New Grade-Separated Intersection Alternatives

NCDOT Webinar

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Overview

- Introduction
- New Grade-Separated Intersection Ideas
- Operational Results
- Safety Results
- Patent Survey
- Other Considerations
- Summary and Conclusions

Definition

Grade-separated intersections consist of:

- Two or more arterials
- Elevation of at least one movement
- Interrupted flow for through movements on each arterial

Why not an Interchange?

Safety: Interchange designs for crossing arterials may result in higher speeds and less pedestrian/bicycle accessibility.

Operations: Interchanges are ideal for high through demand on one arterial while GSI can accommodate balanced demand or heavy turning movements.

Context Sensitive: GSI designs can utilize the existing network and have compact low speed ramps to minimize Right of Way need.

Why not an Interchange?

Frontage: Interchange designs with free flowing ramps limit frontage and access in suburban/urban areas

Metering: Uncontrolled movements on interchange designs may overload downstream signals

Poor progression: Signalized intersections at interchange often are critical intersection on the corridor while GSI can often utilize two phase signals and allow coordination options to limit ramp spillback

NCDOT Research Project

2018-20: Reasonable Alternatives for Grade Separated Intersections

Objective: Identify alternatives to interchange designs for separation at arterial intersections and

Research Goal: To develop the operational and safety performance evaluation methods for grade-separated intersection designs

Grade-Separated Intersection Designs

DISCLAIMER

All designs and drawings shown are not standards or typicals. These designs and drawings are meant to communicate the core design concepts and many components are adaptable to specific project needs.

Existing Design in NC

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Hillsborough St & Hillandale Rd - Durham

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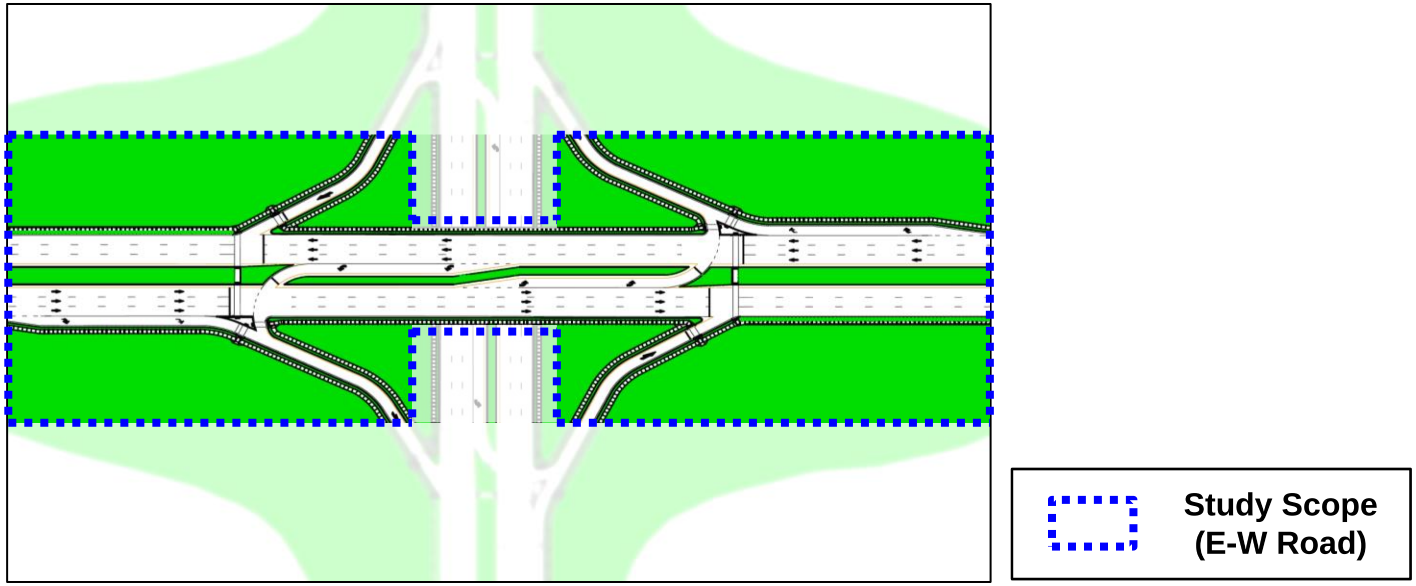
Scope of Study Designs

- In order to provide an engineer or planner the most flexibility during concept or design stages of a project, our study provides the operational and safety analysis results only for one of the two roads (e.g. East-West road) that could intersect.



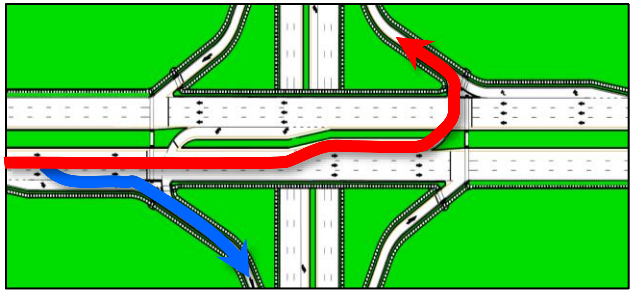
Study Scope: East-West Road (example: Direct Left - Downstream)

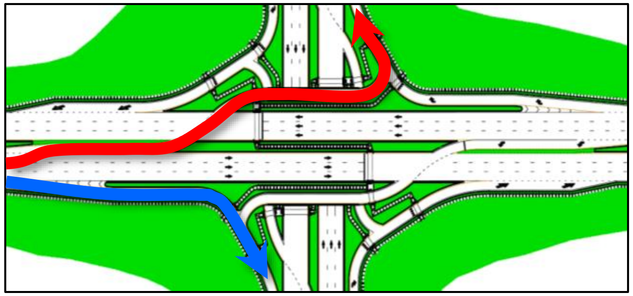
Study Designs

Grade-Separated (GS) Intersection Designs

- This study investigates the operational & safety effects of seven different designs
  - Two types of Direct Left (DL-Downstream and DL-Upstream)
  - Three types of Restricted Crossing U-turn (RCUT (U-R), RCUT (R-U), and Contra-RCUT)
  - Single Point Left (SPL)
  - Quadrant Left (Southeast)

