Signal Progression and Pedestrian Safety

Eric Stein, PE
Senior Engineer
Transportation Mobility Engineering
Denver Department of Transportation and Infrastructure

Goals

Safety

Reduce fatal and serious bodily injury crashes

Accessibility

Reduce pedestrian and side street delay

Sustainability

Accelerate mode shift by improving the experience of pedestrians and micromobility

Safe Waves

Developed by Peter G Furth
Northeastern University

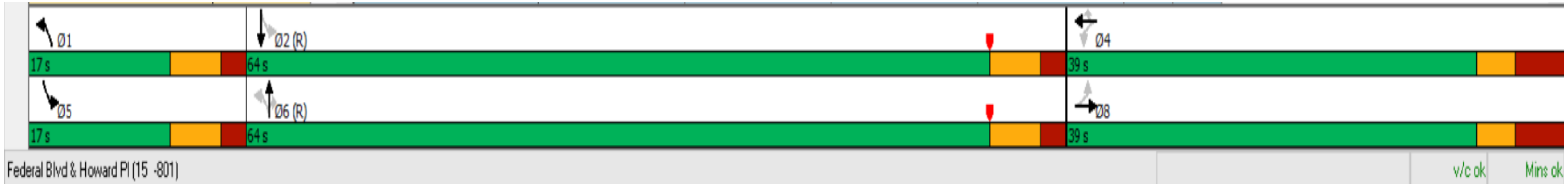
- Reduce speed by reducing Stale Green
- Stale Green: “When a vehicle arrives at an intersection with a green ball with no vehicle ahead of it for 5 seconds”

Safe Waves Principals

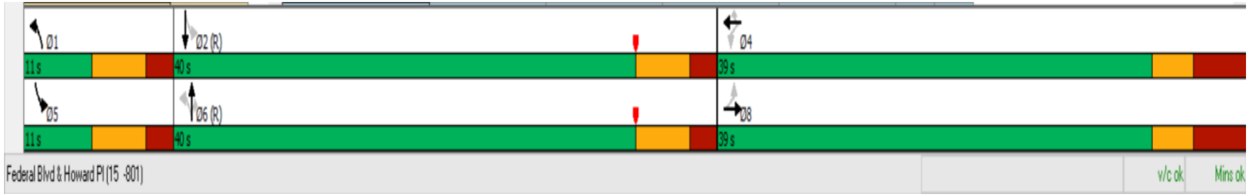
1. Short cycles
2. Target progression speed
3. Smaller coordination zones
4. Pedestrian recall
5. Fully actuated control

Shorter Cycle Lengths

120s cycle length



90s cycle length

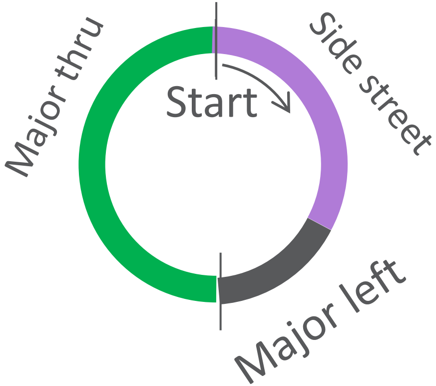


- Less main street green = fewer speeding opportunities
- Decreased pedestrian delay
- Improved service of side street

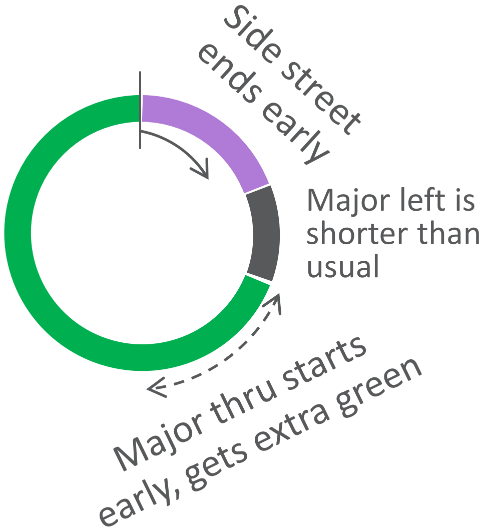
Note: decreasing a cycle length from 120s to 90s results in 33% more crossing opportunities (30 per hour to 40 per hour)

Pedestrian Recall

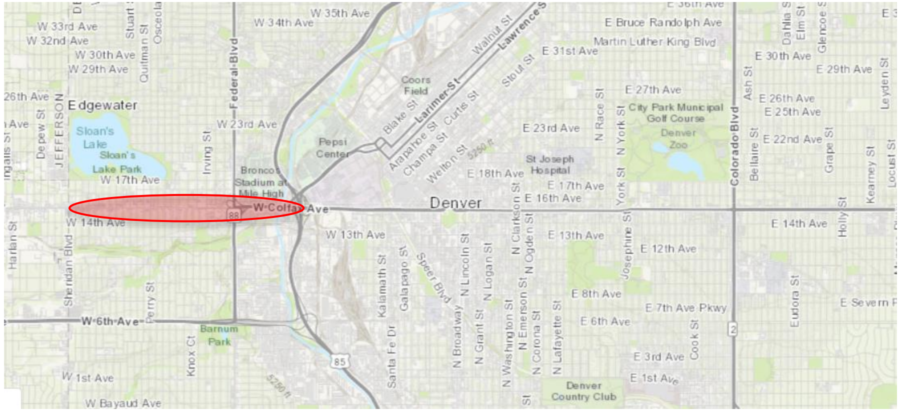
A coordinated cycle with ped recall



How if works when side street ped service is skipped



West Colfax



1. Reduced off-peak Cycle Length from 120s to 60s
2. 71% reduction in fatalities, 39% reduction in SBI's

Denver's Additions

1. Leading Pedestrian Intervals (LPI's)
2. Protected left turns
3. Late night timing

Q&A

Eric Stein, P.E.
eric.stein@denvergov.org
(720) 865-3270

Risk Factors for Fixed-Object Crashes and Potential Countermeasures

GDOT / ARC Regional Safety Task Force

September 30, 2025

Mark Doctor, PE, PTOE

Senior Engineer

Gresham Smith

What is a Fixed-Object Crash?

Utility Pole

Guardrail/Barrier Wall

House/Building

Bridge Pier/Abutment Wall

Tree

Fence

Mailbox

Fire Hydrant

?

Other

Sign/Signal/Luminaire

What is a Roadway Departure Crash?

A crash which occurs after a vehicle crosses an edge line, center line, or otherwise leaves the travelled way.

- FHWA

Factors Contributing to a Roadway Departure Crash

- **Driver Error**
  - Sleepy / Distracted
- **Collision Avoidance**
- **Vehicle Failure**
  - Tires
- **Road Condition**
  - Wet / Icy
  - Diminished Pavement Friction

https://cdn.atlantaregional.org/wp-content/uploads/arc-regional-safety-strategy-9-may-23.pdf

THE NUMBERS

Deaths (per year)* / Serious Injuries (per year)**

A comprehensive, data-informed approach.

