aspect of his project was comparing SPUIs and compressed DIs (CDIs) to identify differences in accident severity, collisions type, and number of accidents. The data indicated that the accidents that occurred at CDIs were more severe than those at SPUIs. A comparison of accident frequency and accident rates between the two interchanges showed that the rates at CDIs were significantly higher than those of SPUIs. In general, this study concluded that from the viewpoint of safety, the SPUI is a better option than the CDI when designing an interchange outside the CBD. It was decided that its safety advantage is probably achieved due to the fewer possible points of conflict at the single intersection.[1]

Conflicts as a Safety Measure

Traffic conflict is defined in the NCHRP Project 17-3 as follows:

> A traffic conflict is a traffic event involving two or more road users, in which one user performs some atypical or unusual action, such as a change in direction or speed, that places another in jeopardy of a collision unless an evasive maneuver is undertaken.[21]

The study and observations of conflicts at intersections can be used to identify operational and roadway characteristics that contribute to safety problems.[22] The remainder of this section describes why and how conflicts provide a measure of safety similar to that found using historical accident data.

Reasons for Studying Conflicts

Traditionally, an analysis of reported accidents has been the principal method of measuring highway safety. Accident reports alone, however, pose many limitations and problems in the analysis of safety. Some drawbacks and restrictions are as follows:

- Accident records contain only *reported* accidents, which are just a fraction of total accidents.
- There is a growing, nationwide trend by law enforcement agencies not to report property-damage-only accidents.
- Accident records commonly provide incomplete, inaccurate, or biased information. Errors in accident location, changes in report forms, etc., can create sources of error in accident analysis.

- At many locations, accidents occur infrequently and sporadically, so a longer time is needed to collect enough accident data for analysis purposes. (This is a particular problem in the study of SPUIs due to the newness of the interchange.)

For these reasons, other indicators or measures of safety, such as conflicts, can be beneficial to a safety analysis. Conflict studies are useful in identifying specific accident problems that would otherwise go undetected in a conventional accident analysis.[22]

Relationships Between Traffic Conflicts and Accidents

An FHWA study that examined the relationship between traffic conflicts and accidents used the traffic conflicts technique (TCT) methodology, which has been studied and applied in the United States and abroad for several years.[23] Based on the TCT data collected, several recommendations and conclusions were reached, the following of which are pertinent to this study[23]:

1. Of the 12 basic conflict types possible (see Appendix D for illustrations), some are fairly common and others are so rare that they should be discounted as being impractical for operational applications. At signalized intersections specifically, same direction conflicts and opposing left-turn conflicts are common, whereas cross traffic conflicts can occur only if a driver violates the red signal phase and, therefore, are exceedingly rare.

2. Considering the rarity and infrequent occurrence of certain accident and conflict types, in applying the TCT as a safety indicator, emphasis must be placed on a limited set of conflict types. It is impractical to examine conflict types that require excessive time periods to observe adequate samples. In addition, these conflict types correspond to accidents that rarely occur, so the need or desire to collect data on them is insignificant. The practical conflict types for signalized intersections are same direction conflicts and opposing left-turn conflicts.

3. Although accident estimates based on conflicts may not have been quite as accurate as those based on previous accidents, they were very close. The differences in the number of more precise cases were not statistically significant; in other words, one cannot reject the null hypothesis that the conflicts method yields estimates that are as precise as those obtained by reviewing accident histories.

4. In general, traffic conflicts of certain types are, indeed, good surrogates of accidents in that they produce estimates of average accident rates nearly as accurate, and just as precise, as those produced from historical data. Therefore, if there are insufficient accident data, a TCT study should be very helpful.

Based on these findings, one can safely conclude that conflicts may be used as accurate safety measures in analyzing the safety of the SPUI and DIs.

The literature review indicated a need for further safety study and analysis of the SPUI, as more SPUIs are being built with very little historical accident data on which to base engineering design judgments. The observation of conflicts, however, adds an extra dimension to the safety study of SPUIs, as conflicts can indicate potential safety problems that would otherwise go undetected using accident rates alone. Through the literature review, it was established that conflict studies do, indeed, provide an accurate safety measure for this study. The conflict analysis used in conjunction with available accident data will provide a reliable means of analyzing the safety characteristics of the two interchange types.

Data Collection

The data collection task consisted of the following subtasks:

1. a nationwide survey on SPUIs
2. an operational and accident data questionnaire survey
3. site identification for field data collection
4. accident data collection
5. field data collection.

Nationwide Survey on SPUIs

Because of the relatively small number of SPUIs in operation in Virginia, a questionnaire was sent to appropriate traffic engineers throughout the United States to obtain sufficient data on the operational and safety characteristics of the interchange. The purpose of the questionnaire was to identify and obtain available data for the existing SPUIs in the United States and obtain information on the efficiency and safety of these SPUIs.

First, the appropriate engineers for each state were identified, contacted, and informed about the study. Each engineer was then asked to participate in the study. It was envisioned that this procedure would yield a better response rate than if the recipient had not been notified before receiving the survey. A questionnaire was then sent to each state addressing the following areas:

- the number of SPUIs in operation in each state

- the number of SPUIs being considered or planned for construction within the next 5 to 10 years
- the reason for selecting SPUIs over other types of interchanges
- the extent to which SPUIs have met with expectations
- the advantages and disadvantages of SPUIs, including opinions and complaints from the public
- the availability of traffic and accident data for the SPUIs now in operation.

The questionnaire is provided in Appendix A, and the results are tabulated in Appendix B. The efforts made to yield a good response rate were quite successful, as 96 percent of the engineers contacted responded.

Operational and Accident Data Questionnaire Survey

To supplement the data collected in Virginia, states that indicated in the first survey that they had operational and safety data available for use were contacted, and a second questionnaire was sent to obtain the necessary information. The purpose of this second survey was to obtain any delay and accident data for the interchanges in each state. Because delay data were unlikely to be found, the relevant traffic, phasing, and geometric data were also requested. These input data were used later to determine the level of service at these locations using TRAF-NETSIM. To simplify the questionnaire further, the engineers were invited to provide plans or their own phasing system diagrams and timing sheets instead of filling in each dimension individually. This created a more difficult and lengthy data reduction process, requiring further contact with most of the engineers to fill "holes" in the data provided. The efforts of this second questionnaire along with the Virginia sites yielded accident and/or operational data for nine SPUIs and eight DIs throughout the United States. Further contact with engineers provided even greater insight into opinions and design suggestions based on each state's experience. The questionnaire used is shown in Appendix C.

Site Identification for Field Data Collection

The selection of appropriate interchanges for this project was a complex and important task. All three Virginia SPUIs were used. Identifying suitable DIs, however, involved selecting sites that were similar in relevant ways to the chosen SPUIs. Among the criteria for similarity were:

- volume characteristics

- geometric configuration
- lane usage
- land use activity.

Last, it had to be feasible to collect the necessary data at the chosen interchanges. A good location for equipment setup had to be available, and, more important, the location had to be a safe one in which to work. This last factor turned out to be the most difficult to achieve, since many of the interchanges are in tight urban areas, with relatively narrow shoulders, not allowing for the necessary safety requirements for equipment and work crews. Based on these criteria, the following DIs were selected for the study:

1. DI-1: Aberdeen Road and I-664, Hampton, Virginia
2. DI-2: Sunset Drive and SR 826, Dade County, Florida
3. DI-3: NW 74th Street and SR 826, Dade County, Florida
4. DI-4: Elm Avenue and I-44, Webster Groves, Missouri
5. DI-5: Page Avenue and I-170, St. Louis, Missouri.

Accident Data Collection

Virginia Sites

The accident data for each interchange were collected. First, police accident reports for 1991, 1992, and 1993 were acquired. Reports were obtained for any accident that occurred within 45.72 m (150 ft) of the signalized intersection and all locations along the on- and off-ramps. Each report was studied in detail, and relevant accident characteristics were obtained including the following:

- traffic control where the accident occurred
- weather and road surface condition
- time of day
- type of accident
- severity
- vehicle maneuver

- fixed object involvement
- whether driver vision was obscured
- skidding involvement
- points of impact on the vehicle(s)
- location on the interchange.

These characteristics were used to analyze the possible safety problems or characteristics associated with each interchange

The average annual daily traffic (AADT) for each interchange was then obtained from the existing Virginia Department of Transportation (VDOT) traffic data to calculate accident rates for each interchange. These 24-hr counts, however, were not available for every interchange. To estimate these counts, the 6-hr counts of peak traffic activity counted during the field study in 1994 were converted proportionately into 24-hr counts. This was performed using 24-hr counts from areas adjacent to the interchange, by assuming that hourly volume variations were similar. A ratio was determined consisting of the vehicles traveling during the 6 hr to the total number of vehicles traveling during the 24-hr period. This proportion was applied to the 6-hr counts for each interchange to obtain an estimated total daily approach volume for 1994. A growth rate for the area was then applied to determine the vehicles per day for the years 1991–1993. This rate was determined by using the ADT for 2 years at a location near the interchange. It was assumed that the traffic growth at this location was similar to the growth of traffic at the interchange itself because of the proximity and similarities of the traffic conditions at each location and the associated interchange.

The accident rates were calculated in terms of accidents per 100,000,000 vehicles approaching the interchange. They were computed by severity, type of accident (e.g., rear-end, angle), and traffic stream (e.g., left-turns, straight ahead).

Out-of-State Sites

Accident data were obtained from other states through completion of the second questionnaire. Most states simply provided the computer printouts of the raw data for each accident and a code sheet indicating the different accident characteristics. For each set of records, the codes were converted to match the Virginia codes to create a consistent data base from which to analyze the safety characteristics of the interchanges. Most of the accident characteristics used for the Virginia DIs were found in the other states' files.

For almost all of the other states, the ADT for each year of data was provided. In one state, however, the ADT was available for only 1 year. In this case, the planning division was contacted for an appropriate growth factor for the interchange location, which was used to calculate the following years' ADT. This growth factor was similar to the factors used in the Virginia sites. The ADT was then included in the accident rate calculations, in the manner described previously.

Field Data Collection

For each interchange site chosen, a strict procedure was followed in preparation for the data collection. First, a preliminary visit to each site was necessary to conduct a thorough investigation at the interchange and determine the feasibility of camera locations. One entire day was generally devoted to this preliminary task.

During the preliminary investigation, a camera was brought around to each leg of the intersection, and exact camera locations and angles were determined. Several cameras were needed to tape each approach, as many different angles were necessary to conduct a conflict study from the videotapes. At some sites, because of limited shoulder area needed for safety purposes, cameras were placed on scaffolding a bit further away, which provided an even better view than from the ground itself.

Also during this period, a general sketch of the interchange was drawn, indicating the number of lanes, lane usage, ramp details and channelization. This sketch was later completed by inserting detailed geometric measurements of the interchange. Photographs were taken at each approach and the speed limit on the cross road and the ramps were recorded. Last, the land use activity for the area surrounding the interchange was noted. Figures 7, 8, and 9 depict approaches at the three Virginia SPUI sites.

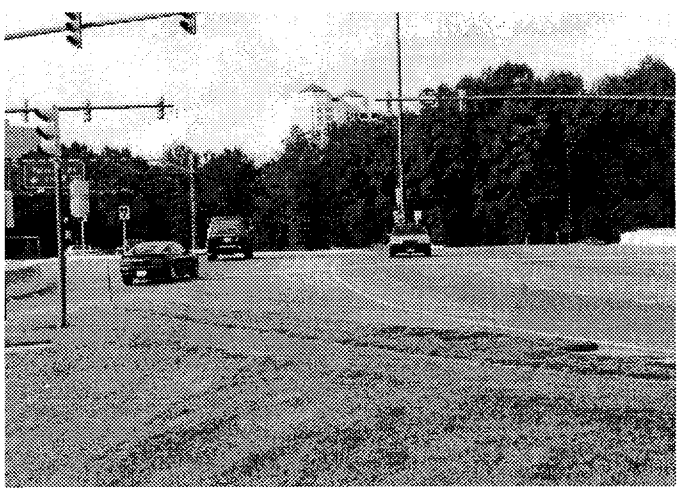


Figure 7. SPUI at Fairview Park and Arlington Boulevard, Crossing Left Turns

Figure 8. SPUI at Magruder Boulevard and Hampton Roads Center Parkway, Westbound Off Ramp

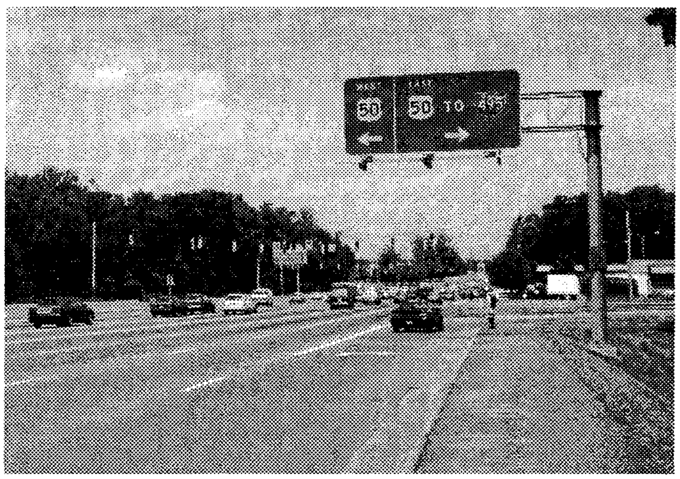


Figure 9. SPUI at Gallows Road and Arlington Boulevard, Northbound Cross Road

Following the preliminary visit, each study site was again visited for the collection of field data. At that time, video cameras were extensively used to record the traffic operations. For each intersection leg, four or five cameras were used at strategic locations. On the cross road approaches, two cameras were placed in the median to tape left-turn vehicles: one to view left-turning vehicles close to the stop line, and one further back for a view of the entire left-turn pocket. This second left-turn camera also provided a view of the through vehicles, and another through-vehicle camera was also placed on the shoulder of the cross road. For right-turning vehicles, a camera was placed on the shoulder as well, and a second camera was placed on the island of the on-ramp to obtain a close view of the merge point of the right- and left-turning vehicles at the on-ramp.

