SPUI Design Considerations for the Grand Parkway in Harris County

Matthew Brannen, PE[1], Federico Mendoza, PE, PTOE[1], Douglas Emery, PE[2]

1.0 Introduction

The Harris County Toll Road Authority (HCTRA) retained Brown & Gay Engineers, Inc. (BGE) to serve in the capacity of Program Management Consultant for the construction of Segment E of the Grand Parkway in Harris County. BGE's role in the project includes managing the overall design of Segment E of the Grand Parkway including the coordination with more than 30 consultants.

1.1 Project Location

The Grand Parkway is a proposed scenic highway circling the Houston area consisting of more than 180 miles of roadway through seven counties. There are twelve segments of the Grand Parkway in various stages of development with two segments having been constructed to date. One of the constructed segments, Segment D, is an existing 20-mile stretch of roadway between US 59 in Sugar Land, Texas, and IH-10 in Katy, Texas.

Segment E of the Grand Parkway will connect Segment D to proposed Segment F-1 to the north. Segment E begins at IH-10 and runs north to US 290 just west of Cypress, Texas, and will consist of over 15 miles of controlled access tollway including nine interchanges. A project location map is displayed below in **Figure 1**.

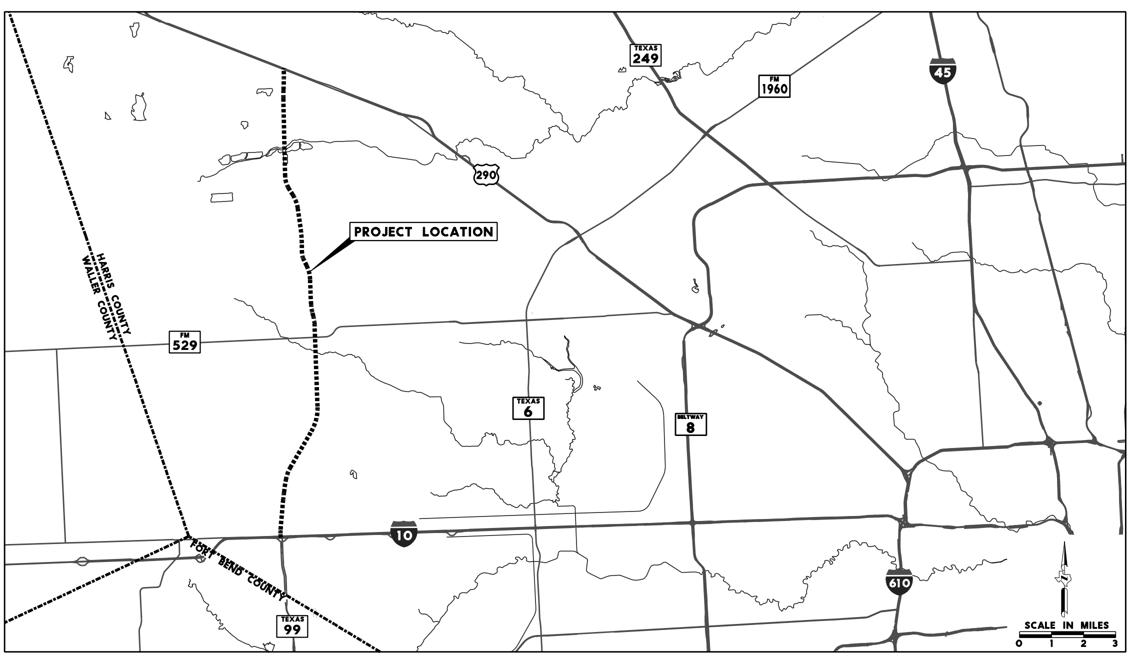

Figure 1. Project Location Map

1. Brown & Gay Engineers, Inc., 10777 Westheimer, #400, Houston, TX 77042, 281-558-8700
2. Harris County Toll Road Authority, 330 Meadowfern, Houston, TX 77067, 832-601-7800

1.2 Project History

The idea of designing a third loop around the greater Houston area to reduce future congestion and increase regional mobility was first proposed by the City of Houston Planning Commission in 1961. The project eventually began to move forward as State Highway 99, administered by the Texas Department of Transportation (TxDOT). Planning work on Segment E began in 1993, but was halted shortly thereafter for funding reasons. Planning work resumed in 2000 and this work resulted in a Record of Decision from the Federal Highway Administration (FHWA) on the Final Environmental Impact Statement for Segment E in June 2008. At the same time that the planning work was being performed, the schematic design of the facility was completed.

A lack of available construction funding from TxDOT caused the agency to look into alternate funding options in order to construct the project in an expeditious time frame. HCTRA came forward as a potential developer for the project and began negotiations with TxDOT to design, build, operate and maintain Segment E of the Grand Parkway. An Advance Funding Agreement was agreed to by both parties in early 2009. This agreement allows HCTRA to develop the project and to be reimbursed by TxDOT for any expenses that they incur, should TxDOT choose a different developer for the project at some point in the future.

Final design on the project began in March 2009. During the examination of the schematic design by Harris County personnel, it was requested that the diamond interchanges along the project be replaced with a single point urban interchange (SPUI) design where possible.

