MASTER'S THESIS DEFENSE

Evaluation of Highway Safety Countermeasures in Maryland

Case Studies of Superstreets and Automated Speed Enforcement

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Photo sources: FHWA

OVERVIEW

Agenda

01

Research Background & Motivation

Maryland's Vision Zero Commitment — Evaluating Highway Safety Countermeasures

563

Traffic fatalities in Maryland (2022)
Unchanged from 2021

Source: Maryland Highway Safety Office, 2023

2030

Vision Zero Target Year
Zero fatalities by 2030

Source: Maryland Highway Safety Office, 2026

- Maryland has committed to eliminating traffic fatalities through its Vision Zero initiative by 2030.
- One of the primary ways this goal is pursued is through the Strategic Highway Safety Plan, which uses safety countermeasures as part of its strategies to improve road safety.
- Maryland's Strategic Highway Safety Plan organizes safety strategy around the “Four Es”: Engineering, Enforcement, Education, and Emergency Medical Services (EMS).
- My research focuses on two of these pillars: Engineering, represented by superstreet intersections, and Enforcement, represented by Automated Speed Enforcement.

Two Complementary Countermeasures

E

Engineering

Superstreet Intersections

- Superstreet geometric design
- Reduces vehicle conflict points by ~56% vs. conventional intersections
- FHWA Reduced Left-Turn Conflict Intersections Camera Proven Safety Countermeasure
- Permanent, site-specific infrastructure

F

Enforcement

Automated Speed Enforcement

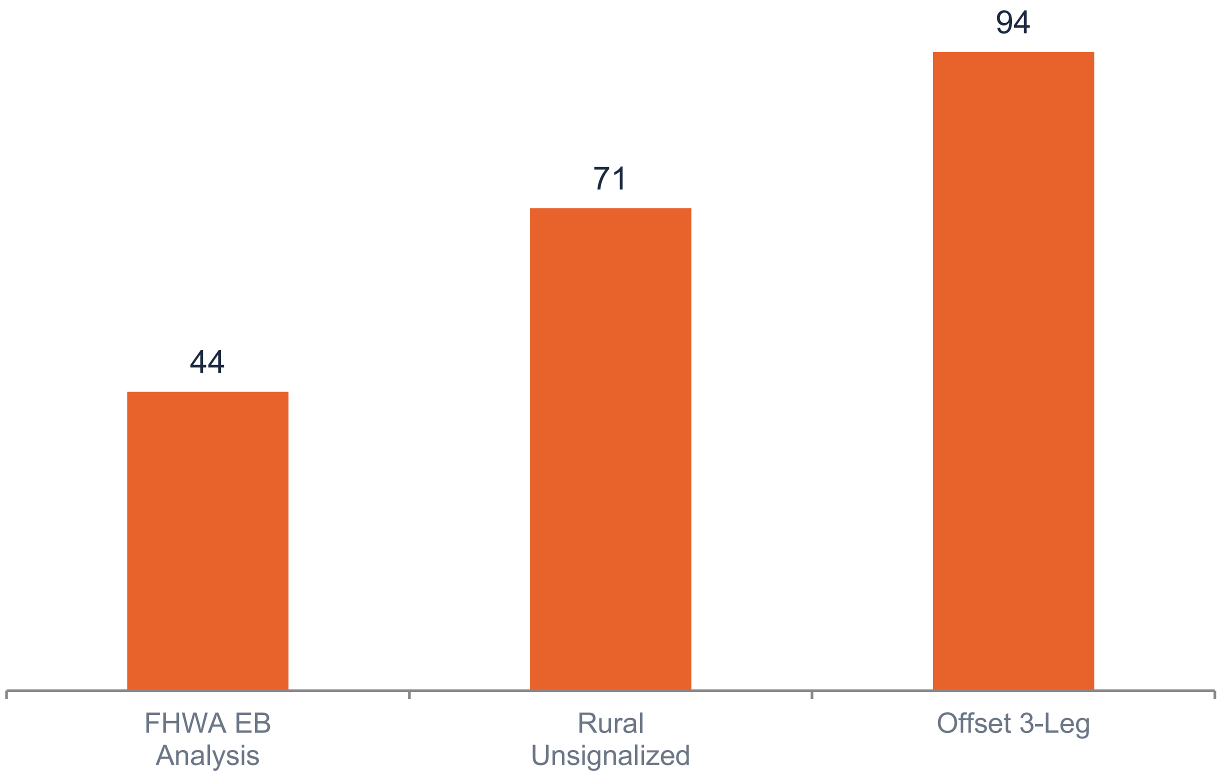
- Camera-based detection of work-zone speeding
- Maryland's SafeZones program, active since 2010
- FHWA Speed Safety Camera Proven Safety Countermeasure
- Temporary, mobile deployment across work zones