On the off-ramps, four cameras were used: two for right-turning vehicles and two for left-turning vehicles, with close and far views similar to those described for the cross road placement. Figures 10 and 11 depict the general setup, although some minor changes were necessary, depending on the geometric characteristics of the interchange.

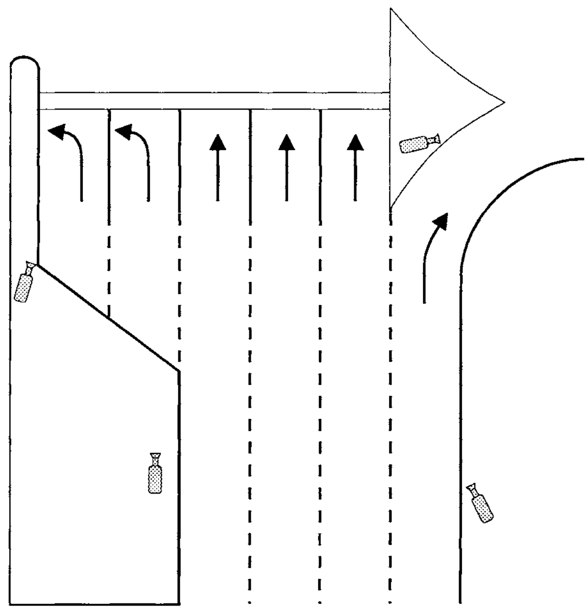


Figure 10. Cross Road Camera Placement

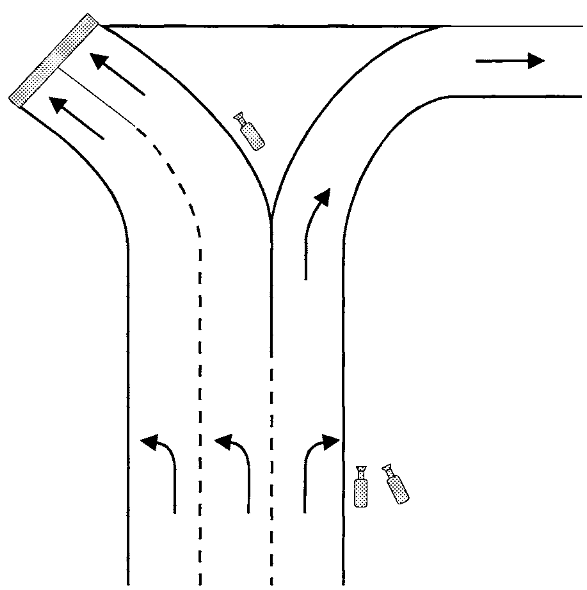


Figure 11. Off Ramp Camera Placement

Each ramp was videotaped for approximately 3 hr in the morning and 3 hr in the afternoon (during the A.M. and P.M. peak periods). An extra day (A.M. and P.M.) was also devoted to taping the left turns that crossed to the left of each other in the center of the intersection, since it was mentioned in past studies that this unique and unconventional design may cause safety problems.

From these videotapes, a complete delay study and a conflict study were performed. These two procedures, along with all the other data and measurements, would have required several more days at each site and more crew members if the cameras were not used. Also, in several instances, the tapes were used to fill "holes" in the data and answer questions at the office during data reduction, both of which would have required repeat visits to the site. The use of cameras for data collection allowed for a greater amount and variety of data to be collected in a shorter period of time.

Traffic and Geometric Data

While each leg was being filmed, several other measurements had to be collected. First, a sketch of the approach was made, indicating more detailed information:

- lane widths
- turn pocket lengths
- distance to the nearest downstream intersection(s)
- length of tapered sections of ramps
- exact location of all cameras on the approach
- intersection width at SPUIs
- distance between intersections at Dis.

Traffic data were also collected for the full 3 hr of taping. First, traffic counts were taken in 15-min intervals for each movement on each approach. These were used in the determination of the peak hour, peak hour factor, vehicle classification, and calculation of conflict rates. Signal timing data were also collected including cycle lengths, phase lengths, interval lengths (green, amber, and all-red) and phasing sequence. Because all of the sites used actuated systems, several (20 to 30) of these signal timings were taken throughout the 3 hr, to generate an average length for each interval.

Traffic Conflict Data

The collection and analysis of traffic conflict data were performed according to standard FHWA procedures and guidelines. In general the procedure was broken down into three parts[22]: (1) planning the survey, (2) conducting the study, and (3) summarizing conflict data. These steps are outlined in detail in *Traffic Conflict Techniques for Safety and Operations Observer Guide.*[24]

Planning the Survey. It was first necessary to gather preliminary information before conducting the conflict study itself. Included in the preliminary data was a complete list of intersection study sites, the intersection approaches of interest, and exactly what data were to be collected at the site. These additional data could include updated traffic volumes, existing roadway inventory information, or photographs, in addition to the counts of the indicated conflict types.

Conducting the Traffic Conflict Study. Conflict data were collected on weekdays and during peak periods. This is because traffic conflicts will occur most frequently when traffic volumes are heavy.

Having determined the peak hour for each approach, tapes (approximately 4 or 5 tapes per approach) from every camera used at each approach during the peak hour were observed. In this way, we were sure to see all possible conflicts that had occurred.

The 6-hr observation at each interchange was adequate to analyze the stated conflicts and met the data collection requirements as outlined in the FHWA procedure.[24] All conflict types were noted during the observation period to identify any unusual trends in conflicts that might occur at SPUIs.

The conflicts were summed by type (same direction and cross traffic types) for each approach. Using the volumes for each approach during the time period, the conflict rates were calculated. These rates were used later to analyze and compare the safety characteristics of the two interchange types.

Summarizing Conflict Data. The categories and representative set of data are shown in the data form in Appendix D. The conflict rates were then calculated as the number of conflicts of a given type that occur for every 1,000 entering vehicles:

$$Conflict\ rate = \frac{Number\ of\ conflicts\ by\ type}{One\text{-}way\ approach\ volume} x(1{,}000)$$

The resulting conflict rates were used to identify specific safety problems at each intersection. The simple observation of the sites during the conflict study also provided a useful perspective into the causes of particular problems, which was eventually used in the development of guidelines.

Data Reduction

Extraction of Delay Data from Videotapes

First, at every intersection approach, the peak hours were determined. For each peak hour, the videotapes were observed and the relevant data for computing average stopped delay were extracted. The average stopped delay was computed using the stopped vehicle count methodology as described in the *Highway Capacity Manual (HCM)*.[25]

The methodology consisted of the following steps.

1. The farthest extent of standing queues was identified at the approach of interest.

2. At regular intervals of 10 sec, the number of vehicles stopped on the approach for the particular movement under investigation was counted. Only those vehicles that stopped completely were counted, and only those inside the limits of the intersection (from the limit in Step 1 to the exit boundaries of the intersection).

3. The peak hour volume was determined. (This was already collected in the field.)

4. All of the stopped-vehicle counts for the entire study period were summed to compute the total of all density observations.

5. The average stopped delay per vehicle was then computed as

$$Delay = \frac{(\sum V_s)(I)}{V}$$

where

Σv_s = sum of stopped vehicle counts

I = interval between stopped vehicle counts, in sec

V = total volume for the particular movement observed during study period.

This process was carried out for each left-turn and through movement of each approach to obtain the operational characteristics in terms of the stopped delay of each interchange. These results were, in turn, used to determine whether significant differences existed in the operational characteristics between SPUIs and DIs.

Appendix E shows the field worksheet used for the recording of observation from the tapes and the computation of average stopped-time delay.

Computer Simulation to Determine Operational Characteristics

TRAF-NETSIM was used to simulate the operation of the interchanges to determine the delay for each movement and each interchange as a whole. The data (volumes, signal timings, geometric characteristics, and dimensions) used for these simulation values were determined from the existing SPUI and DIs. The results of this analysis were used to compare the operational characteristics of the two types of interchanges.

To exercise the TRAF model, several components of the traffic environment must be specified for each interchange. These components were obtained either at field sites in Virginia or from other states through the second questionnaire. The necessary inputs consisted of the following[26]:

- topology of the roadway system (in the form of a link-node diagram)
- geometrics of each roadway component
- channelization of traffic (left, thru, right, buses, carpools, etc.)
- motorist behavior that determines the operational performance of vehicles in the system
- traffic control devices (stop, yield, signal timing)
- traffic volumes entering the roadway system
- turning movements
- transportation modes.

In the NETSIM model, the physical environment is represented as a network composed of nodes and directional links. In general, the links represent the roadway sections of the interchange, and the nodes represent intersections or points where a geometric property of the link changes, e.g., a lane drop. Figure 12 illustrates a typical SPUI link-node diagram.

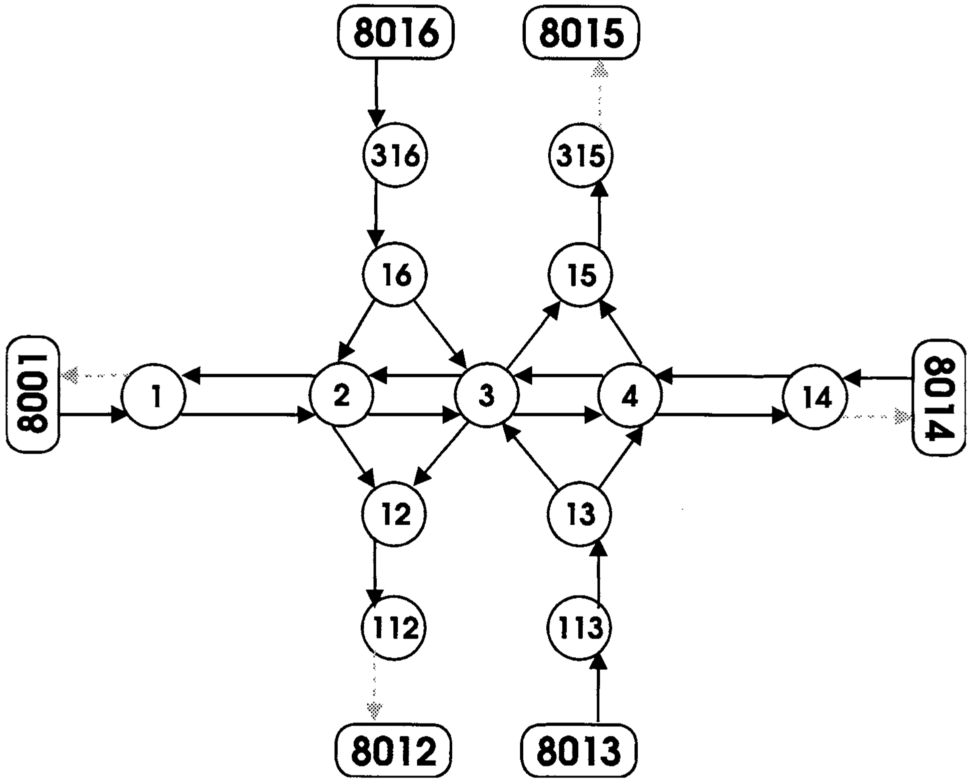


Figure 12. SPUI Link-Node Diagram

The output of the computer model contains information for each link such as:

- average speed
- average and maximum queues
- percentage of stops
- delay (movement specific and total).

Using the delay from the model, the level of service of each approach and the interchange was determined, using the *HCM*.[25]

To verify that the NETSIM model determined delay that appropriately represents that in the field, the NETSIM results were compared with the corresponding field results obtained at the Virginia sites using the stopped vehicle count procedure. This comparison confirmed that the NETSIM delay simulations were very similar to the field delays.

Analysis

The comparison of the DI and the SPUI was carried out in three parts: (1) operational characteristics, (2) accident rates, and (3) conflicts. The accident and conflict rate comparisons were conducted using the *t* test. In each case, the test was carried out to determine significant differences at $\alpha = 0.05$.

Comparing Operational Characteristics

The direct comparison of the operational characteristics of the two interchange types was carried out under the following two tasks.

1. comparing overall delays at the existing DI and SPUIs using the TRAF-NETSIM simulation results

2. substituting an SPUI configuration for an existing DI and comparing the results of simulated delay with that of the original corresponding DI.