1.3 Standard Highway Interchanges

In urban areas where traffic volumes on the cross streets require multiple lanes in each direction, the highway interchange design can be a difficult task. The interchange must allow for future lane widening to both the highway and cross street with minimal reconstruction. This is typically achieved by designing an interchange where the highway crosses over the cross street to allow maximum volume through the interchange. The most frequently used urban interchange in Texas is known as a *diamond interchange*. However, an alternative interchange design, the *single point urban interchange* or *SPUI*, has been utilized in other parts of the country.

1.3.1 The Diamond Interchange

A diamond interchange creates a grade separation between the highway and the cross street. This separation is typically formed by the highway passing over the cross street with entrance and exit ramps to the cross street. The entrance and exit ramps intersect the cross street on each side of the highway, creating two intersections. Each intersection is controlled by either stop signs or, if volume warrants, traffic signals. A typical geometric layout of a diamond interchange is shown in **Figure 2.**

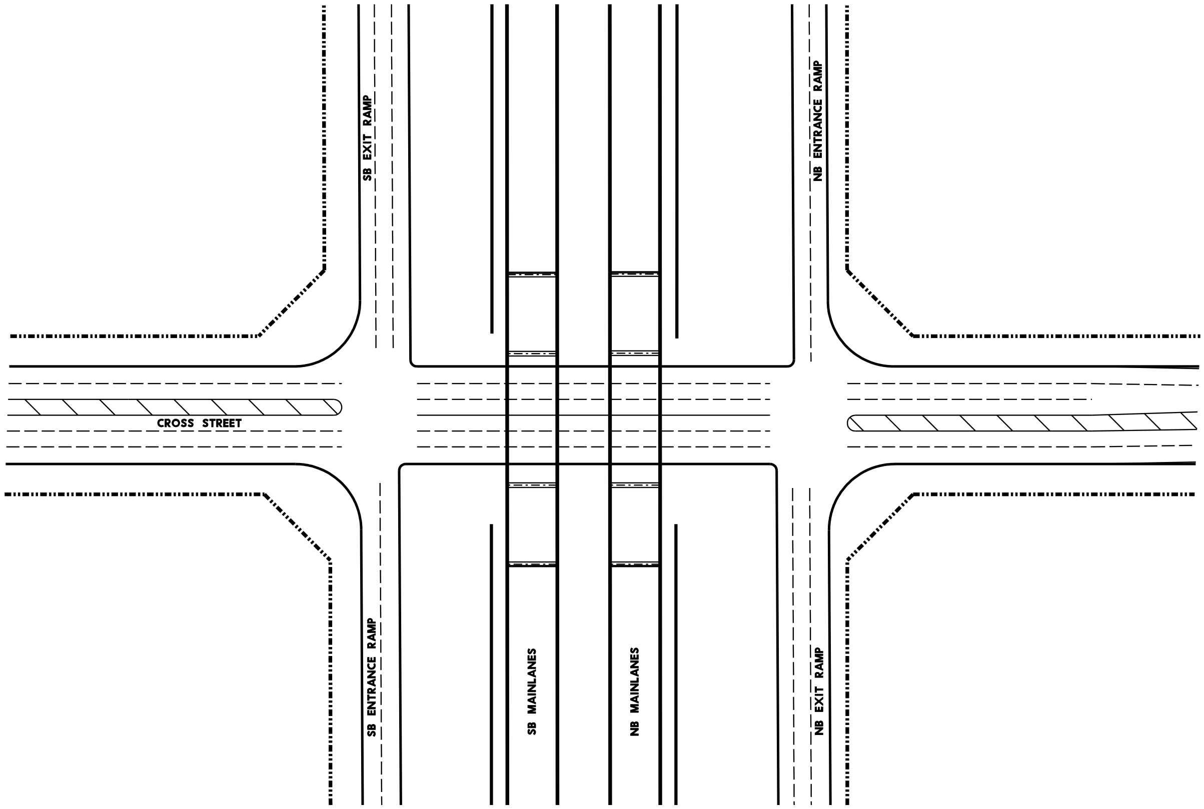

Figure 2. Diamond Interchange Geometric Layout

1.3.2 The Single Point Urban Interchange

The name single point urban interchange comes from the fact that all traffic turning left from either the exit ramps or cross streets meet at a single point. One advantage to this geometry is the reduction of a signal phase, thereby reducing the amount of intersection delay. The SPUI configuration does not allow for through movements along the ramps. Vehicles turning right from the ramp onto the cross street make a channelized turn and depart with an auxiliary lane dedicated to that particular movement. Vehicles making a left turn from the ramp to the cross street do so during the same signal phase as the opposing lefts.

The vehicles on the cross street are allowed the same movements as a diamond interchange. The left turns from the cross street to the ramps occur simultaneously. The through movements on the cross street occur simultaneously and can be led or lagged to accommodate corridor progression.

