Design Guidance for Intersection Auxiliary Lanes (NCHRP Project 03-102 Report 780)

September 13, 2016

Today’s Presenters

1. **Double Left Turn Lanes**
   Kay Fitzpatrick, Texas A&M Transportation Institute

2. **Speed and Deceleration of Left Turning Vehicles in Deceleration Lanes Approaching Signalized Intersections**
   Marcus Brewer, Texas A&M Transportation Institute

3. **Typical Designs**
   Paul Dorothy, S-E-A, Limited

4. **Overview of Researcher’s Recommended Changes to the AASHTO Green Book (next edition)**
   Kay Fitzpatrick, Texas A&M Transportation Institute

NCHRP is...

A state-driven national program

- The state DOTs, through AASHTO's Standing Committee on Research...
  - Are core sponsors of NCHRP
  - Suggest research topics and select final projects
  - Help select investigators and guide their work through oversight panels

NCHRP 03-102 PANEL

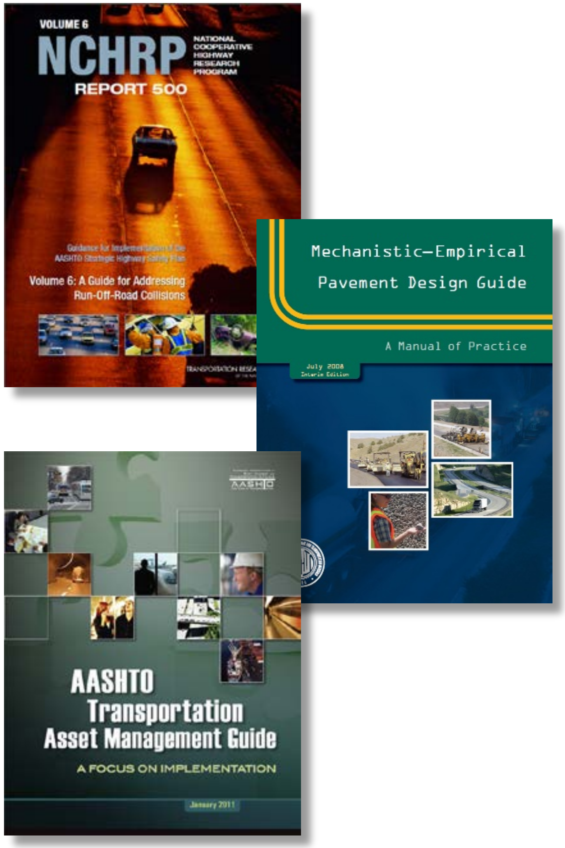
- **B. Ray Derr,** *NCHRP Senior Program Officer*

- **Michael S. Fleming,** *Washington State DOT, Olympia, WA*
- **Aaron M. Frits,** *Kansas DOT, Topeka, KS*
- **Evangelos I. Kaisar,** *Florida Atlantic University, Boca Raton, FL*
- **Lawrence T. Moore,** *California DOT, Sacramento, CA*
- **James L. Pline,** *Pline Engineering, Inc., Boise, ID*
- **Lisa Schletzbaum,** *Massachusetts DOT, Boston, MA*
- **Anthony D. Wyatt,** *North Carolina DOT, Garner, NC* (Chair)
- **Jeffrey Shaw,** *FHWA Liaison*
- **Richard A. Cunard,** *TRB Liaison*

NCHRP delivers...

Practical, ready-to-use results

- Applied research aimed at state DOT practitioners
- Often become AASHTO standards, specifications, guides, manuals
- Can be directly applied across the spectrum of highway concerns: planning, design, construction, operation, maintenance, safety

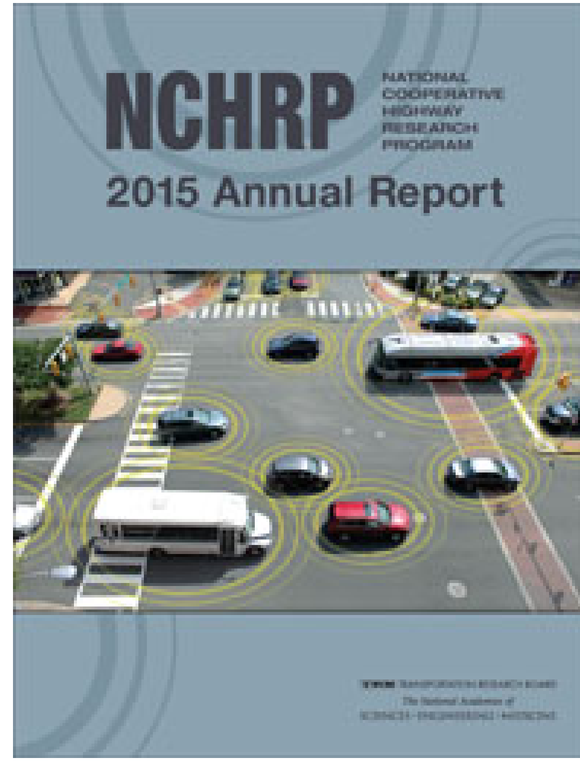


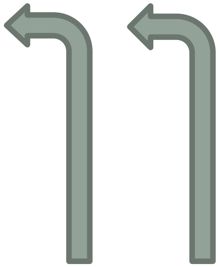
A range of approaches and products

- Traditional NCHRP reports
- Syntheses of highway practice
- IDEA Program
- Domestic Scan Program
- Quick-Response Research for AASHTO
- Other products to foster implementation:
  - *Research Results Digests*
  - *Legal Research Digests*
  - *Web-Only Documents and CD-ROMs*

NCHRP Webinar Series

- Part of TRB's larger webinar program
- Opportunity to interact with investigators and apply research findings.





Double Left-Turn Lanes Operational Field Study

Kay Fitzpatrick, Eun Sug Park, Pei-Fen Kuo, James Robertson, and Marcus Brewer
Texas A&M Transportation Institute

Acknowledgments

- Sponsor = NCHRP
  - NCHRP 3-102 “Design Guidance for Intersection Auxiliary Lanes”
- Comments from Panel
- Assistance with data collection
  - TTI staff
  - TRA (subcontractor)
  - CDM Smith Research Program

State of Practice
Double Left-Turn Lanes

- Most have guidance, not always very detailed
- Installation often based on:
  - Current / expected turning demand
  - Signalization
- Receiving leg design
- Capacity less than 2× single lane (GB says 180%)
- Desired guidance on adjustments to length

Study Variables

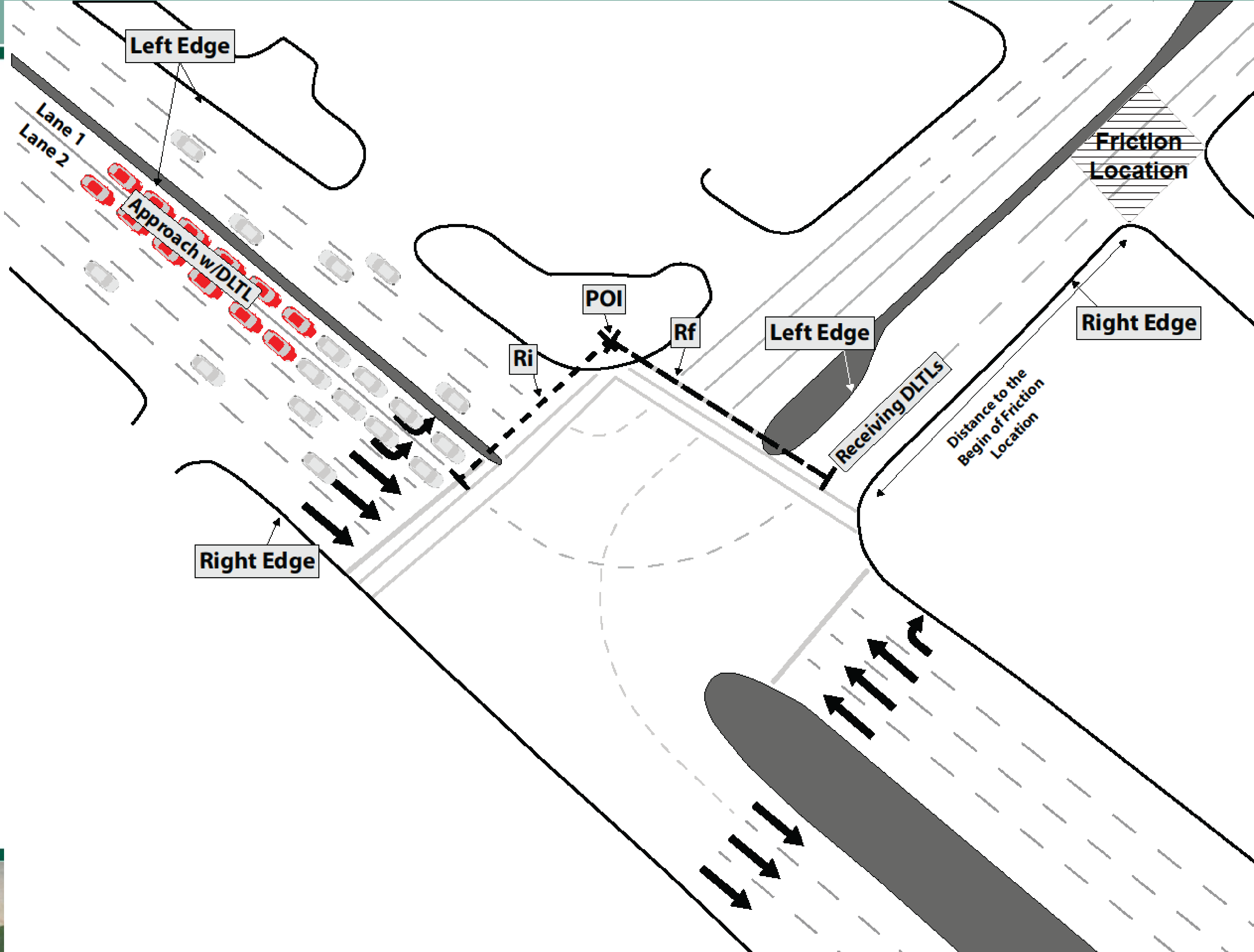
	Variable	Range
Study Variables	Receiving leg width	• Narrow, < 26 ft • Moderate, 26 to 30 ft • Wide, > 30 ft
	Left-turn lane width	• Less than 11.5 ft • 11.5 ft or more
	Downstream friction point – type	Bus stop, driveway, right-turn lane, none
	Downstream friction point – distance	• Near, < 150 ft • Medium, 150 to 350 ft • Long, > 350 ft

Data Collection

- 26 sites in:
  - Arizona (Flagstaff, Phoenix, Tucson)
  - California (San Leandro, Palo Alto)
  - Texas (Houston, Bryan, College Station)
- Video

Data Reduction

- Saturation flow rate (SFR)
  - Time each left-turning vehicle crossed stop bar
  - Whether veh is truck or in queue at start of cycle
  - ITE Manual of Transportation Engineering Studies → use 7th, 8th, 9th, 10th vehicle in queue
  - We used 5th to 10th vehicle


Left Edge
Lane 1
Lane 2
Approach w/DLTL
POI
Ri
Rf
Left Edge
Receiving DLTLs
Friction Location
Right Edge
Distance to the Begin of Friction Location
Right Edge

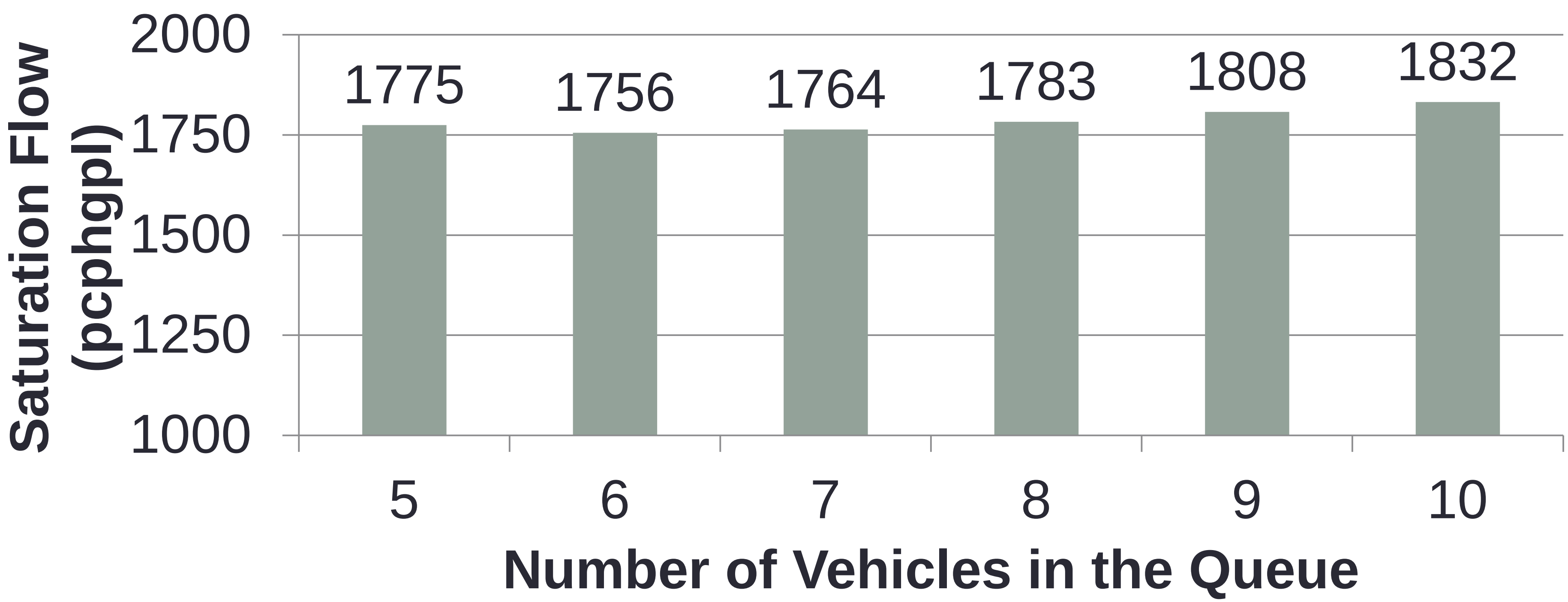
Results-Not Significant Variable

- Lane (inside or outside)