As noted earlier, the overall delay comparison (task 1) was carried out using the delays obtained from the TRAF-NETSIM simulation on the data obtained for the existing interchange. The input requirements for this program include turning movement peak hour volumes, which were difficult to obtain from most city and state traffic departments. However, field data for 11 sites were used: 6 SPUIs and 5 DIs. The sites and their locations, along with the number used to identify and discuss them in this report, are listed in Appendix F. The *t* test was used to test for significance (at $\alpha = 0.05$) for the following null hypotheses:

1. The average stopped delay per vehicle (sec/veh) during peak periods on SPUIs and DIs are equal.

2. The average stopped delay per vehicle on the off-ramps during peak periods on SPUIs and DIs are equal.

3. The average stopped delay per vehicle on the cross road during peak periods on SPUIs and DIs are equal.

To gain further insight into the operational advantages and disadvantages of the interchanges, task 2 was carried out. For each DI, an SPUI counterpart was designed. In other words, the same volumes and geometric characteristics, such as number of lanes and lane usage, were input into an SPUI configuration designed with the same right-of-way restrictions. The signal timings were designed using the Highway Capacity Software to achieve the minimum delay. This was assuming that if an SPUI had, in fact, been designed in place of the DI, the optimum signal phasing would have been used. In doing this, the particular traffic and geometric characteristics that favored one interchange type over the other would become more noticeable. This would have allowed a complete and unbiased analysis of the two interchange forms. The delay results obtained from this portion of the analysis were also tested using the *t* test in the same manner described for the original delay analysis.

To develop guidelines for each type of interchange based on an operational comparison, it was necessary to analyze further the various traffic volume scenarios that could affect the operation of each interchange type. Based on different scenarios, the SPUI may be a more favorable design selection than the DI and vice versa. To investigate this, 10 volume scenarios for both low- and high-volume interchange designs were developed and simulated using the computer software PASSER III for the DI and TRAF-NETSIM for the SPUI. This was not a direct comparison between the operational characteristics of the two types of interchanges. It was an investigation on how the operational characteristics of each type of interchange varied with changes in the volume characteristics of the interchange. The PASSER-III model was, therefore, used for the DI since it was a more appropriate model for that type of interchange. These volume scenarios include varying the balance in through and left-turn traffic at the different locations, to identify the ways in which volume characteristics affect the performance of the two interchange types. These results were also used to develop the design guidelines.

Comparing Accident Rates

The accident information used for comparison purposes included the accident data extracted from the police accident reports in Virginia and the accident data obtained from other states. In comparing the accident rates for SPUIs with those for DIs, the following hypotheses were tested:

4. The total accident rates on SPUIs and DIs are equal.

5. The injury accident rates on SPUIs and DIs are equal.

6. The property damage accident rates on SPUIs and DIs are equal.

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

7. The proportional distribution of accidents by location is the same for SPUIs and DIs.

8. The proportional distribution of accidents by collision type is the same for SPUIs and DIs.

The accident rates for each collision type were also calculated to evaluate and compare along with the collision type distribution. The results of these analyses were used to indicate the extent to which the accident characteristics of SPUIs and DIs are different.

Comparing Conflicts

A field conflict study was performed at 4 interchange locations (3 SPUIs and 1 DI). Because of the low number of available DI field sites, statistical analyses and comparisons could not be conducted. However, several vehicle conflicts were observed. These conflicts are discussed in detail in the Results section.

Development of Guidelines

The results of the operational and safety analyses combined with an analysis of geometric, traffic, and phasing characteristics were used to develop guidelines. These guidelines identify traffic and geometric conditions that favor one type of interchange over the other. Also, several guidelines were developed based on the feedback from state and city traffic engineers. These opinions and suggestions were obtained from survey results and the many conversations with the engineers based on their own experiences with the interchanges.

RESULTS

Nationwide Survey on SPUIs

Fifty-one engineers were contacted and received questionnaires. Forty-nine responded, yielding a 96 percent response rate.

Table 1 shows the number of existing SPUIs and the number planned or considered for construction. The number being planned or constructed is almost *twice* the number currently in operation. The results, however, do not show evidence that either the overpass or underpass design is preferable.

Table 1. Statistics on U.S. SPUIs

	SPUIs in Operation	**SPUIs Considered or Planned**
Number of SPUIs	59	117
Number of states with SPUIs	20	29
Number and percentage of overpass SPUIs	26 (44%)	61 (55%)
Number and percentage of underpass SPUIs	33 (56%)	49 (45%)

Table 2 lists the engineers' reasons for selecting the SPUI over other interchange types. All respondents cited restricted right of way as a reason.

Fifty-six SPUIs were then rated on a scale of 1 to 5 (1 being poor and 5 being excellent) as compared with a similar DI for the following five areas:

1. construction cost
2. safety
3. arterial coordination
4. congestion relief
5. increased capacity.

The relative average ratings of the interchanges are shown in Figure 13. The higher ratings found here coincide with the reasons for SPUI selection.

The noted advantages of the SPUI were as follows:

- better for large truck operation
- less right of way required

Table 2. Reasons for Selecting or Considering SPUI Over Other Interchange Types

Reason	Number of Responses
Restricted right of way	29
Increase traffic carrying capacity	21
Accommodate extremely high left-turn volumes	19
Efficient signal phasing to obtain minimum delay	18
Relieve congestion	17
Signalization at only one major intersection simplified coordination on arterial	15
Safer design as compared with DI	5
Easier access to surrounding land use	5
Excessive large-truck operations involving left-turn movements	3

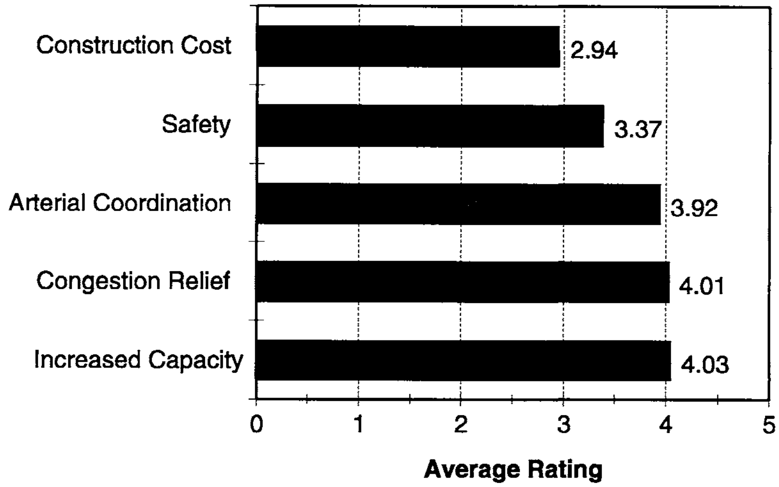


Figure 13. Average Ratings of SPUIs in Operation on Scale of 1 to 5

- added capacity
- drivers need to stop only once
- excellent turning
- accommodates access to businesses well
- reduced overall delay
- handling of traffic during construction is better facilitated
- accommodates large left-turn volumes
- ease of traffic control
- better arterial coordination with one signal
- good alternative in preliminary planning
- reduced congestion
- increased traffic flow
- easy for motorists to understand.

Disadvantages of the SPUI were as follows:

- more expensive due to higher construction cost of bridge and maintenance cost of retaining walls
- lack of driver familiarity (confusing)
- sight clearance is a problem (visibility between off-ramp and cross road)
- more maintenance necessary
- room for improvement in phasing and operational characteristics
- long clearance intervals required
- does not accommodate pedestrian facilities easily
- startup delays are higher
- poor placement of signal heads
- pavement markings are confusing.

Delay and Level of Service Results

The delay results for the direct comparison of the two interchange types were obtained from the output of TRAF-NETSIM. Table 3 shows the results of these calculations and their corresponding levels of service. The operational performance did not vary among the 6 SPUI sites as much as it did at the 5 DI sites. Both sets of interchanges had a large range of different total interchange approach peak hour volumes. The SPUI volumes varied from approximately 1,200 to 5,700 vph, and the DI sites carried 2,400 to 6,200 vph. However, there was no trend regarding whether the DI performed any worse or better than the SPUI as the total approach volume increases. For this reason, it was important to analyze and compare the interchanges on more equal terms and look more closely at the changes in operational performance with changes in the volume patterns. One specific geometric factor observed from field operations that influenced delay, particularly at the DI, was the lack of a full right-turn lane on the off-ramp. The right-turning vehicles, which would need only to yield, are blocked by the left-turn vehicles that are stopped, waiting for a green indication. This led to higher off-ramp delay values.

Table 4 shows the delay results obtained by simulating the operation of each DI as an SPUI. The signal timings used in the simulations, however, pose many questions as to the credit of these results. The actual signal timings currently in operation at these five DIs was used for their simulation. For the SPUI counterparts, however, the optimal cycle length and phasing system were used. One may say that this gives more of an advantage to the SPUI performance or

Table 3. Delay and Level of Service Results

Average Stopped Delay per Vehicle (sec/veh) and Level of Service					
SPUIs	Delay	LOS	DIs	Delay	LOS
SPUI-1			**DI-1**		
WB Off-ramp	23.0	C	NB Off-ramp	17.7	C
EB Off-ramp	17.3	C	SB Off-ramp	13.6	B
NB CROSS RD	34.4	D	EB CROSS RD	11.0	B
SB CROSS RD	22.1	C	WB CROSS RD	9.6	B
OVERALL	26.0	D	OVERALL	11.6	B
SPUI-2			**DI-2**		
NB Off-ramp	29.5	D	NB Off-ramp	55.4	E
SB Off-ramp	19.3	C	SB Off-ramp	24.9	C
EB CROSS RD	15.2	C	EB CROSS RD	12.1	B
WB CROSS RD	14.6	B	WB CROSS RD	12.6	B
OVERALL	18.0	C	OVERALL	17.6	C
SPUI-3			**DI-3**		
WB Off-ramp	21.6	C	NB Off-ramp	10.3	B
EB Off-ramp	25.7	D	SB Off-ramp	37.6	D
NB CROSS RD	19.8	C	EB CROSS RD	40.0	D
SB CROSS RD	24.3	C	WB CROSS RD	109.6	F
OVERALL	24.2	C	OVERALL	63.1	F
SPUI-4			**DI-4**		
NB Off-ramp	21.8	C	WB Off-ramp	16.0	C
SB Off-ramp	15.4	C	EB Off-ramp	25.6	D
EB CROSS RD	39.5	D	NB CROSS RD	24.4	C
WB CROSS RD	32.5	D	SB CROSS RD	28.3	D
OVERALL	31.5	D	OVERALL	24.2	C
SPUI-5			**DI-5**		
WB Off-ramp	15.4	C	NB Off-ramp	139.1	F
EB Off-ramp	21.5	C	SB Off-ramp	59.6	E
NB Off-ramp	24.1	C	EB CROSS RD	46.7	E
SB Off-ramp	24.1	C	WB CROSS RD	95.0	F
OVERALL	22.7	C	OVERALL	76.9	F
SPUI-6					
NB Off-ramp	37.6	D			
SB Off-ramp	20.8	C			
EB CROSS RD	16.7	C			
WB CROSS RD	31.1	D			
OVERALL	25.8	D			

Table 4. Delay and Level of Service Results for DI and Designed SPUI

Average Stopped Delay per Vehicle (sec/veh) and Level of Service				
Interchange	**DI Delay and LOS**		**SPUI Delay and LOS**	
DI-1				
NB Off-ramp	17.7	C	30.3	D
SB Off-ramp	13.6	B	18.0	C
EB CROSS RD	11.0	B	9.8	B
WB CROSS RD	9.6	B	15.7	C
OVERALL	11.6	B	15.2	C
DI-2				
NB Off-ramp	55.4	E	12.7	B
SB Off-ramp	24.9	C	22.0	C
EB CROSS RD	12.1	B	14.6	B
WB CROSS RD	12.6	B	17.8	C
OVERALL	17.6	C	17.1	C
DI-3				
NB Off-ramp	10.3	B	6.4	B
SB Off-ramp	37.6	D	22.6	C
EB CROSS RD	40.0	D	28.9	D
WB CROSS RD	109.6	F	13.9	B
OVERALL	63.1	F	17.6	C
DI-4				
WB Off-ramp	16.0	C	12.5	B
EB Off-ramp	25.6	D	19.2	C
NB CROSS RD	24.4	C	21.3	C
SB CROSS RD	28.3	D	14.2	B
OVERALL	24.2	C	16.9	C
DI-5				
NB Off-ramp	139.1	F	129.2	F
SB Off-ramp	59.6	E	20.9	C
EB CROSS RD	16.7	E	50.3	E
WB CROSS RD	95.0	F	92.7	F
OVERALL	76.9	F	70.4	F

results. When looking at the cycle lengths of each interchange, it became even more questionable whether the optimal system was being used in the field for these DIs. The cycle lengths at the DIs were often more than 40 sec greater than the optimum cycle length used to simulate their SPUI counterparts. This goes against the common belief that the SPUI requires a greater cycle length than does the DI. For these reasons, the results obtained from this portion of the analysis were not used for guideline development; instead, the results obtained from the more fair comparison of various volume scenarios that followed were more heavily weighted.