Regional Emphasis Areas

INTERSECTION	ROADWAY DEPARTURE	PEDESTRIANS AND BICYCLES
346*	173*	140*
1568**	540**	251**

Focus Facility Types and Roadway Characteristics

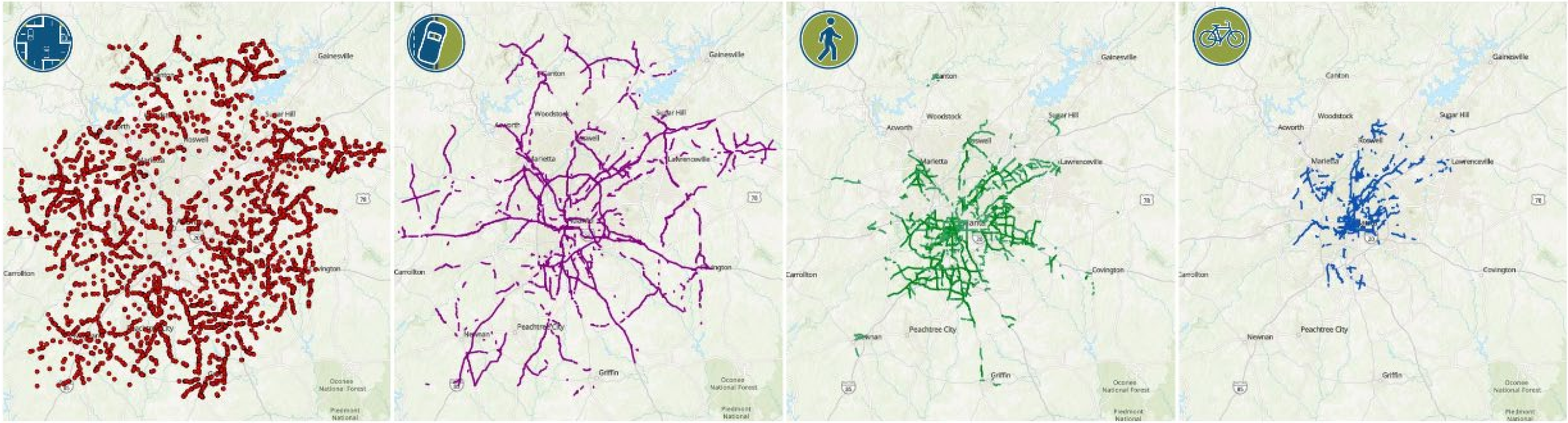


Figure 4. High-Risk Locations.

Risk factors do not represent causal relationships but help to identify locations with the greatest potential for safety improvement and the greatest need for investment.

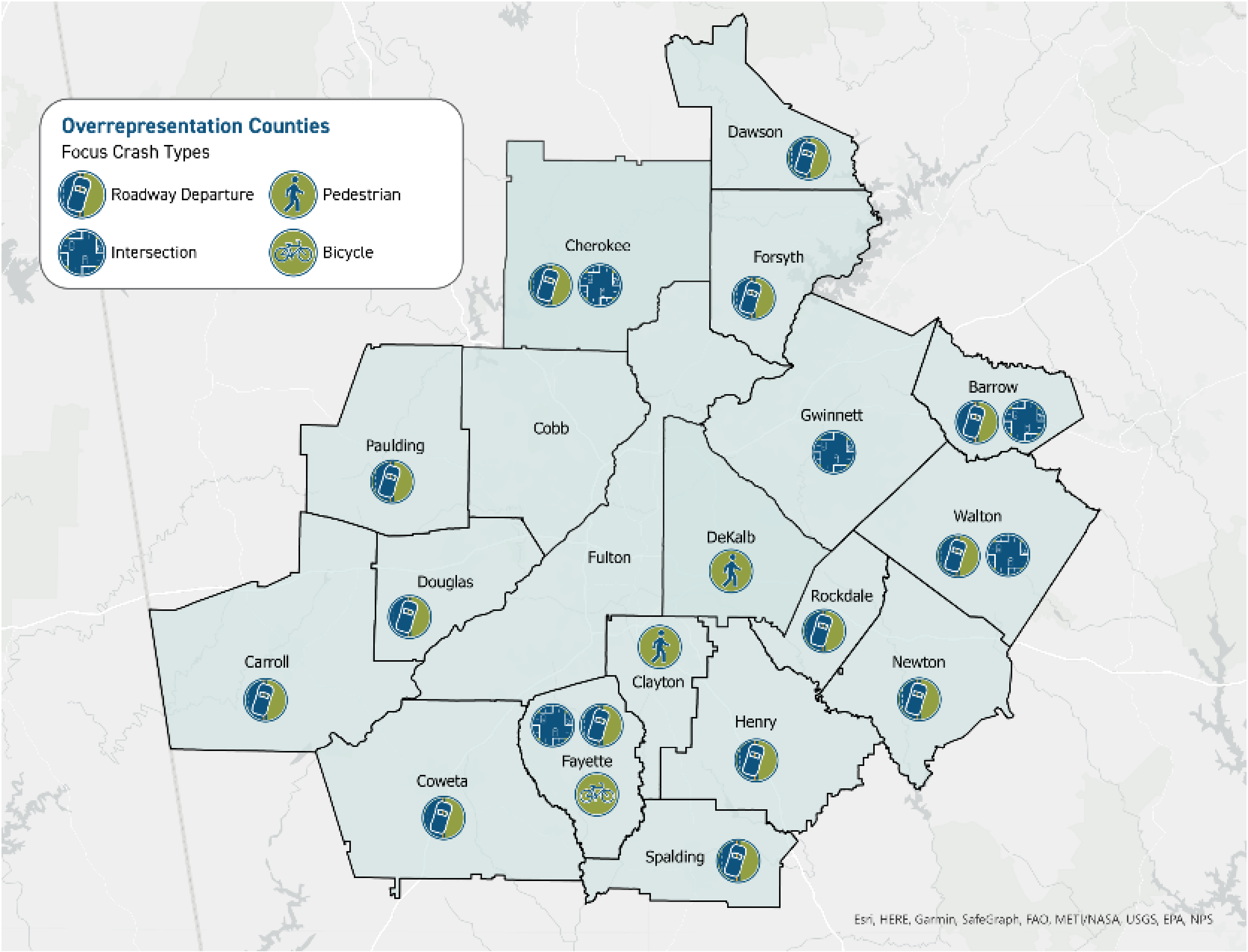


Figure 16. Counties Where Focus Crash Types are Overrepresented.

TABLE 2. ROADWAY DEPARTURE RISK FACTORS

Risk Factors	Values Associated with Increased Risk
Functional class	Urban interstates Rural minor arterials Rural major collectors
Ownership	GDOT
Traffic volume	5,000 – 15,000 vehicles per day
Posted Speed	45+ mph on arterial streets 35+ mph on collector roads
Community context	Rural areas and lower intensity development

ROADWAY DEPARTURE

The following are priority facility types to target severe roadway departure crashes:

- Urban, GDOT-owned Interstates with 6+ lanes
- Urban, GDOT-owned minor arterials with 2 lanes
- Urban, County-owned minor arterials with 2 lanes
- Urban, County-owned major collectors with 2 lanes

The analysis also indicates that non-interstate roadway departure crash risk tends to skew toward rural, two-lane roads. Based on statistical analysis, the following characteristics tend to be indicative of severe roadway departure crashes in the region:

- **More local, rural roads** – Severe roadway departure crashes tend to occur on lower functional classifications, particularly in more rural areas with lower intensity development. This may relate to narrower paved widths and lack of shoulders or a recoverable area for vehicles that depart the travel lane. In urban areas, severe roadway departure crashes tend to be overrepresented on interstates.
- **Relatively moderate traffic volumes** – Severe roadway departure crashes tend to occur on roads with relatively moderate traffic volumes (5,000 to 15,000 vehicles per day).
- **Higher speeds** – Higher operating speeds are correlated with an increased likelihood of a severe roadway departure crash (Figure 22 and Figure 23). The threshold for what constitutes higher operating speed decreases on lower functional classification roads. Higher posted speed limits (45+ mph for arterials and 35+ mph for collectors) and greater differences between posted and operating speeds are also correlated with an increased likelihood of a severe roadway departure crash.