02

Literature Review & Research Objectives

Literature Review: Superstreet Safety

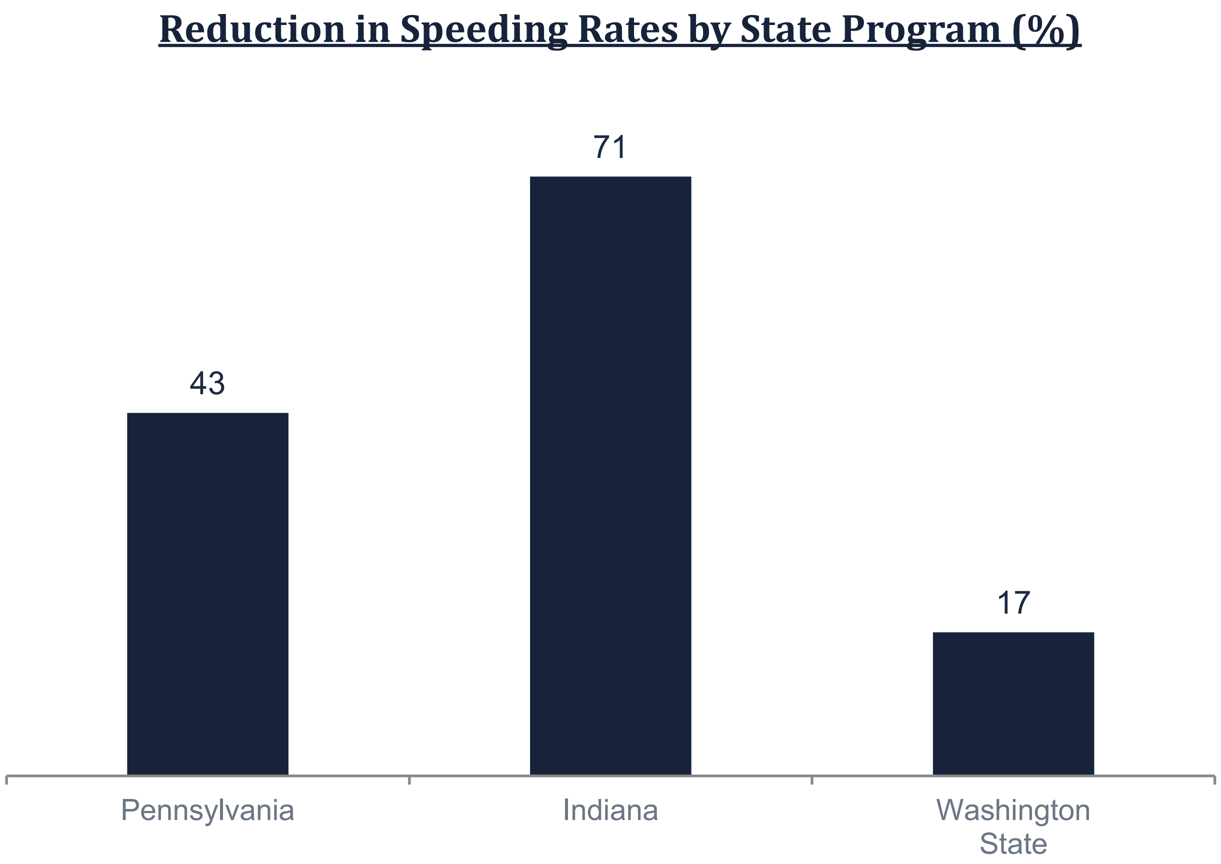
Documented Crash Reductions (%)



Sources: Inman and Haas 2012 (EB Analysis); Mishra and Pulugurtha 2022 (Rural Unsignalized, Offset 3-Leg)

- Empirical Bayes analyses consistently show the largest, most reliable crash reductions (Inman and Haas 2012; Ott et al. 2012).
- Right-turn-U-turn (RTUT) movements generate far fewer conflicts than direct left turns (2.4 vs. 6.7 per hour) (Lu et al. 2005).
- But certain design elements, short crossover distances, and driver unfamiliarity can offset the expected safety benefits (FHWA 2017).

Literature Review: Work Zone ASE



Sources: Pennsylvania DOT 2020–2026; Desai et al. 2025 (Indiana); Washington State DOT 2025

- Work zones show consistently elevated crash risk (Khattak et al. 2002: +21.5% crash rate).
- Multiple state ASE programs report significant speed and speeding-rate reductions, such as those in Illinois and Oregon (Benekohal et al. 2008, 2010; Joerger 2010).
- Delaware and Pennsylvania confirm speed reductions translate into fewer work zone crashes (−46%, −30%) (Delaware DOT 2022; Pennsylvania DOT 2020–2026).

The Research Gap: The Common Thread

Both bodies of literature establish that these countermeasures work, on average.

Neither explains site-level variation, or gives practitioners a standardized, replicable tool for diagnosis and deployment decisions.

Research Objective

Rather than assessing whether countermeasures are effective on average, both studies examine the site-specific factors underlying differences in performance, resulting in replicable decision-support tools.

Aggregate Evaluation → **Site-Level Diagnosis** → **Design / Deployment Guidance**

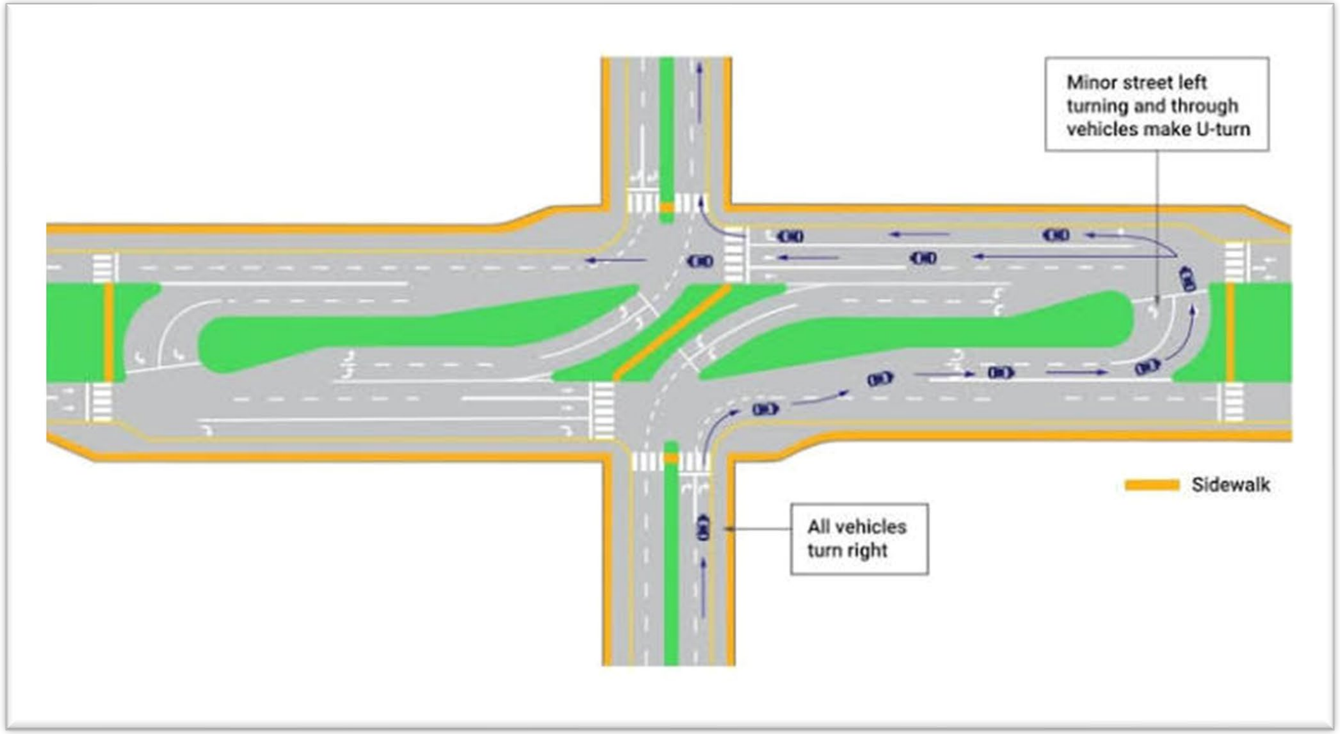
03

Study 1: Superstreet Safety Audit

A spatial statistical framework for auditing unconventional intersection design

What Is a Superstreet?