To determine the effect of different volume characteristics on interchange performance, the delay results of 10 volume scenarios were analyzed for both a low-volume and high-volume interchange. The exact movement volumes for each scenario are in Appendix G. In general, the following five cross road volume patterns were simulated for balanced off-ramp left turns (where both off-ramp left-turn volumes are equal) and imbalanced off-ramp left turns (where one off-ramp left-turn volume is significantly higher than the other):

Volume Scenarios

1 & 2	equal through volumes and equal left-turn volumes
3 & 4	imbalanced left-turn volumes and imbalanced through volumes where the heavier through volume opposes the heavier left-turn volume
5 & 6	imbalanced left-turn volumes and imbalanced through volumes where the heavier through volume opposes the lighter left-turn volume
7 & 8	balanced left-turn volumes and imbalanced through volumes
9 & 10	imbalanced left-turn volumes and balanced through volumes

The delay results for the lower volume and higher volume interchanges are shown in Figures 14 and 15, respectively. The total interchange average delay per vehicle is plotted on the

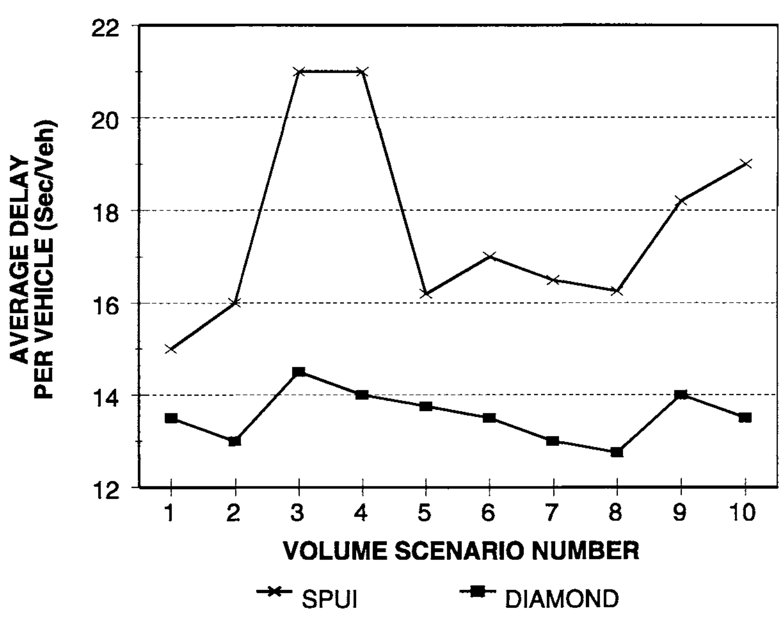


Figure 14. Operational Performance Comparison Under Low-Volume Traffic Scenarios

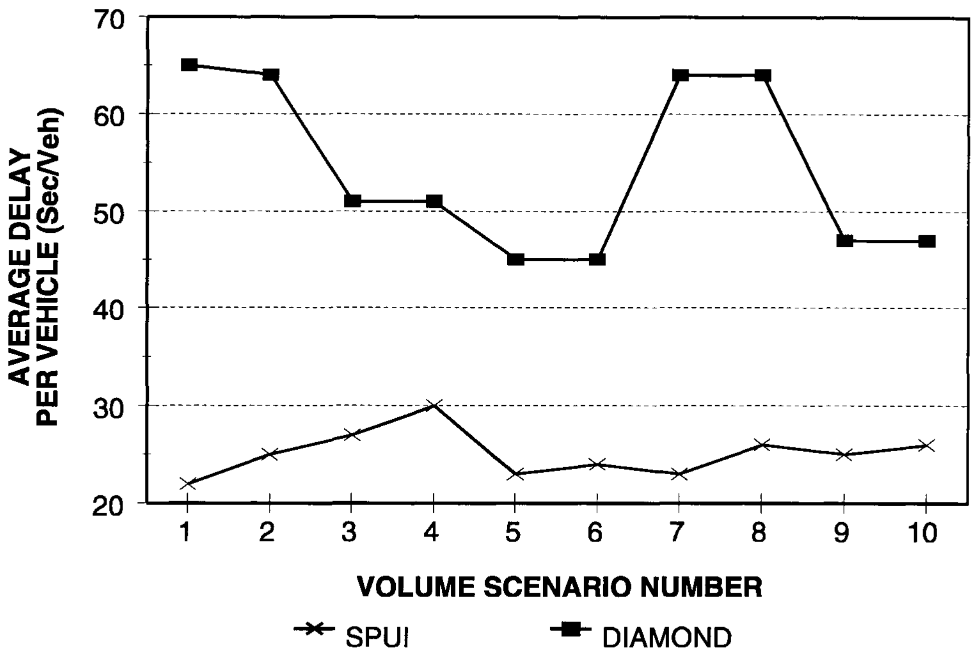


Figure 15. Operational Performance Comparison Under High-Volume Traffic Scenarios

same graph for the SPUI and DI. Looking at Figure 14, the increase in delay is significant for volume scenarios 3 & 4, where the higher through volume opposes the higher left-turn volume. For both the high-volume and low-volume interchanges, the SPUI delay increased approximately 30 percent for these scenarios. In general, the SPUI performance varied by scenario in the same way for the lower volumes as for the higher volumes. The DI, however, did not exhibit the same trend in the high and low-volume situations.

In general, the DI delay was lower than the SPUI delay for the lower volume scenarios and vice versa for the higher volume interchange. To examine this further, the existing volumes at the lower volume interchange were increased by a factor of 1.5, 2.0, and 2.5 to study the effect it would have on the delay at the two interchange types. These results are shown in Figure 16. The DI delay increases more dramatically with an increase in the total interchange approach volume than does the SPUI delay.

The delay results of the 6 SPUIs and 5 DIs were tested using the *t* test according to the following hypotheses:

H_o: $\mu_s = \mu_d$
H_1: μ_s < or > μ_d

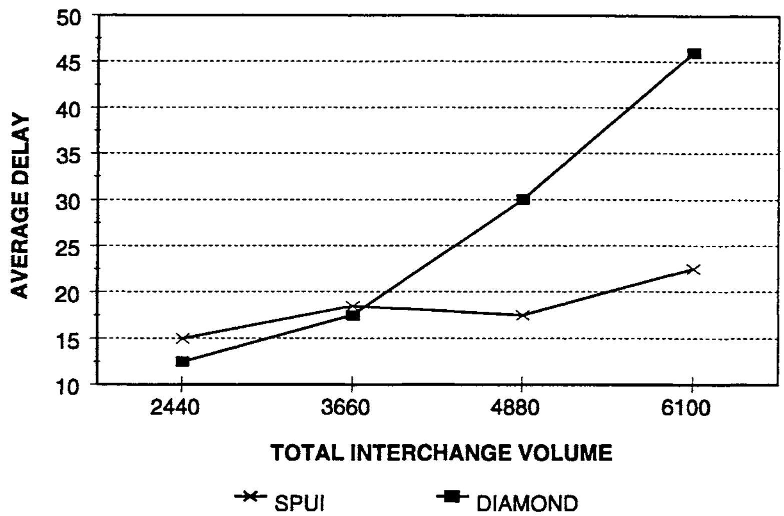


Figure 16. Operational Performance with Increasing Approach Volume

This was to test for a significant difference in the average stopped delay per vehicle during the peak hour at the SPUI and DI (at $\alpha = 0.05$). This test was performed for the total interchange, off-ramp, and cross road delay. Table 5 provides the results of these *t* tests.

Table 5. Results of *t* Tests of Average Stopped Delay per Vehicle (sec/veh)

Test	t	t_α	Result
Total interchange delay	1.1637	1.8331	Do not reject H_0
Off-ramp delay	1.5530	1.7247	Do not reject H_0
Cross road delay	1.3255	1.7247	Do not reject H_0

The test results indicated that there was not enough evidence to suggest a significant difference in the average stopped delay per vehicle at SPUIs and DIs. Hypotheses 1, 2, and 3 cannot, therefore, be rejected. The individual delay results in Table 3, however, were still used along with the geometric and traffic conditions to identify characteristics that contribute to the operational performance of the two interchanges.

The *t* tests were also conducted on the delay results of the DIs as compared with their newly designed SPUI counterpart. Table 6 shows the results of these tests. These results were, however, not used to develop guidelines for the reason given earlier.

Table 6. Results of *t* Tests of Delay at DIs and Corresponding SPUIs

Test	t	t_α	Result
Total interchange delay	0.6626	1.8595	Do not reject H_0
Off-ramp delay	0.6360	1.7341	Do not reject H_0
Cross road delay	0.7904	1.7341	Do not reject H_0

This analysis also showed no significant difference in the means of the delay at the two interchange forms at a significance level of 0.05.

Accident Analysis Results

Accident data were available for 8 SPUIs and 5 DIs. These sites and their locations are indicated in Appendix H. For each interchange, accidents were classified according to severity, collision type, and the location on the interchange where they occurred. The results are summarized for the SPUI and DIs in Tables 7 and 8, respectively.

Comparing the results of the two accident data sets was done graphically and statistically using the proportionality test and *t* test. The analysis was separated into three major study areas:

1. accident severity
2. accident location
3. collision type.

Table 7. SPUI Accident Data Summary

SPUI Accidents Summarized by Severity, Collision Type, and Location										
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**TOT**	**%**
Severity										
PDO	23	22	26	21	5	10	57	47	211	70.8
Injury	11	13	4	6	3	3	25	20	85	28.5
Fatal	0	1	0	0	0	0	0	1	2	0.7
Collision Type										
Rear-end	16	16	8	13	0	5	49	49	153	51.3
Off-ramp	5	1	2	2	0	1	22	31	64	21.5
On-ramp	1	0	2	0	0	4	1	2	10	3.3
At/between intersections	10	15	4	11	0	0	26	13	79	26.5
Angle	12	6	5	9	4	5	10	11	62	20.8
Sideswipe	3	6	7	4	0	0	9	2	31	10.4
Fixed object	2	6	4	0	3	2	7	0	24	8.1
Backed into	0	1	0	0	0	0	3	1	5	1.7
Other	1	1	6	1	1	1	4	8	23	7.7
Collision Location										
On-ramp	2	0	6	2	4	5	5	2	26	8.8
Off-ramp	8	8	4	2	1	1	30	33	87	29.3
Center	6	12	13	10	2	5	17	17	82	27.6
Cross road	18	16	7	13	1	2	30	15	102	34.3
Accident Rate (Per 100 Million Vehicles)										
Overall	56	57	60	6	64	93	118	190		
Injury	18	22	8	14	24	21	36	58		
PDO	38	35	52	47	40	72	82	132		

Table 8. DI Accident Data Summary

DI Accidents Summarized by Severity, Collision Type, and Location							
	D1	D2	D3	D4	D5	Total	%
Severity							
PDO	27	12	131	13	13	196	73.4
Injury	14	16	28	8	5	71	26.6
Fatal	0	0	0	0	0	0	0
Collision Type							
Rear-end	11	9	102	4	2	128	47.9
Off-ramp	4	5	36	2	0	47	17.6
On-ramp	2	0	1	0	0	3	1.1
At/between intersections	5	4	65	2	2	78	29.2
Angle	13	16	29	15	14	87	32.6
Sideswipe	3	0	12	1	0	16	6.0
Fixed object	4	3	2	0	1	10	3.7
Backed into	1	0	1	0	0	2	0.8
Other	9	0	13	1	1	24	9.0
Collision Location							
On-ramp	6	3	2	0	0	11	4.2
Off-ramp	8	5	45	2	1	61	23.0
Center	23	17	51	19	7	117	44.2
Cross road	4	3	59	0	10	76	28.7
Accident Rate (Per 100 Million Vehicles)							
Overall	67	73	208	337	49		
Injury	23	42	37	128	14		
PDO	44	31	171	209	35		

Severity

Of the 565 accidents in the data base analyzed, only two were fatal, and for this reason fatal accident rates were not investigated or tested. However, between the SPUI and DI, the total, injury, and property damage accident rates were tested for differences in the means, and the severity distributions for each type of interchange were studied.

Figure 17 shows the severity distributions for both interchanges. The distribution of accidents according to severity were very similar at the SPUI and DI. For more information, the means of the accident *rates* were tested for the following hypotheses at $\alpha = 0.05$:

H_o: $\mu_s = \mu_d$
H_1: $\mu_s < \text{or} > \mu_d$

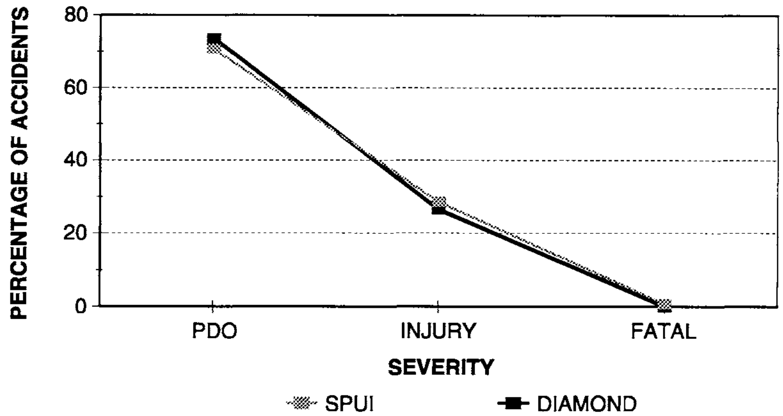


Figure 17. Accident Severity Distribution

The results of this test are shown in Table 9 and indicated that there is not enough evidence to conclude that accident rates (total, injury and property damage) are significantly different for the SPUI and DI. Hypotheses 4, 5, and 6 cannot, therefore, be rejected.