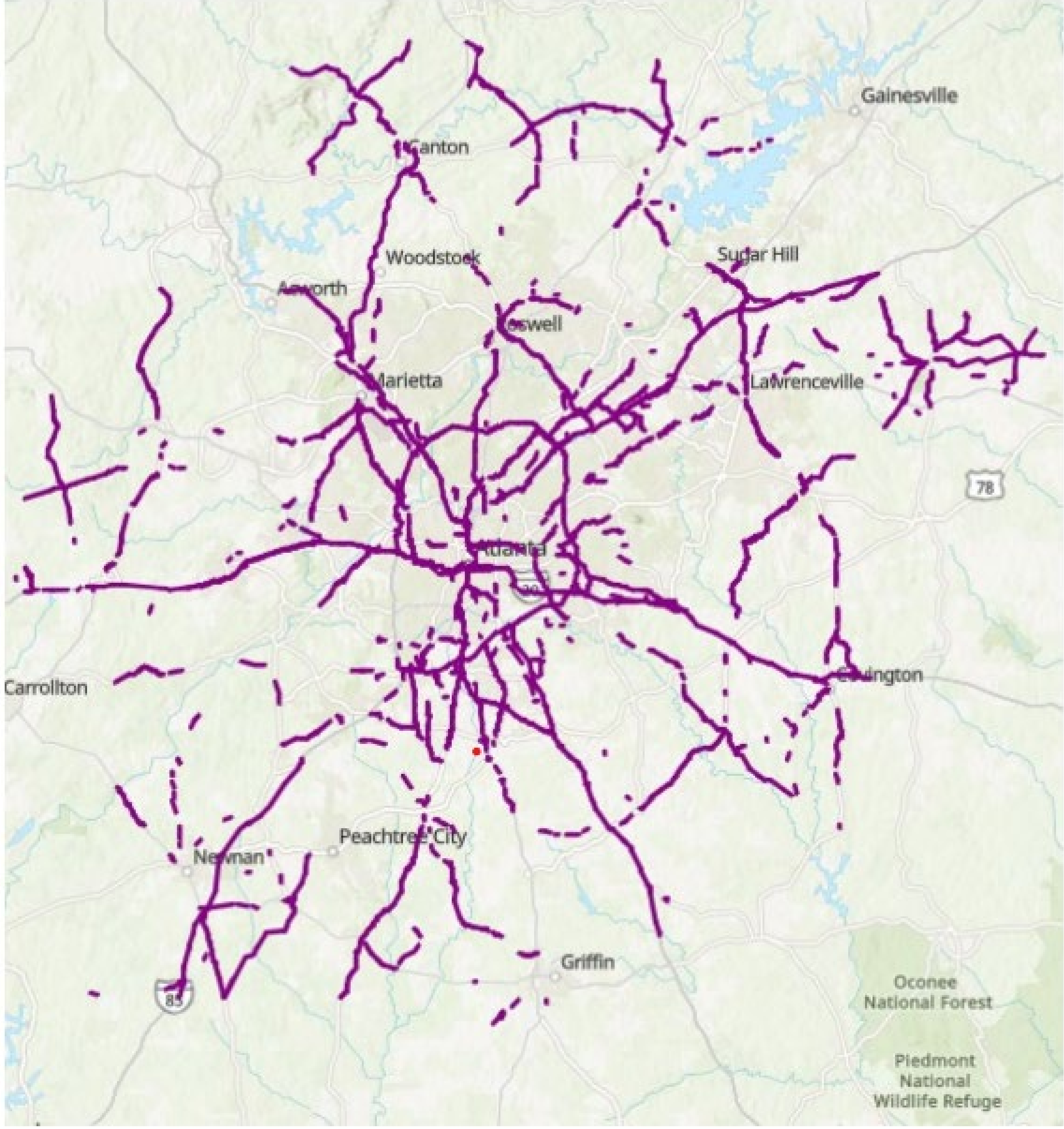


Figure 24. Locations with 6+ Roadway Departure Risk Factors.

TABLE 8. ROADWAY DEPARTURE COUNTERMEASURES

COUNTERMEASURE	NARROW ROAD	NARROW SHOULDER	UNPAVED SHOULDER	HIGH SPEEDS	MULTIPLE LANES	SHARP CURVES	STEEP SLOPES
Advance markings for curves	✓	✓	✓	✓		✓	
Advance signs	✓	✓		✓		✓	
Enhanced delineation for horizontal curves	✓			✓		✓	
Enhanced friction for horizontal curves	✓			✓		✓	
Median barriers				✓	✓		
Median buffer				✓	✓		
Raised pavement markers	✓	✓		✓	✓	✓	
Roadside design improvements				✓		✓	✓
Rumble strips/stripes	✓	✓	✓	✓		✓	✓
SafetyEdge^{SM}	✓	✓	✓	✓	✓	✓	✓
Wider pavement markings	✓	✓		✓	✓	✓	
Wider shoulder	✓	✓	✓	✓		✓	✓

Proven Safety Countermeasures

Focus Crash Type: Roadway Departure

There are a range of flexible and cost-effective countermeasures that have been proven effective in reducing roadway departure crashes in a variety of settings and contexts. They can be used individually or in combination depending on budget and setting, among other things. The Federal Highway Administration (FHWA) has identified three primary objectives to reducing roadway departures: 1) Keep vehicles in their lanes; 2) Reduce the potential for crashes; and 3) Minimize crash severity. Each of the proven countermeasures below works toward one or more of these objectives.

For details and more information, visit: https://safety.fhwa.dot.gov/provencountermeasures/

Source: FHWA

Wider Edge Lines

Wider edge lines increase define the edge of the travel lane and can provide a safety benefit to all facility types (e.g., freeways, multilane divided and undivided highways, two-lane highways) in both urban and rural areas. "Wider" edge lines are when the marking width is increased from the normal 4 inches to 6 inches. They are most effective in reducing two-lane single vehicle crashes on rural highways.

Wider edge lines can reduce crashes up to

37%

for non-intersection, fatal and injury crashes on rural, two-lane roads

Enhanced Delineation for Horizontal Curves

Enhanced delineation alerts drivers to upcoming curves, the direction and sharpness of the curve, and appropriate operating speed. Potential strategies include advance pavement markings, in-lane curve warning pavement markings, retroreflective strips on sign posts, curve delineators, chevron signs, larger fluorescent or retroreflective signs, dynamic curve warning signs or speed radar feedback signs.