A superstreet is an unconventional intersection that prohibits direct left turns and through movements from minor roads, replacing them with a right turn followed by a downstream U-turn. This movement reduces conflict points by about 56% compared to conventional intersections, thereby improving safety.



Even with this benefit, certain crash types persist post-implementation:

- Rear-end collisions at U-turn locations
- Wrong-way entries
- Issues tied to insufficient sight distance or turning geometry

STUDY 1 — BACKGROUND

Study Motivation & Objectives

M Motivation

- Past studies on superstreets focus on overall crash reductions, not where or why these crashes occur
- Lack of a standardized safety audit to identify design-based crash risks
- Current methods cannot separate random vs. geometry-related crashes

O Objectives

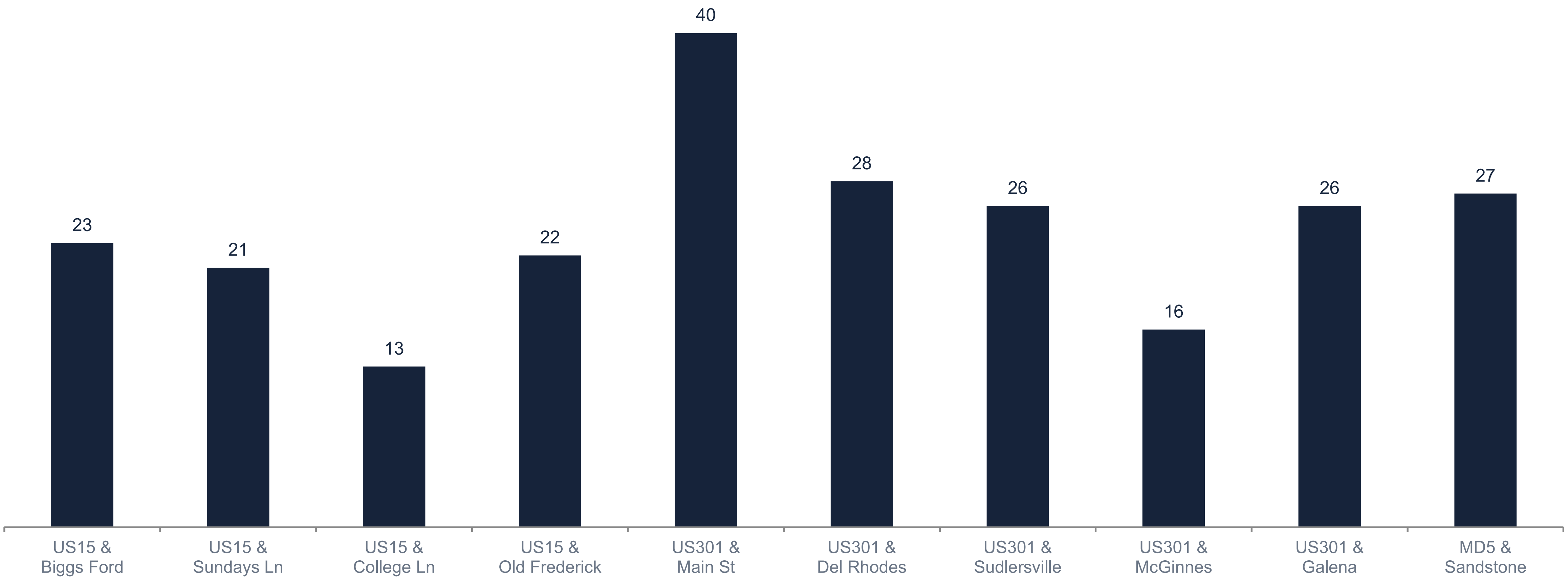
- Develop a structured safety audit for unconventional intersections
- Determine the robustness of this method using Maryland superstreets as a case study
- Identify geometry-related crash clusters using spatial analysis
- Recommend design refinements to guide standards

Six-Step Safety Audit Methodology

1 Data Collection	Crash, speed, and geometric data needed to conduct the safety audit are collected.
2 Crash Map Development	Crash maps are developed and used to visualize the spatial distribution of crashes relative to intersection geometry.
3 Preliminary Screening	Crash impact zones (areas where crashes are impacted by geometry) are defined using speed-based braking distances to filter out random crashes.
4 Spatial Statistical Analysis	Identify and isolate geometry-related crash patterns using global and local spatial clustering methods (Moran's I and Getis-Ord).
5 Zonal Crash Cluster Analysis	Segment intersections into zones and subzones to identify systematic spatial patterns in the location of crash hotspots.
6 Causal Investigation	Use crash reports and intersection characteristics to assess links between crash hotspots and geometric design features and recommend design improvements.

STUDY 1 — CASE STUDY

Ten Maryland Superstreet Sites (2015–2023)



Preliminary Screening

Superstreet	Crash Total	Crashes Within Impact Zone
U.S. 15 & Biggs Ford Road	23	23
U.S. 15 & Sundays Lane	21	21
U.S. 15 & College Lane	13	10
U.S. 15 & Old Frederick Road	22	18
U.S. 301 & Main Street	40	40
U.S. 301 & Del Rhodes Avenue	28	27
U.S. 301 & Sudlersville Road	26	23
U.S. 301 & McGinnes Road	16	13
U.S. 301 & Galena Road	26	21
MD 5 & Sandstone St., Waldorf	27	20

Nearly all crashes occurred within crash impact zones for all 10 superstreets, confirming possible geometry influence.