Direct Left Turn Options





Direct Left - Downstream

The left turn is

- separated downstream of the signal on the major road
- conflicting with opposing left turn and opposing through

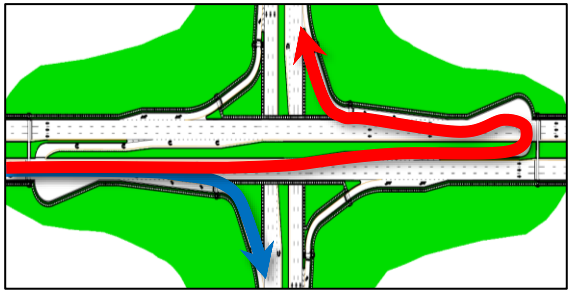
Direct Left - Upstream

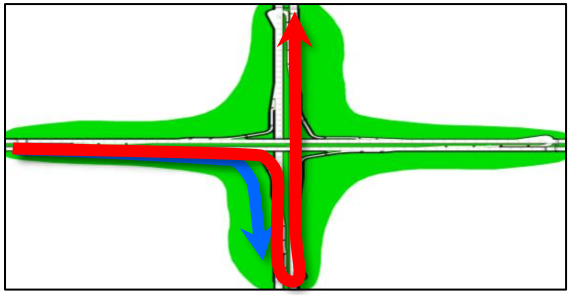
The left turn is

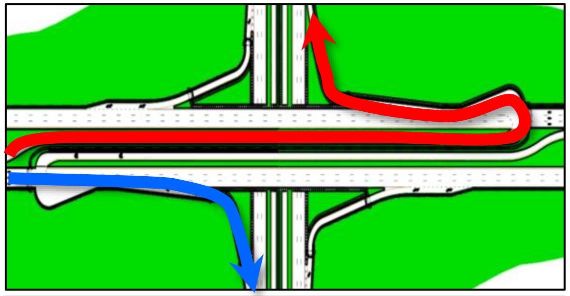
- separated upstream of the signal on the major road
- conflicting with opposing through

Note: For illustration purposes, major & minor roads designs are same; however, they could be any combination of designs for the major and minor.

RCUT/RCI Options







RCUT (U-R)

The left turn is

- separated downstream of the signal on the major road
- conflicting with opposing U-turn and opposing through at U-turn point on the major road

RCUT (R-U)

The left turn is

- separated downstream of the signal on the major road and then detoured to the minor road
- conflicting with opposing U-turn on the major road and the opposing through at U-turn point on the minor road

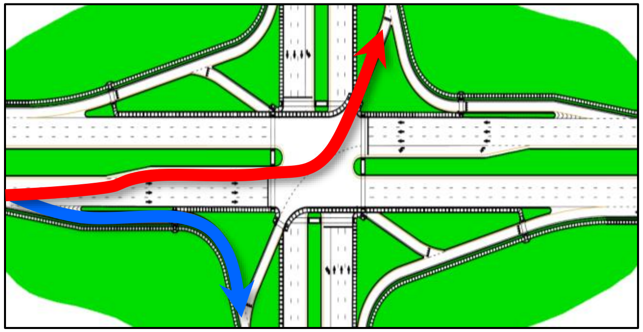
Contra-RCUT

The left turn is

- separated upstream of the signal on the major road
- conflicting with opposing through at U-turn point on the major road

Note: For illustration purposes, major & minor roads designs are same; however, they could be any combination of designs for the major and minor.

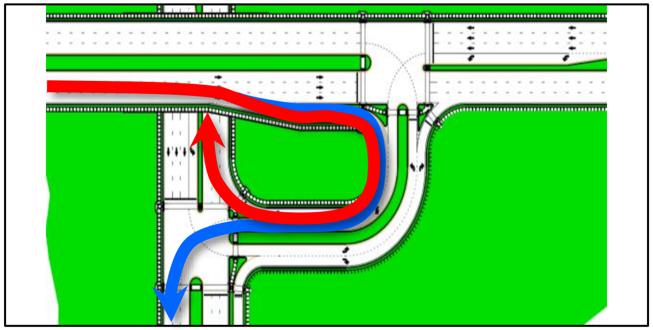
Combined Movements Options



Single Point Left (SPL)

The left turn is

- separated at the signal on the major road
- conflicting with the opposing through on the major road



Quadrant Left (Southeast)

The left turn is

- separated upstream of the signal on the major road and then move to the right turn ramp
- not conflicting with any movement

* There are three signal phases on major & minor roads

Note: For illustration purposes, major & minor roads designs are same; however, they could be any combination of designs for the major and minor.