Chevron signs can reduce nighttime crashes up to

25%

and have been show to reduce non-intersection fatal and injury crashes up to

16%

Longitudinal Rumble Strips and Stripes on Two-Lane Roads

Longitudinal rumble strips are milled or raised elements on the pavement intended to alert drivers through vibration and sound that their vehicle has left the travel lane. They can be installed on the shoulder, edge line, or at or near the center line of an undivided roadway.

Shoulder Rumble Strips can reduce run-off-road crashes up to

13-51%

for single vehicle, fatal and injury crashes on two-lane rural roads

SafetyEdge℠

The SafetyEdge℠ shapes the edge of the pavement at approximately 30 degrees from the pavement cross slope during the paving process. Over time, the edge may become exposed due to settling, erosion and tire wear. The SafetyEdge℠ is preferable to the traditional vertical edge because it gives drivers the opportunity to maintain control and return their vehicle to the travel lane.

SafetyEdge℠ can reduce run-off-road crashes up to

21%

and can reduce fatal and injury crashes up to

11%

Roadside Design Improvements at Curves

Proper roadside design can reduce the severity of a crash when a vehicle leaves the road. Wider shoulders, flattener sideslopes, and wider clear zone provide drivers with an opportunity to regain control or come to a safe stop before rolling over or encountering a fixed object. Not all roadside hazards can be removed, but countermeasures such as cable barriers, metal-beam guardrails, and concrete barriers can help reduce crash severity.

Flattening sideslopes can reduce single-vehicle crashes up to

8-12%

and increasing the distance to roadside features can reduce all crashes up to

22-44%

Median Barriers

Median barriers are longitudinal barriers (can be cable, metal, or concrete) that separate opposing traffic on a divided highway and are designed to redirect vehicles striking either side of the barrier. Median barriers significantly reduce the number of cross-median crashes, which are attributed to the relatively high speeds that are typical on divided highways. AASHTO's *Roadside Design Guide* provides recommendations for use of median barriers depending on the width of the median and average daily traffic volumes.

Median barriers can reduce cross-median crashes up to

97%

on rural four-lane freeways

Roadway Departure Countermeasure Hierarchy

1st - Keep vehicles on the road

- Curve Signing
- Pavement Markings
- Friction Treatments
- Rumble Stips/Stripes

2nd - Reduce the crash potential

- Shoulders
- SafetyEdge$_{SM}$
- Center Line Buffer
- Clear Zone
- Traversable Slopes

3rd - Minimize the crash severity

- Breakaway Devices
- Barriers

BEFORE

SCENARIO 4 HIGHER RISK

Focus Crash Types

Risk Factors

- ✓ Higher speeds
- ✓ Horizontal curvature
- ✓ Dark conditions
- ✓ Lack of separation between travel lanes

SCENARIO 4 LOWER RISK

AFTER

Focus Crash Types

Countermeasures

- ✓ Wider edge lines
- ✓ Enhanced delineation for horizontal curves (chevron signs)
- ✓ Longitudinal rumble strips and stripes
- ✓ Lighting
- ✓ Wider clear zone
- ✓ Walkways

SCENARIO 4

Focus Crash Types

Focus Facility Types and Risk Factors

- Two lanes
- Minor arterial or major collector
- GDOT-owned
- Posted speed limit 45 mph or higher
- Traffic volumes between 5,000 and 15,000 vehicles per day
- Not in a densely populated area
- Not adjacent to medium- or high-intensity development (more rural/suburban setting)

Site-Specific Safety Issues

- High speeds
- Horizontal curve
- Limited sight distance through the curve
- Lack of separation between travel lanes
- Lack of designated pedestrian and bicycle facilities
- Narrow shoulders
- Faded pavement markings

Countermeasures

Enhanced delineation including **wider edge lines** and raised reflective pavement markers along the corridor and **chevrons within horizontal curves** improve lane keeping and alert drivers to the presence of the curve. This reduces the likelihood of roadway departure and head-on collisions.

Longitudinal rumble strips or stripes alert drivers that leave the travel lane. This reduces the chance of roadway departure crashes.

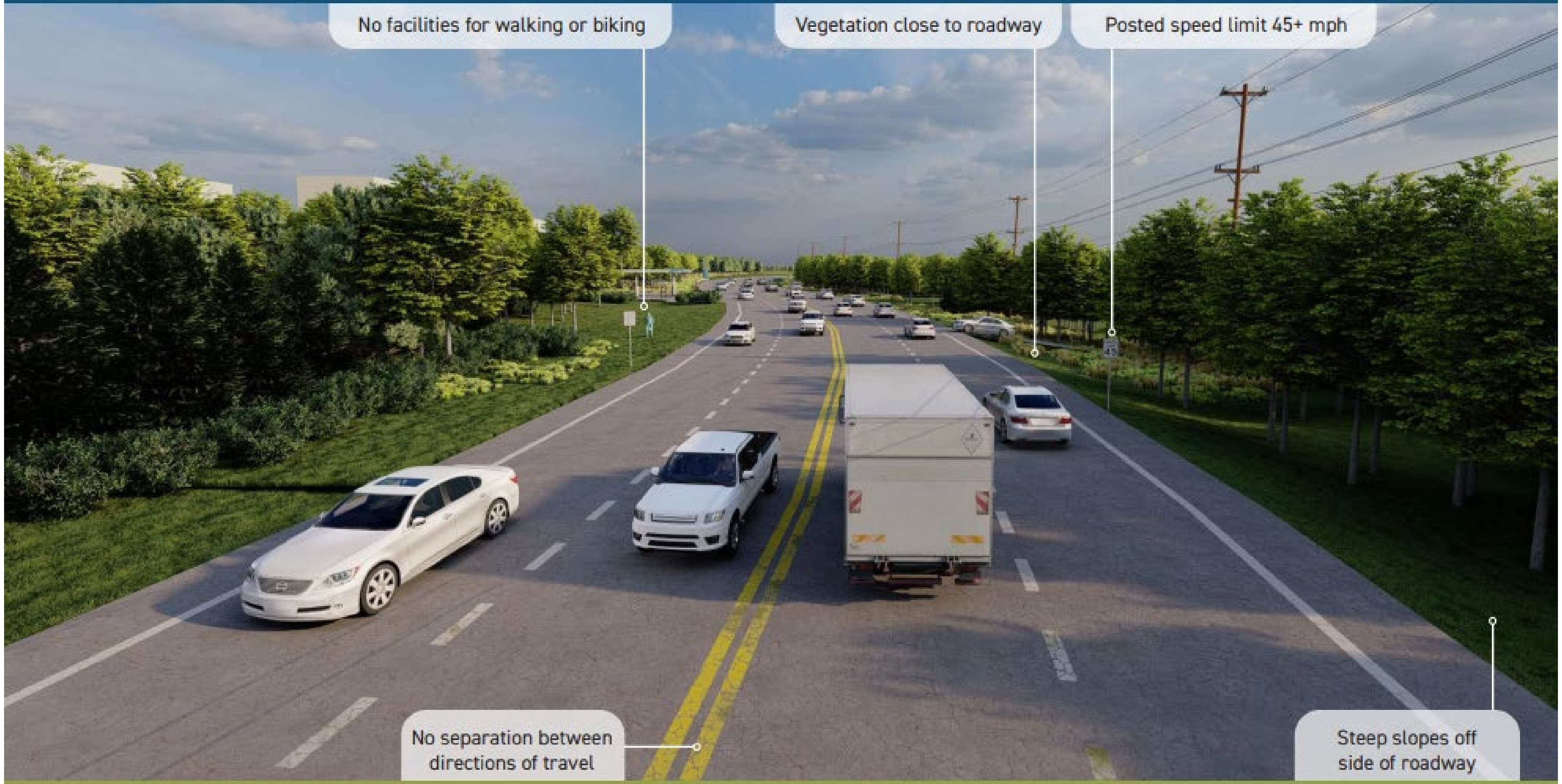
Roadside design improvements (wider clear zone) improves sight distance through the curve, reduce the potential for crashes with fixed objects, and provide drivers the opportunity to recover if they run off the road. Roadside design improvements such as wider clear zones reduce crash severity and are particularly effective at targeted locations such as horizontal curves.