Lane	Unit	Findings
Lane 1 (inside lane)	SFR Average	**1,774 pcphgpl**
	Count	4,992 passenger cars
Lane 2 (outside lane)	SFR Average	**1,776 pcphgpl**
	Count	5,031 passenger cars
Both lanes	SFR Average	1,775 pcphgpl
	Count	10,023 passenger cars

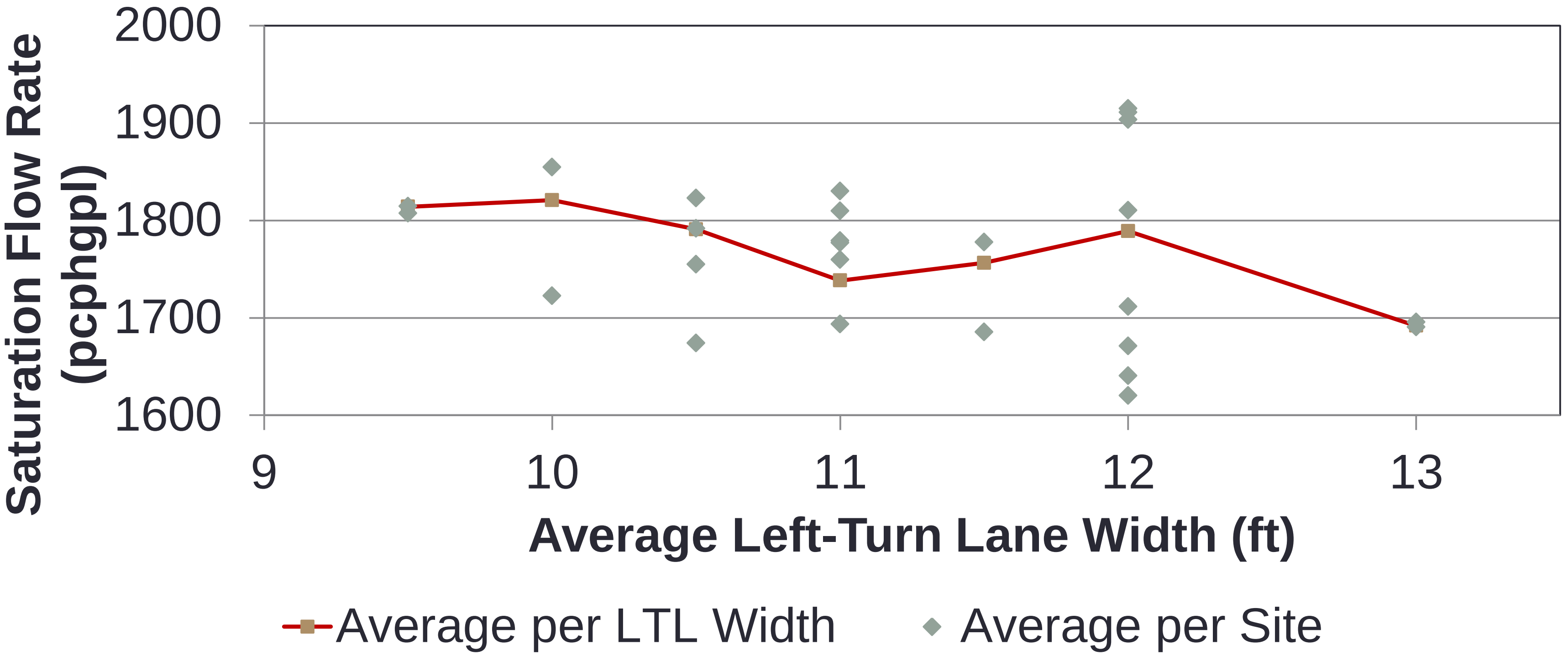
Results-Not Significant Variable

- Queue length (5, 6, 7, 8, 9 or 10 vehicles)



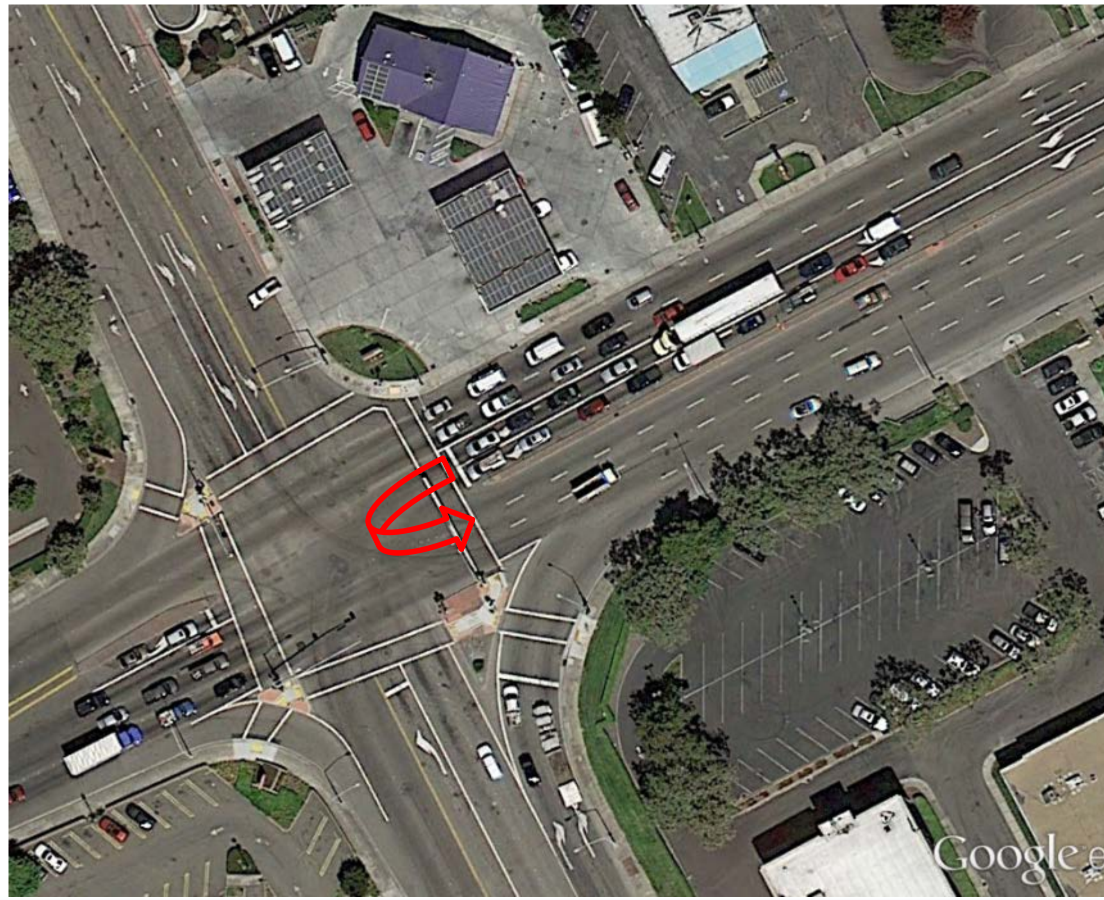
Results-Not Significant Variable

- Left-turn lane width



Results-Significant Variable

- U-turns: each U-turning vehicle decreases SFR by 56 pcphgpl

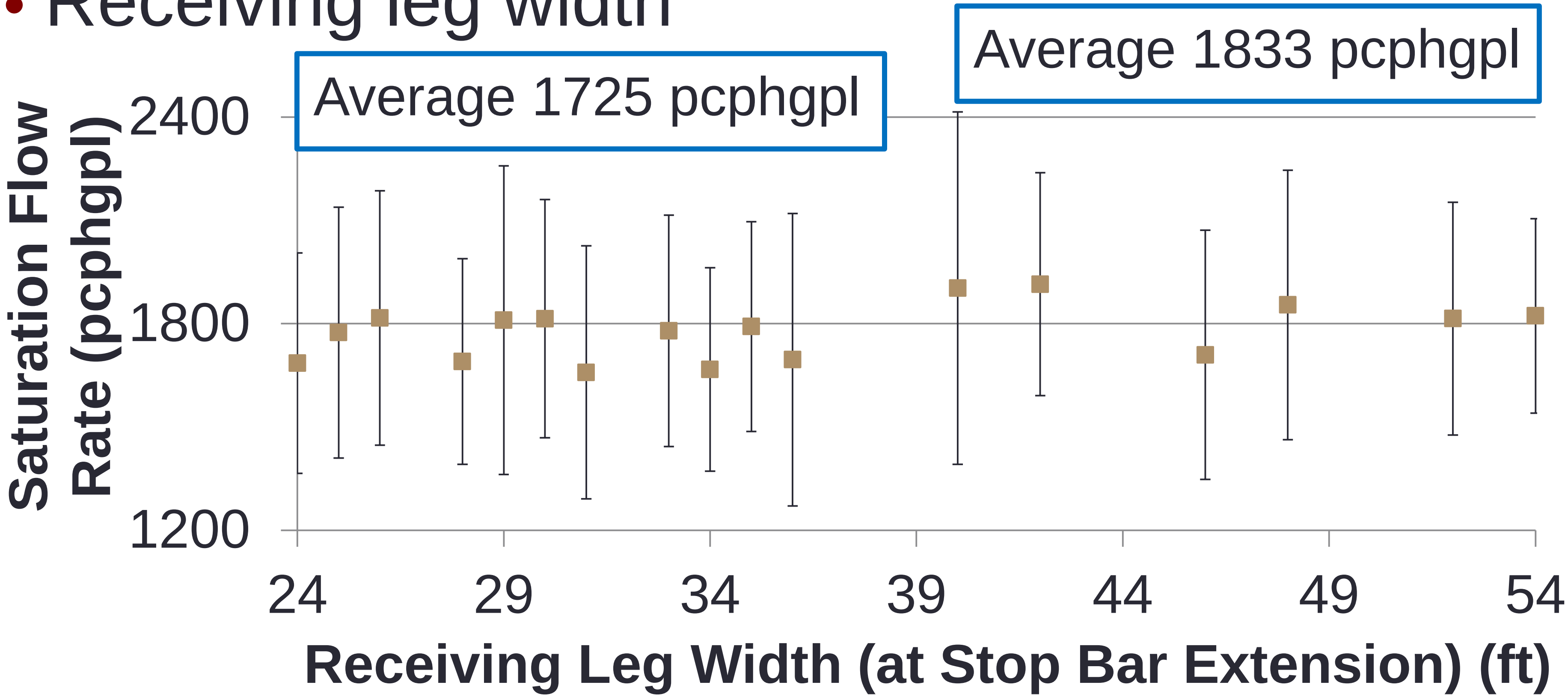


Results-Significant Variable

- Add lane from channelized right turn
  - Increase SFR by 52 pcphgpl

Results-Significant Variable

- Receiving leg width



Suggested Changes to *Green Book*

- Capacity
  - GB → approximately 180%
  - This study → 196%
- Receiving leg
  - GB → 30 ft used by several agencies
  - Previous study → 36 ft desirable, 30 ft acceptable
  - This study → supports 36 ft

Potential Cautions to add to *Green Book*

- **U-turning vehicles** have a significant impact on operations of double left-turn lanes
- When receiving leg is 2 lanes plus 3rd lane due to **dedicated downstream lane** from channelized right-turn lane – left-turning vehicles observed to move into additional lane as soon as physically possible

Speed and Deceleration in Left-Turn Lanes at Signalized Intersections

Image: Dan Walker

Marcus Brewer and
Kay Fitzpatrick
Texas A&M Transportation Institute

Research Objective

- To recommend improvements to the guidance provided in the AASHTO *Green Book* for auxiliary lanes at intersections, leading to improved safety and operations.

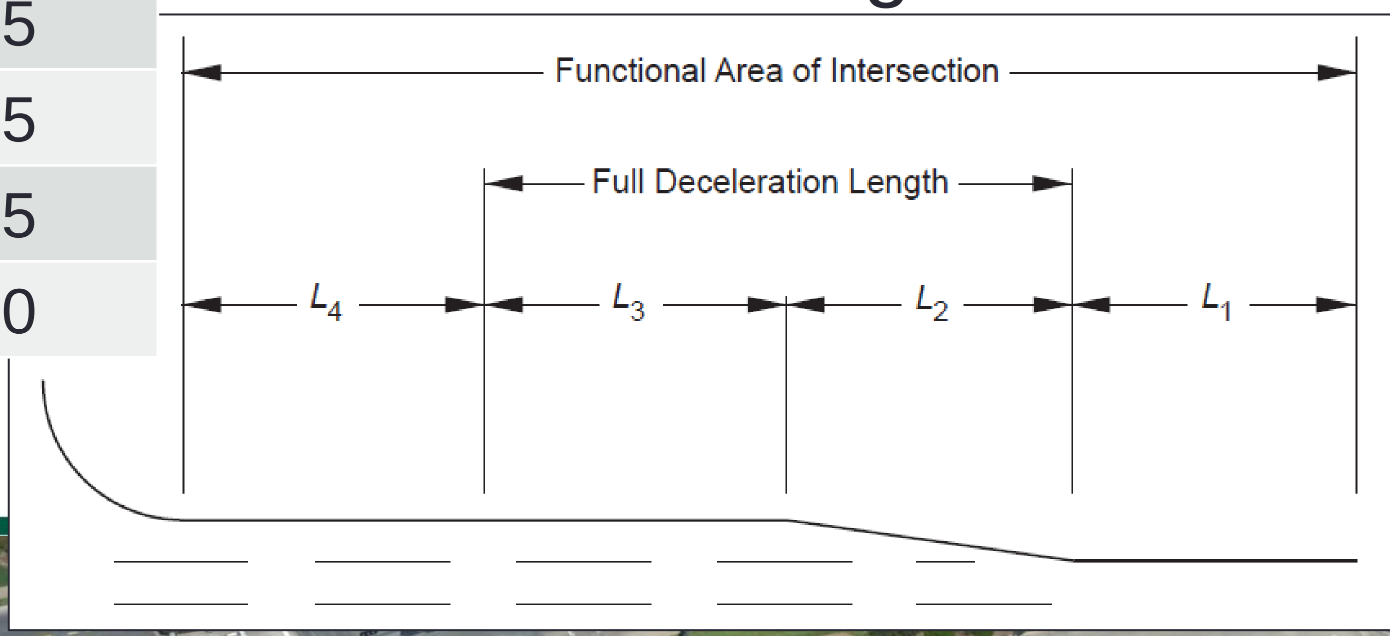
Image: Marcus Brewer

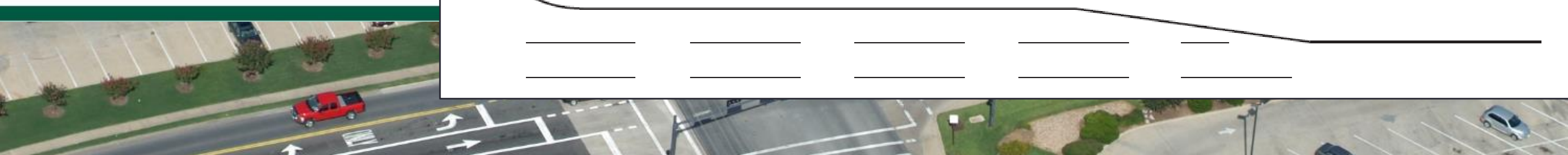
Current AASHTO Policy
2011 *Green Book*, Chapter 9

Speed (mph)	Distance (ft)
20	70
30	160
40	275
50	425
60	605
70	820

Table 9-22

Figure 9-48





Literature
Deceleration Rates

- Fambro, et al (NCHRP Report 400, 1997)
  - 11.2 ft/s^2 for SSD, 24.5 ft/s^2 for maximum/emergency
- ITE *Traffic Engineering Handbook* (1999)
  - 11.2 ft/s^2 maximum, up to 10 ft/s^2 “reasonably comfortable”
- Gates, et al (2007)
  - Greater than 40 mph: 9.2, 10.9, and 13.6 ft/s^2
  - Less than 40 mph: 6.4, 8.3, and 11.6 ft/s^2

Deceleration Study Questions

- What is speed differential for turning vehicles?
- How does speed differential vary based on taper length and/or posted speed limit?
- Are the 2011 *Green Book* deceleration rates representative of current left-turn drivers?

