Analyzing Driver Behaviors at Intersections with RLC deployment

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Comparison of the crash patterns before and after the RLC deployment – (From the literature review)

Types of crash patterns	Findings reported in the literature
Type-1 Angled Crashes: Reduced Rear-end Crashes: Reduced	[Government Reports]: Brooksville, Clermont, Davie, Miami, Pinecrest, Council Bluffs, Davenport, Howard, Portland, Knoxville, Austin
Type-2 Angled Crashes: Reduced Rear-end Crashes: Increased	[Literature]: Bochner et al. (2010), Erke et al. (2009), Høye et al. (2013), Kangwon et al.(2007), Ko et al. (2013), Persaud et al. (2005), Radali et al. (2001), Retting et al. (2002), Ahmed et al. (2015), Shin et al.(2007); [Government Reports]: Phoenix, Scottsdale, San Diego, Apopka, Boynton Beach, Campbellton, Fort Lauderdale, Manatee, New Port Richey, Ocoee, Palatka, Palm Beach, Sarasota, West Park, Lafayette, Greensboro, Newark, Suffolk, Amarillo, Denton, Diboll, Frisco, Mesquite, Port Lavaca, Fairfax, Falls Church, Vienna
Type-3 Angled Crashes: Increased Rear-end Crashes: Reduced	[Literature]: Council et al. (2005), [Government Report]： Houston, Cunningham
Type-4 Angled Crashes: Increased Rear-end crashes: Increased	[Literature]: Claros et al. (2017) [Government Reports]： Boca Raton, Clewiston, Jacksonville, Lakeland, Maitland, Miami Beach, Miami Spring, Orange, Orlando, Osceola, Palm Coast, Sunrise, Tamarac, Tampa, West Miami, Bedford, Cleveland, Garland, Haltom City, Richland Hills, University Park, Willis, Arlington

Before-and-after comparison at 27 RLC MD intersections
(consistent with the findings in the literature)

Period of Comparison Before | After	Angled "Increase" / Rear-end "Increase"	Angled "Decrease" / Rear-end "Decrease"	Angled "Increase" / Rear-end "Decrease"	Angled "Decrease" / Rear-end "Increase"
B:5-yr| A:3-yr	P3	H1^{AR}, H2^{A}, M1, M2^{A}, M5, M6, M7, M8, M12, P2, P4, P8	M13^{R}, P10	M3, M4^{A}, M11^{A}, M14, M15, P1, P5, P6^{R}, P7, P9^{R}
B:3-yr| A:3-yr	M3, P3, P10	H1^{R}, H2, M1, M2^{A}, M5, M7, M8, P1, P4	M6, M13^{R}, P8	M4, M12, M14^{A}, M15, P2, P5, P6, P7, P9,M11^{A}
B:2-yr| A:3-yr	M3, M5, P3, P10	H1, H2^{A}, M2^{A}, M6, M8, M15, P1^{R}, P4	M1, M7, M12, M13^{R}, P8	M4^{R}, M14^{R},M11^{A},P2, P5, P6, P7, P9^{R}
B:5-yr| A:2-yr	M9, P3	H1^{A}, H2, M1, M2^{A}, M3, M5, M6, M7, M8, P4^{A}	M12, M13^{R}, P8, P10	M4^{A}, M10, M14, M15, P1, P2, P5, P6, P7, P9,M11
B:3-yr| A:2-yr	M9, M12, P3	H1, H2, M2^{A}, M5, M7, M8, P1, P4	M1, M3, M13^{R}, P8, P10	M4, M6, M10, M14, M15, P2, P5, P6, P7, P9, M11^{A}
B:2-yr| A:2-yr	M5, P3	H1, H2^{A}, M2^{A}, M6, M8, P1, P4^{A}	M1, M3, M7, M12, M13^{R}, P8, P10	M4^{R}, M9, M10, M14, M15, P2, P5, P6, P7, P9, M11^{A}

Note:

P: Prince Georg's County

H : Howard county

M: Montgomery county

^{A}: denotes the statistically significant Angled crash change

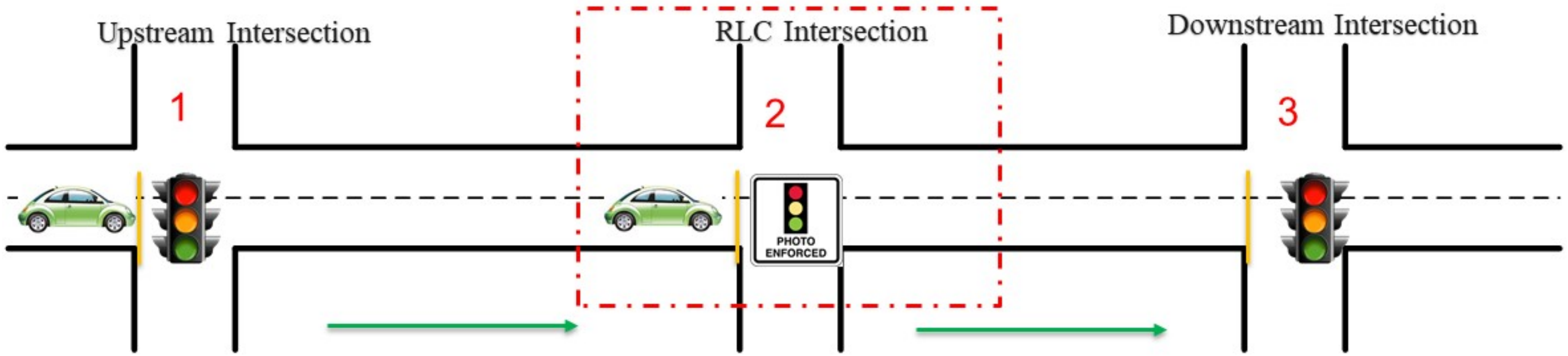
^{R}: denotes the statistically significant Rear-End crashes change

^{AR}: Both angled and rear-end crashes experienced statistically significant changes

Phase-II: Empirical observations of driver behaviors at RLC intersections

Key questions to be answered:

- Any **spillover impacts** due to the RLC deployment?
- **Behavioral Factors** contributing to different levels of RLC effectiveness?



Data collection sites:

Site 1: MD 650 from Oakview Dr. (Upstream), Adelphi Rd. (RLC), to Northampton Dr. (Downstream)

Site 2: US 301 from Frank Tippett Rd. (Upstream), Old Indian Head Rd. (RLC), to Fairhaven Ave. (Downstre

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Data collection sites

A. 3-intersection Site 1: **MD 650 – Effective RLC (i.e., reduction in the angled-crash frequency)**

Oakview Dr. **(Upstream),** Adelphi Rd. **(RLC),** to Northampton Dr. **(Downstream)**

B- 3-intersection Site 2: **US 301 – Ineffective RLC (i.e., no impact on both types of accidents)**

Frank Tippett Rd. **(Upstream),** Old Indian Head Rd. **(RLC),** to Fairhaven Ave. **(Downstream)**

C. Individual intersections: MD 410 @ MD 450 – Effective (i.e., reduction in the angled-crash frequency)

MD 97 @ MD 28 – Ineffective (i.e., no impact on angled-crash frequency)

Variables measured from field observations

Traffic characteristics at all 3 intersectionson each RLC study site:

- The **approaching speed** of vehicles by type
- **Speed variation** of each individual vehicle at the stop line, 100, 250, 400, and 550 feet from
- the target intersection
- **Distance** to the stop line when a vehicle choose to stop at the intersection

Responses to the yellow signal at each RLC study site:

- A driver's **decision to stop or to pass** at the onset of a yellow phase, given the detected **speed**
- and **distance** from the intersection stop line
- The **speed**, **acceleration,** and **deceleration** rate of each approaching vehicle when encountering
- a yellow phase
- The **time stamp** during the yellow or the red phase when a vehicle first traverses the
- intersection stop line
- The **number of vehicles** crossing the stop line during the all-red and/or red phase

Overview of the RLC study site (MD650)

Distribution of the approaching speeds

The RLC-effective (reduce the number of angled crashes) intersection:

- much lower percentage of aggressive drivers than the RLC-ineffective intersection

- The RLC deployment has no significant impacts on the average approaching speed.

MD 650 (**EFFECTIVE** SITE), SPEED LIMIT: **40 MPH**

% of vehicle	<40 mph	40 – 45 mph	45 – 50 mph	>50 mph	Average
Upstream (N = 202)	71.29%	14.85%	12.87%	0.99%	35.3
RLC (N = 104)	40.38%	36.54%	13.46%	**9.62%**	41.5
Downstream (N = 103)	36.89%	33.98%	21.36%	**7.77%**	41.9

US 301 (**INEFFECTIVE** SITE), SPEED LIMIT: **55 MPH**

% of vehicle	<55 mph	55 – 60 mph	60 – 65 mph	>65 mph	Average
Upstream (N = 203)	25.12%	24.14%	30.54%	20.20%	59.1
RLC (N = 206)	19.9%	16.02%	24.27%	**39.81%**	61.5
Downstream (N = 457)	62.82%	19.23%	11.54%	**6.41%**	54.7