Multiuse path provides a dedicated place for pedestrians and bicycle riders and separates them from vehicles. The buffer between the walkway and travel lanes increases comfort and safety for pedestrians and bicycle riders.

Lighting improves visibility for drivers and also improves visibility for pedestrians and bicycle riders along the corridor.

BEFORE

SCENARIO 5 HIGHER RISK



Focus Crash Types

Risk Factors

- ✓ Higher speeds
- ✓ Lack of separation between travel lanes
- ✓ Steep slopes off side of roadway

SCENARIO 5 LOWER RISK

AFTER

Focus Crash Types

Countermeasures

- ✓ Raised median
- ✓ Guardrail
- ✓ Dedicated biking and walking facilities
- ✓ Lighting
- ✓ Corridor access management

SCENARIO 5

Focus Crash Types

Focus Facility Types and Risk Factors

» Four or more lanes
» Minor arterial
» GDOT-owned
» Posted speed limit 45 mph or higher
» Traffic volumes between 5,000 and 15,000 vehicles per day
» Not in a densely populated area
» Not adjacent to medium- or high-intensity development (more rural/suburban setting)

Site-Specific Safety Issues

» High-speed, multilane road
» Moderate traffic volumes
» Lack of separation between opposing directions of travel
» Difficult for pedestrians to cross the road
» Lack of designated pedestrian and bicycle facilities
» Steep roadside slopes and fixed objects close to the road

Countermeasures

Raised median increases separation between opposite directions of traffic, reducing the likelihood for head-on collisions.

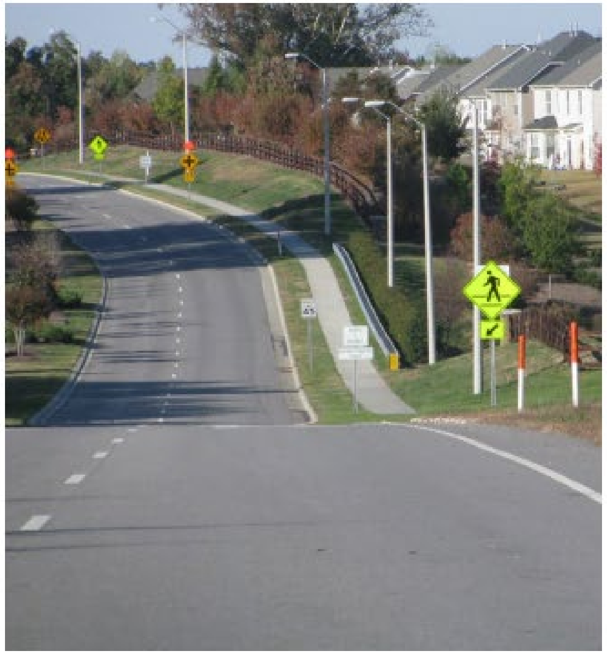
» Raised medians provide a refuge for pedestrians crossing the road.
» The use of a raised median necessitates median openings to allow for U-turns and access to adjacent businesses and side streets.
» A flush painted median is another option depending on the context and setting.
» On state routes, GDOT design guidance prevails.

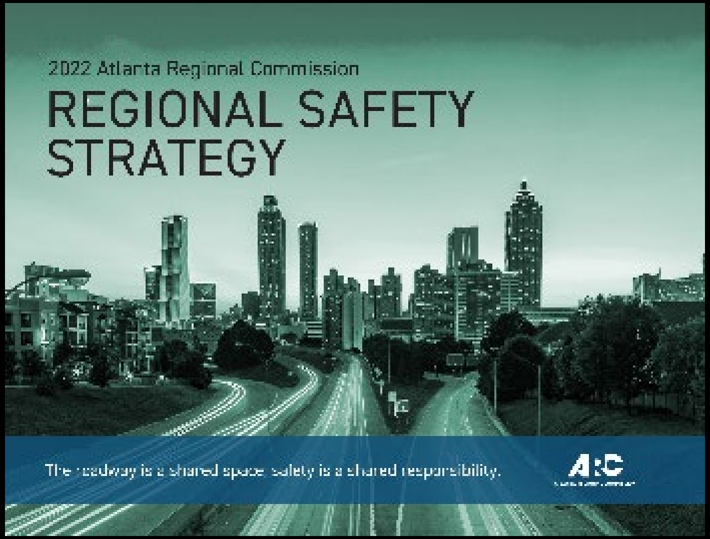
Guardrail can minimize the severity of roadway departure crashes, especially in locations where flattening slopes and removing fixed objects along the roadside is infeasible.

Multiuse path provides a dedicated place for pedestrians and bicycle riders and separates them from vehicles. The buffer between the walkway and travel lanes increases comfort and safety for pedestrians and bicycle riders.

Lighting improves visibility for drivers and also improves visibility for pedestrians and bicycle riders along the corridor.

Corridor access management reduces the number of potential conflict points between turning vehicles, pedestrians, and bicycle riders. Corridor access management can also improve the flow of traffic and general mobility along a corridor.





Traditional approach		Safe System approach
Prevent crashes	→	Prevent death and serious injuries
Improve human behavior	→	Design for human mistakes/limitations
Control speeding	→	Reduce system kinetic energy
Individuals are responsible	→	Share responsibility
React based on crash history	→	Proactively identify and address risks

Questions?

High Friction Surface Treatment 101

Frank Julian
GDOT / ARC Regional Safety Task Force

September 30, 2025

1

Roadway Departure Crash Countermeasures

1st - Keep vehicles on the road

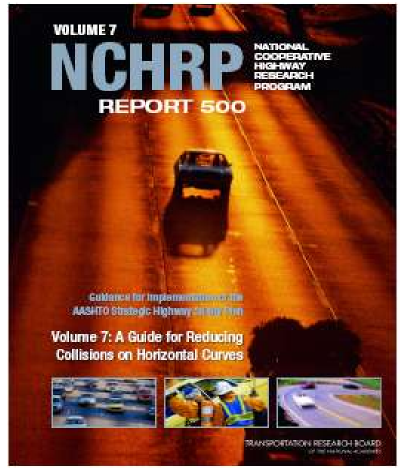
2nd - Reduce the potential for crashes

3rd - Minimize the severity

2

Provide Skid-Resistant Pavement Surfaces

15.2 A - Reduce the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve



3

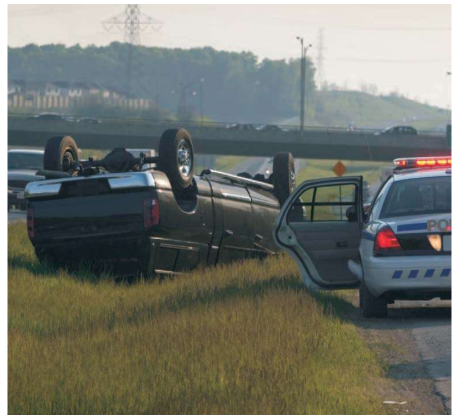
Provide Skid-Resistant Pavement Surfaces