Deceleration Study
Site Selection Controls

- Taper Length above or below *Green Book*
  - 8:1 (L:T) for speeds up to 45 mph – **96 ft**
  - 15:1 (L:T) for speeds 50 mph and above – **180 ft**
- Posted Speed Limit (30-65 mph)
- 4 legs, signalized
- 4-lane major, 2- or 4-lane minor
- Straight, level, no skew

Study Sites

PSL (mph)	Taper Length (ft)	Below Taper Threshold	Above Taper Threshold
30-35	96	2 sites	2 sites
40-45	96	2 sites	2 sites
50-55	180	--	2 sites
60-65	180	1 site	1 site

- 3 sites each in Mobile, Tallahassee, Biloxi, and Austin

Data Collection

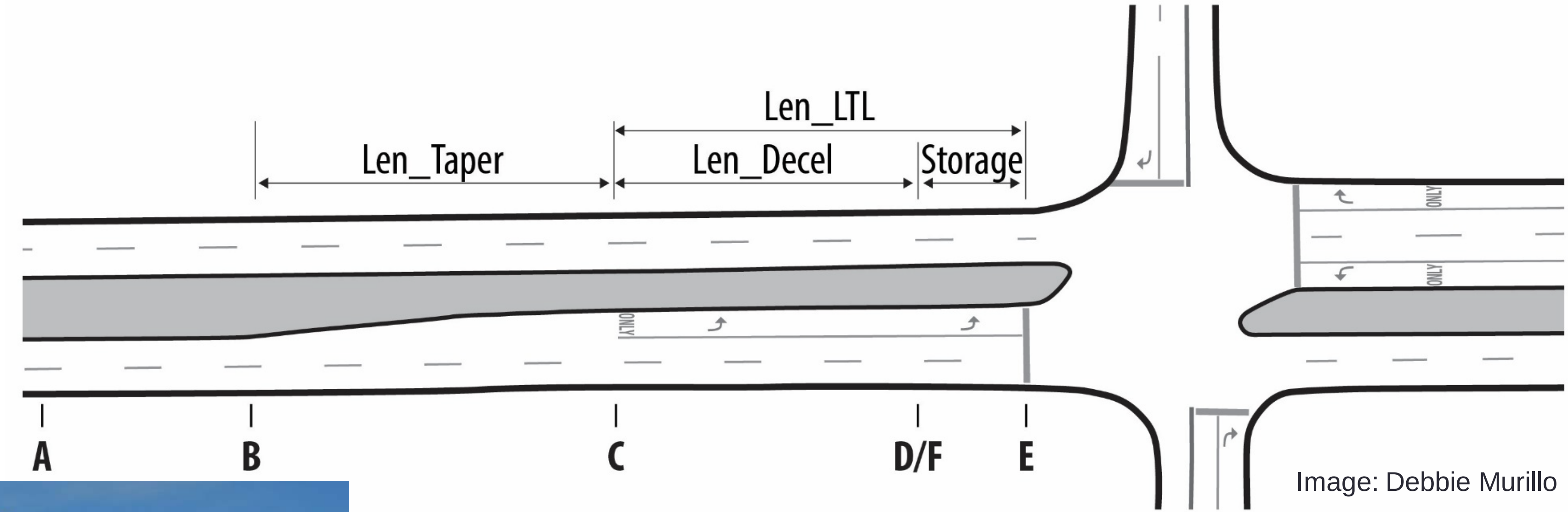


Image: Debbie Murillo

Data Analysis

- Focus on three key guidelines from *Green Book*:
  - 10 mph speed differential when the turning vehicle clears the through traffic lane (Note 3 in Table 9-22)
  - 5.8 ft/s^2 average deceleration moving from the through lane into the left-turn lane (Note 4)
  - 6.5 ft/s^2 average deceleration after moving laterally into the left-turn lane (Note 4)

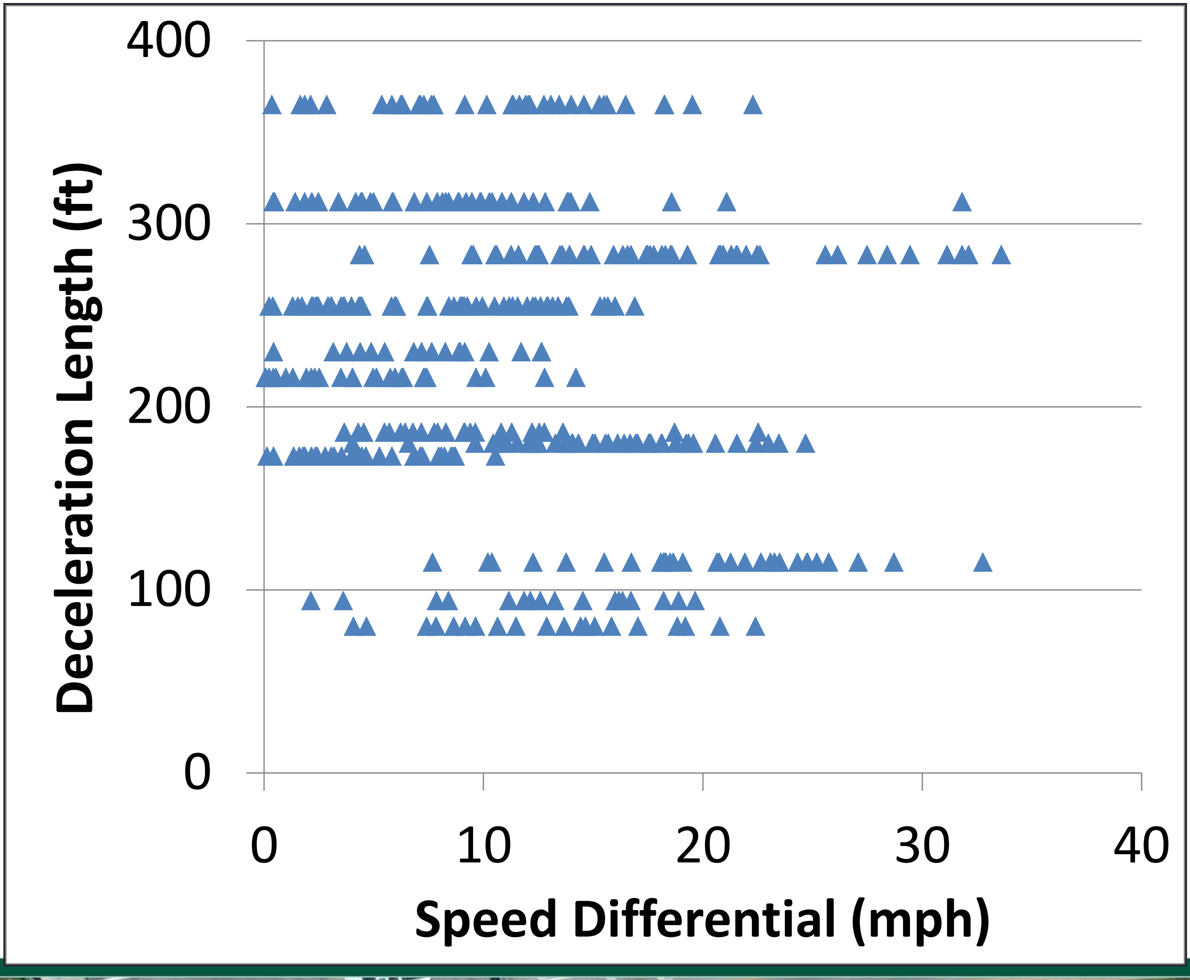
Analysis of Speed Differential

- Observed larger differentials at larger upstream speeds, statistically significant predictor

Upstream Speed (mph)	# Vehicles with a Speed Differential (mph) of …				
	0-10	10-20	20-30	> 30	Total
20-29	7	2	0	0	9
30-39	47	21	1	0	69
40-49	93	54	4	0	151
50-59	38	72	26	1	137
60-69	4	22	13	3	42
≥ 70	0	0	0	2	2
Total	189	171	44	6	410
Percent	**46%**	**42%**	**11%**	**1%**	**100%**

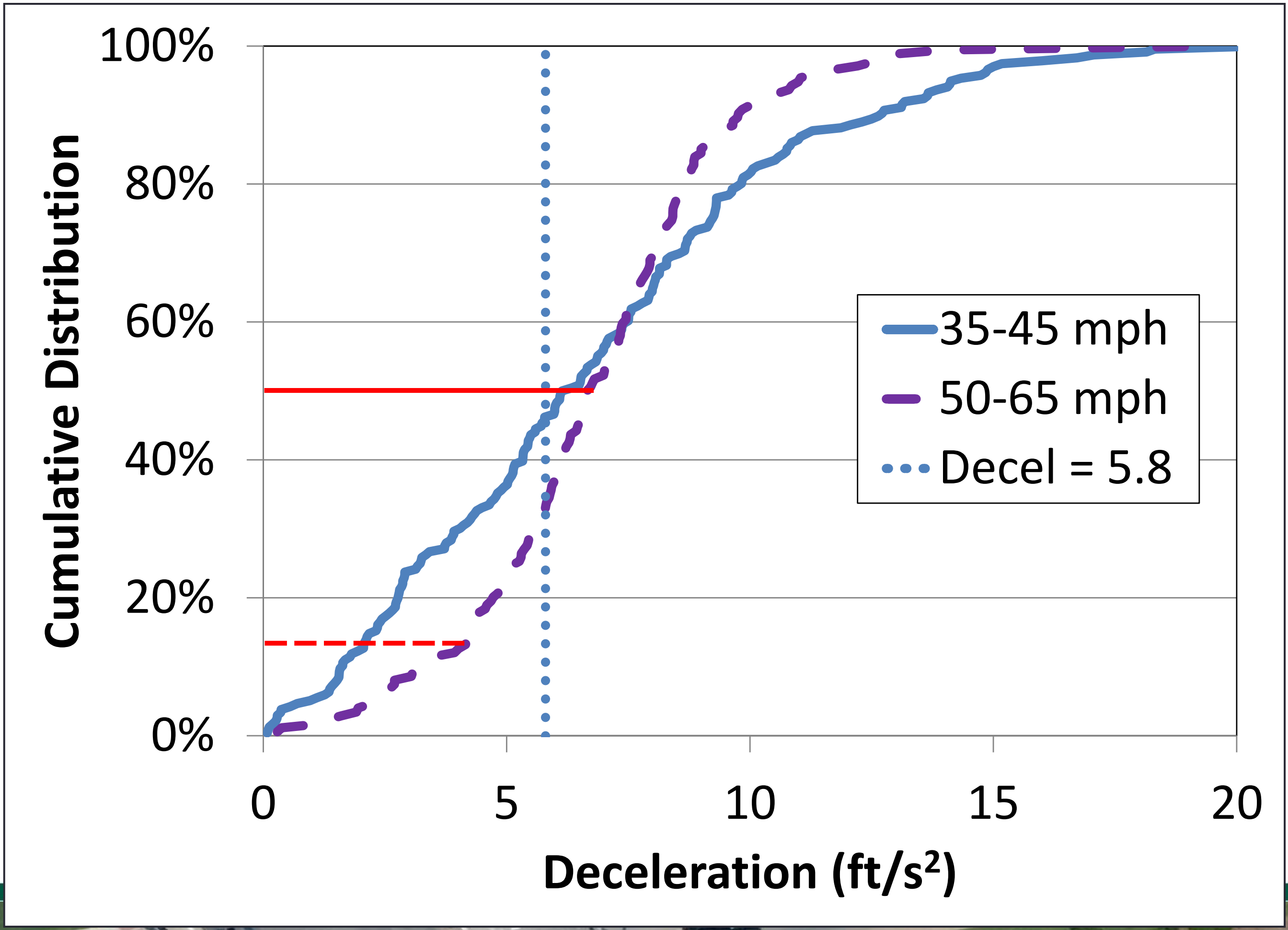
Speed Differential and *Green Book*

- No strong statistical relationship between deceleration length and speed differential



Deceleration Upstream of Taper

- About half of observed drivers were 6.1 ft/s^2 or more
- 85% of high-speed were $\geq$ 4.2 ft/s^2