Spatial Statistical Analysis

Consistent results were shown across spatial statistical tests:

- Global Moran's I and Getis-Ord General G identified statistically significant crash clusters (hotspots) at the same 7 of 10 intersections.
- Local Moran's I and Getis-Ord Gi* identified statistically significant crash clusters (hotspots) at the same locations on the superstreets. (* $p < 0.05$)

Superstreet	Global Moran's I	Getis-Ord General G		Consistent Results Across Both Tests
	Moran's I Statistic	General G	Expected General G	
U.S. 15 & Old Frederick Road	4.312e-02*	1.732e-02*	1.381e-03	Yes
U.S. 15 & Biggs Ford Road	0.096*	4.329e-02*	9.043e-03	Yes
U.S. 15 & Sundays Lane	0.037*	2.105e-02*	6.539e-03	Yes
U.S. 15 & College Lane	−2.208e-03	0.000e+00	1.564e-03	Yes
U.S. 301 & Main Street	1.502e-01*	3.205e-02*	2.335e-03	Yes
U.S. 301 & Del Rhodes Avenue	0.075*	0.026*	0.005	Yes
U.S. 301 & McGinnes Road	1.221e-02	8.333e-03	2.157e-03	Yes
U.S. 301 & Galena Road	1.314e-01*	4.558e-02*	2.301e-03	Yes
U.S. 301 & Sudlersville Road	1.068e-02	6.153e-03	3.009e-03	Yes
MD 5 & Sandstone St., Waldorf	0.137*	6.535e-02*	3.447e-03	Yes

Zonal Crash Cluster Analysis

Four Functional Zones

Intersections were divided into four functional zones based on geometry and direction of traffic.

1. Minor Street
2. Left-Turn Lane
3. Right-Turn Area
4. Lane-Change Area

Zone 1 Subdivision

Zone 1 was subdivided into two subzones for detailed crash causation review.

1. Vehicle Merging Area
2. Minor Street

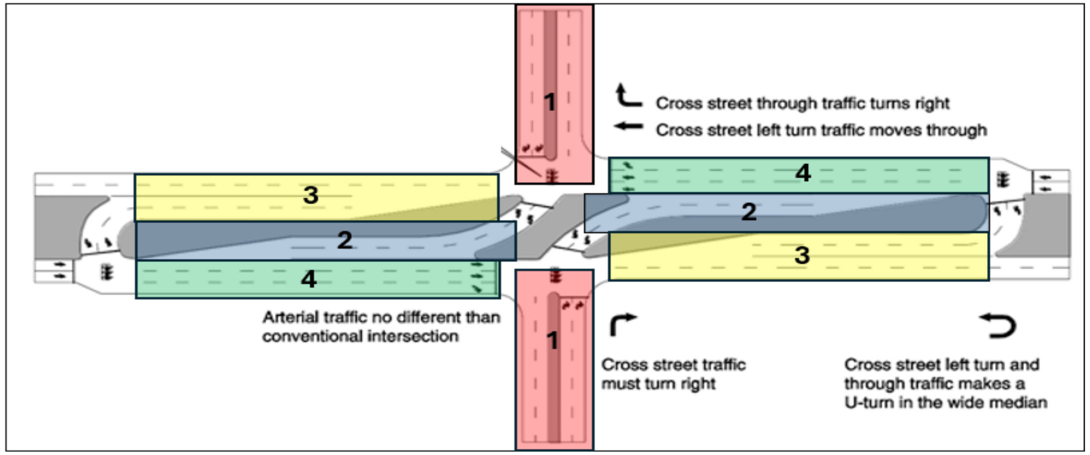


Figure 3.9. Cluster Zones

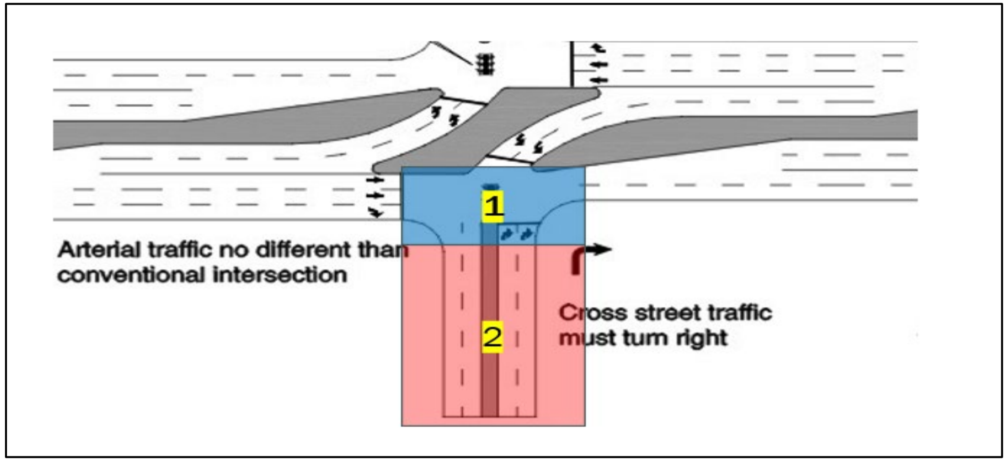


Figure 3.10. Zone 1 Subzones

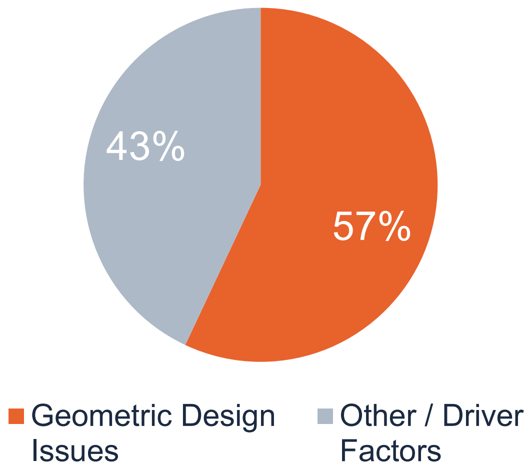
9/10 superstreets had crash hotspots in **Zone 1**, indicating potential geometric deficiencies there.