Table 9. *t* Test Results of Accident Rate Comparison

Accident Rate Tested	t	t_α	Result
Overall	1.2463	1.796	Do not reject H_o
Injury	1.3901	1.796	Do not reject H_o
PDO	1.0988	1.796	Do not reject H_o

Location

For the purposes of this analysis, the interchanges were broken down into four major areas or locations: on-ramps, off-ramps, center of the signalized intersection, and cross road. The accidents were sorted further by exact location, i.e., by particular on-ramp or off-ramp, and direction on the cross road. This detailed breakdown was used to identify significant geometric conditions at specific locations that may affect the safety of the interchange.

Figure 18 shows the distribution of accidents according to their location for the SPUI and DI. This graph shows a distinct difference in the percentage of accidents that occurred in the center of the intersections at each interchange type, with almost *half* of the DI accidents occurring there. This contradicts the original misconception that the SPUI is less safe due to its

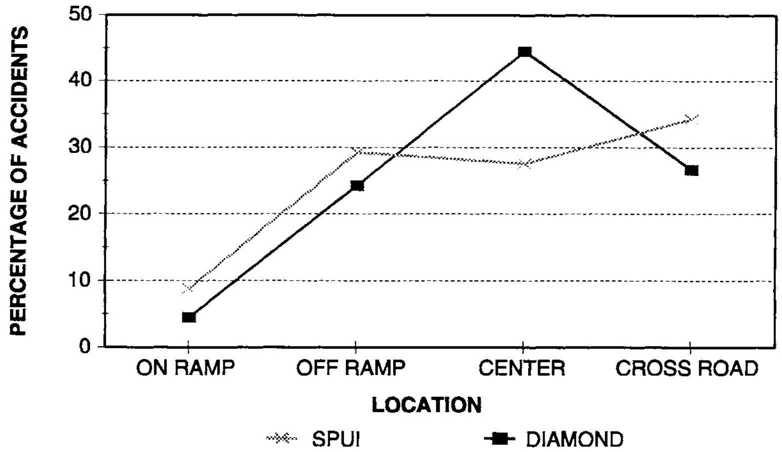


Figure 18. Accident Location Distribution

large, uncontrolled, open signalized intersection and the potential safety problems associated with it. In fact, the percentage of accidents that occurred in the center of the SPUI intersections was 16 percent lower than those at the DI, and a greater percentage of accidents at the SPUI occurred at the off-ramp and cross road areas than in the center of the SPUI.

A proportionality test was performed to determine if there was a significant difference in the proportion of accidents that took place at these four locations for the SPUI and DIs. The hypotheses tested (at $\alpha = 0.05$) were as follows:

H_o: $p_s = p_d$
H_I: p_s < or > p_d

The results of this analysis, in Table 10, confirm most of what is seen from the distribution in Figure 18: that there is enough evidence to reject the hypotheses that the proportion of accidents

Table 10. Proportionality Test Results of Location Distribution

Location	z	Result	Evidence Suggests
Off-ramp	1.6847	Reject H_o	$p_S > p_D$
On-ramp	2.1956	Reject H_o	$p_S > p_D$
Center	-4.0928	Reject H_o	$p_S < p_D$
Cross road	1.4399	Do not reject H_o	

Where p_S is SPUI proportion, and p_D is DI proportion.

at the on- and off-ramps and center of the intersection was the same for the SPUI and DI. The evidence suggests the following:

- The proportion of on-ramp accidents is greater at the SPUI.
- The proportion of off-ramp accidents is greater at the SPUI.
- The proportion of accidents in the center of the intersection is greater at DIs.

There was, however, no significant difference in the accident proportions on the cross road of the two interchange forms. Hypothesis 7 is, therefore, rejected for the on-ramp, off-ramp, and center locations at the interchange but cannot be rejected for the cross roads.

The accident *rates*, according to location, were not calculated because the 24-hr counts for each approach were not available at most interchanges; rather, the total 24-hr approach volume was supplied.

Collision Type

Five types of collisions were most common: rear-end, angle, sideswipe, fixed object, and backed into. All others were placed into an "other" category. The rear-end accidents were also broken down further by location.

The collision type distributions are shown in Figure 19 for the SPUI and DI. The largest difference in the shape of the two distributions was in the percentage of angle accidents. This is also shown in Figure 20, a graph of the accident rates by collision type. The angle accident rate at the DI is more than 3 times that at the SPUI. This result, however, is not surprising since the location distribution examined earlier indicated a large difference in the percentage of accidents in the centers of the SPUI and DI, where angle accidents occur.

The proportionality test was performed again to investigate whether a significant difference existed in the proportion of each collision type at SPUIs and DIs. The results in Table 11 indicate the following at $\alpha = 0.05$:

- The proportion of total, off-ramp, and cross road center rear-end accidents at SPUIs are not significantly higher than at DIs.
- The proportion of on-ramp rear-end accidents at SPUIs are significantly higher than at DIs.

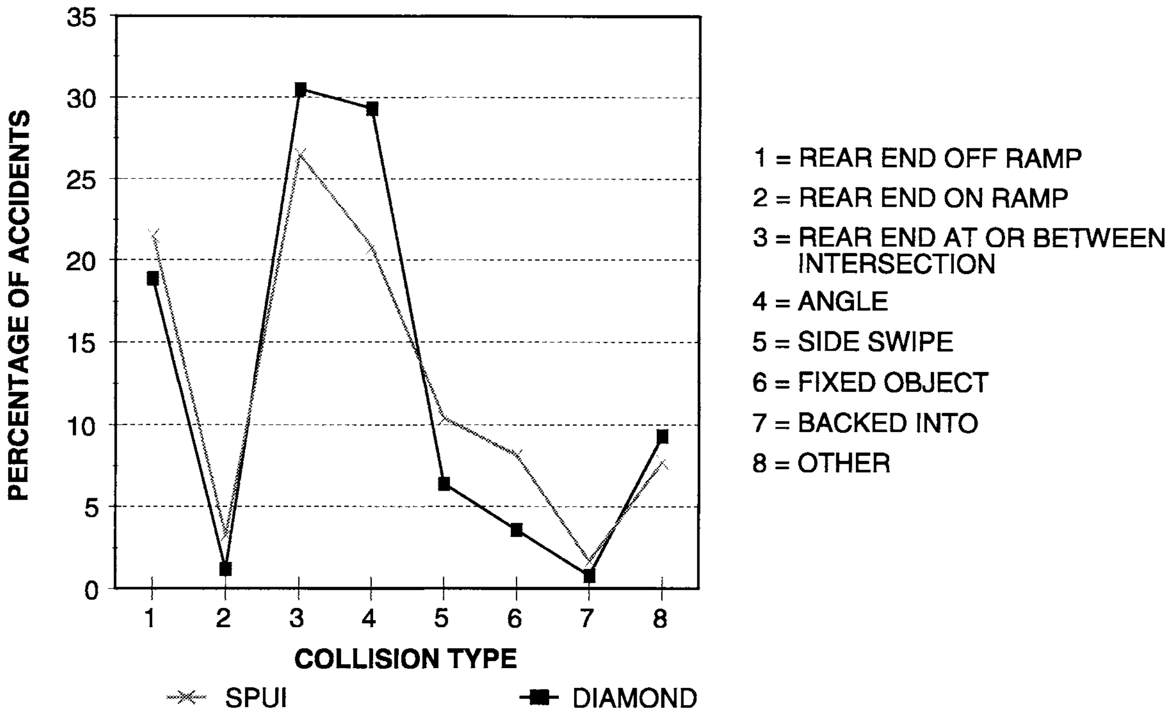


Figure 19. Collision Type Distribution

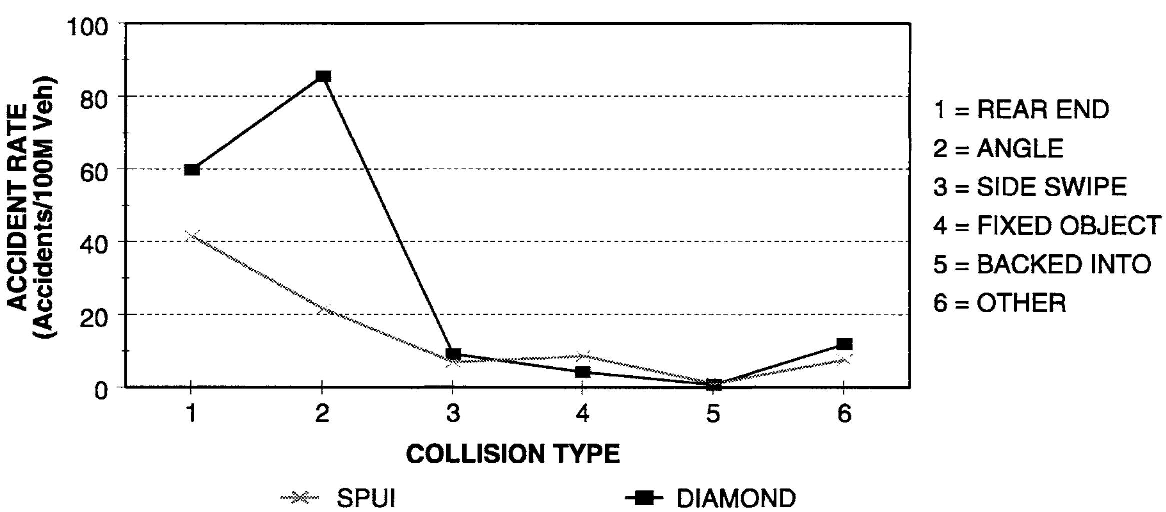


Figure 20. Accident Rates by Collision Type

Table 11. Proportionality Test Results of Collision Type Distribution

Collision Type	z	Result	Evidence Suggests
Rear-end total	0.807	Do not reject H_o	
Rear-end off-ramp	1.1588	Do not reject H_o	
Rear-end on-ramp	1.7733	Reject H_o	$p_S > p_D$
Rear-end cross rd/center	-0.7153	Do not reject H_o	
Angle	-3.17	Reject H_o	$p_S < p_D$
Sideswipe	1.1895	Reject H_o	$p_S > p_D$
Fixed object	2.1453	Reject H_o	$p_S > p_D$
Backed into	0.9973	Do not reject H_o	
Other	0.1683	Do not reject H_o	

Where p_S is SPUI proportion, and p_D is DI proportion.

- The proportions of sideswipe and fixed object accidents at SPUIs are significantly higher than at DIs.

- The proportion of angle accidents at SPUIs are significantly lower than at DIs.

Hypothesis 8 cannot, therefore, be rejected for angle, sideswipe, and fixed object accidents. Of the 10 rear-end on-ramp accidents that occurred at 8 SPUIs, 5 (half) took place at a particular on-ramp with a unique, signalized configuration. Because of this, further investigation was carried out for specific locations on the interchanges to find out whether they also created safety problems. No other locations caused such problems.

Conflicts

One conflict frequently observed occurred between the off-ramp right-turning vehicles and their opposing cross road through vehicles at a site where the nearest downstream intersection was approximately 76.20 m (250 ft) from the SPUI signalized intersection. The traffic signal at this downstream intersection was not coordinated with the SPUI signals, and because of its proximity, the vehicle queue was extending back to the point where the off-ramp right-turning vehicles enter the cross road. This problem was intensified because the location of the downstream signal was the only entrance to a shopping mall. The cross road vehicles in the far left lane (which came from both the opposing off-ramp left-turn and the cross road through traffic), were attempting to change lanes to get into the far right lane to enter the mall. Also, the far right lane on which the off-ramp right-turning vehicles entered ended at approximately 30.48 m (100 ft) past the downstream intersection, so vehicles were also attempting to change lanes toward the left. All of this lane-changing activity and constant weaving in an area of only

76.20 m (250 ft) caused very significant safety problems at this site. In fact, 33 percent of the accidents at this SPUI occurred in the vicinity of this downstream intersection.

Another noticeable and frequent conflict at SPUIs occurred where the cross road right-turning vehicles merge with the opposing cross road left-turning vehicles at the on-ramp. At a particular SPUI, the two traffic streams at this merge point were controlled by a signal. This on-ramp was signalized because two left-turn lanes and two right-turn lanes merged onto the ramp. Directly downstream of this signalized point, however, the ramp split into two ramps, one leading to an adjacent interstate and the other onto the major road beneath the SPUI. The problem was that vehicles in both traffic streams did not anticipate the signal or the stop, causing many on-ramp rear-end accidents and conflicts. Approximately 39 percent of all accidents at this intersection occurred at this location. This design, although rare, was necessary because of the characteristics of the adjacent highways.

Another common safety problem observed at the SPUI involved the off-ramp left-turning vehicles. The drivers traveling down the ramp into the intersection could not see the signal head until they were so near the stop line that they were not able to stop in time and, consequently, used the all-red clearance interval to traverse the intersection. The drivers "ran' the red and mature yellow intervals. This was due to the inadequate sight distance as the vehicles approached the intersection from the ramp. This conflict was not observed at the DI because the off-ramps were perpendicular to the cross road; therefore, the signals were visible from most points on the ramp. The SPUI ramps, however, were inverted, "hiding" the signal heads, usually behind the bridge structure.