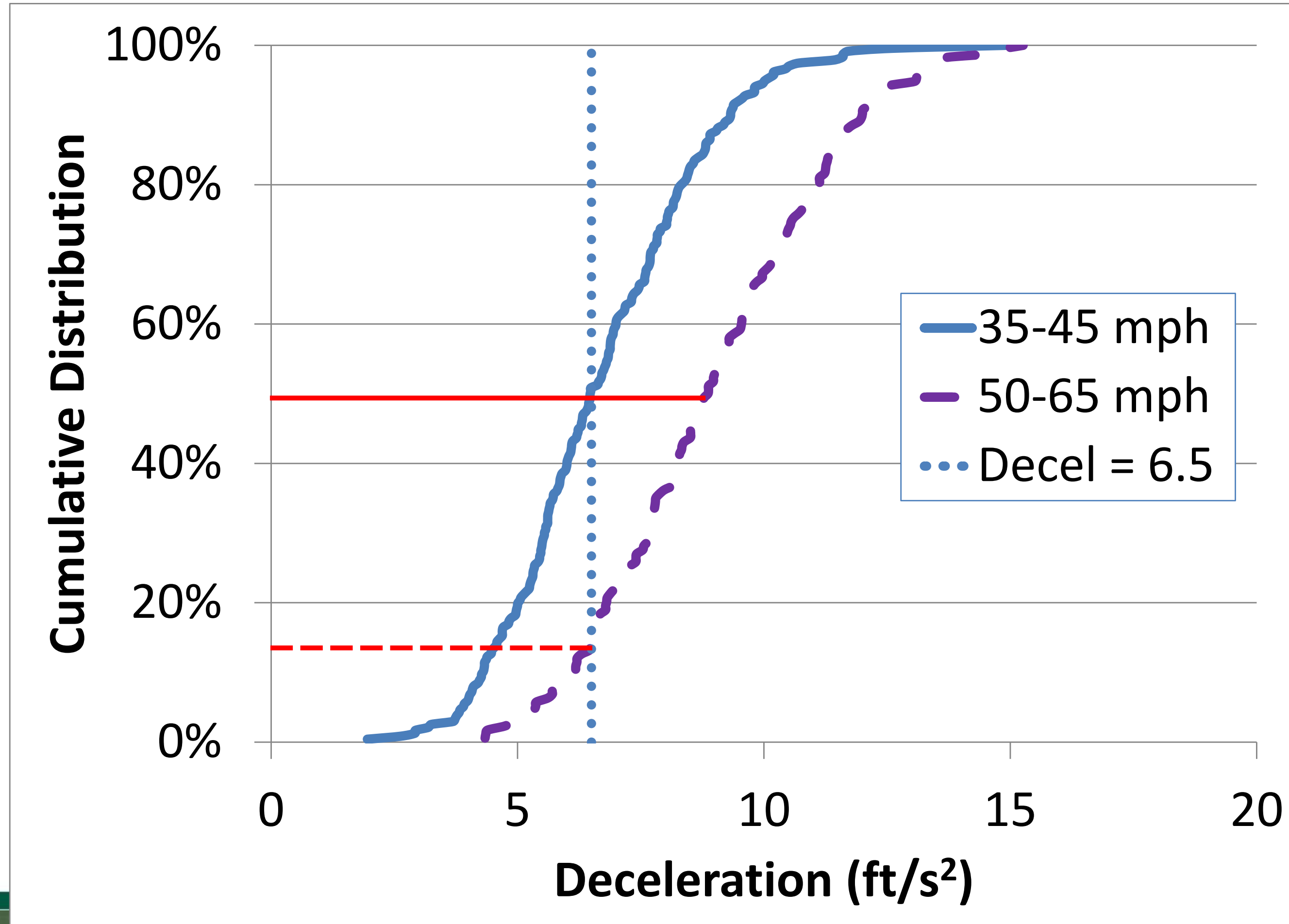


Upstream Decel and *Green Book*

- GB guidelines recognize influence of speed, but decel rates/lengths not directly linked
- Guidelines flexible between 30 and 50 mph and allow consideration of other site characteristics
- Rate of 4.2 ft/s^2 in taper matches more drivers, especially at high-speed sites
- Tradeoffs for higher rate/shorter length

Deceleration in Decel Lane

- About half of low-speed drivers and 85% of high-speed were ≥ 6.5 ft/s^2

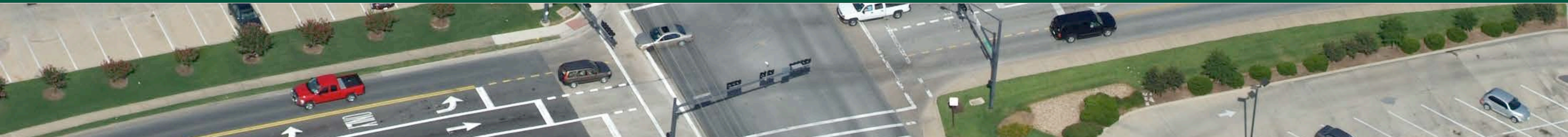


Decel Length and *Green Book*

- GB: “it is not practical” to provide full decel length in many locations
- Most study sites did not have full GB decel length
- Decel length and vehicle speed were statistically significant
- 10-ft increase in decel length reduces decel rate by 0.2 ft/s^2

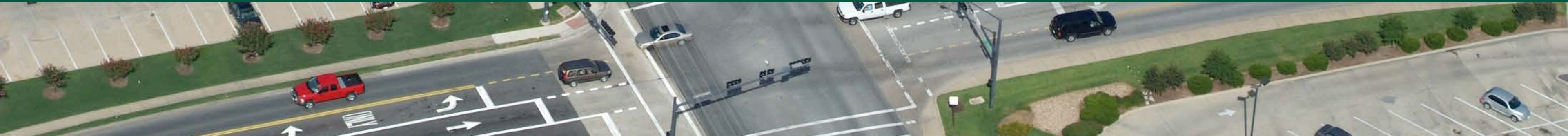
Typical Designs

Paul Dorothy



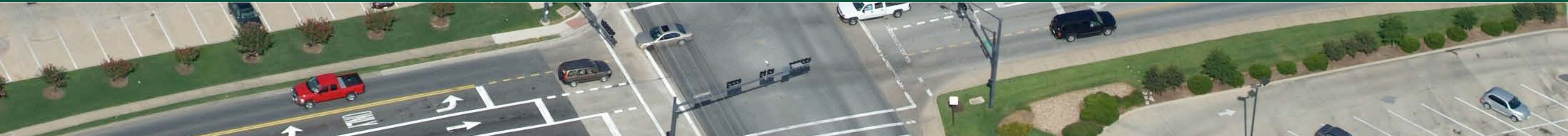
Case Studies

- Island design
- Deceleration lane design
- Double left-turn lane design
- Triple left-turn lane design
- Double right-turn lane design



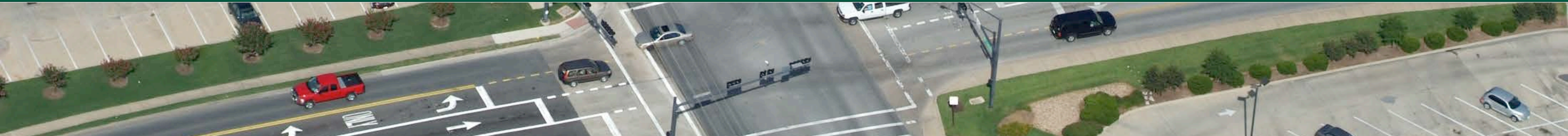
State-of-the-Practice Survey

- Request for “best practice” sites for each category (up to 3)
- 43 recommendations from 6 states



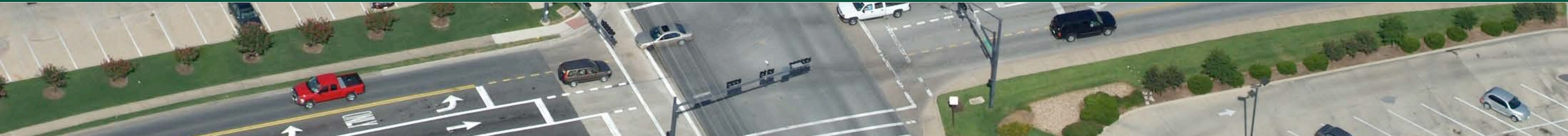
Island Design

- Island – defined area between traffic lanes used to control vehicle movements and to provide an area for pedestrian refuge and placement of traffic control devices.
- Channelized Intersection – at-grade intersection in which traffic is directed into definite paths by islands.



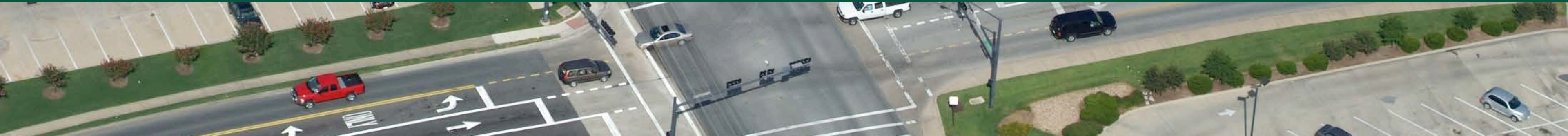
Island – Purpose

- Separation of conflicts
- Control of angle conflicts
- Reduction of excessive pavement areas
- Regulation of traffic and indication of proper use of intersection

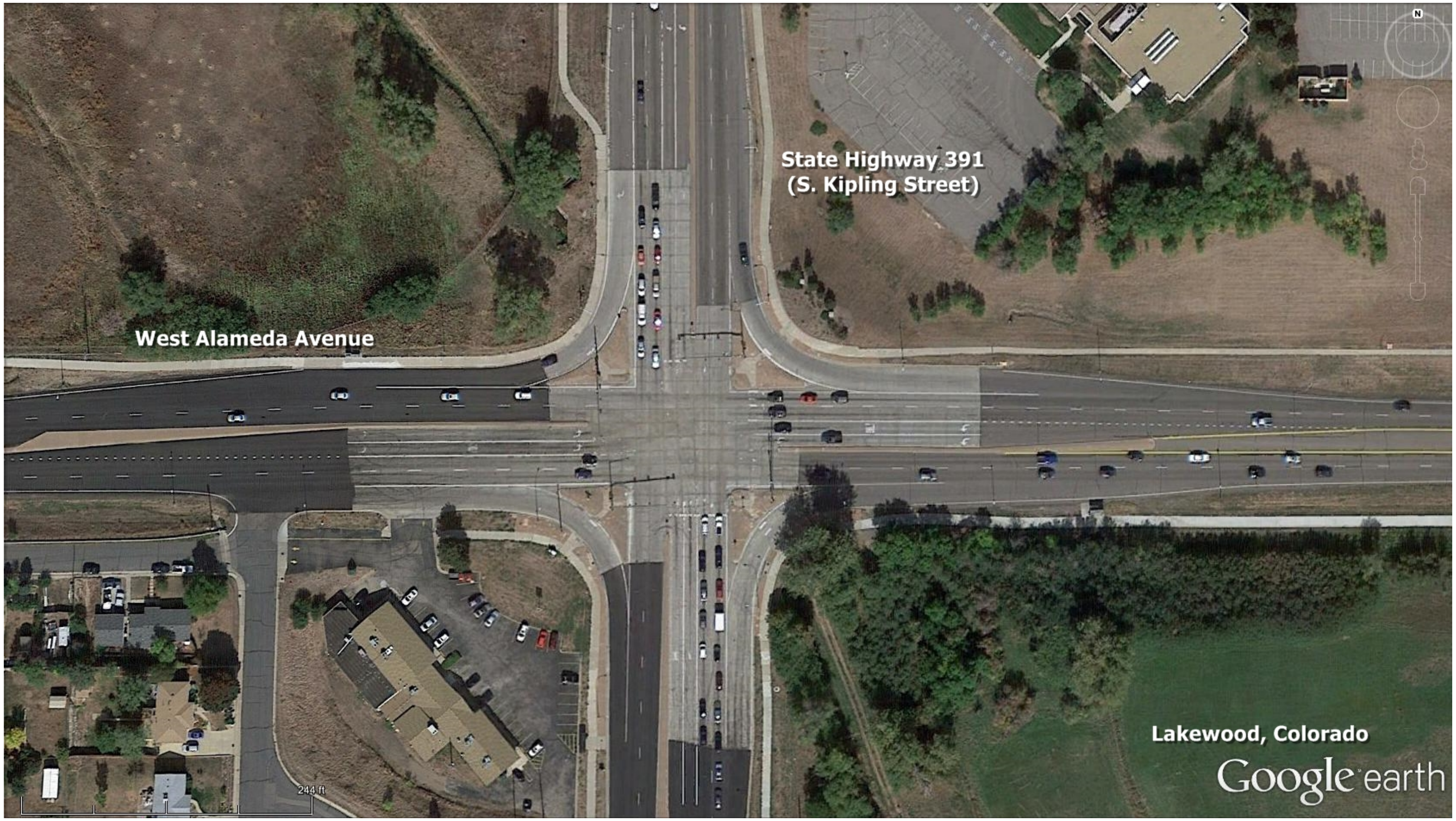


Island – Purpose

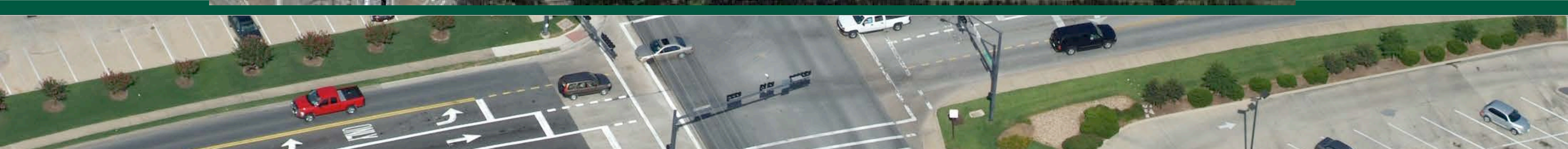
- Arrangements to favor a predominant turning movement
- Protection of pedestrians (must consider ADA)
- Location of traffic control devices
- Access control