Since the 1920's it has been recognized that Pavement-Tire friction can make a significant contribution to highway safety, particularly the probability of wet skidding crashes

4

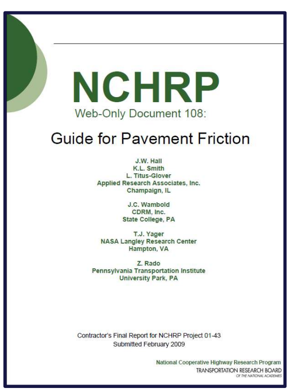
Skid Related Crashes are Determined by Many Factors:

- Tire issues
- Weather Conditions
- Aggregate Friction Characteristic
- Friction Demand



5

Pavement Friction and Crash Risk Relationship



NCHRP
Web-Only Document 108:

Guide for Pavement Friction

J.W. Hall
K.L. Smith
L. Titus-Glover
Applied Research Associates, Inc.
Champaign, IL

J.C. Wambold
CDRM, Inc.
State College, PA

T.J. Yager
NASA Langley Research Center
Hampton, VA

Z. Rado
Pennsylvania Transportation Institute
University Park, PA

Contractor's Final Report for NCHRP Project 01-43
Submitted February 2009

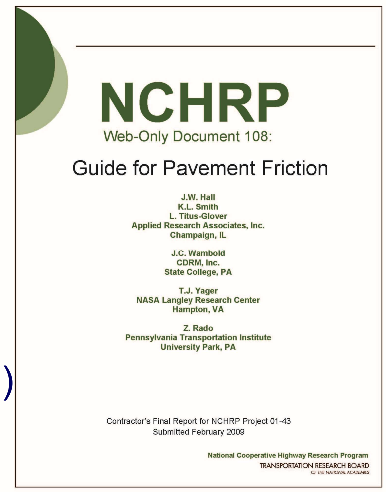
National Cooperative Highway Research Program
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Viner et al., 2004

6

Provide Skid Resistant Pavement Surfaces

- **Crash Types addressed by improving pavement friction:**
  – wet weather
  – curves
  – other skidding (e.g. too fast for conditions)


NCHRP
Web-Only Document 108:
Guide for Pavement Friction
J.W. Hall
K.L. Smith
L. Titus-Glover
Applied Research Associates, Inc.
Champaign, IL
J.C. Wambold
CDRM, Inc.
State College, PA
T.J. Yager
NASA Langley Research Center
Hampton, VA
Z. Rado
Pennsylvania Transportation Institute
University Park, PA
Contractor's Final Report for NCHRP Project 01-43
Submitted February 2009
National Cooperative Highway Research Program
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

7

Some Common Methods to Restore or Add Friction

- Chip Seal (pavement preservation)
- Micro Milling
- Shot Blasting
- Grooving (concrete)
- Resurface with a friction course
  - Nova Chip (UTBWC)
  - HFST (critical spot Improvement)

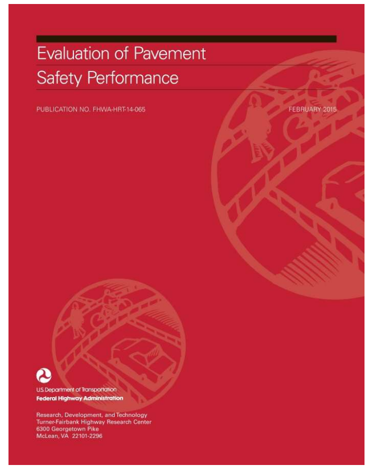
Any of these methods may be an appropriate solution depending on the definition of the problem

8

U.S.Department of Transportation
Federal Highway Administration

Evaluation of Low-Cost Safety Improvements Pooled Fund Study

Phase VI - Pavement Safety Performance



http://www.fhwa.dot.gov/publications/research/safety/14065/14065.pdf

9

What defines HFST?

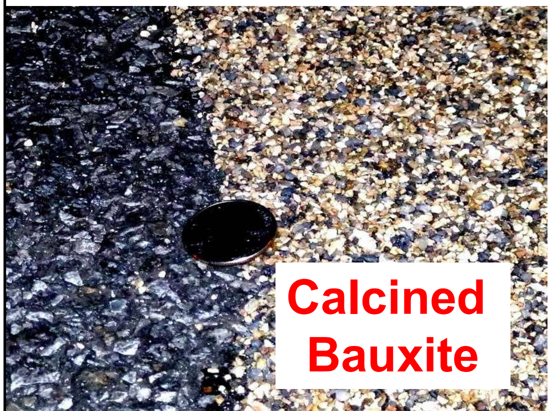
AASHTO M 354 - 24 “Standard Practice for High Friction Surface Treatment for Asphalt and Concrete Pavements” requires **Calcined Bauxite.**

In-place friction characteristics must meet a minimum requirement of 65 FN40R when tested in accordance to AASHTO T242 upon completion of the installation.

Some State requirements exceed 65

10

What defines HFST?



3 mm aggregate pavement surfacing overlay systems used for spot **Safety Treatments**

The aggregate that defines HFST is Calcined Bauxite which provides the highest resistance to polishing and friction durability.

11

12

What defines HFST?

- The 3 run average, SN40 wet value on the concrete pavement was 52
- The 3 run average, SN40 wet value on the HFST was 85
- Regardless of the speed, the stopping difference was **<u>25% - 30%.</u>**

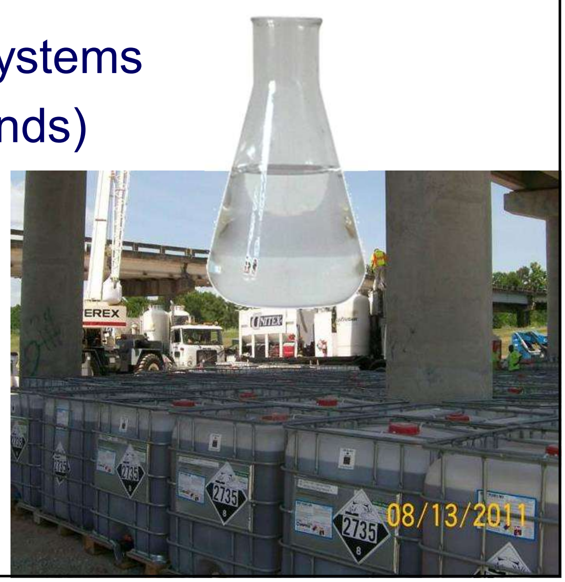
Texas Transportation Institute Friction Test Results 13