The vehicle merging area (sub-zone 1) had more **than 3 times** as many crashes as the minor street (sub-zone 2)

Causal Investigation – Zone 1

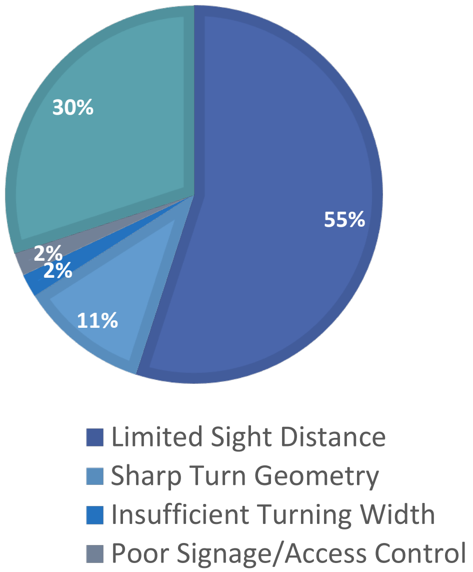
Out of a total of 61 crashes analyzed in **Zone 1**:

- **57%** of all crashes were attributable to geometric design issues
- The remaining could not be attributed to a geometric design issue



Main issues identified in the merging area:

- Limited Sight Distance **(55%)**
- Sharp Turn Geometry **(11%)**
- Signage/Turning Width Deficiencies **(4%)**



STUDY 1 — CONTRIBUTION

Conclusions

1

Crashes at existing superstreets were not randomly distributed

Spatial clustering was tied to specific design features, particularly in vehicle merging and right-turn zones

2

Zone 1 crash causation was predominantly geometric

57% of 61 crashes were attributable to geometric design issues, with limited sight distance the predominant factor; the merging area accounted for over 3 times as many crashes as the minor-street approach

3

These findings were confirmed through complementary methods

Spatial cluster detection (Local Moran's I, Getis-Ord Gi*), zonal segmentation, and systematic crash causation review all pointed to the same design-related patterns

4

The methodology provides a replicable framework for design improvement

Offering practical guidance on possible sight distance standards, merge zone geometry, and turn radius requirements for superstreet configurations

04

Study 2: ASE Effectiveness Evaluation

A site-level evaluation of Maryland's SafeZones Automated Speed Enforcement program

Maryland's SafeZones ASE Program

- Camera-based enforcement of work-zone speed limits, active in Maryland since 2010, one of the longest-running ASE programs in the U.S.
- Mobile enforcement units rotate among eligible work zones on expressways and controlled-access highways
- Near-universal deployment across eligible sites means there are no unenforced control sites for a crash-based comparison

101

work zone deployments evaluated

Nationally, work zone crashes are a persistent problem: ~113,000 crashes and 850 fatalities in 2024 alone.

Study Motivation & Objectives

M Motivation

- Work zone crashes remain a significant safety concern in Maryland, averaging more than 1,300 crashes annually.
- Most existing ASE studies report aggregate, program-level outcomes only, not which sites respond best
- Spatial analyses of ASE effects remain limited; most research compares only one or two points, not a full distance-decay profile

O Objectives

- Assess ASE's impact on vehicle speeds across 101 work zone deployments
- Identify the site-level characteristics associated with successful deployments
- Develop a pre-deployment assessment guide to support future site selection

STUDY 2 — METHODOLOGY

Four Complementary Methods

1

Violation Trend Analysis

Classify sites by monthly violation-rate trajectory

2

Speed Variation Analysis (DiD)

Temporal & spatial before-during speed comparison

3

Statistical Modeling

Logistic regression + dominance analysis of predictors

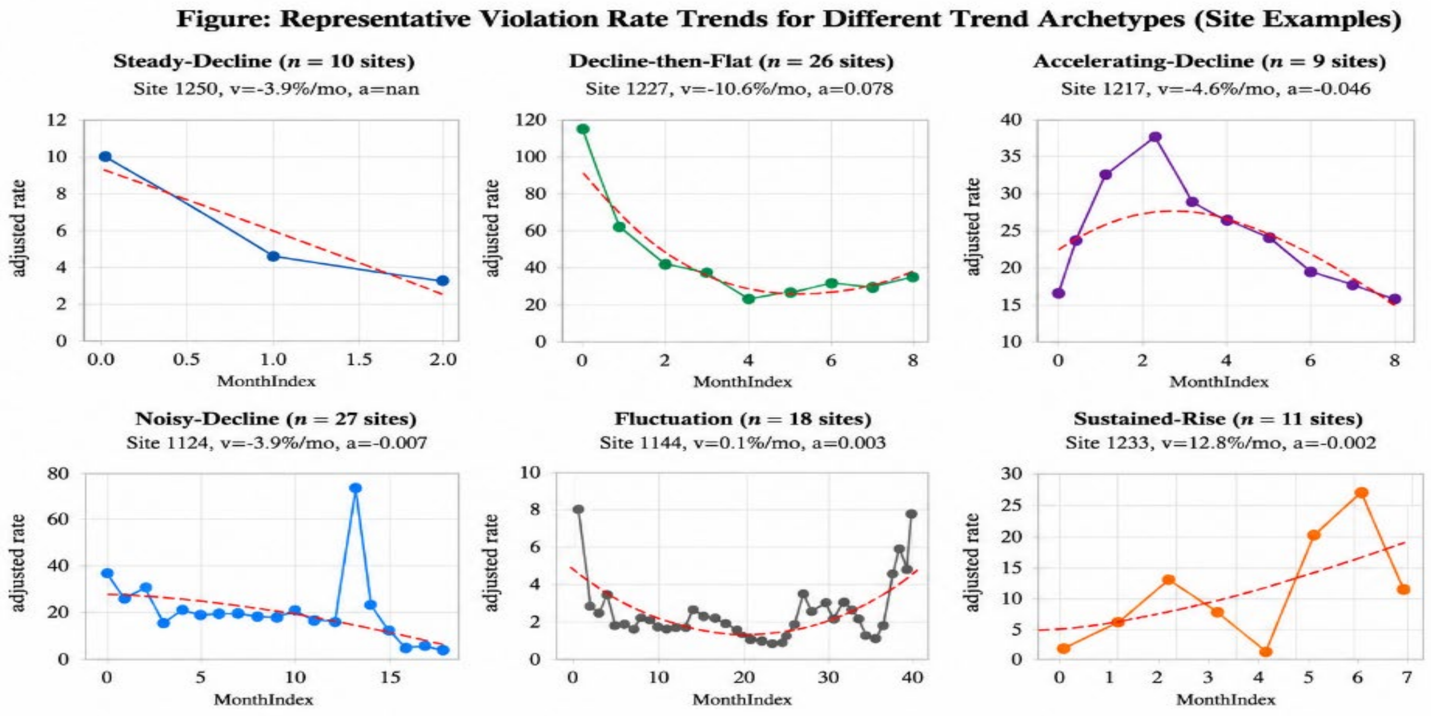
4

Decision Tree Analysis

Validation and interpretable rules for pre-deployment assessment

Violation Trend Analysis

Each site's monthly violation rate trend was summarized using two kinematic descriptors: velocity (the average change in the violation rate per month) and acceleration (trajectory curvature). Based on these descriptors, the 101 sites were classified into six trajectory archetypes. These six archetypes were further consolidated into two groups: Decreasing Trend and Non-Decreasing Trend sites



Note: Adjusted violation rate is shown on the y-axis and month index (relative to the start of analysis period) on the x-axis.
v = linear trend (% change per month); a = quadratic term (curvature).