Lakewood, Colorado

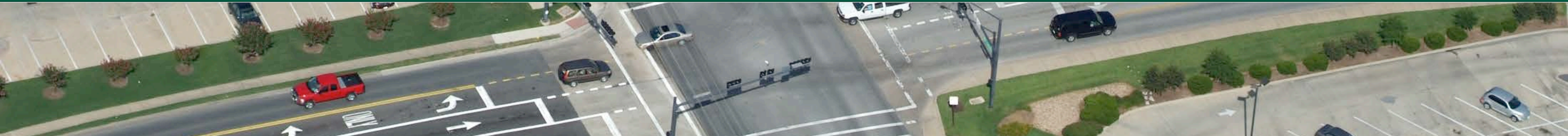


Turning Roadway – 5 Components



Approach Taper

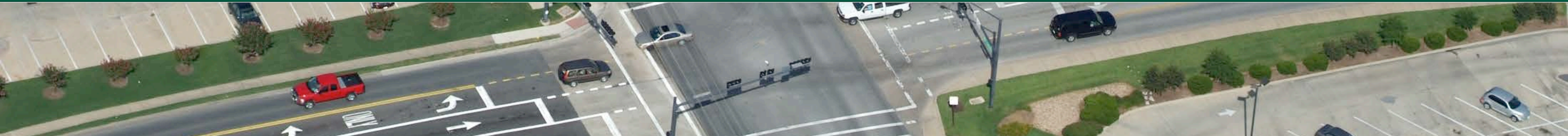
- Design speed = 50 mph
- Recommended taper = 15:1



Deceleration Lane

- Design speed 50 mph
- Assumes 10 mph decel. occurs in through lane
- Assumes 15 mph curve
- Length for 25 mph decel. required

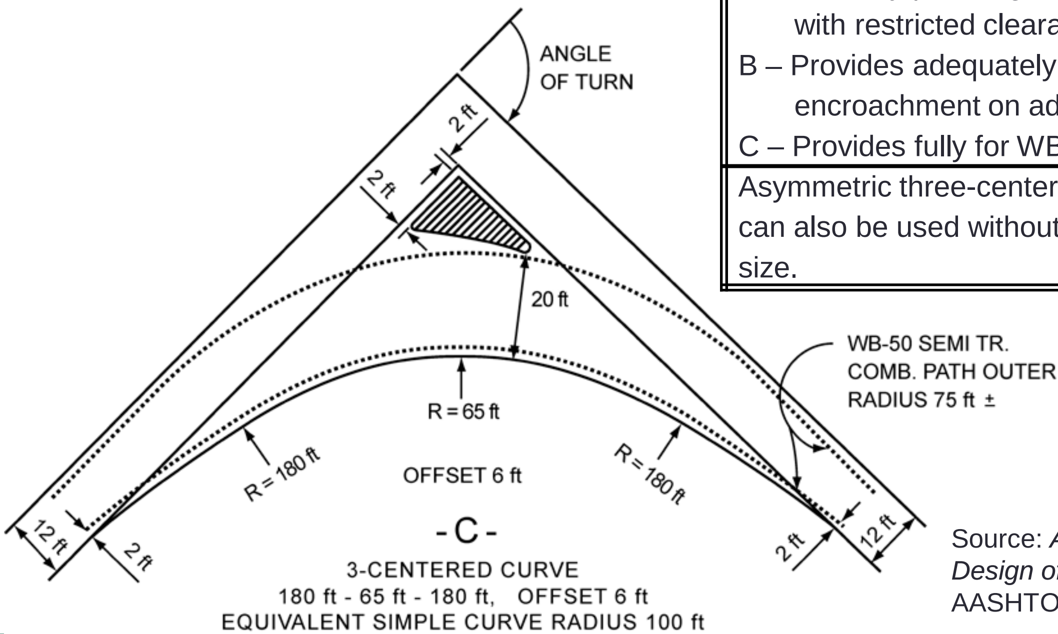
- Note: A more conservative design may assume stop condition due to ped. crossing.



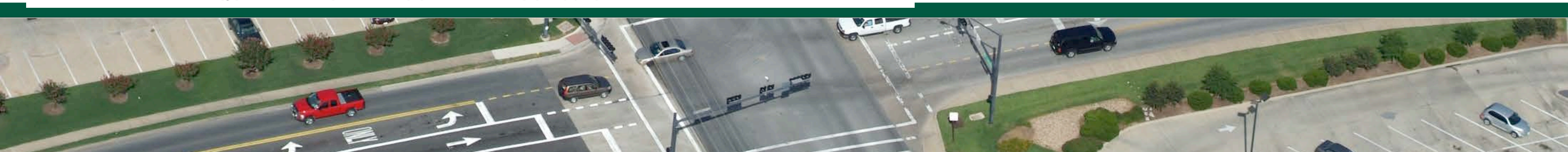
Turning Roadway Curve

		Three-Centered Curve			
Angle of Turn (degrees)	Design Classificatio n	Radii (ft)	Offset (ft)	Width of Lane (ft)	Approximate Island Size (sq ft)
90	A	150-50-150	3.0	14	50
	B	150-50-150	5.0	18	80
	C	180-65-180	6.0	20	125
A – Primarily passenger vehicles: permits occasional design single-unit truck to turn with restricted clearances. B – Provides adequately for SU: permits occasional WB-50 to turn with slight encroachment on adjacent traffic lanes. C – Provides fully for WB-50					
Asymmetric three-centered compound curves and straight tapers with a simple curve can also be used without significantly altering the width of roadway or corner island size.					

Source: *Colorado Roadway Design Guide*, Colorado Department of Transportation, 2005 (Updated Nov. 2011).

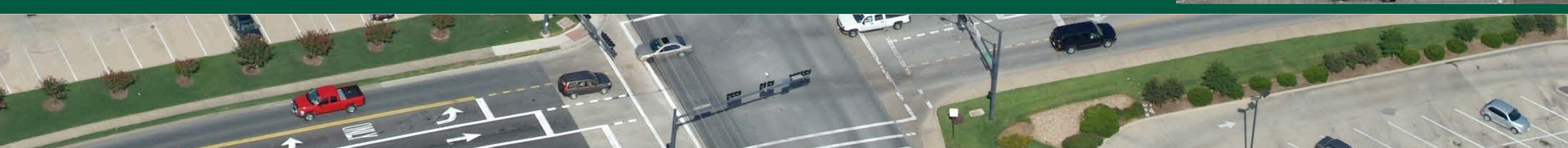


Source: *A Policy on the Geometric Design of Highways and Streets*, AASHTO, 2004.



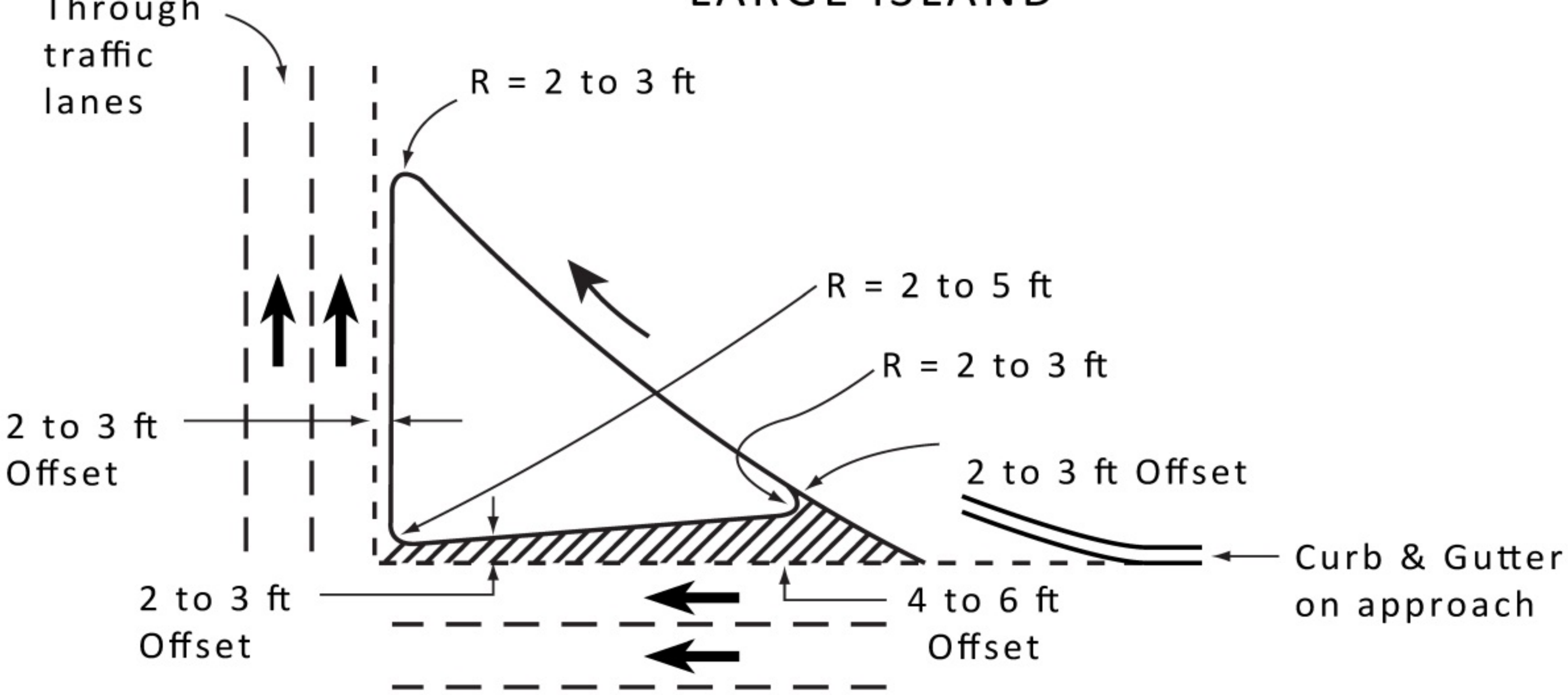
Acceleration Lane/Merging Taper

- Configuration
  - 130 ft. full 20-ft width accel. lane
  - 170 ft. taper from 20-ft to 12-ft lane
  - 200 ft. auxiliary lane
  - Total 500 ft. distance provided



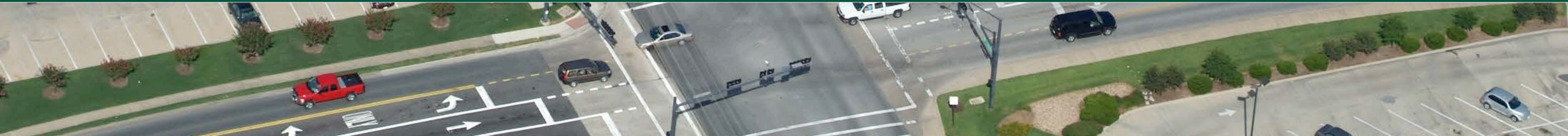
Large Island (Urban)

LARGE ISLAND



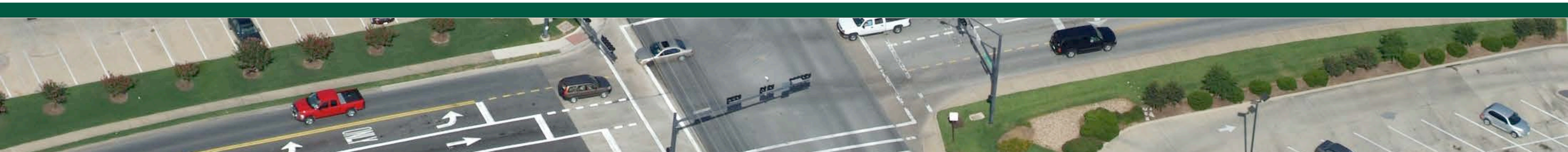
TRIANGULAR CURBED ISLAND ON URBAN STREETS

Source: *A Policy on the Geometric Design of Highways and Streets*, AASHTO, 2004.



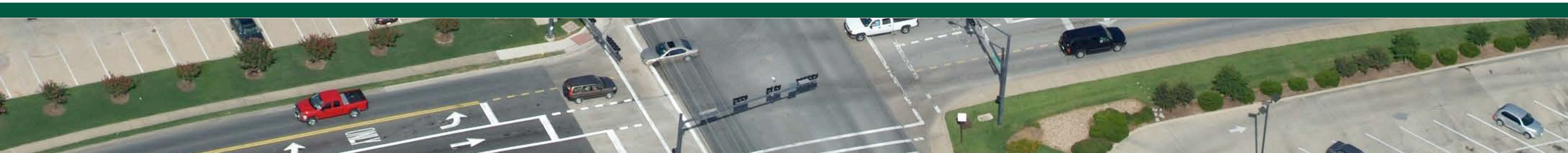
Pedestrian Concerns

- Refuge
- At-grade or cut-through installations
- Texture and guidance
- Logical
- Clearly delineated



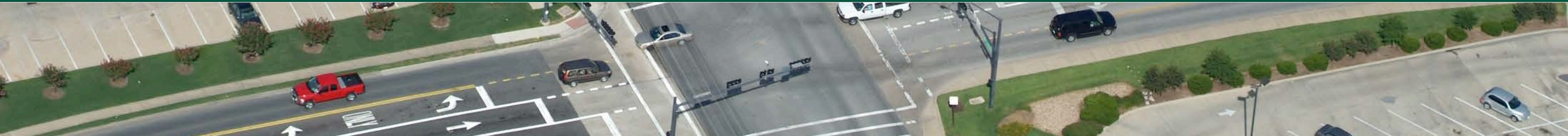
Additional Concerns

- Reduced visibility
- Snow removal
- Access control in functional intersection area

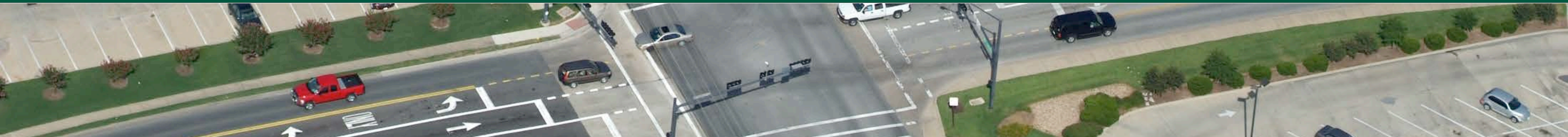


Deceleration Design

- “Provision for deceleration clear of the through-traffic lanes is a desirable objective on arterial roads and streets and should be incorporated into design, whenever practical.” – *Green Book*



Fuquay Varina, North Carolina



Intersection West Leg

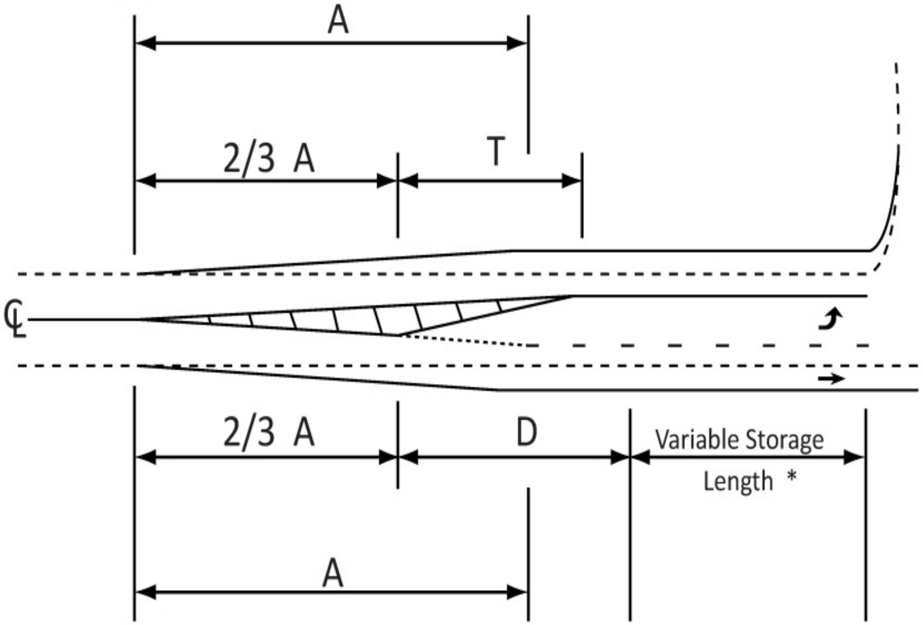
- Left- and right-turn deceleration lanes
- Approach is 2 11-ft. lanes
- Intersection 4 10-ft. lanes (2 thru, 1 LT, 1 RT)

Intersection West Leg

- 9 ft. symmetric widening about center line
- Design speed 50 mph
- Approach taper formula – A=WS
  - W = 9 ft.
  - S = 50 mph
  - A = 450 ft.