A typical geometric layout of a SPUI is shown in **Figure 3.**

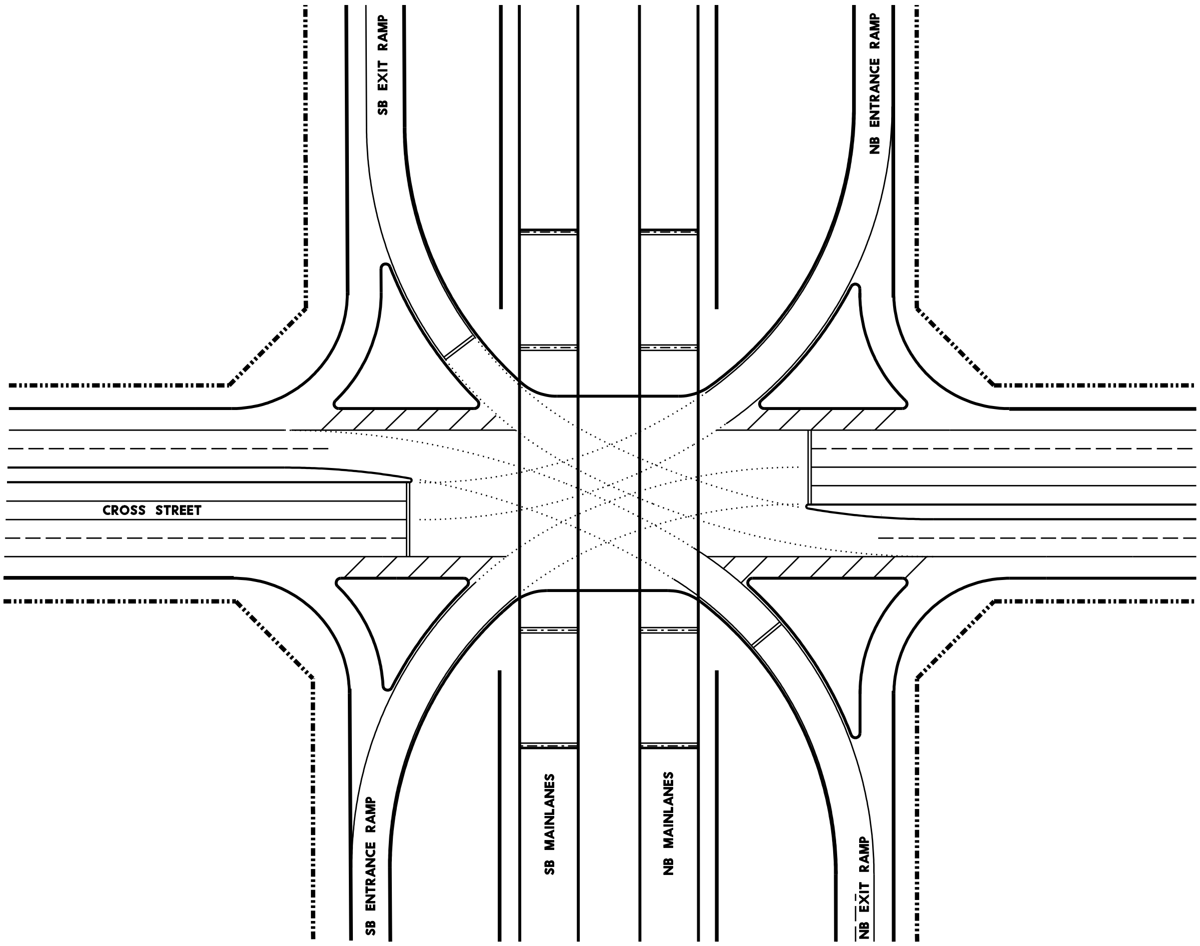

Figure 3. SPUI Geometric Layout

2.0 Decision to Construct SPUIs Versus Diamond Interchanges

There are nine proposed interchanges along Segment E at either existing or future cross streets. These interchange locations are shown in **Figure 4**. The decision to construct SPUIs instead of diamond interchanges at five of the interchanges was based on several factors including the absence of frontage roads, heavy turning volumes, and improved traffic operations.