72

sites — Decreasing Trend

Steady-Decline, Accelerating-Decline, Decline-then-Flat, or Noisy-Decline

29

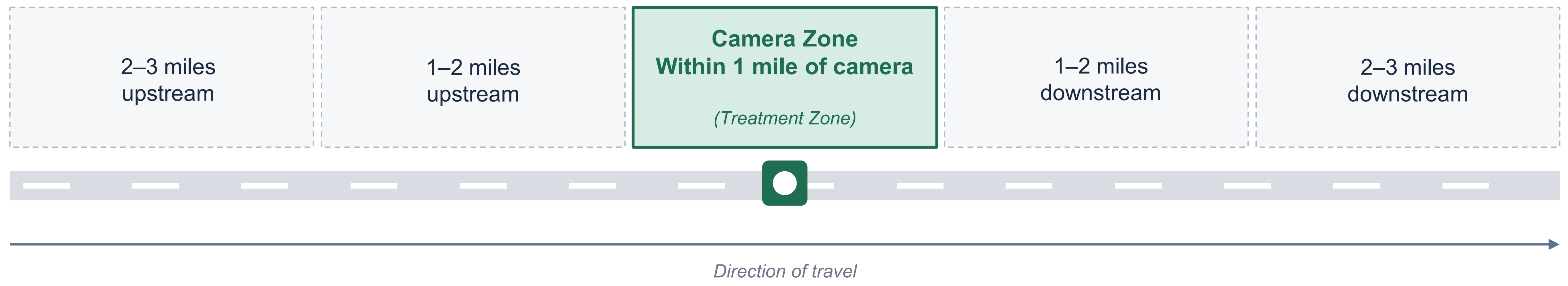
sites — Non-Decreasing Trend

Fluctuation, or Sustained-Rise patterns

STUDY 2 — METHODOLOGY

Speed Variation Analysis (DiD)

A difference-in-differences (DiD) design was used as a surrogate measure of ASE safety effectiveness, comparing speeds before and during enforcement across five spatial zones.



T

Temporal Analysis

Evaluates whether speeds dropped during ASE enforcement across all 5 zones.

S

Spatial Analysis

Evaluates whether the camera zone (within 1 mile) saw larger speed drops than the buffer zones during enforcement.

Statistical Modeling

- **Logistic regression** was used to determine the driving factors of a decreasing vs. non-decreasing violation trend across sites.
- Sites were divided into two groups based on deployment duration:

  Group A: deployment duration ≥ 9 months (N = 39)

  Group B: deployment duration < 9 months (N = 62)

- A threshold of nine months, selected via two-cluster analysis, was chosen to ensure sufficient sample size in both groups for stable estimation.
- **Dominance analysis** was used to rank the contributing factors by their share of the model's explanatory power, identifying which factors had the most impact on the outcome.

Site-level factors (e.g., AADT, citation volume, out-of-state driver share) were used as predictors for these analyses.

Decision Tree Analysis

- Decision tree analysis was conducted for two main purposes:
  - To validate results from the logistic regression and dominance analysis
  - To develop a pre-deployment assessment guide
- Both trees were split at the root node by deployment duration, consistent with the logistic regression and dominance analysis.

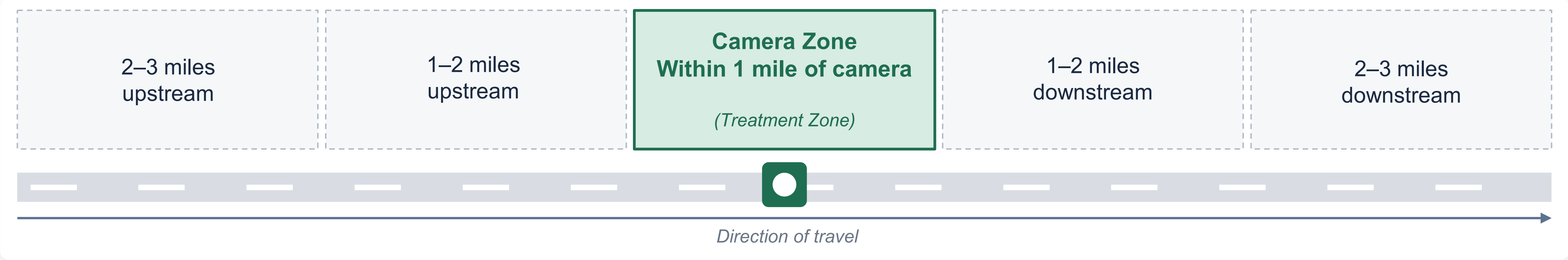
Validation Tree

Built using the same variables used in the logistic regression and dominance analysis. Results were compared across all three methods to validate consistency.

Pre-Deployment Tree

Built to develop a guide for ASE site selection before deployment, using only variables available pre-deployment.

ASE Reduces Speeds — Strongest Near the Camera



Zone	Decreasing Trend Sites			Non-Decreasing Trend Sites		
	Sites (n)	Avg Δ (mph)	p-value	Sites (n)	Avg Δ (mph)	p-value
2–3 mi upstream	50	−1.77	0.0223 *	18	−1.01	0.0224 *
1–2 mi upstream	56	−1.46	<0.0001 ***	19	−1.71	0.0048 **
Within 1 mile	68	−3.18	—	25	−2.96	—
1–2 mi downstream	55	−1.85	0.0001 ***	20	−1.40	0.0044 **
2–3 mi downstream	59	−1.66	0.0002 ***	21	−0.94	0.0114 *

- Speed reductions were strongest at the camera zone compared to the buffer zones.
- For Decreasing Trend sites, the downstream 1–2 mile zone (−1.85 mph) showed a greater reduction than the upstream 1–2 mile zone (−1.46 mph), suggesting drivers maintain reduced speed after passing the camera rather than only slowing in anticipation of it.
- Peak hours (6–10 AM, 3–7 PM) showed larger reductions than non-peak: +0.57 mph for Decreasing Trend sites, +1.12 mph for Non-Decreasing Trend sites.