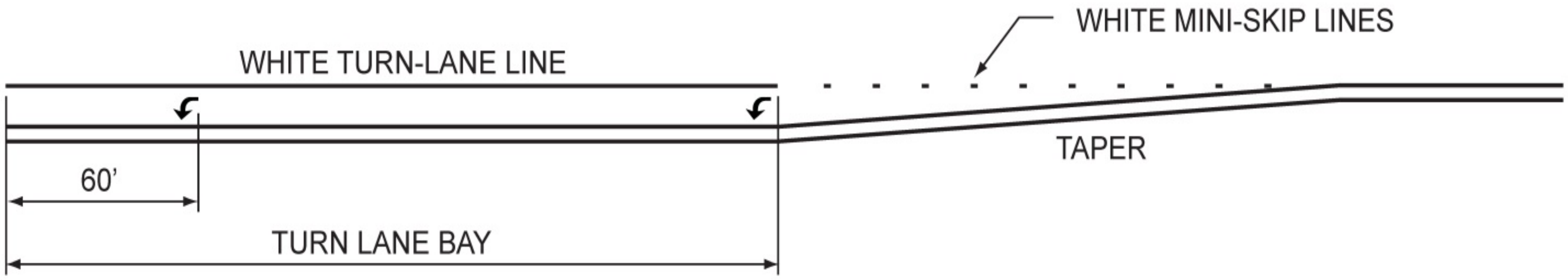
Intersection West Leg

- 2/3 A = 300 ft.
- Recommended T = 100 ft.
- T = 75 ft. used



Source: *North Carolina Roadway Design Manual*, North Carolina Department of Transportation, 2002.

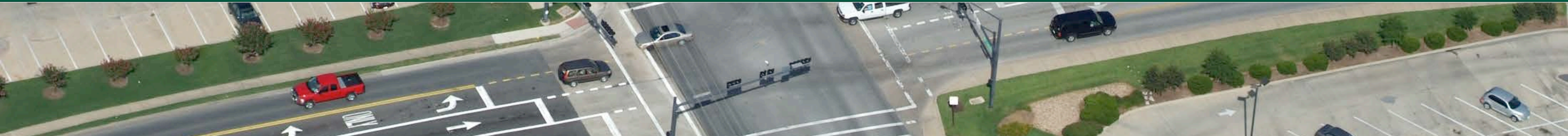
Intersection West Leg



Source: *North Carolina Roadway Standard Drawings*, North Carolina Department of Transportation, 2006.

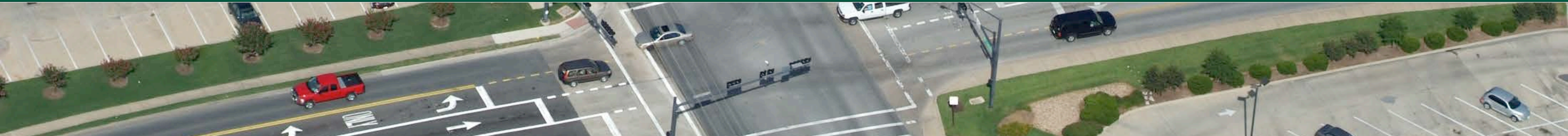
Recommended Revisions to AASHTO *Green Book*

Kay Fitzpatrick



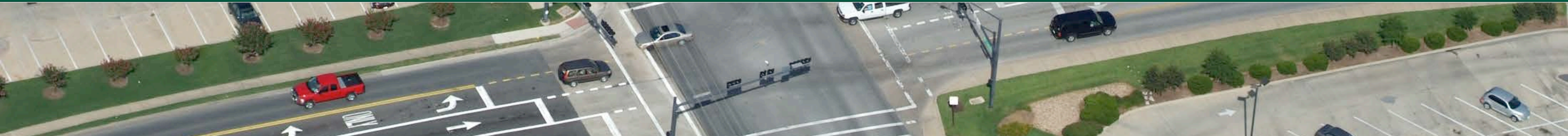
“Disclaimer”

- This presentation represents the authors opinions
- Material is documented in Appendix A of NCHRP 780
- We have provided this material to and have talked with members of the AASHTO Technical Committee on Geometric Design; however, what they will (or will not) include is not currently known



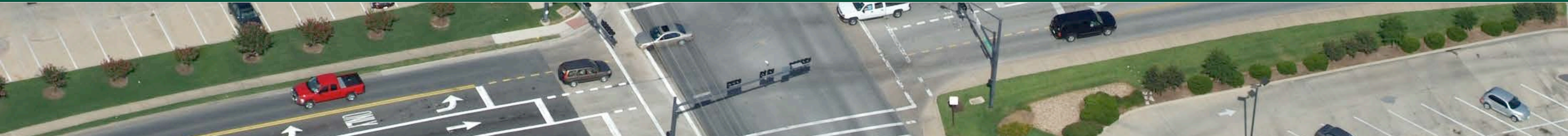
9.3.1 Three-Leg Intersections

- Add discussion about bypass lanes, including a cross-reference to warrants suggested for Section 9.7.3, based on research in NCHRP Report 745
- Recommended revisions to some existing diagrams to improve legibility, provide additional detail, and add conflict diagrams



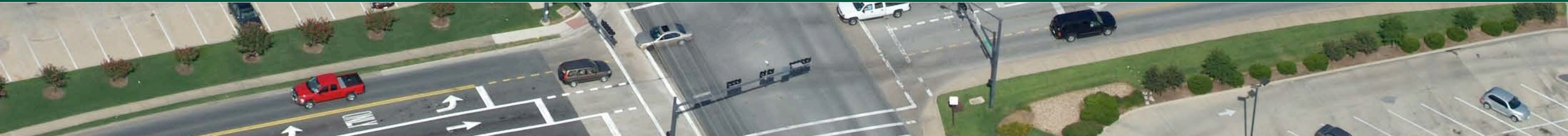
9.3.2 Four-Leg Intersections

- Provide new material to connect to other sections
- New material regarding skew:
  - …where right-of-way is not restricted, all intersecting roadways should meet at a 90-degree angle.
  - …where right-of-way is restricted, intersection roadways should meet at an angle of not less than 75 degrees.
- Several publications support the 75 degree limit



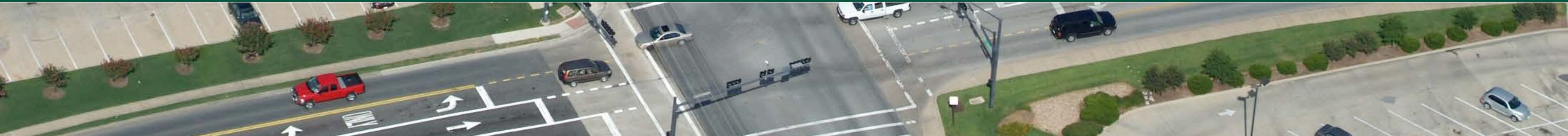
9.6.1 Types of Turning Roadways

- Added material on Channelized Right-Turn Lanes based on NCHRP 3-89 research
  - Crosswalk location
  - Island type
  - Radius of turning roadway
  - Deceleration lanes
  - Acceleration lanes
  - Others



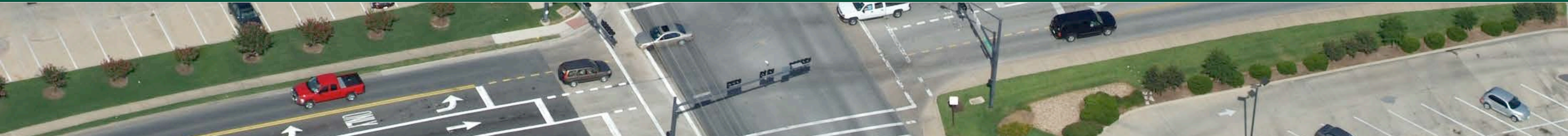
9.6.1 Types of Turning Roadways

- Curb radii should accommodate the expected amount and type of traffic and allow for safe turning speeds at intersections.
- 15 ft = typically used…residential street
- 25 ft = typically used…arterial streets
- Refuge islands are provided when crossing distance exceeds 60 ft



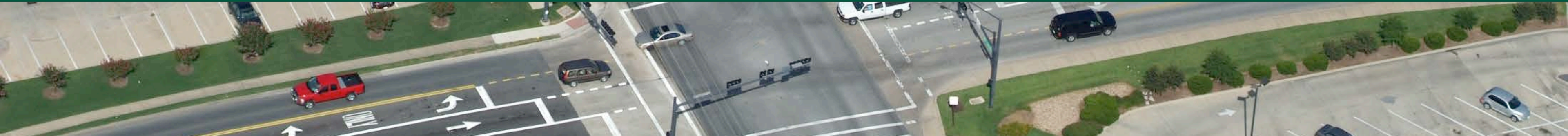
9.6.2 Channelization

- Added clarity to a bullet
  - Motorists should not be confronted with more than one decision at a time; as such, sufficient median storage should be provided to permit through and left-turning traffic to make a two-stage maneuver.



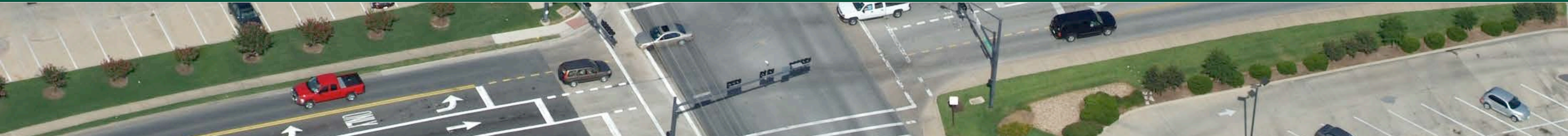
9.6.2 Channelization

- Remove the use of the term “refuge” when describing a vehicle storage area so to not confuse that space with space for pedestrians or bicycles
  - ~~Refuge areas for turning vehicles should be provided separate from through traffic.~~
  - For locations with sufficient turning volumes and/or safety concerns, separate storage lanes should be used to permit turning traffic to wait clear of through-traffic lanes.



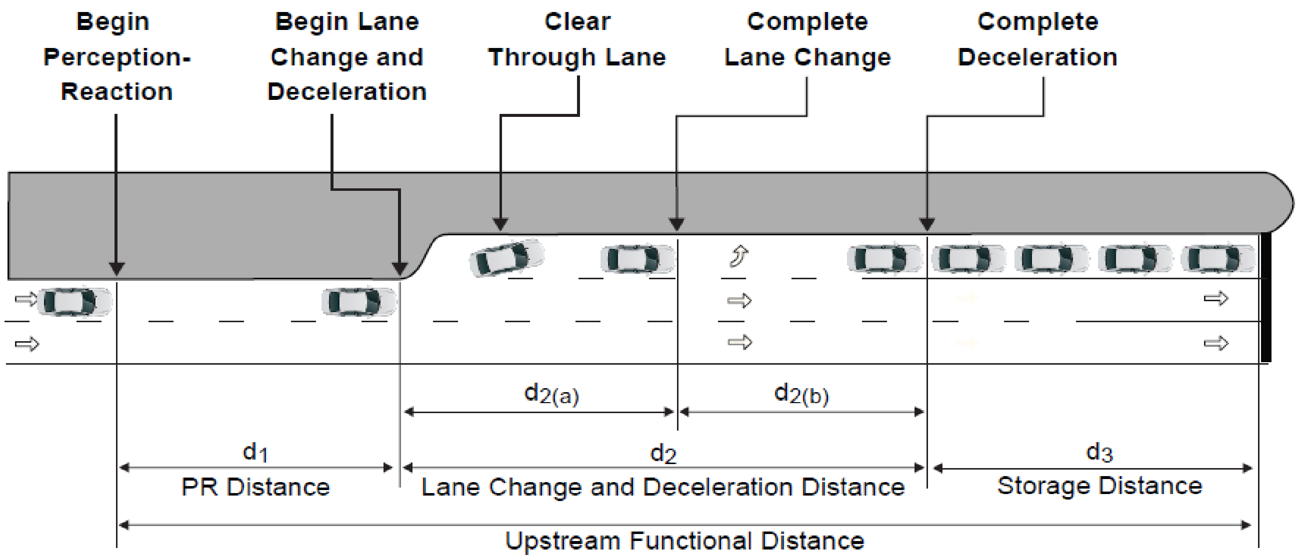
9.7.1 General Design Considerations

- Provided additional guidance / clarity about acceleration lanes
  - Acceleration lanes are advantageous on roads without stop control, particularly those with higher operating speeds and/or higher volumes. Acceleration lanes are not desirable at all-way stop-controlled intersections where entering drivers can wait for an opportunity to merge without disrupting through traffic.