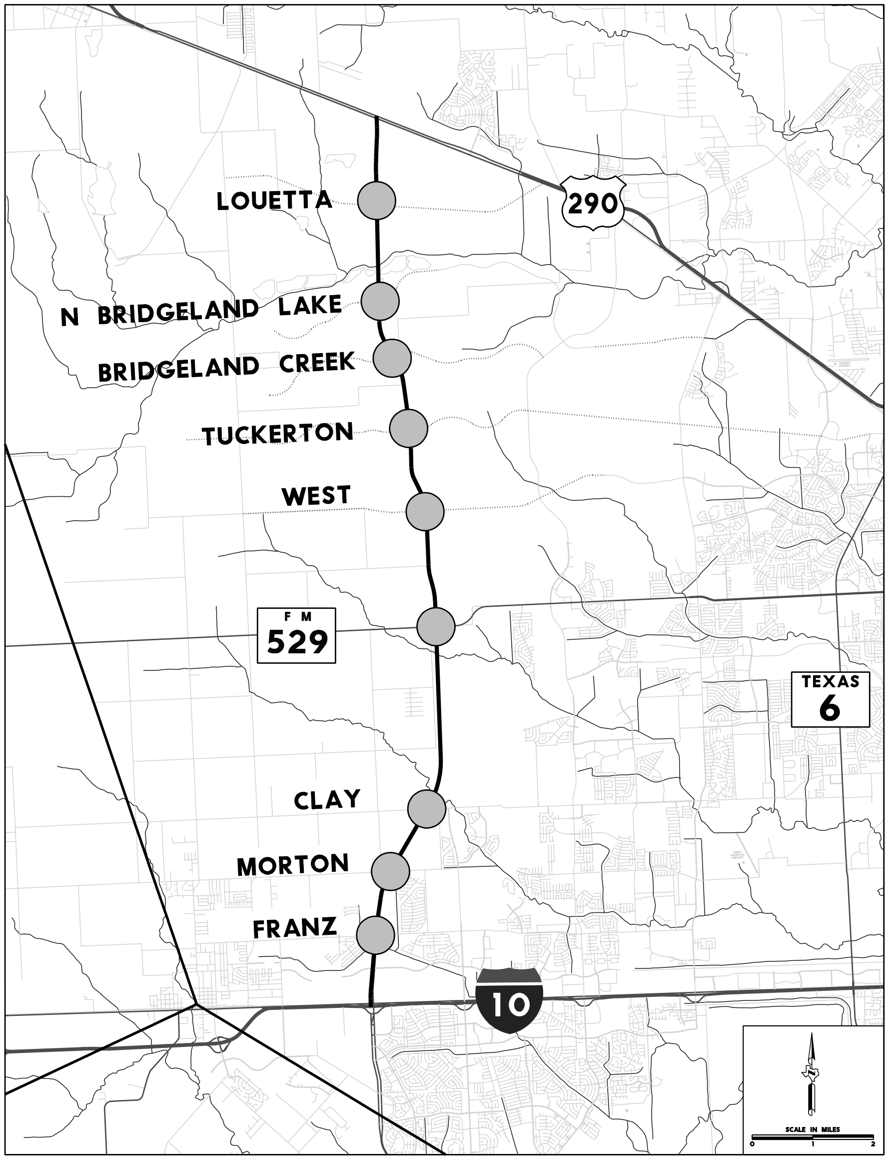

Figure 4. Interchange Locations

The proposed Grand Parkway design schematic for Segment E, developed in 2005, showed traditional diamond interchanges capable of maintaining a reasonable level of service for the 2025 design year traffic volumes. These traffic volumes were adjusted to project the design year volumes for the year 2030 and to take into account recent accelerated growth in the project area. After re-evaluating the traffic projections versus the proposed geometry, there was no doubt that many of the interchanges would be operating at capacity much earlier than expected.

The proposed cross street geometry at many interchanges would either need to be widened to accommodate the future volumes or a new design altogether would need to be implemented. HCTRA decided that many of these interchanges would be good candidates for a SPUI.

Of the nine project interchanges, five will be designed with a SPUI configuration. These five interchanges showed high traffic volumes for the 2030 design year and low levels of service with a diamond configuration. Additionally, the five intersects with cross streets, either existing or proposed, extend as critical east-west arterials in the City of Houston Major Thoroughfare Plan. It was determined that these five cross streets had the highest potential for growth that could exceed the traffic projections. The SPUI configuration has a greater capacity for maintaining acceptable levels of service under saturated traffic volume conditions than a diamond interchange.

In summary, the nine interchanges along Segment E of the Grand Parkway will consist of four traditional diamond interchanges and five SPUIs. SPUIs will be designed at the following locations:

- Grand Parkway at Clay Road
- Grand Parkway at FM 529
- Grand Parkway at West Road (future)
- Grand Parkway at Tuckerton Road (future)
- Grand Parkway at North Bridgeland Lake Parkway (future)

Currently, only Clay Road and FM 529 exist at the proposed location of the intersection with the Grand Parkway. Interchanges with the three future cross streets will be constructed when those cross streets are constructed across the Grand Parkway.

2.1 Roadway Characteristics

Typical Texas urban freeway design includes continuous frontage roads within the freeway corridor. The fact that these interchanges will not have connecting frontage roads eliminates the need to allow for a straight movement through the intersection along the ramps. Once traffic exits the main lanes, it will turn right or left at the intersection. There will not be any adjacent property access permitted from either the exit or the entrance ramps.

2.2 Traffic Operations

The improved traffic operations will become apparent when the facility reaches saturated conditions in the design year of 2030. Under these conditions, a signalized diamond is typically run under a four-phase operation. A SPUI would be run under a three-phase operation, except when the pedestrian phase is activated which would represent a fourth phase. The three-phase operation offers significantly improved operation over the four-phase operation.

Table 1 shows the level of service (LOS) and intersection delay for a diamond, a diamond with added lanes, and a SPUI for three of the interchanges: Clay Road, FM 529, and West Road for comparison purposes. The diamond configuration typically had six lanes in the east-west direction and two-lane ramp approaches. The diamond interchange with the added lanes condition typically had eight lanes in the east-west direction and four lanes on the ramp approaches. The SPUI configuration typically had eight lanes in the east-west direction and three lanes on the ramp approaches.

Table 1 shows that the SPUI will perform consistently better than the diamond and the diamond with added lanes for the overall operation and for the individual approaches. The SPUI levels of service are mostly Cs with two Ds, while the diamond with added lanes levels of service are mostly Ds with one E. The diamond will breakdown faster than the SPUI during saturated conditions. The SPUI shows higher capacity with no breakdown in level of service. **Table 1** shows the results of the capacity analyses using the TxDOT projections for the Grand Parkway Segment E and the adjusted Houston-Galveston Area Council (H-GAC) projections for the east-west arterials. The H-GAC projections were adjusted using the NCHRP 255 screen line method, as well as an aggressive traffic growth rate of 2.1% per year.