What Predicts a Strong Response? — Group A (Long-Duration Sites)

Logistic Regression

Variable	Odds Ratio	Sig.
Double Fines Citations	~1.000	***
Out-of-State Violations (%)	0.722	*
Speeding 6–10 mph (%)	1.626	†
Violation Rate	1.005	†
Speeding 0–5 mph (%)	1.171	n.s.
AADT	~1.000	n.s.
Rural/Urban Classification	3.244	n.s.
Posted Speed Limit	0.979	n.s.

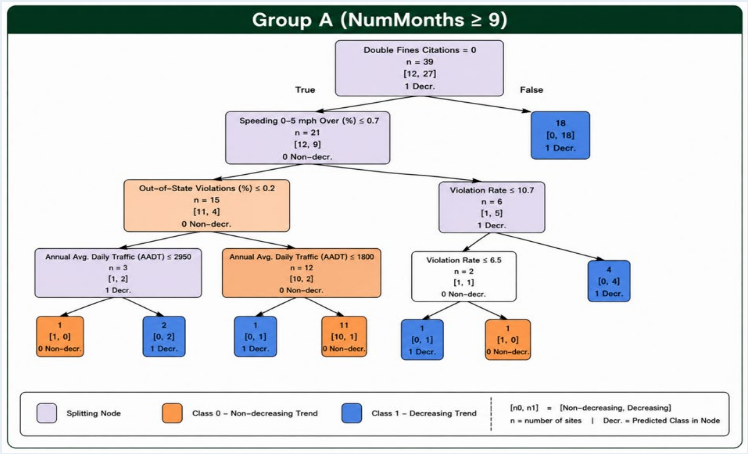
*Sig.: *** p<.001, ** p<.01, * p<.05, † p<.10, n.s. p≥.10*

Dominance Analysis

Rank	Variable	% of R^2
1	Speeding 6–10 mph (%)	23.7%
2	Out-of-State Violations (%)	22.6%
3	Speeding 0–5 mph (%)	20.5%
4	Violation Rate	12.5%
5	AADT	7.7%
6	Rural/Urban	6.8%
7	Double Fines Citations	3.6%
8	Posted Speed Limit	2.6%

Top 3 factors account for 66.8% of model R^2

Decision Tree



Validation Tree — Right Branch (Group A)

- Enforcement- and speeding-severity factors dominate: Speeding 6–10 mph, Out-of-State Violations, and Speeding 0–5 mph together account for ~67% of the model's explanatory power.
- Significance and importance diverge: Double Fines Citations is the most statistically significant predictor but explains only 3.6% of model variance, while Speeding 6–10 mph is only marginally significant ($p < 0.10$) yet is the single strongest driver.
- Findings were consistent across three independent methods.

What Predicts a Strong Response? — Group B (Shorter-Duration Sites)

Logistic Regression

Variable	Odds Ratio	Sig.
AADT	~1.000	***
Out-of-State Citations (%)	0.597	*
Posted Speed Limit	0.922	†
Speeding 0–5 mph (%)	1.249	†
Average Violator Speed	0.968	n.s.
Speeding 6–10 mph (%)	1.658	n.s.
Speeding 11–20 mph (%)	0.456	n.s.
Speeding >20 mph (%)	0.854	n.s.
Double Fines Citations	~1.000	n.s.
Rural/Urban Classification	1.877	n.s.

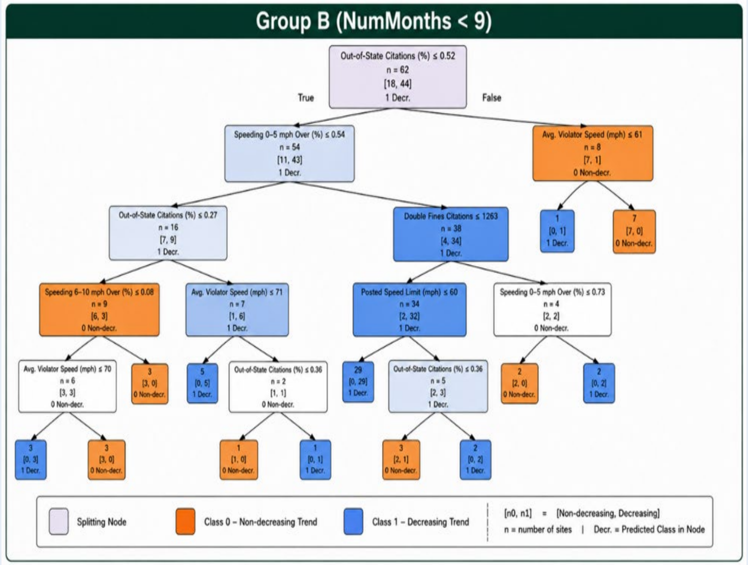
*Sig.: *** p<.001, ** p<.01, * p<.05, † p<.10, n.s. p≥.10*

Dominance Analysis

Rank	Variable	% of R^2
1	AADT	30.8%
2	Out-of-State Citations (%)	20.1%
3	Posted Speed Limit	10.6%
4	Speeding 0–5 mph (%)	9.7%
5	Double Fines Citations	7.7%
6	Avg Violator Speed	7.2%
7	Speeding 6–10 mph (%)	5.6%
8	Speeding >20 mph (%)	4.0%
9	Speeding 11–20 mph (%)	2.3%
10	Rural/Urban	1.9%