9.7.2 Deceleration Lanes
P-R Dist, Lane Change/Decel Dist

- Extensive changes based on recent research (including this project)



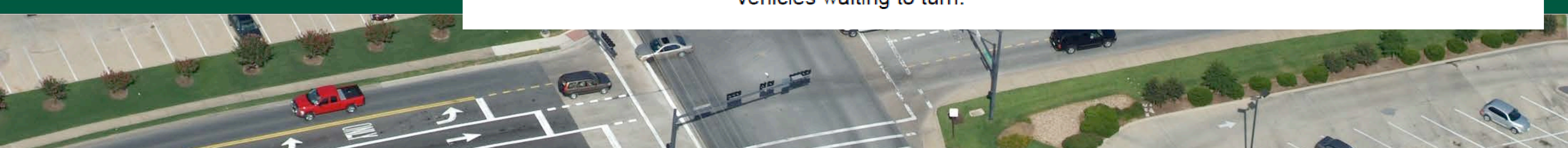
Where:

d_1 = Distance traveled while driver recognizes upcoming turn lane and prepares for the left-turn maneuver.

$d_{2(a)}$ = Distance traveled while decelerating and changing lanes from the through lane into the turn lane.

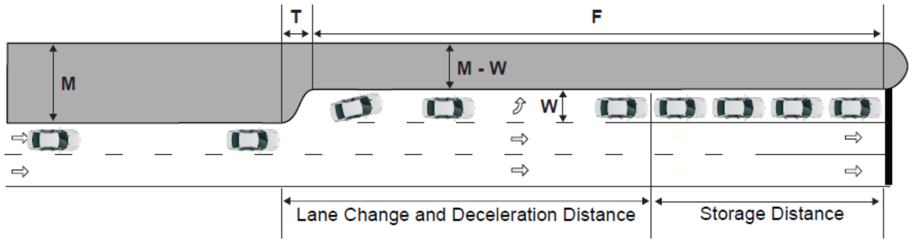
$d_{2(b)}$ = Distance traveled during deceleration after lane change.

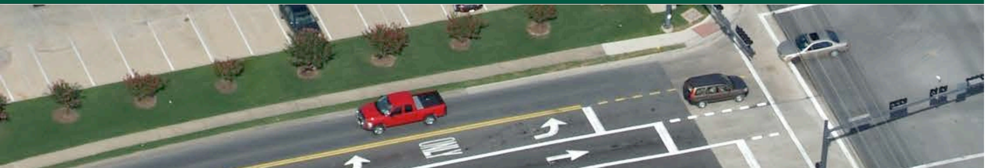
d_3 = Distance provided for the storage of the queue of stopped vehicles waiting to turn.



9.7.2 Deceleration Lanes Taper Length

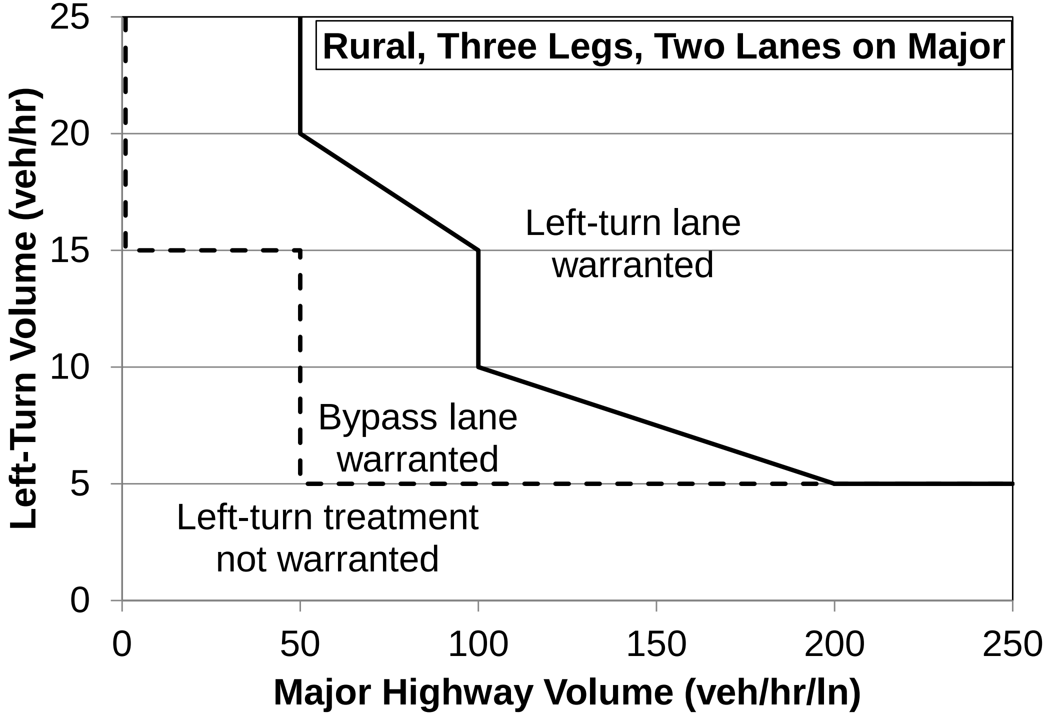
- Provide discussion on different approaches for calculating taper length
  - For example: Jurisdictions across the country are increasingly adopting the use of taper lengths ~~such as short~~ as ~~30~~ 15 m [~~100~~ 50 ft] for a single-turn lane and ~~45~~ 30 m [~~150~~ 100 ft] for a dual-turn lane for urban streets.

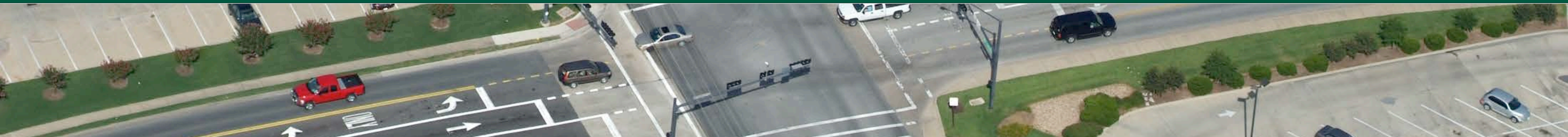




9.7.3 Design Treatments for Left-Turn Maneuvers

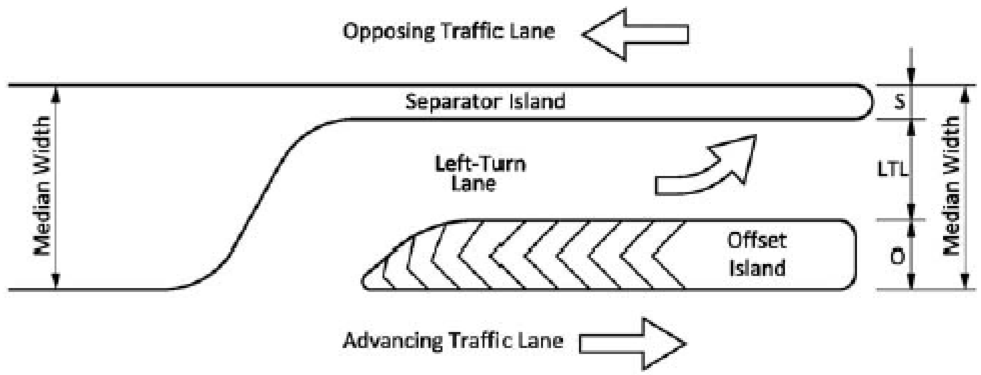
- New material for warrants for left-turn lanes and bypass lanes (based on research documented in NCHRP Report 745)



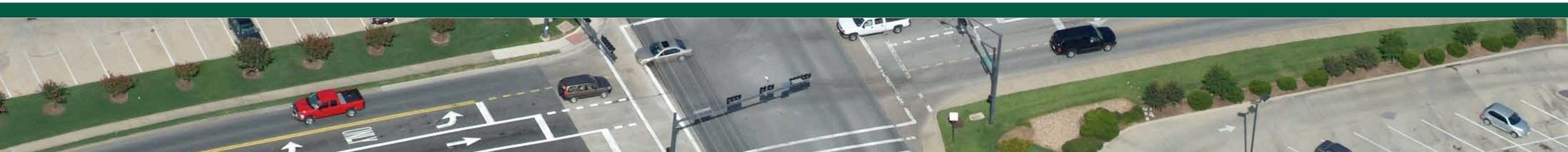


9.7.3 Design Treatments for Left-Turn Maneuvers, Offset Left-Turn…

- From draft Access Management Manual, 2nd edition (exhibit 17-7)

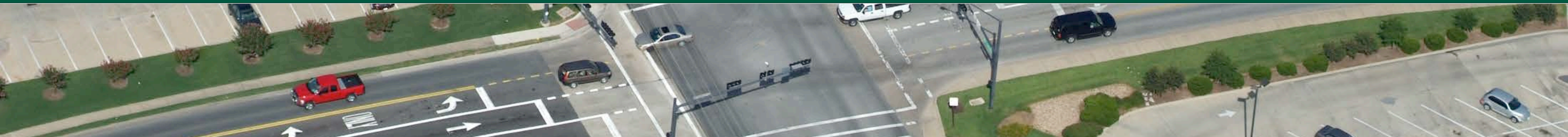


Condition	S Separator Island (feet)	LTL Left-Turn Lane (feet)	O Offset Island (feet)	Minimum Median Width (feet)
Standard Design:				
Pedestrians	≥ 6	12	≥ 3.5	≥ 21.5
No Pedestrians	≥ 4	12	≥ 3.5	≥ 19.5
Permitted by Variance:				
Pedestrians	≥ 6	12	≥ 2	≥ 20
No Pedestrians	≥ 4	12	≥ 2	≥ 18
No Pedestrians	≥ 3	11	≥ 2	≥ 16



9.7.3 Design Treatments for Left-Turn Maneuvers, Double…

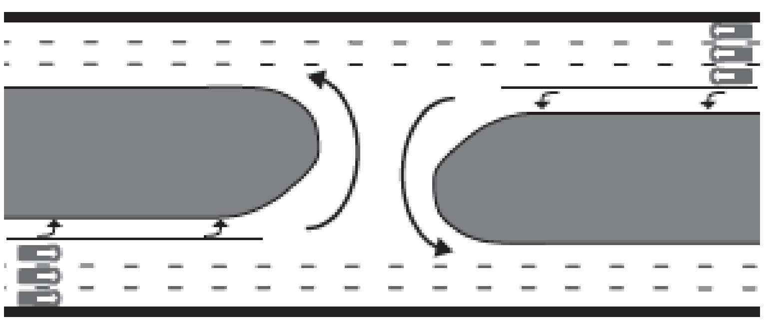
- Multiple left-turn lanes are becoming more widely used at signalized intersections where traffic volumes have increased beyond the design volume of the original single left-turn lane. The following are design considerations for double or triple left-turn lanes:
  - Width of receiving leg.
  - Width of intersection (to accommodate the two or three vehicles turning abreast).
  - Clearance between opposing left-turn movements if concurrent maneuvers are used.
  - Turning path width for design vehicle.
  - Pavement marking visibility.
  - Location of downstream conflict points.
  - Weaving movements downstream of turn.
  - Potential for pedestrian conflict.



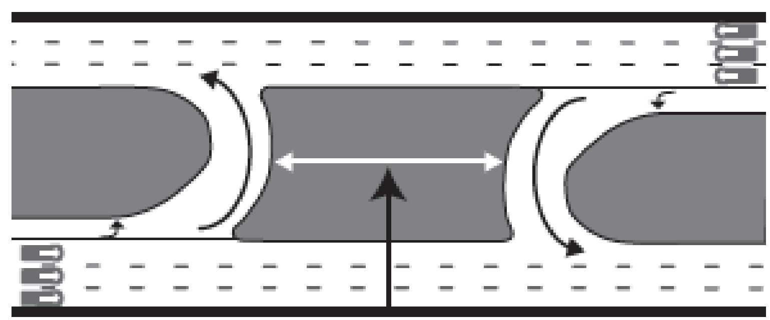
9.8 Median Openings

- Provide discussion on differences between bidirectional and directional crossovers

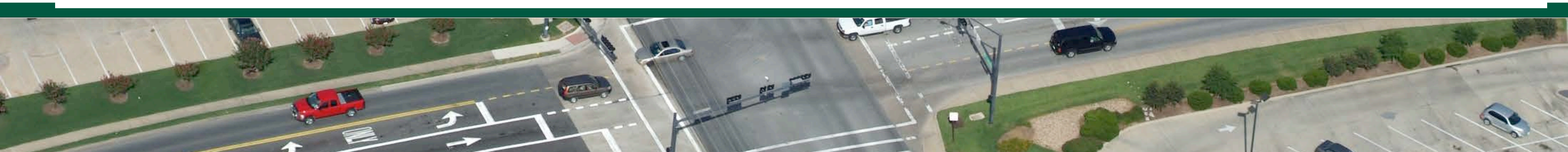
Bidirectional Crossover



Directional Crossover

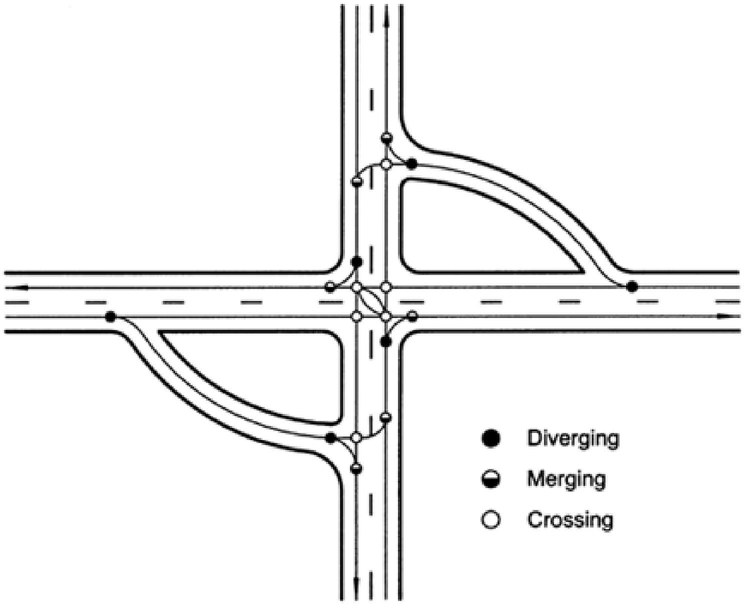


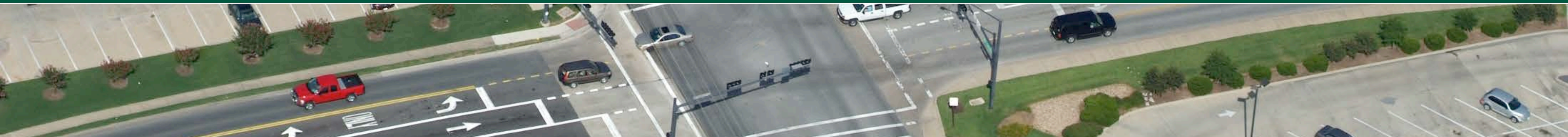
100 ft minimum
150 ft desirable



9.9.2 Intersections with Jughandle or Loop Roadways

- Example Graphic for Replacing *Green Book* Figure 9-60. Intersection with Jughandle Roadways for Indirect Left Turns
- From FHWA Signalized Intersections: Informational Guide