Study Designs

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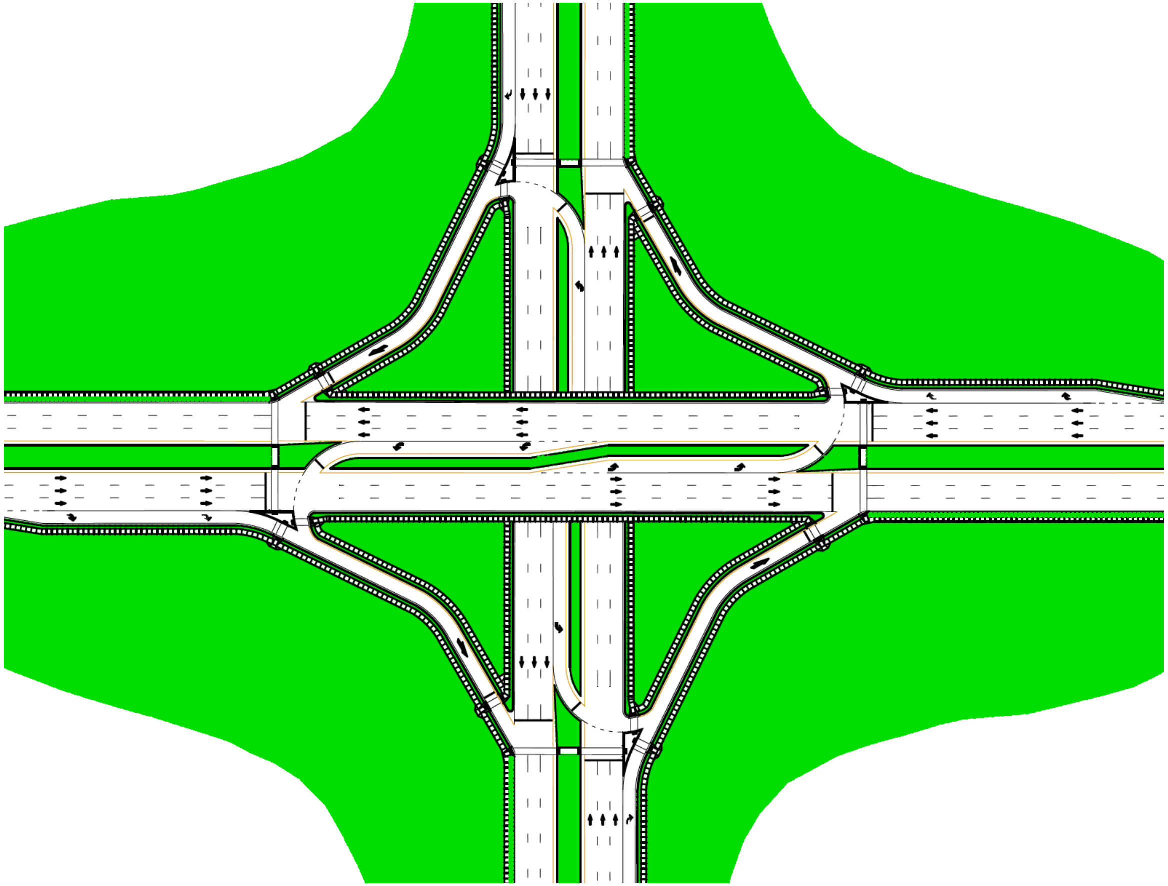
Matrix of Study Design Combinations

Top/Overpass

Bottom/Underpass

		1	2	3	4	5	6	7
		DL-Downstream	DL-Upstream	RCUT (U-R)	Contra RCUT	RCUT (R-U)	Single Point Left	Quadrant (SE)
A	DL-Downstream	O	O	O	O	X	O	X
B	DL-Upstream	O	O	O	O	X	O	X
C	RCUT (U-R)	O	O	O	O	X	O	X
D	Contra RCUT	O	O	O	O	X	O	X
E	RCUT (R-U)	O	O	O	O	X	O	X
F	Single Point Left	O	O	O	O	O	O	X
G	Quadrant (SE)	O	O	O	O	X	O	O

Example Study Design Combination 1A



Operational Analysis

Operational Analysis Methodology

Volume Scenarios

- Balanced vs Unbalanced
- Turn Percentages

Critical Movement Analysis

- Signal Zones
- Critical V/C for Scenarios

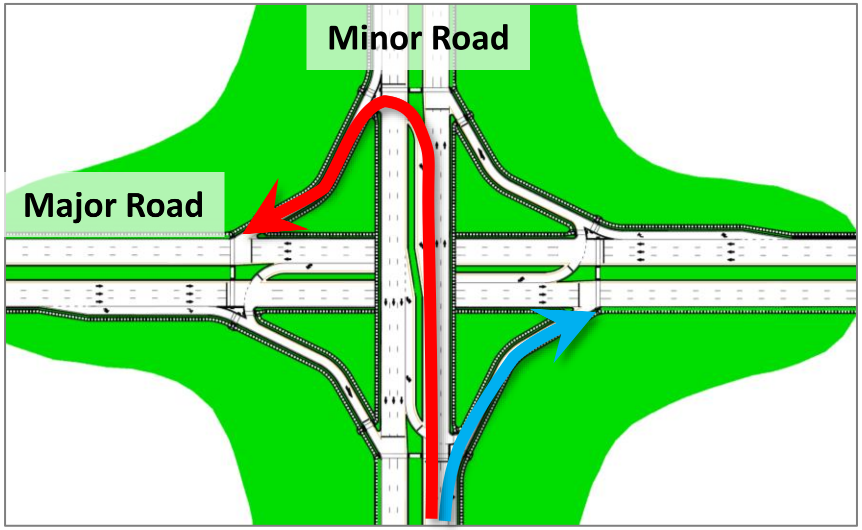
Microsimulation

- Group Similar Designs
- Queue Length, Delay

Volume Scenario Design

Scoping Turning Movement Volumes

- In the grade-separated intersection, the minor (N-S) street TM traffic merges into the major (E-W) road through ramps, and for simplification can be considered independently of major street traffic.



Example of Turning Movement Traffic (DL-Downstream & DL-Downstream)

Critical Movement Analysis

- **What is the critical movement analysis?**

  Critical movement analysis is an effective tool to quickly estimate the overall performance of intersection in terms of v/c ratios

- **Basic principle**

  Critical movement analysis identifies the set of movements that cannot time concurrently and require the most time to serve demand

Operational Analysis – Macroscopic Analysis

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Assumptions for Macroscopic Analysis

- We modified the CAP-X to analyze the eight GS intersection designs
- The inputs are designed or assumed as follows

Traffic Volume Demand						
	Volume (Veh/hr)				Percent (%)	
	U-Turn	Left	Thru	Right	Truck	Volume Growth
Eastbound	0	300	2400	300	0.00%	0.00%
Westbound	0	450	2100	450	0.00%	0.00%
Southbound	0	0	0	0	0.00%	0.00%
Northbound	0	0	0	0	0.00%	0.00%
Adjustment Factor	0.80	0.95		0.85		
Suggested	**0.80**	**0.95**		**0.85**		
Truck to PCE Factor				**Suggested = 2.00**	2.00	
Critical Lane Volume				1600		