Top 3 factors account for 61.5% of model R^2

Decision Tree



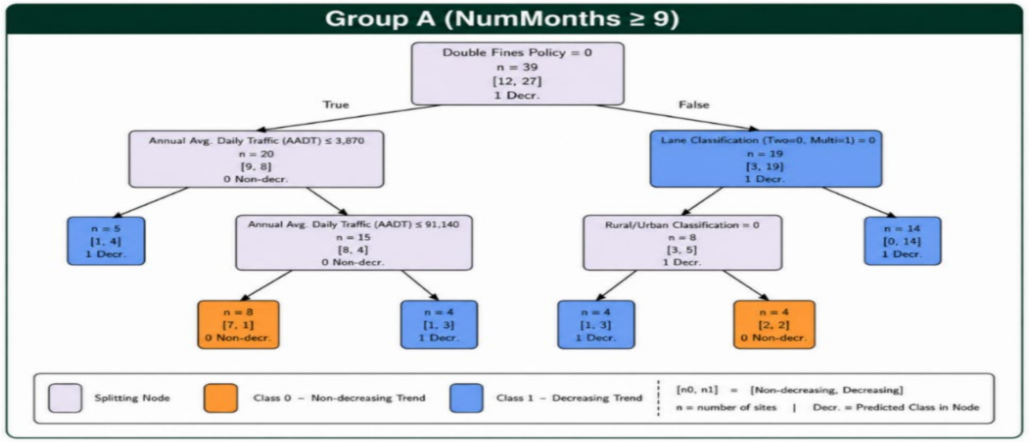
Validation Tree — Left Branch (Group B)

- Roadway and traffic characteristics dominate: AADT, Out-of-State Citations, and Posted Speed Limit together account for 62% of the model's explanatory power.
- AADT and Out-of-State Citations show strong alignment between significance and importance: both are highly significant and rank 1st and 2nd in dominance.
- Overall agreement across methods is consistent but weaker than Group A.

Pre-Deployment Assessment Guide

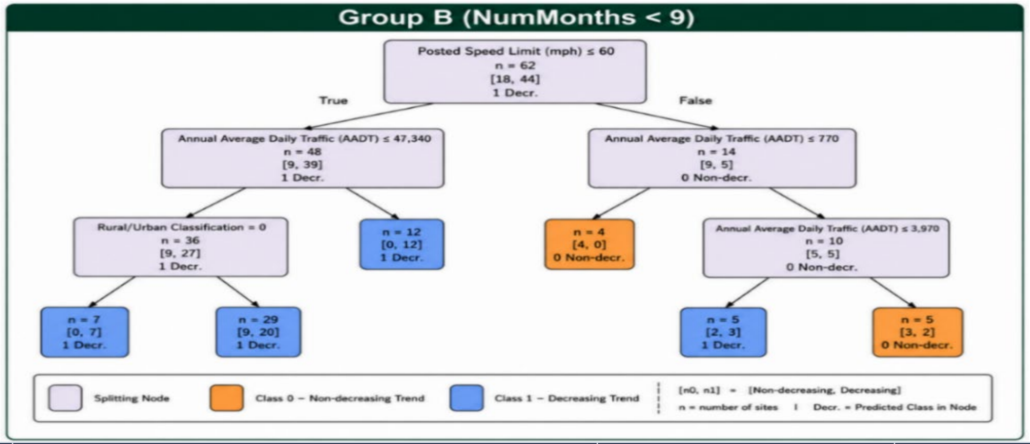
Decision tree rules were translated into a practical, interpretable tool for prioritizing future ASE deployment sites based on deployment duration.

Group A (Long-Duration Sites)



#	IF... AND Conditions	THEN (Outcome)	Accuracy
1	Double Fines Policy = NO AND AADT ≤ 3,800	Decreasing Trend	80.0% (4/5)
2	Double Fines Policy = NO AND 3,800 < AADT ≤ 91,000	Non-Decreasing Trend	87.5% (7/8)
3	Double Fines Policy = NO AND AADT > 91,000	Decreasing Trend	75.0% (3/4)
4	Double Fines Policy = YES AND Two-Lane AND Rural	Decreasing Trend	75.0% (3/4)
5	Double Fines Policy = YES AND Two-Lane AND Urban	Non-Decreasing Trend	50.0% (2/4)
6	Double Fines Policy = YES AND Multi-Lane	Decreasing Trend	100.0% (14/14)

Group B (Shorter-Duration Sites)



#	IF... AND Conditions	THEN (Outcome)	Accuracy
1	Posted Speed ≤ 60 AND AADT ≤ 47,000 AND Rural	Decreasing Trend	100.0% (7/7)
2	Posted Speed ≤ 60 AND AADT ≤ 47,000 AND Urban	Decreasing Trend	69.0% (20/29)
3	Posted Speed ≤ 60 AND AADT > 47,000	Decreasing Trend	100.0% (12/12)
4	Posted Speed > 60 AND AADT ≤ 800	Non-Decreasing Trend	100.0% (4/4)
5	Posted Speed > 60 AND 770 < AADT ≤ 4,000	Decreasing Trend	60.0% (3/5)
6	Posted Speed > 60 AND AADT > 4,000	Non-Decreasing Trend	60.0% (3/5)

Conclusion

1. **Speed reductions were consistent during active deployment**

   Strongest near the camera zone and diminishing with distance, a clear spatial decay pattern

2. **Site-level predictors of a favorable response differed by deployment duration**

   Enforcement-related factors (citation volume) dominated at long-duration sites; roadway and traffic characteristics (AADT, speed distribution) dominated at short-duration sites

3. **These relationships were confirmed across three independent methods**

   Logistic regression, dominance analysis, and decision tree modeling produced consistent results

4. **A pre-deployment assessment guide translates these findings into practice**

   An interpretable, replicable tool for prioritizing future ASE deployment sites

05

Conclusions & Contributions

Synthesizing two site-level evaluation frameworks for Maryland highway safety

Summary of Findings & Contributions

Combined Contributions

- Both studies produce the same kind of output: a replicable, site-level decision-support tool, not a one-time evaluation
- Together they cover both the Engineering and Enforcement pillars of Maryland's Strategic Highway Safety Plan
- Both had to work around the same constraint, incomplete outcome data, pointing to a shared opportunity: expanding structured, site-level data collection at transportation agencies

Moving from “does it work?” to “where and why?” — for both engineering and enforcement countermeasures.

Limitations & Future Research

Limitations

- Both studies are geographically limited to Maryland
- Because nearly all eligible work zones already have ASE, there are no unenforced sites to serve as a control group for isolating its causal effect.
- Speed analysis was used as a surrogate in place of direct crash outcomes for ASE

Future Research

- Test both frameworks at sites outside Maryland for generalizability
- Expand structured, site-level data collection for both countermeasure types
- Move from surrogate measures toward direct crash-based effectiveness estimates

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Thank You

Questions & Discussion