Table 1. Level of Service Summary

OVERALL OPERATION						
	LEVELS OF SERVICE			INTERSECTION DELAY (SEC/VEH)		
CROSS STREET	CURRENT DESIGN*	ADDED LANES**	SPUI	CURRENT DESIGN	ADDED LANES	SPUI
CLAY	C	C	C	30.4	30.7	24.8
FM 529	E	D	C	63.7	30.9	24.9
WEST	D	C	C	36.1	27.8	24.0
NB RAMP OPERATION						
	LEVELS OF SERVICE			APPROACH DELAY (SEC/VEH)		
CROSS STREET	CURRENT DESIGN*	ADDED LANES**	SPUI	CURRENT DESIGN	ADDED LANES	SPUI
CLAY	D	D	C	49.3	42.5	23.4
FM 529	F	D	C	83.3	47.4	34.8
WEST	D	D	C	54.5	45.8	23.0
SB RAMP OPERATION						
	LEVELS OF SERVICE			APPROACH DELAY (SEC/VEH)		
CROSS STREET	CURRENT DESIGN*	ADDED LANES**	SPUI	CURRENT DESIGN	ADDED LANES	SPUI
CLAY	D	D	D	45.8	43.7	35.2
FM 529	E	D	D	78.6	50.5	42.1
WEST	D	D	C	47.5	44.0	32.6
WB CROSS STREET OPERATION						
	LEVELS OF SERVICE			APPROACH DELAY (SEC/VEH)		
CROSS STREET	CURRENT DESIGN*	ADDED LANES**	SPUI	CURRENT DESIGN	ADDED LANES	SPUI
CLAY	D	D	C	41.7	39.1	22.8
FM 529	F	D	B	110.6	46.0	19.8
WEST	D	D	C	43.0	43.0	22.7
EB CROSS STREET OPERATION						
	LEVELS OF SERVICE			APPROACH DELAY (SEC/VEH)		
CROSS STREET	CURRENT DESIGN*	ADDED LANES**	SPUI	CURRENT DESIGN	ADDED LANES	SPUI
CLAY	D	D	C	52.4	47.1	25.1
FM 529	F	D	C	121.0	47.8	20.6
WEST	F	E	C	82.4	56.8	23.9

* 8-lane cross street with 3-lane ramp approaches

** 8-lane or 10-lane cross street with 4-lane ramp approaches

2.3 Construction Cost

When considering the conversion of interchanges from traditional diamond to a SPUI, the construction cost of a typical interchange was examined. The bridge span lengths necessary for the SPUI configuration necessitate steel beam construction. The diamond interchange main lane overpass structures are planned to be concrete beam construction. The switch to steel beams almost triples the expected construction cost of the bridge from $1.5 million for concrete construction to $4.3 million for steel construction at a typical mainlane overpass. When examined on an individual intersection basis, construction cost appears to be a significant point against the conversion to a SPUI. However, the increase to the overall project construction cost was deemed by HCTRA to be minimal enough to warrant the conversion of five interchanges to a SPUI configuration.

3.0 SPUI Design Considerations

The SPUI is an innovative way of improving mobility and requires the consideration of many design aspects to be constructed as efficiently as possible. Although new to this area, SPUIs have been used efficiently in other parts of the country. Design speed, sight distance, and roadway curvature must be analyzed to provide drivers with an acceptable level of safety. The bridge type can also be extremely important since a long bridge span generated by a SPUI can increase construction cost dramatically. In addition to roadway geometry, traffic operations must be considered to design an efficient SPUI. Traffic signal locations must be taken into account to provide drivers with enough time and distance to react to traffic control. Pedestrian access will also need to be considered.

3.1 Design Speed

Since the interchange geometry is designed based on the design speed, the design speed within the interchange of a SPUI is an extremely sensitive variable since the interchange geometry is designed based on the design speed. An increase or decrease in design speed can result in an inefficient interchange, or even worse, a potentially unsafe interchange.

Furthermore, design speed heavily affects traffic operations as well as design geometry. Particularly, design speed contributes to the LOS of the interchange due to its effect on clearance times. Clearance times are greater within a SPUI than those of a traditional diamond interchange, due to the increased dilemma zone.

"Single Point Urban Interchange Design and Operational Analysis," published by the Transportation Research Board(1) suggests that efficient operations can be achieved when design speeds of 25 mph to 35 mph are used for left turn lanes. In order to balance the construction costs of the interchange with operational efficiency and safety, the SPUIs in Segment E of the Grand Parkway were designed for a speed of 25 mph.

3.2 Sight Distance

Sight distance is another important factor in the geometric design of a SPUI. Sight distance considerations are similar to those at other major highway interchanges and should be designed similarly. Sight distance on the cross street approaching the interchange will not be any different whether the interchange is designed as a diamond or a SPUI.