Example of CAP-X Volume Input Table

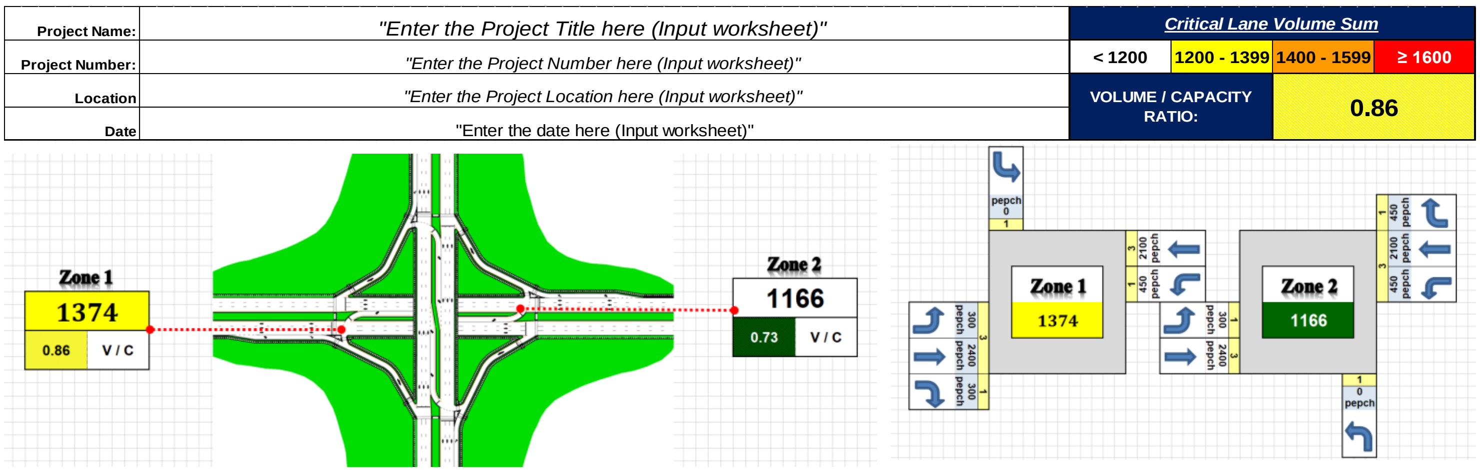
- Total (EB+WB) volume of 6,500 vph is used
- Truck percentage = 0% (assumed)
- Adjustment factors for TM:

  0.95 for the left turn, 0.85 for the right turn, and 0.80 for the U-Turn (default)
- Critical sum = 1800 vphpl (default)
- Minor road total volume = (Major road total volume / 2)
- Minor road TM volume proportions = Normal TM condition (left turn of 15%, through of 70%, and right turn of 15%)

Operational Analysis - Macroscopic Analysis

Performance Measure: Critical v/c Ratio

- The intersection critical v/c is determined by the max zonal v/c on the E-W road



Example Results of Critical Movement Analysis

* The assumptions for the number of lanes

- Every approach has three lanes at the up/downstream of intersection
- Every turning movement has one exclusive lane

Operational Analysis - Macroscopic Analysis

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Critical Movement Analysis Results

Scenario	Approach Volume	Direct Left - Downstream	Direct Left - Upstream	Single Point Left	RCUT (U-R)	Contra-RCUT	RCUT (R-U)	Quadrant Left (SE)
EBN-WBN	EB: 50% WB: 50%	0.80	0.71	0.71	0.94	0.85	0.77	1.28
EBT-WBN		0.83	0.77	0.77	0.94	0.88	0.77	1.34
EBL-WBN		1.08	0.99	0.99	1.28	1.19	0.77	1.22
EBLT-WBN		0.89	0.80	0.80	1.05	0.96	0.77	1.28
EBT-WBT		0.73	0.67	0.67	0.83	0.77	0.77	1.15
EBL-WBT		1.11	1.05	1.05	1.28	1.22	0.77	1.03
EBLT-WBT		0.92	0.86	0.86	1.05	0.99	0.77	1.09
EBT-WBL		1.11	1.05	1.05	1.28	1.22	0.77	1.53
EBN-WBN	EB: 60% WB: 40%	0.84	0.73	0.85	0.99	0.88	0.89	1.25
EBT-WBN		0.88	0.81	0.81	0.99	0.92	0.89	1.32
EBL-WBN		1.09	1.02	1.12	1.29	1.22	0.89	1.17
EBLT-WBN		0.88	0.79	0.96	1.02	0.95	0.89	1.25
EBT-WBT		0.80	0.73	0.81	0.90	0.83	0.89	1.17
EBL-WBT		1.12	1.07	1.12	1.29	1.25	0.89	1.02
EBLT-WBT		0.89	0.84	0.96	1.02	0.98	0.89	1.09
EBT-WBL		1.11	1.03	1.03	1.26	1.19	0.89	1.47

Low V/C ratio High

Intro | Designs | Operations | Safety | Patents | Other | Conclusions

Critical Movement Analysis Results (cont.)

Scenario	Approach Volume	Direct Left - Downstream	Direct Left - Upstream	Single Point Left	RCUT (U-R)	Contra-RCUT	RCUT (R-U)	Quadrant Left (SE)
EBN-WBN	EB: 50% WB: 50%	0.80	0.71	0.71	0.94	0.85	0.77	1.28
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EBT-WBL		1.11	1.03	1.03	1.26	1.19	0.89	1.47

