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 $2 \times$ single lane (GB says 180%)
- Desired guidance on adjustments to length
# Study Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving leg width</td>
<td>- Narrow, &lt; 26 ft</td>
</tr>
<tr>
<td></td>
<td>- Moderate, 26 to 30 ft</td>
</tr>
<tr>
<td></td>
<td>- Wide, &gt; 30 ft</td>
</tr>
<tr>
<td>Left-turn lane width</td>
<td>- Less than 11.5 ft</td>
</tr>
<tr>
<td></td>
<td>- 11.5 ft or more</td>
</tr>
<tr>
<td>Downstream friction point – type</td>
<td>Bus stop, driveway, right-turn lane,</td>
</tr>
<tr>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Downstream friction point – distance</td>
<td>- Near, &lt; 150 ft</td>
</tr>
<tr>
<td></td>
<td>- Medium, 150 to 350 ft</td>
</tr>
<tr>
<td></td>
<td>- Long, &gt; 350 ft</td>
</tr>
</tbody>
</table>
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
### Results - Not Significant Variable

#### Lane (inside or outside)

<table>
<thead>
<tr>
<th>Lane</th>
<th>Unit</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane 1 (inside lane)</td>
<td>SFR Average</td>
<td>1,774 pcphgpl</td>
</tr>
<tr>
<td></td>
<td>Count</td>
<td>4,992 passenger cars</td>
</tr>
<tr>
<td>Lane 2 (outside lane)</td>
<td>SFR Average</td>
<td>1,776 pcphgpl</td>
</tr>
<tr>
<td></td>
<td>Count</td>
<td>5,031 passenger cars</td>
</tr>
<tr>
<td>Both lanes</td>
<td>SFR Average</td>
<td>1,775 pcphgpl</td>
</tr>
<tr>
<td></td>
<td>Count</td>
<td>10,023 passenger cars</td>
</tr>
</tbody>
</table>
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

Average 1725 pcphgpl

Average 1833 pcphgpl
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

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.
## Current AASHTO Policy

### 2011 Green Book, Chapter 9

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>160</td>
</tr>
<tr>
<td>40</td>
<td>275</td>
</tr>
<tr>
<td>50</td>
<td>425</td>
</tr>
<tr>
<td>60</td>
<td>605</td>
</tr>
<tr>
<td>70</td>
<td>820</td>
</tr>
</tbody>
</table>

**Table 9-22**

**Figure 9-48**

Functional Area of Intersection

Full Deceleration Length

$L_1$, $L_2$, $L_3$, $L_4$
Literature
Deceleration Rates

  - 11.2 ft/s\(^2\) for SSD, 24.5 ft/s\(^2\) for maximum/emergency

  - 11.2 ft/s\(^2\) maximum, up to 10 ft/s\(^2\) “reasonably comfortable”

  - 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

<table>
<thead>
<tr>
<th>PSL (mph)</th>
<th>Taper Length (ft)</th>
<th>Below Taper Threshold</th>
<th>Above Taper Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-35</td>
<td>96</td>
<td>2 sites</td>
<td>2 sites</td>
</tr>
<tr>
<td>40-45</td>
<td>96</td>
<td>2 sites</td>
<td>2 sites</td>
</tr>
<tr>
<td>50-55</td>
<td>180</td>
<td>--</td>
<td>2 sites</td>
</tr>
<tr>
<td>60-65</td>
<td>180</td>
<td>1 site</td>
<td>1 site</td>
</tr>
</tbody>
</table>

- 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/s² average deceleration moving from the through lane into the left-turn lane (Note 4)
  - 6.5 ft/s² 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

<table>
<thead>
<tr>
<th>Upstream Speed (mph)</th>
<th># Vehicles with a Speed Differential (mph) of</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-10</td>
<td>10-20</td>
</tr>
<tr>
<td>20-29</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>30-39</td>
<td>47</td>
<td>21</td>
</tr>
<tr>
<td>40-49</td>
<td>93</td>
<td>54</td>
</tr>
<tr>
<td>50-59</td>
<td>38</td>
<td>72</td>
</tr>
<tr>
<td>60-69</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>&gt; 70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>189</td>
<td>171</td>
</tr>
<tr>
<td>Percent</td>
<td>46%</td>
<td>42%</td>
</tr>
</tbody>
</table>
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/s² or more
- 85% of high-speed were ≥ 4.2 ft/s²
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/s² 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 $> 6.5 \text{ ft/s}^2$
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/s²
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

State Highway 391
(S. Kipling Street)

West Alameda Avenue

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

<table>
<thead>
<tr>
<th>Angle of Turn (degrees)</th>
<th>Design Classification</th>
<th>Radii (ft)</th>
<th>Offset (ft)</th>
<th>Width of Lane (ft)</th>
<th>Approximate Island Size (sq ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>A</td>
<td>150-50-150</td>
<td>3.0</td>
<td>14</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>150-50-150</td>
<td>5.0</td>
<td>18</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>180-65-180</td>
<td>6.0</td>
<td>20</td>
<td>125</td>
</tr>
</tbody>
</table>

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.


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

2 to 3 ft Offset

R = 2 to 3 ft

R = 2 to 5 ft

R = 2 to 3 ft

2 to 3 ft Offset

4 to 6 ft Offset

Curb & Gutter on approach

THREE CURB ED ISLAND ON URBAN STREETS

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

Intersection West Leg

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)

![Deceleration Lanes Diagram](image)

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)
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
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.

<table>
<thead>
<tr>
<th>Conflict type</th>
<th>Four-Leg Signalized Intersection</th>
<th>Continuous-Flow Intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merging/diverging</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>Crossing (left turn)</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Crossing (angle)</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>30</td>
</tr>
</tbody>
</table>
9.9.4 Wide Medians with U-Turn Crossover Roadways

- U-turn…for indirect left turns…with wide median
- ….restricted crossing U-turn intersections
9.9.4 Wide Medians with U-Turn Crossover Roadways

- U-turn...for indirect left turns...with wide median
- ....restricted crossing U-turn intersections
9.9.5 Location and Design of U-Turn Median Openings

- Figure A-20. Example Graphic for New Green Book Figure 9-XK: Dual U-Turn Directional Crossover Design (part B).
- 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