Sight distance on the exit ramp is typically the most critical, especially for the left turn movements. Drivers must have enough time to exit the highway and decide whether a lane change is needed before they proceed in their desired route. Drivers turning left from the exit ramp onto the cross street must negotiate a curve while paying attention to traffic control. For the intersection designs along the Grand Parkway, this left turn sight distance was the determining factor for the abutment location for a single span bridge configuration and for the location of the interior bents for a 3-span configuration. The sight distance calculations also needed to include the constraint of the future widening of the main lanes. The minimum sight distances for the SPUI designs are based on design speed and can be found on Exhibit 3-71 of the AASHTO's "Policy on Geometric Design of Highways and Streets"(2).

As higher design speeds were examined, the sight distance length increased. A graphical example of the sight distance calculation for the left turn movement at a SPUI is shown below in **Figure 5**. Increasing the sight distance requirement caused an increase in the main bridge span length over the cross street due to the set back requirements of the abutment/bent location. As the bridge span length increased, the structure depth increased causing larger quantities of fill for the overpass and increased retaining wall heights and lengths. All of these factors resulted in increased construction costs.

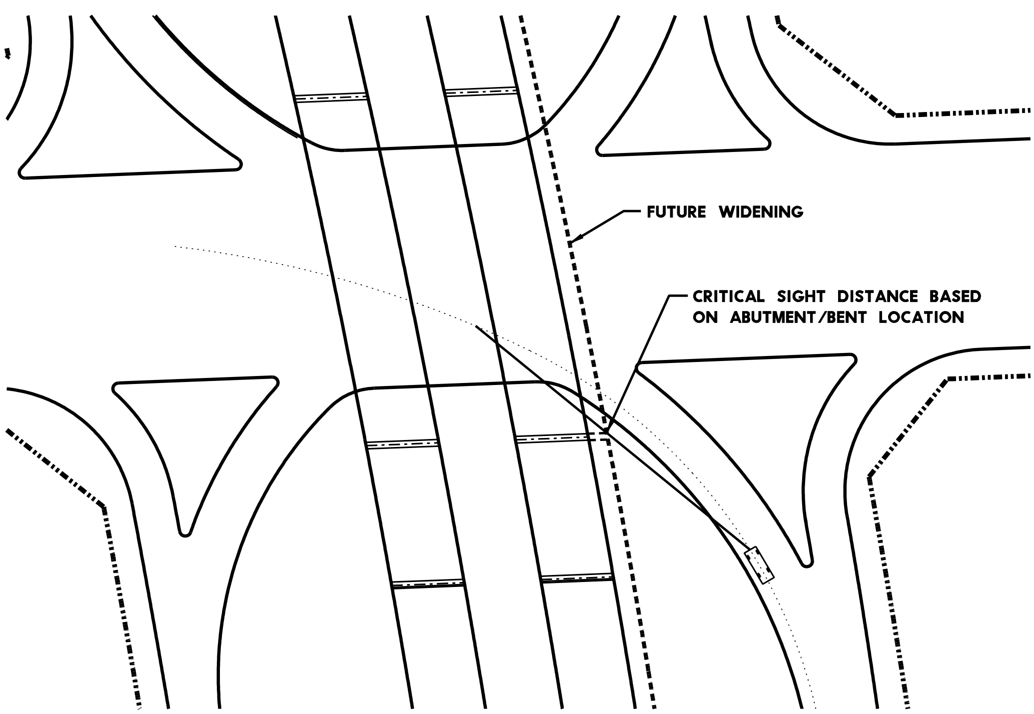

Figure 5. Sight Distance Calculation

3.3 Left Turn Movement

The design of the left turn movement from the highway exit ramps to the cross street is especially challenging since the curvature of the roadway directly affects the length of the highway bridge span. There is a direct relationship between the curve radius and the associated sight distance increasing the curve radii increases the sight distance and the bridge span, and thus increases the construction cost. Similarly, reducing the curve radii can reduce the bridge length, but can potentially create a dangerous situation for drivers.

In addition to curvature constraints, a minimum lateral offset is required to ensure safety. For the design speed of 25 mph, the inner left turn lane approaching and departing the interchange must be at least 16 feet from any fixed obstruction, measured to the center of the travel way. The distance between the left turn lanes and bridge abutments was therefore fixed at 16 feet, allowing the bridge spans to remain as short as possible.

Another constraint is the separation between the two opposing left turns within the intersection. According to the "Single Point Urban Interchange Design and Operational Analysis" by the Transportation Research Board (1), a minimum distance of 10 feet is recommended to ensure safety. Again, this distance was fixed to provide adequate separation while minimizing the bridge span.

Originally, the SPUI designs provided simple curves for all left turn movements, resulting in radii varying from 300 feet to 400 feet for most interchanges. The radii at Clay Road varied from 200 feet to more than 700 feet due to the 30 degree skew at the intersection. The long radii resulted in single bridge spans between 220 feet and more than 250 feet. In an attempt to reduce the bridge spans, compound curves were designed for each interchange.

The compound curves reduced the approach radii and increased the departure radii for the left turn movement from the exit ramp to a cross street. Conversely, the left turn movement from the cross street to the entrance ramp was designed with an increased approach radii and decreased departure radii. The use of compound curves resulted in a bridge span length reduction of up to 20%. The compound curves used at Clay Road reduced the single bridge span from 250 feet to 215 feet. All left turn radii meet or exceed values published in Table 5 of the "Single Point Urban Interchange Design and Operational Analysis" by the Transportation Research Board (1) for a design speed of 25 mph.