13

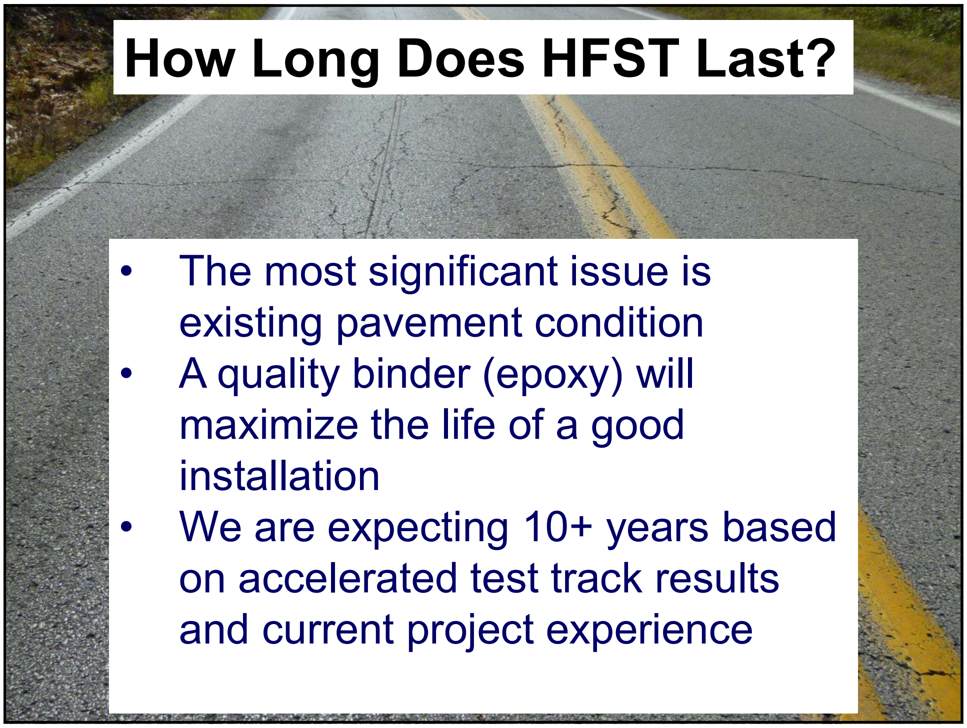
What defines HFST?

Resin Binder Systems (proprietary blends)

- Epoxy
- Polyester



14



15

Why use HFST?

- The most important reason is to improved safety!
- Milton et al. stated that the likelihood of a crash becoming fatal could be reduced by increasing pavement surface friction.
- HFST resist polishing better than other known aggregates, so the improvement last longer
- In locations with excessive friction demand, HFST is the only answer other than modify the geometrics by rebuilding the road.

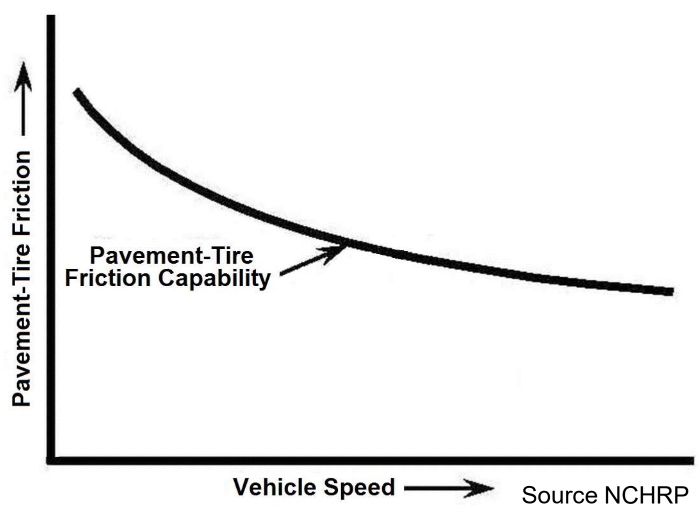
16

Agency Goals and Expectation?

- Safety
  1. High Crash
     - Usually wet weather crashes
     - High Friction demand locations
  2. Systemic Safety
     - Risk Based (preventative action)
- Operations
- Longevity (Durability)
  - Return on Investment

17

Conceptual Relationship
(Friction Demand, Speed and Friction Availability)

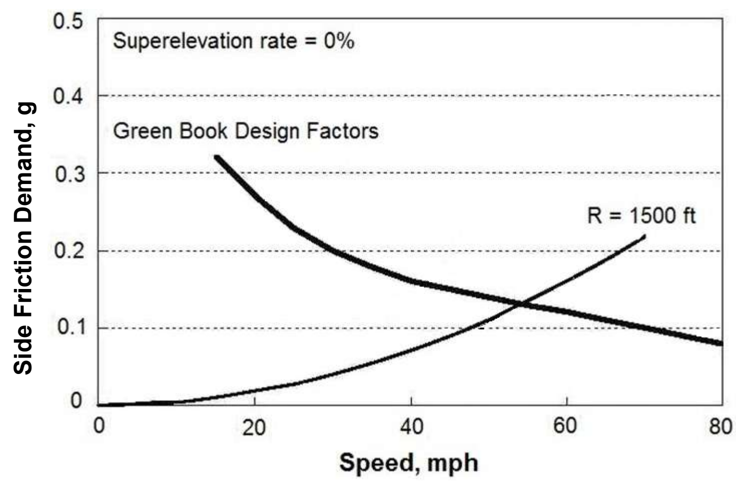


Source NCHRP 108

18

Example of Variable Friction Demand

Relationship between curve speed and side friction demand for two radii

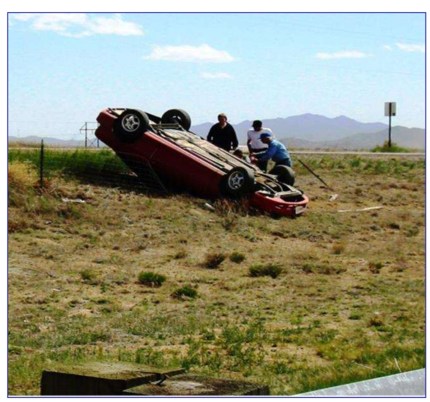


Source TRR 2075

19

Contributing Factors for Friction Demand

- Road Geometry
- Vehicle Speeds
- Driver Actions
- Trucks
  - Tires coefficient of friction is about 70% of passenger cars
  - Tires have about 10% higher friction demand



20

Basis for AASHTO Curve Design Model is **Driver Comfort**

Although the curve design policy stems from the laws of mechanics, the values used in design depend on practical limits and factors determined empirically over the range of variables involved.