A common conflict at the DI occurred when the number of cross road left-turning vehicles exceeded the number that could be stored in the left-turn pocket, thus causing queue spillback into the far left through lane. This, in turn, caused the drivers of the through vehicles to apply their brakes abruptly and change lanes suddenly, immediately after passing through the first signalized intersection.

These conflict observations, along with the corresponding accident data from 13 interchange sites were used to evaluate the safety aspects of each interchange design and develop guidelines based on these characteristics.

Summary of Results

Literature Survey

1. The presence of frontage roads significantly degrades the performance of the SPUI, due to the need for an additional fourth phase to provide for the frontage road through movement, incurring additional lost time and delay.

2. Severe skew in alignment between the two roadways has an adverse effect at SPUIs, increasing clearance distance, negatively affecting sight distance, and increasing cost.

3. The large left-turn radii at SPUIs allow the left-turn movements to operate similarly to a through movement in a capacity sense, with an acceptable saturation flow rate base value of 2,000 passenger cars per hour of green per lane (pcphgpl).

4. Driver unfamiliarity with the new design is not a major factor in accident occurrence.

5. The predominant type of accident at SPUIs, which were investigated in a safety study, was rear-end off-ramp accidents.

6. The accident rates at compressed DIs were higher and more severe than SPUIs.

7. Several conflicting opinions exist among traffic engineers as to the relative operational performance of the SPUI and DI.

Questionnaire Survey

1. The number of SPUIs being planned or considered for construction is almost twice the total number currently in operation.

2. The percentages of overpass and underpass SPUIs currently in operation and being considered for construction are similar, i.e., one type is not preferred to the other.

3. The most noted reason for selecting the SPUI over other interchange design alternatives is restricted right of way.

4. Other major factors contributing to the selection of the SPUI are:

   - increase in capacity and decrease in congestion
   - efficient phasing to minimize delay
   - simplified arterial coordination because of single signal design
   - the presence of high left-turn volumes.

5. The SPUI design does not easily accommodate pedestrian traffic across the arterial that requires an additional pedestrian phase.

6. At SPUI locations with continuous frontage roads, the overall interchange delay is significantly increased due to the requirement of an additional phase.

7. In general, the SPUI is more expensive to construct due to higher bridge and retaining wall costs.

8. The SPUI is more efficient when handling left-turn movements, and the DI is more efficient for the arterial through movement.

9. At SPUIs, signalizing the off-ramp right-turn movement decreases the overall interchange efficiency.

10. Sight distance and visibility are a problem at SPUIs due to the nature of the structure, particularly between the off-ramp and cross road vehicles.

11. The SPUI design can lead to driver confusion, and particular attention to channelization is necessary.

Operational Analysis

1. There is not enough evidence to suggest that there is a significant difference in the average stopped delay per vehicle at SPUIs and DIs (total interchange delay, off-ramp delay, and cross road delay were all tested).

2. Among the interchange sites investigated, the operational performance of DIs varied to a greater extent than did the performance of SPUIs; both sets were within a similar range of total interchange approach peak hour volumes.

3. The lack of a full right-turn lane on the off-ramp, particularly at DIs, significantly affects off-ramp delay.

4. When cross road left-turn and through volumes are both imbalanced and the higher through volume opposes the higher left-turn volume, the interchange average delay at the SPUI can be increased by up to 30 percent.

5. The delay at DIs increases more dramatically with an increase in total interchange approach volume than does the SPUI delay.

Safety Analysis

1. There is not enough evidence to suggest that accident rates (total, injury, and property damage) are significantly different for the SPUI and DI.

2. The proportion of on-ramp and off-ramp accidents at the SPUI is significantly greater than at the DI, at $\alpha = 0.05$.

3. The proportion of accidents occurring in the center of the intersection at DIs (most with permitted left-turn phasing) is significantly greater than at SPUIs, at $\alpha = 0.05$.

4. The proportion of rear-end accidents at on-ramps, sideswipe accidents, and fixed object accidents at the SPUI are significantly greater than at the DI, at $\alpha = 0.05$.

5. The proportion of angle accidents at DIs is significantly greater than those at SPUIs, at $\alpha = 0.05$.

6. At both interchange types, when signalized intersections on the cross road were adjacent to the interchange and the signals were not coordinated, several conflicts were observed, and most of the cross road accidents occurred at that location.

7. At one SPUI location, with a signalized on-ramp, conflicts and rear-end on-ramp accidents were significantly higher than at other locations.

8. At SPUI off-ramps, several conflicts were observed involving left-turn vehicles, due to inadequate sight distance as the vehicles approached the intersection from the ramp.

CONCLUSIONS

- The literature survey showed that no specific guidelines have yet been developed as to the selection of either the DI or SPUI.

- The survey of state engineers indicated that the SPUI is a safe, efficient urban interchange design that can decrease delay and congestion and, generally, uses less land area than other interchange types.

- The analysis of the relative operational performance of the DI and the SPUI revealed no significant differences in terms of off-ramp, cross road, or overall interchange average delay. However, the following operational findings were significant:

- The delay at DIs increases more dramatically with an increase in total interchange approach volume.

- The delay at SPUIs increases significantly under flow conditions where the cross road left-turn and through volumes are imbalanced and the higher cross road through volume opposes the higher left-turn volume, creating up to 30 percent higher delay values.

- The lack of a full right-turn lane, particularly at DIs, can significantly affect off-ramp delay.

• The analysis of accident data of several interchanges throughout the nation revealed no significant differences in the overall safety of the SPUI and DI. However, the safety of the interchanges is reduced at specific locations and under certain conditions:

- When permitted left-turn phasing is used at the DI, the proportion of angle and center accidents is notably higher than at the SPUI.

- Signalized intersections on the cross road that are adjacent to either interchange type create significant safety problems when the downstream signal is not coordinated with the interchange signal and when there is inadequate clear distance to the intersection.

- When on-ramp flows are signalized at the SPUI, conflicts and accidents are increased as compared with SPUIs with merge control.

DESIGN GUIDELINES

Many elements of this project provided important insight and new understanding as to the advantages and disadvantages of the SPUI and DI, based on a variety of operational and safety characteristics investigated. The guidelines are based on the results of the literature review, the questionnaire survey, and the analysis of operational and safety data. For the reader's convenience, the specific result(s) upon which each guideline is based is (are) indicated.

The guidelines are divided into two categories:

1. guidelines for the *selection* of the SPUI or DI

2. guidelines for the *specific design* of the SPUI or DI.

Suggested Guidelines for Interchange Selection

- When adjacent land use is such that restricted right of way is created, the SPUI should be seriously considered because, in general, it uses less land area than the DI. (S*ee Questionnaire Survey, Result 3.)*

- In cases where it is necessary to provide a phasing system that takes into consideration pedestrian movement across the arterial, the DI is preferred, as the SPUI design does not accommodate this pedestrian traffic easily. *(See Questionnaire Survey, Result 5.)*

- It is quite clear that when the interchange is to be constructed at locations with continuous frontage roads, the DI is preferred, as the SPUI's through movement requires an additional fourth phase that significantly increases the overall interchange delay. *(See Literature Survey, Result 1, and Questionnaire Survey, Result 6.)*

- When there is a skew angle between the intersection roadway alignments, the DI is preferred, as the SPUI is generally more expensive to construct due to the more extensive structure required. When skew angles exceed 30 degrees in the acute angle quadrant, AASHTO recommends taking extreme caution, as it not only significantly adds to the cost of the SPUI but also increases clearance distance, and, therefore, lost time, and negatively affects sight distance. *(See Literature Survey, Result 2.)*

- As determined in the safety analysis, when cross road left-turn volumes are high, the SPUI is preferred, as it is superior with regard to safety compared with the DI with permitted cross road left-turn phasing. When permitted phasing is used at the DI, the percentage of angle accidents in the center of the intersection is notably higher. *(See Safety Analysis, Results 3 and 5.)*

- The SPUI is more efficient in situations where the proportion of traffic at the interchange to and from the major road (left-turn movements) is relatively higher than the other movements, whereas the DI is more efficient when the proportion of traffic for the arterial through movement is relatively higher. *(See Questionnaire Survey, Result 8.)*

Suggested Guidelines for Specific Design

- In extreme cases where it is necessary to design an SPUI to accommodate pedestrian traffic across the arterial, two suggested practices are:

    1. Provide a 4-ft median on the arterial for pedestrian refuge and design the phasing of the interchange to allow a pedestrian to cross half way during the arterial left-turn phase and cross the remainder of the street during the following off-ramp phase or vice versa. (S*ee Questionnaire Survey, Result 5.)*

2. Provide an additional pedestrian phase, actuated by push buttons, where all traffic signal indications for vehicular traffic are red. *(See Questionnaire Survey, Result 5.)*

- When signalized intersections on the cross road are adjacent to either type of interchange, some clear distance should be established from the off-ramp right-turn merge point to the next signal. The downstream signal should also be coordinated with the interchange whenever possible, as these intersections affect performance, operation, and safety. *(See Safety Analysis, Result 6.)*

- At SPUIs, whenever possible, signalizing the off-ramp right-turning vehicles should be avoided. A yield sign should be provided with an adequate acceleration lane. The yellow plus all-red clearance intervals will be greatly reduced when such a sign is used, thus improving the capacity of the interchange by increasing the g/C ratio. *(See Questionnaire Survey, Result 9.)*

- When right-turn off-ramp volumes are high, the lack of a full right-turn lane on the off-ramp significantly affects off-ramp delay, particularly at DIs. Therefore, under this condition, a full right-turn lane should be provided so that right-turning vehicles, which need only to yield, are not blocked by the left-turning vehicles that are waiting for a green signal indication. *(See Operational Analysis, Result 3.)*

- For the SPUI, different volume scenarios have similar changes in delay. For low-volume and high-volume situations, however, particular attention should be paid if the cross road left-turn and through volumes are both imbalanced and the higher through volume direction opposes the higher left-turn volume direction. The operational analysis indicates that this particular flow condition may cause up to a 30 percent increase in overall interchange delay as compared with other volume scenarios at the SPUI. *(See Operational Analysis, Result 4.)*

- In the SPUI design, special consideration should be given to the visibility between the off-ramps and the cross road, as visibility of the oncoming traffic from the left is reduced at the SPUI and drivers approaching the bridge from the off-ramp must rely totally on all traffic obeying the signal. *(See Questionnaire Survey, Result 10.)*

- The signalization of on-ramp flows at SPUIs should be avoided whenever possible as this results in a significant increase in rear-end on-ramp accidents. *(See Safety Analysis, Result 7.)*

- The SPUI design requires distinct attention for signing and striping to reduce confusion and possible wrong-way maneuvers. A raised island in the middle of the signalized intersection provides positive delineation and reduces this confusion. *(See Questionnaire Survey, Result 11.)*

- At overpass SPUIs, due to the inverted off-ramp left turn, sight distance is often inadequate and drivers do not anticipate a stop, causing many conflicts. For this reason, special advanced warning signs may be appropriate on the off-ramps. *(See Questionnaire Survey, Result 10.)*

- Some characteristics of the SPUI and DI are important for consideration but do not necessarily call for the selection of one type over the other. One such characteristic is heavy left-turn truck traffic, as mentioned in the questionnaire and found in the literature review: At locations where the percentage of heavy truck traffic is large, it may be appropriate to use an SPUI, as the large turning radii allow for more efficient dual left turns of trucks side by side. *(See Literature Survey, Result 3, and Questionnaire Survey, Result 8.)*

RECOMMENDATIONS FOR FURTHER STUDY

- Based on the operations of several SPUIs and DIs throughout the nation, it is recommended that the existing cycle lengths and signal timings be reinvestigated, as computer simulation showed that, under existing conditions, lower cycle lengths at many locations could yield a lower overall interchange average delay.

- Although this project compared and created guidelines for the SPUI and DIs in urban locations, very little information exists to aid engineers in the selection of the optimum interchange type (among all interchange designs) for any location. A study similar to this one to help designers select the most suitable interchange would result in increased highway efficiency and reduced costs.

- Further study is also recommended as to the cost-effectiveness of the SPUI as compared with the DI. The actual economic benefits of one interchange type over the other, studied in conjunction with their construction and maintenance costs, would provide the economical comparison on which design engineers base many of their decisions.

REFERENCES

1. Cheng, E. Y.-C. 1991. Accident Analysis for Single Point Urban Interchange. In *ITE 1991 Compendium of Technical Papers,* pp. 29-32. Washington, D.C.: Institute of Transportation Engineers.

2. Poppe, M.J.; Radwan, A.E.; and Matthias, J.S. 1991. *Some Traffic Parameters for the Evaluation of the Single-Point Urban Interchange.* Transportation Research Record 1303. Washington D.C.: Transportation Research Board.

3. Garber, N.J., and Hoel, L.A. 1988. *Traffic and Highway Engineering*. New York: West Publishing Company.

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

5. *Single Point Urban Interchange for AASHTO Inclusion*. Unpublished memorandum, December 15, 1993.