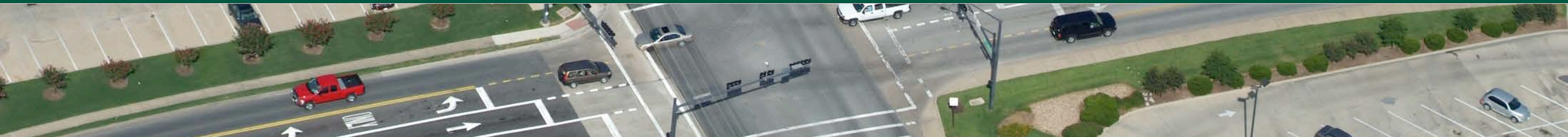




9.9.3 Displaced Left-Turn Intersections

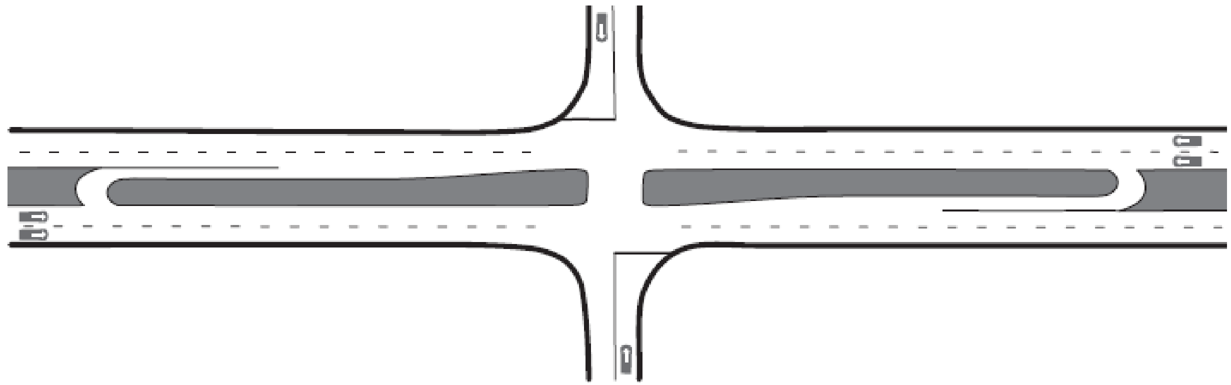
Example Material for New *Green Book* Table 9-X5. Number of Conflict Points at a Four-Leg Signalized Intersection Compared to a Continuous-Flow Intersection with Displaced Left Turns on the Major Street Only.

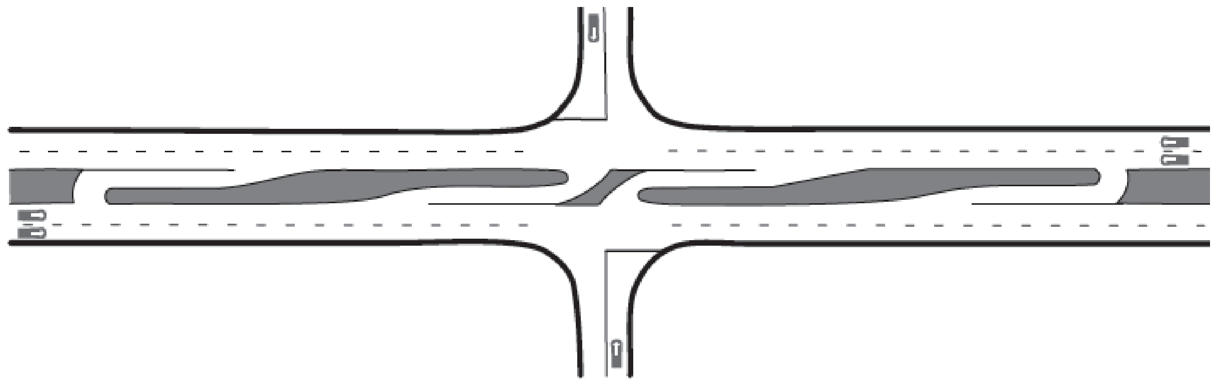
Conflict type	Four-Leg Signalized Intersection	Continuous-Flow Intersection
Merging/ diverging	16	14
Crossing (left turn)	12	6
Crossing (angle)	4	10
Total	32	30

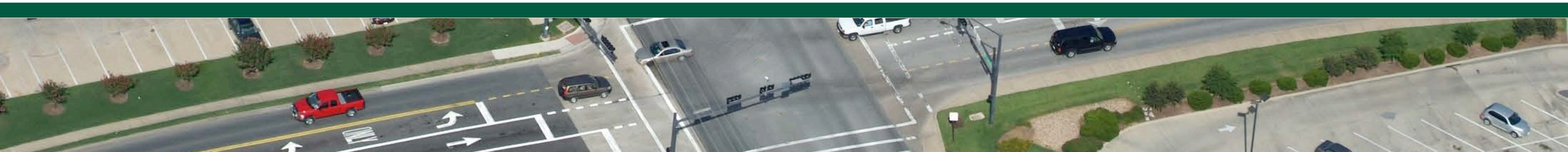


9.9.4 Wide Medians with U-Turn Crossover Roadways

- U-turn…for indirect left turns…with wide median
- ....restricted crossing U-turn intersections







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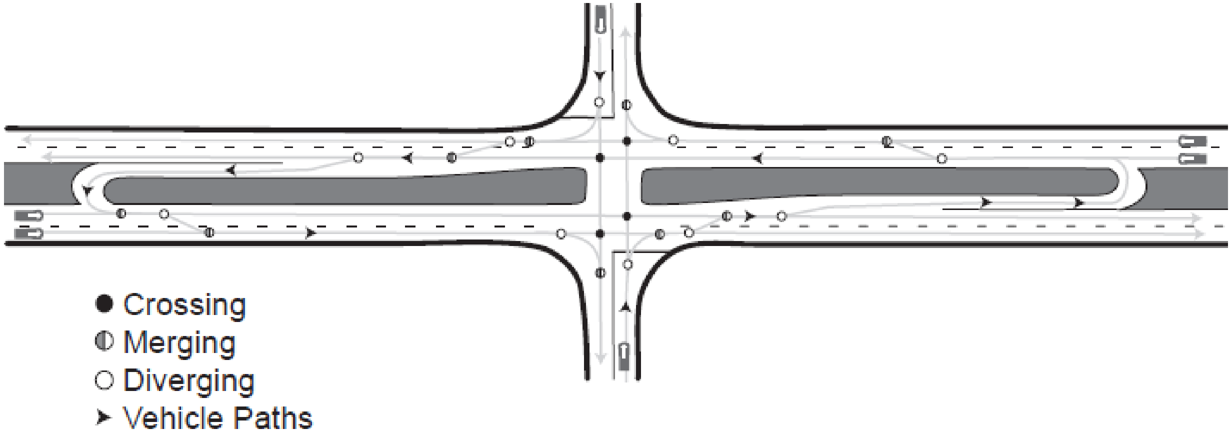
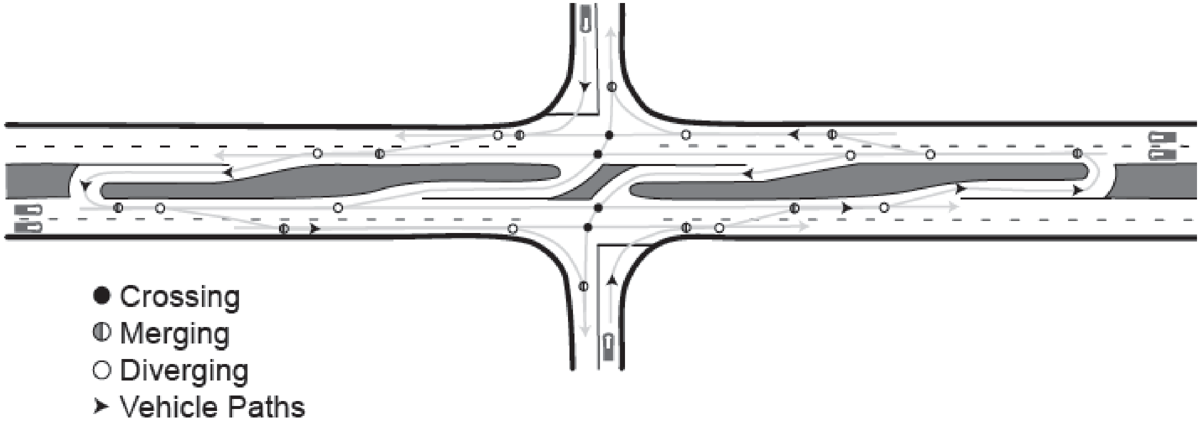
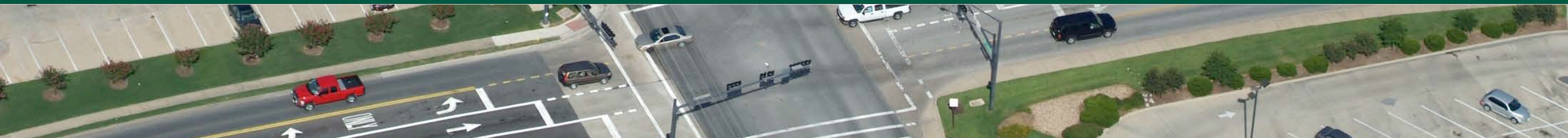
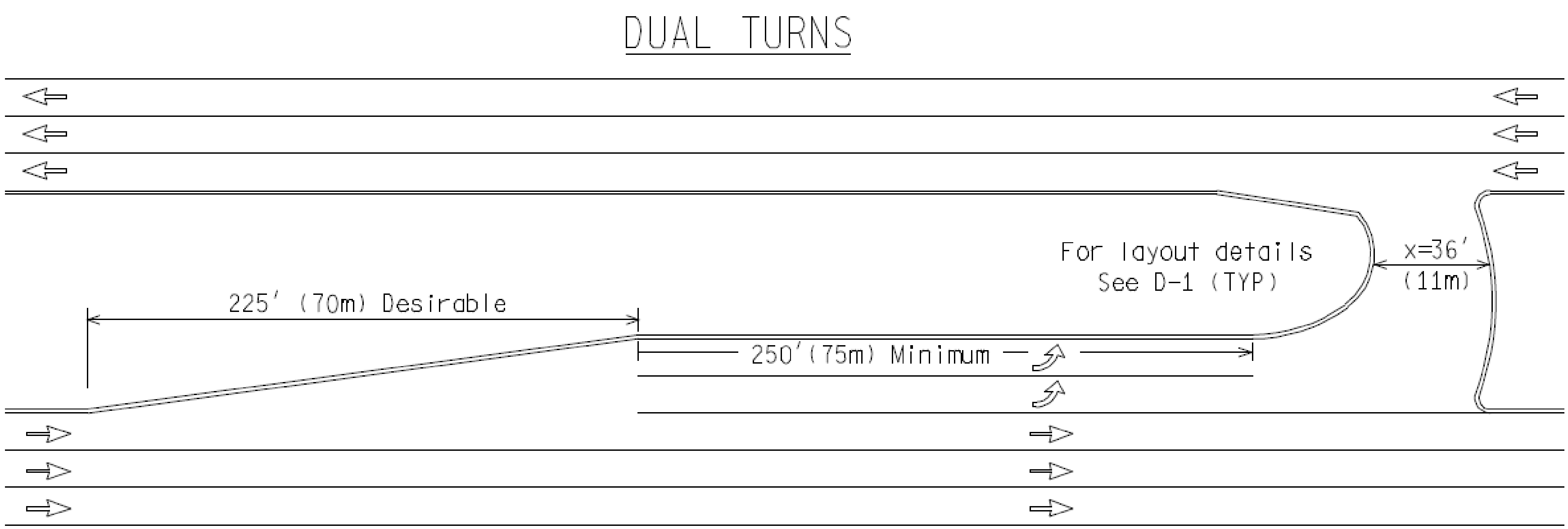






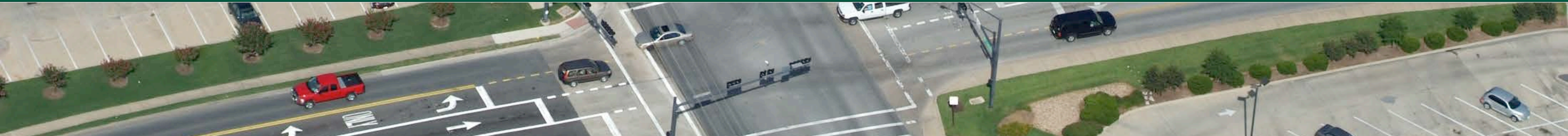
9.9.5 Location and Design of U-Turn Median Openings

- **Figure A-20. Example Graphic for New *Green Book* <u>Figure 9-XK: Dual U-Turn Directional Crossover Design (part B)</u>.**
- Michigan Department of Transportation ***Geometric Design Guide 670***



9.10 Roundabout Design

- New text about:
  - Public outreach
  - Right-turn bypass lanes (slip lanes)
  - Turbo-roundabout concept
  - Accommodating large WB-67 trucks or oversized vehicles



QUESTIONS