One disadvantage of designing compound curves rather than simple curves for the left turn movement from the exit ramps to cross street was an increased departure radius. The increase caused the stop bar and median on the cross streets to be farther from the intersection. A longer intersection means that a longer clearance interval is required for each signal phase, decreasing efficiency of traffic operations. However, the increased clearance time was mitigated by modifying the cross street medians from 4 feet wide to 10 feet wide. By increasing the median width, a portion of the departure radii could be built into the median. This change was responsible for decreasing the intersection length up to 80 feet at some locations.

3.4 Ramp Alignments

In general, the entrance and exit ramp alignments were set using TxDOT design criteria for urban freeways. Part of these criteria was to provide a 15-foot border width between the edge of pavement of the ramp and the right-of-way. This minimizes the retaining wall area and dictates the use of a curb and gutter drainage system. For the SPUI design, this larger separation between the ramps and the main lanes allowed for greater radii to be used for the left turn movements without affecting the bridge span length over the intersection. At one location, Tuckerton Road, the drainage design dictated that a 40-foot border width be used for the ramps to allow for open ditch drainage. In this case, the minimum radii for the 25 mph design speed were used for the left turn movements. This combined with the perpendicular crossing of the cross street allowed for the bridge span length over the intersection to be kept at 200 feet, similar to the other SPUI interchanges.

Other projects in the Houston area have shown that it is possible that future development along the project corridor may dictate the construction of continuous frontage roads for parts of the Grand Parkway. In order to accommodate this possibility, the alignment of the ramps across the intersection was designed such that the SPUI intersection could be reconstructed as a diamond interchange at some point in the future, if necessary, with minimal reconstruction.

3.5 Bridge Type

Each of the preceding design decisions had a direct effect on the span length for the main lane span over the cross street intersection. Along with safety, the decision on bridge type and configuration was a deciding factor that dictated many of the design decisions for the SPUI configuration. Originally, the SPUI designs were based on a single span bridge, with the single span length varying between 220 feet and 250 feet. These long spans required the use of steel beams and generated structure depths of up to 108 inches. This was an increase of almost 4 feet over the original concrete span structure depth, which had a structure depth of 62 inches. Once the initial span length was determined, design decisions on design speed and compound curvature on the left turns were made in order to reduce the span length.

At the same time, the use of a 3-span steel beam configuration was also considered. Both a balanced configuration and an unbalanced span configuration for the structural steel structures were studied. The 3-span bridge configuration offered greater sight distances and "opened up" the overall intersection. Pictures of both a single span and 3-span SPUI layout are shown in **Figure 6**. The use of a 3-span configuration greatly reduced structure depth, but increased the area of the bridge. Additionally, a 3-span structure reduced the retaining wall area by allowing for sloped abutments under the overpass, instead of retaining walls along the face of the abutments. Once the intersection geometry was refined based on other decisions, the main span was reduced to between 200 and 220 feet. Using an unbalanced 3-span configuration, the structure depth was reduced to 62 inches, the same as the original concrete span structure depth.

Figure 6. Single Span Versus 3-Span Bridge Configuration

The combination of the reduction of structure depth and increase in bridge area made the unbalanced 3-span configuration the same estimated construction cost as the single span configuration. The balanced 3-span configuration was rejected because the large increase in bridge area caused the estimated construction cost to significantly exceed the estimated cost for the single span configuration. Since the 3-span configuration created better sight distances and a more open, safer intersection at the same estimated cost, it was chosen over the single span for the SPUI bridge configuration.

3.6 Signalization

There were several options for signalization of the SPUI, particularly for the signalization of the left turn movements from the exit ramps. The decision was made early in the design process to avoid the placement of signals on signal poles within the area of the SPUI where all left turns converge. The reason for this decision was based on the assumption that it would become a maintenance issue as an island and a signal pole in that area would be subject to being hit. Also, an island in that area would end up on the right side of the left turn movements across the intersection, which may be counterintuitive to drivers. The signal configurations that were considered were the following:

For the signals facing the crossing arterial movements, the optimum location of signal heads was to mount them on the bridge structure in front of the traffic lanes. The distance from the signals to the stop lines varied between 70 feet and 100 feet. This distance can be reduced for the through movements with the use of staggered stop lines. **Figure 7** illustrates the location of these signals.

The first option for the location of signals for the left turn lanes from the exit ramps was to place them under the bridge and in front of the left turn lanes. This option utilized advance post mounted signals on the approach to the left turn lanes. The advantage of this option was that the signals would be in front of the left turn lanes and the stop lines would be as close to the intersection as possible. Harris County mounts overhead signals horizontally, which helps minimize the impact on the bridge profile. The disadvantage of this option was that the signal clearance over the pavement would have to be reduced from the Harris County standard of 19 feet to approximately 16 feet. While this vertical clearance is within TxDOT's "Texas Manual on Uniform Traffic Control Devices" (3) allowable guidelines, it was an undesirable design for the County.

The second option was to mount those signals on the bridge structure, at an angle facing the approach lanes. The advantage of this alternative was that it removed any vertical clearance issues. However, it required the stop line to move back 40 feet in order for the signals to be within the cone of vision. The disadvantage of moving the stop line back was the additional clearance time needed for the respective signal phase. This option was selected by Harris County. **Figure 7** illustrates the signal head configuration for one half of an interchange.