6. Hawkes III, T.W., and Falini, M.D. 1987, February. The Urban Interchange. *Public Works,* pp. 45-46.

7. Urban Interchanges Spreading West. 1989, April. *Public Works*, pp. 50-51.

8. Greiner Engineering Sciences. n.d., circa 1970. *The Urban Interchange: A Design Concept.* Tampa, Fla.

9. Cook, K.G. 1989, July. Experience with the SPUI [Letter to the editor]. *Public Works*, p. 104.

10. Pott, J.T. 1989, June. Experience with the SPUI [Letter to the editor]. *Public Works*, p. 117.

11. Messer, C.S. et al. 1991. *Single Point Urban Interchange Design and Operations Analysis* NCHRP Report No. 345. Washington, D.C.: Transportation Research Board.

12. Garber, N.J., and Smith, M.J. 1994. *Results of SPUI Data Collection Survey.* Charlottesville: Virginia Transportation Research Council.

13. Brown, S. J., and Walters, G. 1988. The Single-Signal Interchange. In *ITE Compendium of Technical Papers,* pp. 180-184. Washington, D.C.: Institute of Transportation Engineers.

14. Bonneson, J.A., and Messer, C.J. 1989. *A National Survey of Single Point Urban Interchanges.* Report No. TTI-2-18-88-1148-1. College Station: Texas Transportation Institute.

15. Leisch, J.P., Urbanik, T., and Oxley, J.P. 1989, May. A Comparison of Two Diamond Interchange Forms in Urban Areas. *ITE Journal*, pp. 21-27.

16. Merritt, D.R. 1993. *Geometric Design Features of Single-Point Urban Interchanges.* Report No. TRR 1385. Washington, D.C.:Transportation Research Board.

17. Bonneson, J.A. 1992, June. Operational Efficiency of the Single-Point Urban Interchange. *ITE Journal*, pp. 23-28.

18. Bonneson, J.A. 1992. *Study of Headway and Lost Time at Single-Point Urban Interchanges.* Report No. 1365. Washington, D.C.: Transportation Research Board.

19. Fowler, B.C. 1993, April. An Operational Comparison of the Single-Point Urban and Tight-Diamond Interchanges. *ITE Journal*, pp. 19-24.

20. Hook, D.J.P., and Upchurch, J. 1992. *Comparison of Operational Parameters for Conventional and Single-Point Urban Interchanges.* Report No. 1356. Washington, D.C.: Transportation Research Board.

21. Glauz, W.D., and Migletz, D.J. 1980, February. *Application of Traffic Conflicts Analysis at Intersections.* NCHRP Report No. 219. Washington, D.C.: Federal Highway Administration.

22. Parker Jr., M.R., and Zegeer, C.V. 1988, June. *Traffic Conflict Techniques for Safety and Operations, Engineers Guide.* Report No. FHWA-IP-88-026. Washington, D.C.: Federal Highway Administration.

23. Migletz, D.J., Glauz, W.D., and Bauer, K.M. 1985, July. *Relationships Between Traffic Conflicts and Accidents, Volume 2: Final Report.* Report No. FHWA/RD-84/042. Washington D.C.: Federal Highway Administration.

24. Parker Jr., M.R., and Zegeer, C.V. 1985, July. *Traffic Conflict Techniques for Safety and Operations, Observers Guide.* Report No. FHWA-IP-88-027. Washington, D.C.: Federal Highway Administration.

25. Transportation Research Board. 1994. *Highway Capacity Manual. Special Report 209,* ed. 3. Washington D.C.

26. U.S. Department of Transportation. 1993, April. *TRAF User Reference Guide, Version 4.0.* Washington, D.C.: Federal Highway Administration.

Appendix A

NATIONWIDE QUESTIONNAIRE OF SPUI USE

SINGLE POINT URBAN INTERCHANGE SURVEY

1. How many SPUIs are currently in operation in your state?

   0 1 2 3 4 5 6 7 8 9 10 >10

2. How many SPUIs are being considered or planned for construction within the next 5-10 years?

   0 1 2 3 4 5 6 7 8 9 10 >10

If your answer to both questions 1 and 2 are zero, then it is not necessary to complete the remaining questions. Please fold and return. Thank you for your help.

3. Please indicate the number of SPUIs in your state that are of an overpass or underpass configuration, i.e., if the major arterial is an overpass or and underpass. (Please list number of each.)

   In Operation Overpass _____ Underpass _____
   Under Consideration Overpass _____ Underpass _____

4. What were your reasons for selecting the SPUI over other types of interchanges? (Please mark all that apply.)

   __Restricted right-of-way
   __Efficient signal phasing to obtain minimum delay
   __SPUI expected to increase traffic-carrying capacity
   __Signalization at only one major intersection simplifies coordination on the arterial
   __SPUI design lessens construction cost
   __To accommodate extremely high left-turn volumes
   __Existence of excessive large-truck operations involving left-turn movements
   __SPUI expected to relieve congestion difficulties
   __SPUI is the safer alternative design compared with the Diamond Interchange
   __Easier access to surrounding land use

Others____

5. Rate your SPUIs that are now in operation on a scale of 1 to 5 (1 being poor and 5 being excellent) according to how well they meet the following expectations as compared with a similar Diamond Interchange. Please indicate your rating for each SPUI separately in the table below.

	SPUI 1	SPUI 2	SPUI 3	SPUI 4	SPUI 5	SPUI 6	SPUI 7	SPUI 8	SPUI 9	SPU I 10
Increased Capacity										
Congestion Relief										
Arterial Coordination										
Safety										
Construction Cost										

6. List any advantages or disadvantages of the SPUIs in operation in your state.

Advantages	Disadvantages
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________

7. Do you have available to you any traffic and/or accident data for the SPUIs that are currently in operation in your state?

   Yes   No

8. If yes to question 7, can these data be made available for use in this study?

   Yes   No

Additional Comments: Please add any additional comments you may have on the operational and safety characteristics of the SPUI.

____
____
____
____

NAME: ____

STATE: ____

TELEPHONE NUMBER: ____

Thank you very much for your time!

Please return to:

Nicholas J. Garber, Ph.D.
VDOT Research Council
P.O. Box 3817
University Station
Charlottesville, VA 22903-0817
Questions, call (804) 293-1908
293-1906

Appendix B

QUESTIONNAIRE RESULTS

SUMMARY OF SPUI SURVEY RESULTS

Survey Response

Number of surveys sent:	**51**
Number of responses:	**49**
Overall response rate:	**96%**

SPUIs in Operation

Number of SPUIs in operation in the U.S.: **59**
Number of states with SPUIs in operation: **20 (39%)**
Overpass SPUIs in operation: **26 (44%)**
Underpass SPUIs in operation: **33 (56%)**

SPUIs Considered or Planned for Construction

Number of SPUIs considered or planned for construction: **117**
Number of states considering building new SPUIs: **29 (57%)**
Overpass SPUIs under consideration: **61 (55%)**
Underpass SPUIs under consideration: **49 (45%)**

Reasons for selecting or considering the SPUI over other type interchanges:

REASON	NUMBER OF RESPONSES
Restricted right-of-way	29
SPUI expected to increase traffic carrying capacity	21
To accommodate extremely high left turn volumes	19
Efficient signal phasing to obtain minimum delay	18
SPUI expected to relieve congestion	17
Signalization at only one major intersection simplifies coordination on the arterial	15
SPUI is safer alternative design compared with the Diamond Interchange	5
Easier access to surrounding land use	5
Existence of excessive large-truck operations involving left turn movements	3
SPUI design lessens construction cost	2
Other	2

Note: 29 engineers responded to this question and *all* 29 chose restricted right-of-way as a reason for selecting the SPUI over other interchange types.

Ratings of SPUIs in Operation

56 SPUIs were rated on a scale of 1 to 5 (1 being poor and 5 being excellent) in the following areas:

	Average Rating
Increases Capacity	4.03
Congestion Relief	4.01
Arterial Coordination	3.92
Safety	3.37
Construction Cost	2.94

Advantages and Disadvantages of the SPUIs in Operation

ADVANTAGES

1) better for large truck operation
2) less right-of-way required
3) added capacity due to one signal instead of two
4) drivers need only to stop once
5) excellent turning efficiency
6) accommodates access to business well
7) reduced overall delay
8) handling of traffic during construction is better facilitated
9) accommodates large left turn volumes
10) ease of traffic control
11) better arterial coordination
12) good alternative in preliminary planning
13) reduced congestion
14) increased traffic flow
15) better for large tractor-trailer operation
16) easy for motorists to understand

DISADVANTAGES

1) more expensive due to higher construction cost of bridge and maintenance costs of retaining walls
2) lack of driver familiarity (confusing)
3) sight of clearance is a problem
4) more maintenance necessary
5) room for improvement in phasing and operational characteristics
6) long clearance interval
7) does not accommodate pedestrian facilities easily
8) start up delays are higher
9) poor placement of signal heads
10) pavement markings are confusing

Appendix C

OPERATIONAL AND ACCIDENT DATA QUESTIONNAIRE

SINGLE POINT URBAN INTERCHANGE DATA SHEET

Location

City/County:____

State:____

Major Road: ____

Functional Classification: _________________________________

Cross Road: ____

Functional Classification: _________________________________

Configuration

Does the major road pass over or under the cross road?

___ over ___under

Do frontage roads exist?

___yes___no

Is the interchange skewed (i.e., does the intersection of the two roadway alignments not occur at a 90 degree angle?)

___yes___no

If yes, what is the approximate degree of the intersection angle of the two roadway alignments?___

Surrounding Land Use

Indicate what type of land use exists in the vicinity of the interchange.
(Please check all that apply.)

___residential
___commercial
___industrial
___office park
___other

What is the distance to the nearest intersection stop bar on the cross road from the off-ramp merge point? (off-ramp: ramp from major road onto cross road)

___<200 ft
___200-300 ft
___300-400 ft
___400-500 ft
___500-600 ft
___600-700 ft
___700-800 ft
___800-900 ft
___900-1000 ft
___1000-1100 ft
___1100-1200 ft
___1200-1300 ft
___1300-1400 ft
___1400-1500 ft
___>1500 ft

Geometric Characteristics

Number of Lanes and Dimensions

Please indicate the number of lanes available for each direction and the average lane width for the movements indicated below:

Major Road		# of lanes	avg. lane width
Off-ramp direction 1:	right turn	____	____ ft
	left turn	____	____ ft
	through	____	____ ft
Off-ramp direction 2:	right turn	____	____ ft
	left turn	____	____ ft
	through	____	____ ft

What is the approximate radius of the off-ramp left turns? ____ ft
____ ft

What is the approximate grade of the off-ramps? ____%
(off-ramp: ramp from major road onto cross road)

Cross Road		# of lanes	avg. lane width
Direction 1:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft

Direction 2:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft

What is the approximate radius of the cross road left turns? ____ ft
____ ft

Channelization

What type of channelization exists at the interchange?
(Please check all that apply.)

Off-ramps: (from major road onto cross road)

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

On-ramps: (from cross road onto major road)

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

Cross Road:

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

Volumes

Indicate the peak hour volume (AM/PM) in each direction for each movement below:

Major Road:		AM / PM
Off-ramp direction 1:	right turns	___ / ___
	left turns	___ / ___
	through	___ / ___
Off-ramp direction 2:	right turns	___ / ___
	left turns	___ / ___
	through	___ / ___

Cross Road:

Direction 1:	through	___ / ___
	left turns	___ / ___
	right turns	___ / ___
Direction 2:	through	___ / ___
	left turns	___ / ___
	right turns	___ / ___

24-hr total intersection approach volume___ / ___

Signal Timings

Sketch the phase sequence and signal timings for the intersection:
(Please include overall cycle length and each phase length, indicating also the time needed for the yellow and all-red intervals)

If you prefer, simply attach a copy of the signal timing plans.

Additional Comments:

___

___

___

Delay (if available)

Please indicate the average delay during the peak hour in each direction for each movement below:

Major Road:

Off-ramp direction 1:	right turns	____sec/veh
	left turns	____sec/veh
	through	____sec/veh
Off-ramp direction 2:	right turns	____sec/veh
	left turns	____sec/veh
	through	____sec/veh

Cross Road:

Direction 1:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh
Direction 2:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh

Number of Accidents at the Intersection on the Cross Road

Type of Accident	**PDO**	**Injury**	**Fatal**
Angle			
Rear End			
Left Turn			
Other			

The above data covers the following duration:____years ____months.

In addition to the above questionnaire, if you have any plan sheets or a sketch of the interchange that you could attach, it would be greatly appreciated.

NAME:______________________________________
STATE:______________________________________
TELEPHONE #:________________________________

Thank you very much for your time!

Please return to:

Michelle J. Smith
VDOT Research Council
530 Edgemont Road
Charlottesville, VA 22903
Questions, call (804) 293-1908
(804) 293-1906

DIAMOND INTERCHANGE DATA SHEET

Location

City/County:____
State:____

Major Road: ____
Functional Classification: ________________________________

Cross Road: ____
Functional Classification: ________________________________

Configuration

Does the major road pass over or under the cross road?
___ over ___under

Do frontage roads exist?
___yes___no

Is the interchange skewed (i.e., does the intersection of the two roadway alignments not occur at a 90 degree angle)?
___yes___no

If yes, what is the approximate degree of the intersection angle of the two roadway alignments?___

Surrounding Land Use

Indicate what type of land use exists in the vicinity of the interchange.
(Please check all that apply.)