Low — V/C ratio — High

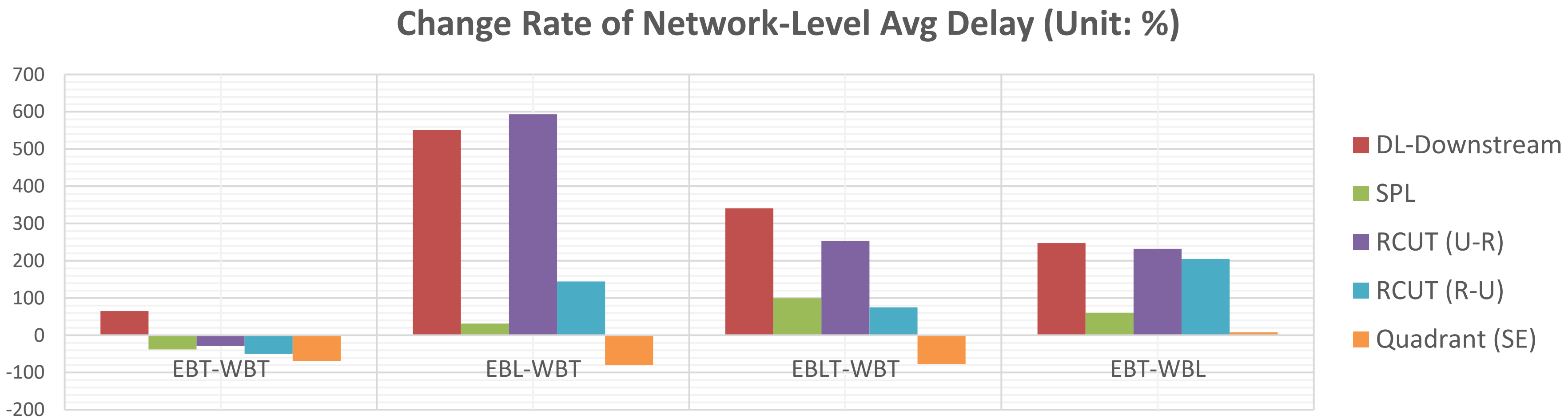
Microsimulation Analysis

- To investigate the change of performance of each design across the designed volume scenarios, the total (EB+WB) volume that satisfies the v/c of 0.65 for the base volume scenario* is determined for seven intersection designs
- In the analysis, the cycle length and split phase are computed by HCM method using the Institute of Transportation Engineers (ITE) equations.
- As a performance measure, the avg. delay is computed for the entire network and the critical movements (EBT & WBL).

* Base volume scenario = Balanced approach volume (EB : WB = 50% : 50%) & No heavy movement on EB and WB (= EBN–WBN)

Microsimulation Analysis

- The DL-Downstream, SPL and RCUT (U-R) showed significant increase in avg. delay for the volume scenarios with heavy EBL, while the RCUT (R-U) and quadrant (SE) show much smaller change rate. Overall trend is varied depending on turning movements.



Change Rate of Avg. Delay for Entire Network

* Results for remaining critical movements show very similar results, so they are not included in this presentation.

Operational Analysis - Recommendations

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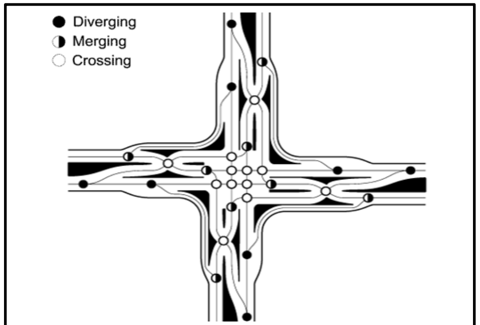
Recommendations

- Critical Movement Analysis can help select a subset of feasible GSI designs and lane configurations
- ITRE modified CAP-X is a starting point for analysis
- During Microscopic modeling, be sure to analyze the GSI “network” rather than isolated sections
- Develop detailed signalization options for simulation
- Turning movement patterns heavily impact GSI design selection, consider each peak and off-peak
- Overall, a project-based alternatives analysis is recommended for these cases in applications.

Safety Analysis

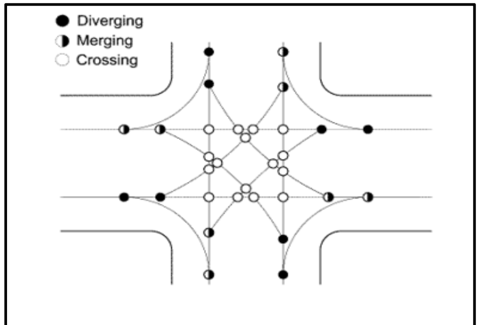
Traditional Planning Level Method: Comparison of Conflict Points

- A simple CP comparison method regards the reduced number of total CPs as the improved safety performance.



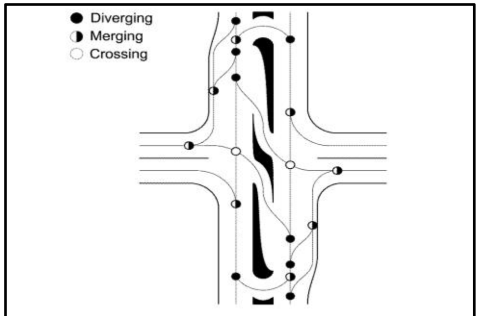
Displaced Left Turn

Conflict Type	Count
Crossing	12
Merging	8
Diverging	8
Total	**28**



Conventional

Conflict Type	Count
Crossing	16
Merging	8
Diverging	8
Total	**32**



Restricted Crossing U-Turn

Conflict Type	Count
Crossing	2
Merging	8
Diverging	8
Total	**18**

Source: Hughes, W., & Jagannathan, R. (2009). Alternative intersections/interchanges: Information report (AIIR)". FHWA. Washington, DC, 1, 2009

Safety Analysis – Literature Review

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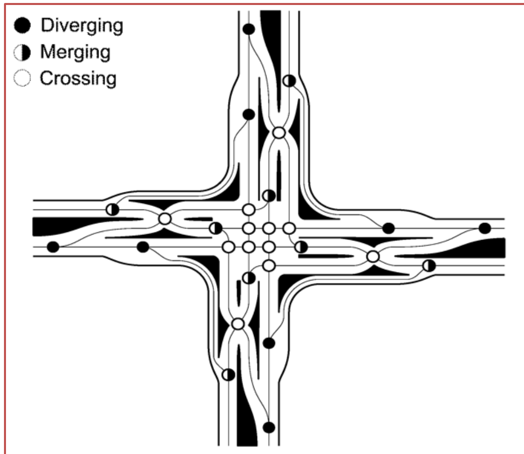
VJuST (Virginia DOT)

- The VDOT accounted for the different crash severity for CP types by weighting system.
- But it still cannot account for different crash rates for CP types and the impact of traffic volume on crash frequency.