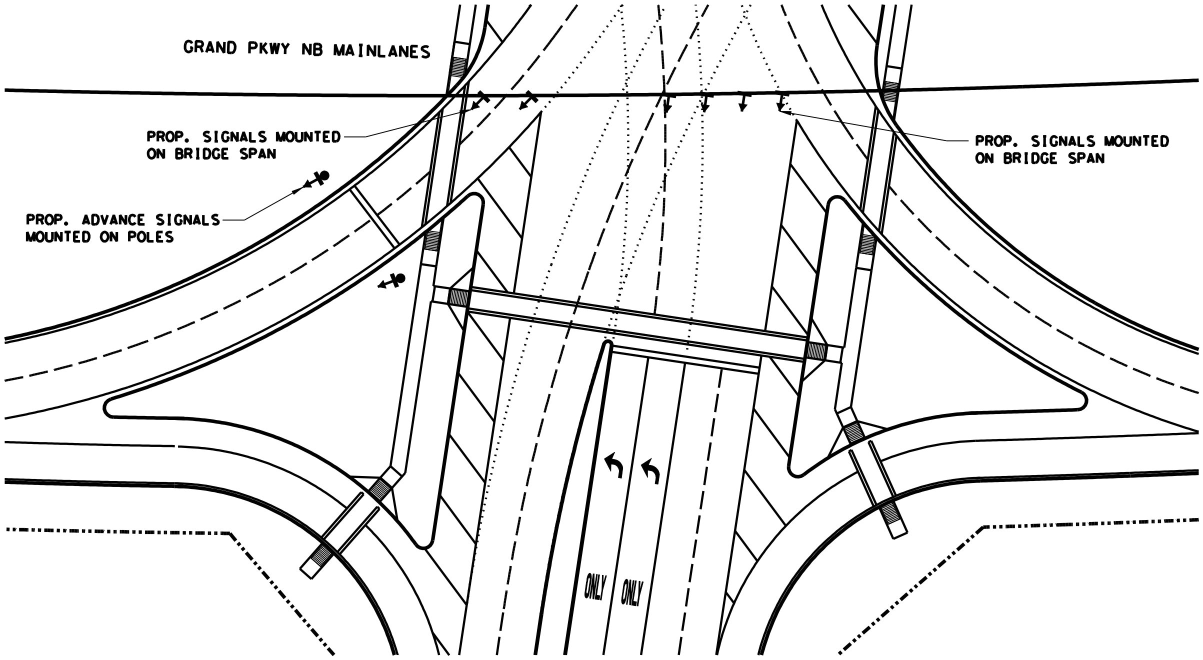

Figure 7. Traffic Signal Location for SPUI

3.7 Pedestrian Consideration

The pedestrian crossings along the arterial will be accommodated using pedestrian phases that run with the through movements on the arterial. These crossings along the arterial are a series of two crossings of the left turn traffic lanes, as well as the crossings from the islands to the outside corners of the interchange which, as is customary in Texas, are not signalized.

The crossings of the arterial presented more of an issue because the SPUI phasing and geometry do not have the customary straight through vehicle phase that accommodates the pedestrian phase. A decision was made to cross pedestrians on the east side of the interchange with the northbound to westbound left turn vehicle phase, and to cross pedestrians on the west side of the interchange with the southbound to eastbound left turn vehicle phase. These pedestrian phases are actuated and therefore only come on when activated by a pedestrian pushbutton. Since not many pedestrians are expected to use these two crossings, the left turn phases would normally operate concurrently, except in the rare occasion when a pedestrian actuates the pushbutton to cross.

3.8 Illumination

The SPUI illumination consists of safety lighting from the approach ramp decision points to the various departure decision points. This illumination strategy results in considerably more pavement being illuminated than at a diamond interchange. This additional illumination was warranted due to the typical driver’s unfamiliarity with SPUIs.

Illumination design software was used to perform photometric analysis of each SPUI to achieve the desired illumination levels dictated in the AASHTO's "An Informational Guide for Roadway Lighting" (4). Standard TxDOT 40-foot, 400 watt, high pressure sodium luminaires are utilized with additional illumination provided by compact fluorescent under-bridge luminaires.

4.0 Conclusion

The Grand Parkway was planned to improve regional mobility around the greater Houston area, and Segment E is the most recent section to contribute to that goal. The interchanges along this segment of the Grand Parkway are an ideal application for the SPUI design.

The SPUI design required consideration to many variables including design speed, sight distance, left turn movements and bridge type. Furthermore, traffic operations, pedestrian facilities, and illumination were analyzed to maximize the benefits of the SPUI design.

Capacity analyses showed that the SPUI performed significantly better than the traditional diamond interchange at the major at-grade crossings along the project, consistently yielding one level of service better. The current design at these interchanges does not have frontage roads, which allows the implementation of the SPUI design without a through movement across the intersection. The SPUI design proved to be on average 30% more efficient than the conventional diamond interchange design.

5.0 References

1. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, D.C.: American Association of State Highway and Transportation Officials, 2004.
2. Messer. C. J., et al. *Single Point Urban Interchange Design and Operations Analysis*, NCHRP Report 345, Transportation Research Board, 1991.
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