21

AASHTO Horizontal Curve Design Model

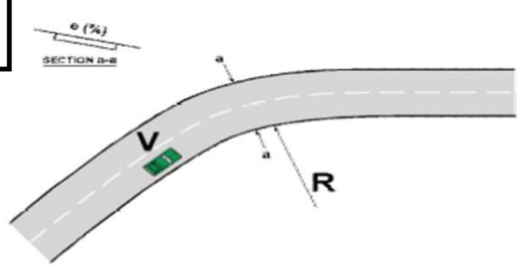
$R = V^2/15(e + f)$
$e + f = V^2/15\ R$

e = superelevation

f = side friction factor

V = design speed (mph)

R = radius of curve (ft)



US Customary	Metric
$R = \frac{V^2}{15\,(e+f)}$	$R = \frac{V^2}{127\,(e+f)}$
where R = Radius of circular curve (ft) V = Design speed (mph) e = Superelevation f = Side "friction" or comfort	where R = Radius of circular curve (m) V = Design speed (km/h) e = Superelevation f = Side "friction" or comfort

22

HC Operating Speed Model

$f = (V^2/15\,R) - e$

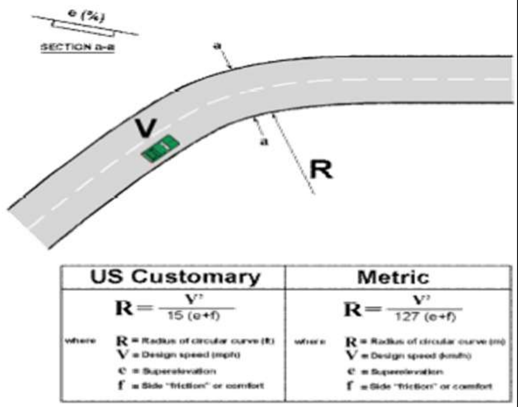
f = friction demand
V= operating speed (mph)

e = superelevation

~~f = side friction factor~~

~~V = design speed (mph)~~

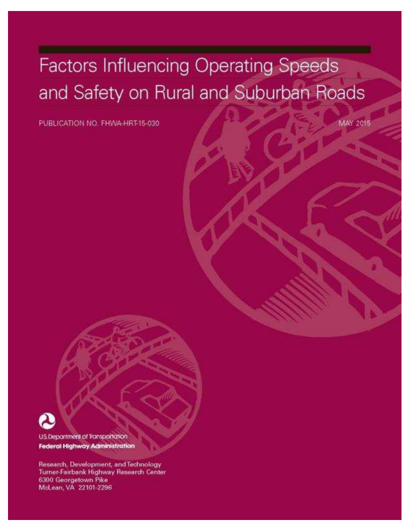
R = radius of curve (ft)



23

Operational Effect of HFST on Vehicular Performance

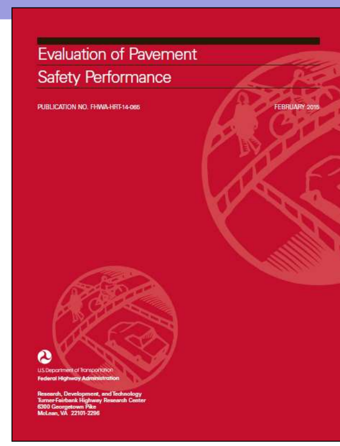
Chapter 4 examined the effect on operating speed when HFST was applied in horizontal curves and found no statistically significant change



https://www.fhwa.dot.gov/publications/research/safety/15030/15030.pdf

24

HFST Safety Effectiveness Study



Total Crashes
- Ramps CMF = 0.48
- Curves CMF = 0.63

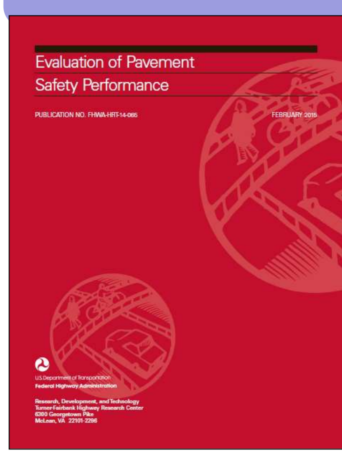
Wet Road Crashes
- Ramps CMF = 0.21
- Curves CMF = 0.37

Details: 8 State Naïve Study
(includes a 25% penalty per HSM)

http://www.fhwa.dot.gov/publications/research/safety/14065/14065.pdf

25

HFST Safety Effectiveness Study



Total Crashes
- Ramps CMF = 0.65
- Curves CMF = 0.76

Wet Road Crashes
- Ramps CMF = 0.14
- Curves CMF = 0.48

Details: Study with comparison sites
(includes a 25% penalty per HSM)

http://www.fhwa.dot.gov/publications/research/safety/14065/14065.pdf

26

HFST CMF from Georgia

CMF	CRF(%)	Quality	Crash Type	Crash Severity
0.672	32.8	★★★☆☆	All	All
0.542	45.8	★★★☆☆	Single vehicle	All
0.607	39.3	★★★☆☆	Other	All
0.445	55.5	★★★☆☆	Other	All

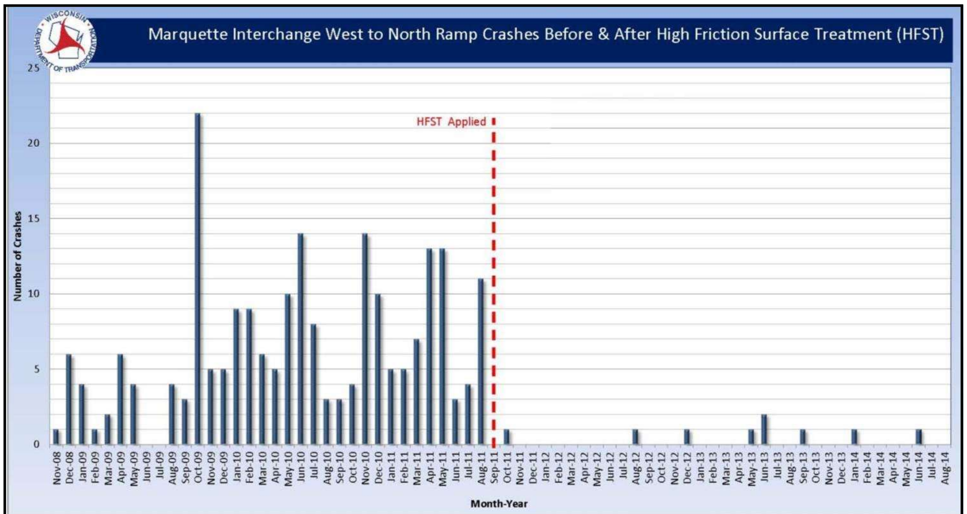
Published HSM Jan. 2023
Georgia Tech

27

HFST Case Study

Systems interchange Junction of I-94, I-43, & I-794
Reconstruction completed in August 2008
Featured Context Sensitive Solutions for the surrounding community

28



TOTALS

Before HFST (11/08 – 8/11) 2 years, 10 months – 219 crashes
HFST Applied – 9/21/2011
After HFST (10/11 – 8/14) 2 years, 11 months – 9 crashes

29

Kentucky HFST Program

Avg. Annual (70 locations)	Before	After
Wet Avg.	212	21
Dry Avg.	65	15
Total Avg.	277	36

(As of 6/22/2015)

30

Kentucky HFST Program

Avg. Annual (70 locations)	Reduction %
Wet Avg.	90%
Dry Avg.	77%
Total Avg.	87%

(As of 6/22/2015) Slide Courtesy of Kentucky Transportation Cabinet

31

PennDOT News Release

"Like a Miracle"

A study of 47 locations with 3 to 5 years of post installation crash history showed:

- 91% reduction in wet weather crashes
- 76% reduction in RwD crashes
- 63% reduction of injury crashes
- 100% reduction in fatalities

No other crash countermeasure gets these results!

32

HFST Conclusion

HFST is not a pavement treatment that happens to have safety benefits!

HFST is a great safety treatment that happens to be a pavement!

To be applicable, HFST must still provide the functions of a pavement for durability, but it must greatly reduce crashes for a significant duration to distinguish its' unique value.

33

Questions and Discussion

34