Conflict Type	Count
Crossing	12
Merging	8
Diverging	8
Total	**28**

Conflict Type	Weight
Crossing	2
Merging	1
Diverging	1

Weighted Total Conflict Points

40

Step 1
Count the Conflict Points

Step 2
Weight x CPs

Step 3
Weighted Total Conflict Points

[VJuST Safety Evaluation Process, Virginia DOT]

Safety Analysis - Methodology

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Movement-Based Safety Performance Functions (MB-SPFs)

Conflict Point Analysis (VJuST)

- Can compare the safety between AIIs
- Cannot account for the impact of traffic volume and different crash rate

Safety Performance Functions (SPFs)

- Can account for the impact of traffic volume
- Not applicable to the safety evaluation of AIIs

Movement-Based SPFs (MB-SPFs)

- Predicts the CP and NCP crashes separately, and then sum up to predict the intersection total crashes.
- Account for the impact of traffic volume as well as the different crash rate for CP types

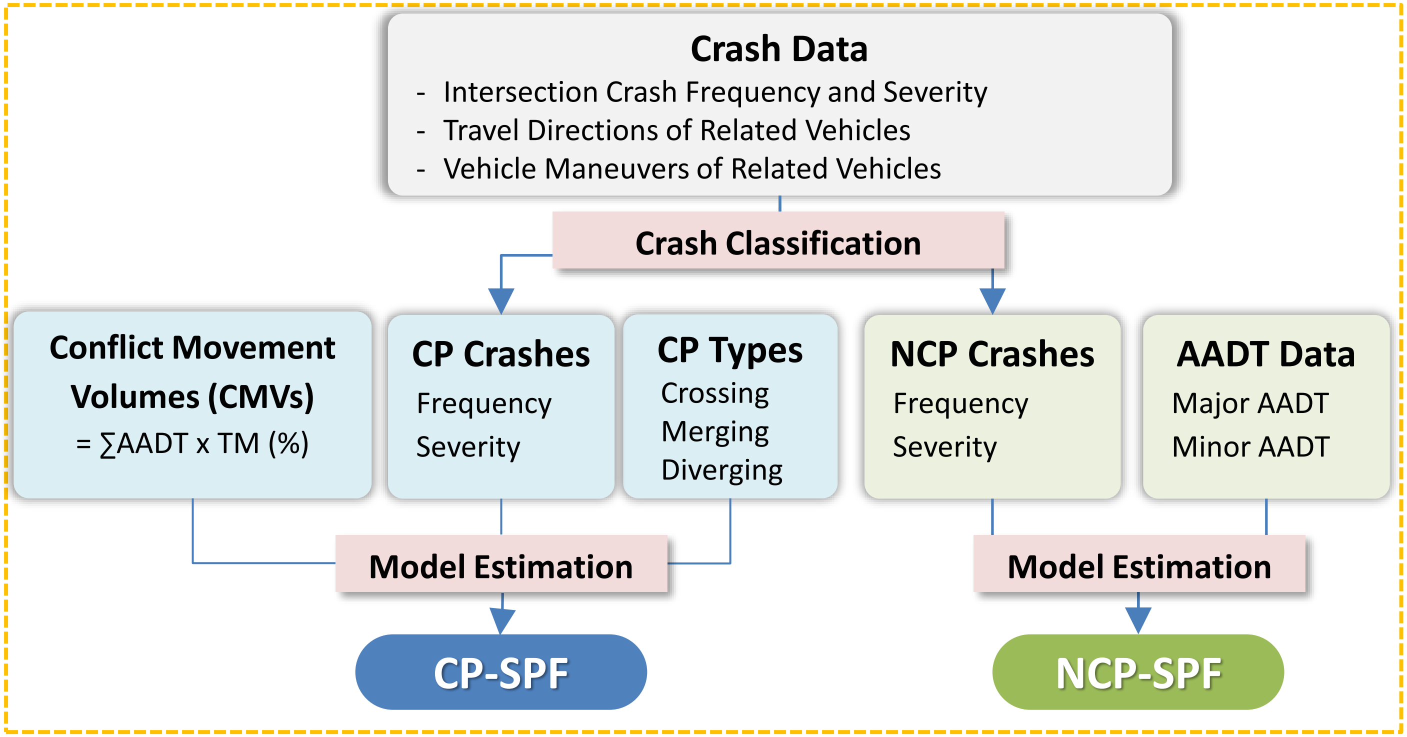
Safety Analysis - Methodology

Movement-Based Safety Performance Functions (MB-SPFs)

- This study defined the CP and NCP crashes as follows.
  - CP crashes (e.g. angle crash) occur between two conflicting movements at a CP
  - NCP crashes (e.g. rear-end or sideswipe crashes) occur between same or adjacent movements
- The basic concept of MB-SPFs is to predict the CP and NCP crashes separately in two different models: CP-SPF and NCP-SPF.
  - The CP-SPF predicts the crashes for a CP using the CP types and major & minor conflicting movement volumes
  - The NCP-SPF predicts the NCP crashes at intersection-level using the major & minor AADTs.