___residential
___commercial
___industrial
___office park
___other

What is the distance to the nearest intersection stop bar on the cross road from the off-ramp merge point?
(off-ramp: ramp from major road onto cross road)

___<200 ft
___200-300 ft
___300-400 ft
___400-500 ft
___500-600 ft
___600-700 ft
___700-800 ft
___800-900 ft
___900-1000 ft
___1000-1100 ft
___1100-1200 ft
___1200-1300 ft
___1300-1400 ft
___1400-1500 ft
___>1500 ft

Geometric Characteristics

Number of Lanes and Dimensions

Please indicate the number of lanes available for each direction and the average lane width for the movements indicated below:

Major Road		# of lanes	avg. lane width
Off-ramp intersection 1:	right turn	____	____ ft
	left turn	____	____ ft
	through	____	____ ft
Off-ramp intersection 2:	right turn	____	____ ft
	left turn	____	____ ft
	through	____	____ ft

What is the approximate radius of the off-ramp left turns?
Intersection 1 ____ ft
Intersection 2 ____ ft

What is the approximate grade of the off-ramps? ____%
(off-ramp: ramp from major road onto cross road)

Cross Road

Intersection 1

		# of lanes	avg. lane width
Direction 1:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft
Direction 2:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft

Intersection 2

		# of lanes	avg. lane width
Direction 1:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft
Direction 2:	through	____	____ ft
	left turn	____	____ ft
	right turn	____	____ ft

What is the approximate radius of the cross road left turns?
Intersection 1 ____ ft
Intersection 2 ____ ft
What is the distance between the two intersections? ____ ft

Channelization

What type of channelization exists at the interchange?
(Please check all that apply.)

Off-ramps: (from major road onto cross road)

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

On-ramps: (from cross road onto major road)

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

Cross Road:

___painted pavement markings
___raised island
___recessed pavement markers
___embedded pavement marking lights

Volumes

Indicate the peak hour volume (AM/PM) in each direction for each movement below:

Major Road:		AM / PM
Off-ramp intersection 1:	right turns	___ / ___
	left turns	___ / ___
	through	___ / ___
Off-ramp intersection 2:	right turns	___ / ___
	left turns	___ / ___
	through	___ / ___

Cross Road:

Intersection 1

Direction 1:	through	___ / ___
	left turns	___ / ___
	right turns	___ / ___
Direction 2:	through	___ / ___
	left turns	___ / ___
	right turns	___ / ___

Intersection 2

Direction 1:	through	___ / ___
	left turns	___ / ___
	right turns	___ / ___
Direction 2:	through	___ / ___
	left turns	___ / ___

right turns ___ / ___

24-hr total intersection approach volume___ / ___

Signal Timings

Sketch the phase sequence and signal timings for the intersection:
(Please include overall cycle length and each phase length, indicating also the time needed for the yellow and all-red intervals)

If you prefer, simply attach a copy of the signal timing plans.

Additional Comments:

Delay (if available)

Please indicate the average delay during the peak hour in each direction for each movement below:

Major Road:

Off-ramp intersection 1:	right turns	____sec/veh
	left turns	____sec/veh
	through	____sec/veh
Off-ramp intersection 2:	right turns	____sec/veh
	left turns	____sec/veh
	through	____sec/veh

Cross Road:

Intersection 1

Direction 1:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh
Direction 2:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh

Intersection 2

Direction 1:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh
Direction 2:	right turns	____sec/veh
	through	____sec/veh
	left turns	____sec/veh

Number of Accidents at the Intersection on the Cross Road

Type of Accident	**PDO**	**Injury**	**Fatal**
Angle			
Rear End			
Left Turn			
Other			

The above data covers the following duration:____years ____months.

In addition to the above questionnaire, if you have any plan sheets or a sketch of the interchange that you could attach, it would be greatly appreciated.

NAME:____
STATE:____
TELEPHONE #:__________________________________

Thank you very much for your time!

Please return to:

Michelle J. Smith
VDOT Research Council
530 Edgemont Road
Charlottesville, VA 22903
Questions, call (804) 293-1908
(804) 293-1906

Appendix D

CONFLICT STUDY SAMPLE DATA FORMS

INTERSECTION TRAFFIC CONFLICTS

Location Magruder (Leg Totals) Leg Number Off Ramp EB

Day________ Date________ Observer________ Length of Recording Period 7:15-8:15

C = Conflict SC = Secondary Conflict

Count Start Time (Military)		Approach Volume	Left-Turn Same Direction		Right-Turn Same Direction		Slow Vehicle		Lane Change		Dooosing Left-Turn		Right-Turn From-Right		Left-Turn From-Right		Through From-Right		Right-Turn From-Left		Left-Turn From-Left		Through From-Left		Right-Turn On-Red		All Same Direction		All Cross Traffic		Other
			c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	c	sc	
7^{15}			10		2		0		7		0		4		0		0		0		0		0		0		19		4		
7^{30}			10		7		0		10		0		8		0		0		0		0		0		0		27		8		
7^{45}			16		9		0		5		0		8		0		0		0		0		0		0		30		8		
8			6		7		0		11		0		4		0		0		0		0		0		0		24		4		
Total		580	42		25		0		33		0		24		0		0		0		0		0		0		100		24		
C+SC			42		25				33				24														100		24		
Comments			72.4		43.1				56.9				41.4												172.4		41.4				

Appendix E

STOPPED VEHICLE DATA COLLECTION WORKSHEET

Intersection: ____________________________
Location: ____________________________
Approach: ____________________________
Movement: **Thru** **Left** **Right**

INTERSECTION DELAY WORKSHEET								
NUMBER OF STOPPED VEHICLES								
MIN/SEC								
Totals								

$V_s =$

$$\text{Delay} = \frac{\Sigma V_s \text{ x } 1}{V}$$

Volume, V =

Intersection: Aberdeen and I 664
Location: Hampton, VA
Approach: SB off-ramp AM 7:45-8:45 V=144
Movement: **Thru** **Left** **Right**

INTERSECTION DELAY WORKSHEET								
NUMBER OF STOPPED VEHICLES								
MIN/SEC	+0	+10	+20	+30	+40	+50		
7:45	0	0	0	0	0	0		
7:46	0	1	0	0	0	0		
7:47	1	0	0	2	3	3		
7:48	3	0	0	1	2	2		
7:49	2	0	0	1	2	2		
7:50	2	0	0	0	1	2		
7:51	0	0	0	1	1	2		
7:52	0	0	0	0	0	0		
7:53	0	0	0	0	1	0		
7:54	1	1	1	2	0	0		
7:55	1	2	2	2	0	0		
7:56	0	0	0	0	2	0		
7:57	0	0	1	1	0	0		
7:58	1	2	2	4	0	0		
7:59	0	1	2	2	0	0		
Totals	11	7	8	16	12	11		

$V_s = 65$ Delay = $\frac{\Sigma V_s \times 1}{V}$

Volume, V =

INTERSECTION DELAY WORKSHEET								
NUMBER OF STOPPED VEHICLES								
MIN/SEC	+0	+10	+20	+30	+40	+50		
8:00	0	0	0	1	0	0		
8:01	1	2	3	0	0	0		
8:02	1	1	2	0	0	0		
8:03	1	1	1	0	0	1		
8:04	1	1	0	1	3	3		
8:05	4	4	0	0	0	0		
8:06	1	0	0	2	3	3		
8:07	4	0	0	1	1	1		
8:08	1	0	0	0	0	1		
8:09	0	0	0	0	2	2		
8:10	0	0	0	1	1	1		
8:11	0	0	0	1	1	0		
8:12	0	0	1	3	3	0		
8:13	0	0	0	1	1	0		
8:14	0	0	1	1	1	0		
Totals	14	9	8	12	16	12		

$V_s = 71$ Delay = $\frac{\Sigma V_s \times 1}{V}$

Volume, V =

INTERSECTION DELAY WORKSHEET								
NUMBER OF STOPPED VEHICLES								
MIN/SEC	+0	+10	+20	+30	+40	+50		
8:15	0	0	1	2	0	0		
8:16	0	1	1	1	0	0		
8:17	0	1	1	2	0	0		
8:18	0	1	1	2	0	0		
8:19	1	1	1	1	0	0		
8:20	1	1	1	3	0	0		
8:21	0	1	3	3	0	0		
8:22	0	0	0	1	0	0		
8:23	0	0	1	1	0	0		
8:24	1	2	2	0	0	0		
8:25	2	2	2	0	0	1		
8:26	2	2	3	0	0	0		
8:27	0	0	0	0	0	1		
8:28	2	3	3	0	0	0		
8:29	0	0	1	0	0	0		
Totals	9	15	21	16	0	2		

$V_s = 63$ Delay = $\frac{\Sigma V_s \times 1}{V}$

Volume, V =

INTERSECTION DELAY WORKSHEET								
NUMBER OF STOPPED VEHICLES								
MIN/SEC	+0	+10	+20	+30	+40	+50		
8:30	0	0	0	0	0	1		
8:31	1	2	0	0	0	0		
8:32	1	2	0	0	0	0		
8:33	1	3	0	0	0	1		
8:34	1	1	0	0	0	1		
8:35	1	1	0	0	1	1		
8:36	2	0	0	1	1	2		
8:37	2	0	0	0	0	0		
8:38	0	0	0	0	0	0		
8:39	0	0	0	0	0	0		
8:40	0	1	0	0	0	0		
8:41	0	0	0	0	0	0		
8:42	0	0	0	0	1	0		
8:43	0	1	1	1	0	0		
8:44	1	1	1	1	0	0		
Totals	10	12	2	3	3	6		

$V_s = 36$ $\quad$ Delay $= \frac{\Sigma V_s \times 1}{V}$

Volume, V =

Appendix F

LIST OF INTERCHANGE SITES FOR OPERATIONAL COMPARISON

Single Point Urban Interchange Sites

SPUI-1	Gallows Road and Arlington Boulevard, Fairfax, Virginia
SPUI-2	Magruder Boulevard and Hampton Roads Center Parkway, Hampton, Virginia
SPUI-3	Fairview Park and Arlington Boulevard, Fairfax, Virginia
SPUI-4	NC 16 and I-85, Charlotte, North Carolina
SPUI-5	Lake Avenue and I-35, Duluth, Minnesota
SPUI-6	Route 180 and I-170, St. Louis, Missouri

Diamond Interchange Sites

DI-1	Aberdeen Road and I-664, Hampton, Virginia
DI-2	Sunset Drive and SR 826, Dade County, Florida
DI-3	NW 74th Street and SR 826, Dade County, Florida
DI-4	Elm Avenue and I-44, Webster Groves, Missouri
DI-5	Page Avenue and I-170, St. Louis, Missouri

Appendix G

VOLUME SCENARIOS

Turning Movement Volumes for the Low-Volume Interchange

Volume Scenario	NB		SB		EB			WB		
	L	R	L	R	L	T	R	L	T	R
1	300	100	300	200	150	590	130	150	590	190
2	200	100	400	200	150	590	130	150	590	190
3	300	100	300	200	300	450	130	100	900	190
4	200	100	400	200	300	450	130	100	900	190
5	300	100	300	200	300	900	130	100	450	190
6	200	100	400	200	300	900	130	100	450	190
7	300	100	300	200	150	450	130	150	900	190
8	200	100	400	200	150	450	130	150	900	190
9	300	100	300	200	300	600	130	150	600	190
10	200	100	400	200	300	600	130	150	600	190

Turning Movement Volumes for the High-Volume Interchange

Volume Scenario	WB		EB		NB			SB		
	L	R	L	R	L	T	R	L	T	R
1	500	350	500	400	800	1000	300	800	1000	300
2	300	350	700	400	800	1000	300	800	1000	300
3	500	350	500	400	400	1200	300	1000	800	300
4	300	350	700	400	400	1200	300	1000	800	300
5	500	350	500	400	400	800	300	1000	1200	300
6	300	350	700	400	400	800	300	1000	1200	300
7	500	350	500	400	800	800	300	800	1200	300
8	300	350	700	400	800	800	300	800	1200	300
9	500	350	500	400	400	1000	300	1000	1000	300
10	300	350	700	400	400	1000	300	1000	1000	300

Appendix H

INTERCHANGE SITES FOR SAFETY ANALYSIS

Single Point Urban Interchanges

S1 Gallows Road and Arlington Boulevard, Fairfax, Virginia

S2 Evans Avenue and Santa Fe Drive, Colorado Springs, Colorado

S3 24th Avenue and I-494, Bloomington, Minnesota

S4 Magruder Boulevard and Hampton Roads Center Parkway, Hampton, Virginia

S5 Lake Avenue and I-35, Duluth, Minnesota

S6 Fairview Park and Arlington Boulevard, Fairfax, Virginia

S7 Garden of the Gods Road and I-25, Colorado Springs, Colorado

S8 Route 180 and I-170, St. Louis, Missouri

Diamond Interchanges

D1 34th Avenue and I-494, Bloomington, Minnesota

D2 Aberdeen Road and I-664, Hampton, Virginia

D3 Page Avenue and I-170, St. Louis, Missouri

D4 5th Avenue and I-35, Duluth, Minnesota

D5 Port Republic Road and I-81, Harrisonburg, Virginia