Safety Analysis - Methodology

Model Estimation Process



Safety Analysis - Methodology

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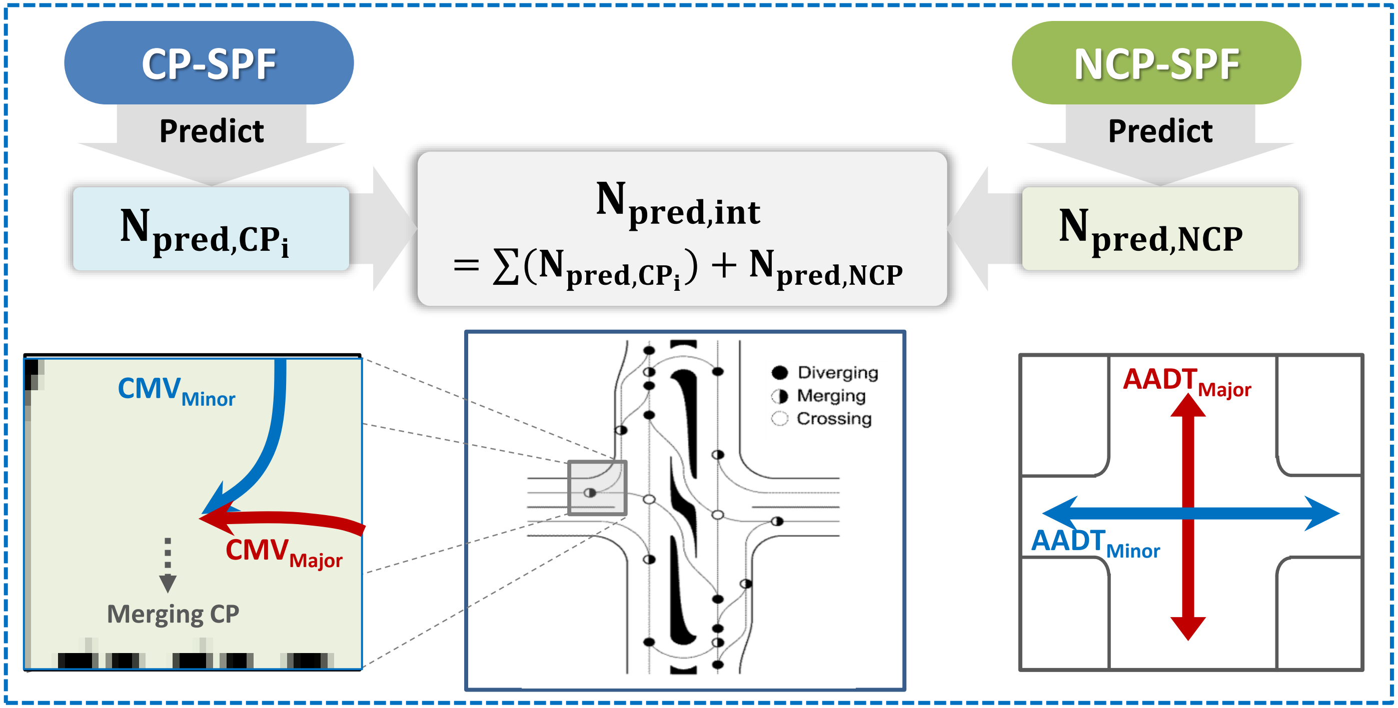
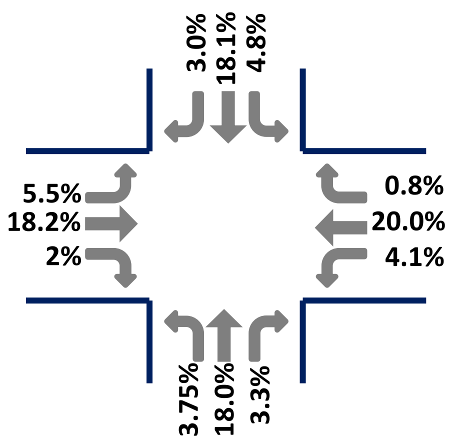
Model Application Process



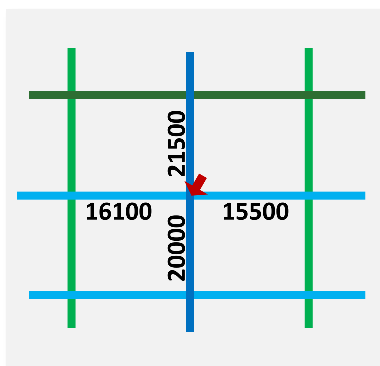
Safety Analysis - Methodology

Conflicting Movement Volumes (CMVs)

- A movement volume is calculated by multiplying the proportion of turning movement (TM) counts to the total entering volume.



TM Counts (%)



AADT

Movement	TM (%)	ΣAADT/2	Movement Volume
SBL	0.03	36550	1097
SBT	0.181	36550	6616
SBR	0.048	36550	1754
NBL	0.0375	36550	1371
NBT	0.18	36550	6579
NBR	0.033	36550	1206

Movement AADT

Safety Analysis - Methodology

Model Development

MB-SPFs

$$N_{\text{pred},int} = \sum_{i=1}^{n}\left(N_{\text{pred},CP_i}\right) + N_{\text{pred},NCP}$$

- CP-SPF

$$N_{\text{pred},CP_i} = \exp(\alpha_{\text{CP},i} + \beta_{\text{CMV}_{Maj}} \cdot \ln(CMV_{Maj}) + \beta_{\text{CMV}_{Min}} \cdot \ln(CMV_{Min}))$$

- NCP-SPF

$$N_{\text{pred},NCP} = \exp(\alpha_{NCP} + \beta_{\text{AADT}_{Maj}} \cdot \ln(AADT_{Maj}) + \beta_{\text{AADT}_{Min}} \cdot \ln(AADT_{Min}))$$

Where,

$N_{\text{pred,CP}_i}$ = predicted CP crashes for a CP (unit: crashes/CP·year);

$\alpha_{\text{CP,i}}$ = constant for CP type i (i = crossing, merging or diverging);

β_{CMV} = coefficient for major and minor CMVs;

CMV = major and minor CMVs (unit: veh/day).

$N_{\text{pred,NCP}}$ = predicted NCP crashes for intersection (unit: crashes/year);

α_{NCP} = constant for NCP-SPF;

β_{AADT} = coefficient for major and minor AADTs (unit: veh/day);

AADT = major and minor road AADTs (veh/day)

Safety Analysis - Methodology

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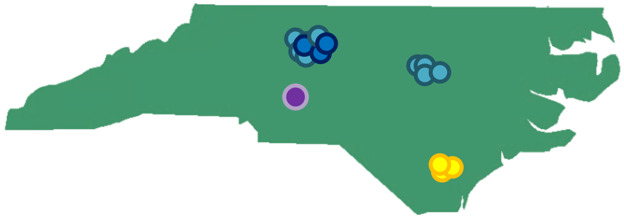
Data Collection

- The crash and traffic volume data are collected from 35 sites[1)] in NC



- 15 Conventional Intersections (4SG)
- 6 Conventional with Channelized Lane (4SG)
- 11 Partial Restricted Crossing U-Turn (RCUT)
- 3 Diverging Diamond Interchange (DDI)

- **Crash data**
  - Crash Type & Location
  - Vehicle Maneuver
  - Crash Severity

- **Traffic Volume**
  - Turning Movement Counts[2)]
  - AADT

1) Each intersection may include multiple signalized zones in an alternative intersection. In this study, we considered each zone as a site.
2) TM counts are observed for 11 ~ 16 hours a day (avg = 13.7 hours). (6AM-7PM: 14 sites, 6AM-10PM: 14 sites, 7AM-6PM: 4 sites, 7AM-7PM: 7 sites)

Model Estimation Results

- The models are estimated for crash severities, TOT (Total), FI (Fatal & Injury), and PDO (Property Damage Only) crashes, using the Negative Binomial (NB) regression model
- The results for CP-SPF show the impact of crossing CP on the crash frequency is significantly higher than the other two (diverging and merging) in all three severity models.

MB-SPFs	TOT Model		FI Model		PDO Model	
CP-SPF	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
$\alpha_{Crossing}$	-8.501	***	-8.267	***	-10.160	***
$\alpha_{Diverging}$	-9.873	***	-10.464	***	-11.073	***
$\alpha_{Merging}$	-9.316	***	-9.706	***	-10.571	***
$\beta_{CMV_{Major}}$	0.689	***	0.663	***	0.749	***
$\beta_{CMV_{Minor}}$	0.109	*	0.015		0.166	**
NCP-SPF	Coefficient	Sig.	Coefficient	Sig.	Coefficient	Sig.
α	-10.874	***	-6.885	***	-13.618	***
$\beta_{AADT_{Major}}$	0.792	***	0.531	**	0.828	***
$\beta_{AADT_{Minor}}$	0.521	***	0.229	***	0.742	***

Statistical Significance Codes: '***' < 0.001, '**' < 0.01, '*' < 0.05, '.' < 0.1

Safety Analysis – Analysis Results

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Safety Performance Comparison

- Overall, the contra-RCUT and RCUT (R-U) showed good performance, and the DL-Downstream and Quadrant Left (SE) showed poor performance than others.

Conflict Points		36	10	10	10	8	8	8	9
Scenario	Approach Volume	Base Conventional	DL-D	DL-U	SPL	R-UR	C-UR	R-RU	Q-SE
EBN-WBN	EB: 50% WB: 50%	7.815	2.19	2.06	2.02	1.51	1.45	1.50	2.13
EBT-WBN		7.936	2.21	2.10	2.07	1.53	1.48	1.54	2.25
EBL-WBN		7.810	2.28	2.04	2.01	1.52	1.44	1.46	2.03
EBLT-WBN		7.905	2.25	2.08	2.05	1.53	1.47	1.50	2.13
EBT-WBT		8.053	2.20	2.12	2.09	1.54	1.50	1.57	2.15
EBL-WBT		7.936	2.28	2.08	2.05	1.54	1.47	1.50	1.96
EBLT-WBT		8.027	2.25	2.11	2.09	1.55	1.50	1.54	2.06
EBT-WBL		7.936	2.28	2.08	2.05	1.54	1.47	1.50	2.33
EBN-WBN	EB: 60% WB: 40%	7.683	2.17	2.03	2.00	1.48	1.42	1.48	2.29
EBT-WBN		7.849	2.16	2.06	2.04	1.50	1.46	1.53	2.40
EBL-WBN		7.706	2.22	1.98	1.95	1.47	1.40	1.43	2.16
EBLT-WBN		7.786	2.21	2.03	2.01	1.49	1.43	1.48	2.29
EBT-WBT		7.937	2.16	2.08	2.06	1.51	1.47	1.55	2.36
EBL-WBT		7.803	2.22	2.00	1.97	1.47	1.41	1.45	2.12
EBLT-WBT		7.879	2.20	2.05	2.03	1.50	1.45	1.50	2.24
EBT-WBL		7.876	2.23	2.06	2.04	1.52	1.46	1.50	2.45

Low CP Crashes High

Safety Analysis - Recommendations

Recommendations

- For new intersection designs, CMFs are not yet available
- Current practice is to measure number of conflict points, VJuST uses weighting factors
- Proposed Movement-Based Safety Performance Functions enable safety screening with planning-level data
- MB-SPF need daily turning movement data
- Definition of conflict point order based on geometry
- MB-SPF has preliminary validation underway but many planned improvements
- MB-SPF method can be applied to existing designs as well for planning-level comparison

Patent Landscape for GSIs

Patent Landscape

Process

- Patent search performed by UNC's Innovate Carolina
- Keyword search: Iterative search based on provided list

Findings

- Search found both international and US patents
- Previous Center Turn Overpass patent is expired- No expected issues
- Echelon and single point over single point (F6) have active US patents

Disclaimer

- A landscape is only a search, not legal opinion

Other Design Considerations

Pedestrian and Bicycle Accommodations

- Lower speeds expected on GSI compared to interchanged designs
- Protected turns possible at all studied designs
- Crosswalk Pathing Impacts:
  - Direct Left Downstream: Diamond style needs additional signals for direct crossing
  - Direct Left Upstream: Contraflow vs Crossover median sidewalks
  - RCUT and Quadrant Designs: Long crossing distances for non-through crossings

Other Design Considerations

Frontage and Driveway Impacts

- Tight Quadrants retain access on up to 6 frontages, All others up to 4

Constructability

- All GSI have major impacts to maintenance of traffic during elevation
- Contraflow and Contra RCUT need concurrent (E/W or N/S) intersection control changes
- Quadrant only needs two intersections and can be used as interim control

Other Design Considerations

Queue Storage

- Storage constraints follow at-grade limitations
- Consider paired movements and ramp queues for spillback

Convertibility to Interchange

- Studied designs utilize standard structures with some modification for contraflow or crossover designs
- Conversion to interchange-style requires new structures for Center Turn Overpass and Echelon

Other Design Considerations

Longitudinal Impact

- Direct left downstream allows very tight intersection and ramps
- Quadrant affects only two of four approaches
- U-turns accommodating right turn to u-turn need additional offset from ramp

Bridge Width Impact

- Single point and crossover designs require additional width to separate opposing movements
- Depending on the location of the quadrant intersections, left turn bay may extend onto bridge

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- Stephen Bolyard
- Kevin Lacy
- Katie Hite
- Jim Dunlop
- Brian Mayhew
- Mike Reese
- Daniel Carter
- Brian Murphy

Reference Links

[NCDOT Research Project 2018-20]

[NCDOT Safety and Mobility Initiatives]

[VJuST Tool and Innovative Intersection Website – Good Graphics]

[ITRE DataLab- Research Tools and Datasets]

Q & A

NC STATE UNIVERSITY

Questions?