Confirm the findings with the data from additional RLC sites:

The RLC-effective intersection has a relatively low percentage of aggressive drivers (10 mph over the speed limit)

MD 410 (**EFFECTIVE** SITE), SPEED LIMIT: **45 MPH**

% of vehicle	<45 mph	45 – 50 mph	50 – 55 mph	>55 mph	Average
RLC (N = 157)	27.39%	33.12%	33.12%	6.37%	47.26

MD 97 (**INEFFECTIVE** SITE), SPEED LIMIT: **50 MPH**

% of vehicle	<50 mph	50 – 55 mph	55 – 60 mph	>60 mph	Average
RLC (N = 203)	30.05%	22.66%	21.67%	25.62%	54.75

Speed changes during the yellow phase for

Moderate "passing " drivers (approaching speed within 10 mph of the speed limit)

Site	Intersection	Difference between the passing speed (at the stop line) and the approaching speeds		
		< -5mph	Unchanged	> 5mph
MD650 (Effective)	Upstream	46%	43%	11%
	RLC	7%	**57%**	36%
	Downstream	13%	**75%**	12%
US310 (Ineffective)	Upstream	9%	56%	35%
	RLC	8%	**46%**	46%
	Downstream	20%	**75%**	5%

# of Samples
MD 650 Upstream: **162**
MD 650 RLC: **120**
MD 650 Downstream: **95**
US 301 Upstream: **62**
US 301 RLC: **63**
US 301 Downstream: **43**

Spillover Impacts at both types of intersections: driving populations become less aggressive!

- Percentage of drivers **reducing** their speed → **increase** at the downstream intersection
- Percentage of drivers **increase** their speed → **decrease** at the downstream intersection
- Percentage of drivers exerising **constant speed increases** from RLC to its downstream intersections.

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Speed change during the yellow phase: Aggressive "passing " drivers
(approaching speed 10 mph above the speed limit)

Site	Intersection	Difference between the passing speed (at the stop line) and the approaching speeds			
		< -10 mph	< -5mph	Unchanged	> 5mph
MD650 (Effective)	Upstream	**6.7%**	70%	20%	10%
	RLC	**28.6%**	57%*	**36%**	**7%**
	Downstream	**30%**	40%	**60%**	**0%**
US310 (Ineffective)	Upstream	0%	0%	89%	11%
	RLC	**11.8%**	24%	41%	**35%**
	Downstream	**40%**	80%	20%	**0%**

Spillover Impacts at both types of intersections: driving populations become less aggressive

- Percentage of drivers **reducing their speed → increase** at the downstream intersection
- Percentage of drivers **increase their speed** → **decrease** at the downstream intersection

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MD650 (Effective site): % drivers take the “stop” decision

Speed limit: 40 mph

MD 650		Vehicle speed at the onset of Yellow (MPH)			
RLC Intersection		<35	35 ~ 45	45 ~ 55	>55
Vehicle’s distance-to-stop-line at the onset of yellow (feet)	<100	6% (18)	0% (14)	0% (4)	**
	100 ~ 200	29% (17)	14% (26)	17% (18)	0% (3)
	200 ~ 300	90% (10)	76% (25)	38% (8)	0% (2)
	300 ~ 400	100% (4)	100% (5)	50% (2)	0% (1)*
	>400	100% (1)			

*The number within the parenthesis is the sample size
** An empty cell denotes no samples were observed for that category

Between RLC and upstream intersections

MD 650		Vehicle speed at the onset of Yellow (MPH)			
% (RLC – Upstream)		<35	35 ~ 45	45 ~ 55	>55
Vehicle’s distance-to-stop-line at the onset of yellow (feet)	<100	0% (14)	0% (14)	0% (4)	
	100 ~ 200	50% (8)	13% (16)	10% (10)	
	200 ~ 300		7%(15)	17% (6)	
	300 ~ 400	0% (3)	0% (3)	17% (2)	
	>400				

Between downstream and upstream intersections; N=168

MD 650		Vehicle speed at the onset of Yellow (MPH)			
% (downSt – UpSt)		<35	35 ~ 45	45 ~ 55	>55
Vehicle’s distance-to-stop-line at the onset of yellow (feet)	<100	7% (14)	0% (16)	0% (12)	
	100 ~ 200	50% (2)	-6% (7)	25% (4)	
	200 ~ 300		13% (5)	33% (4)	
	300 ~ 400	0% (3)	0% (2)	17% (2)	
	>400	0% (1)	0% (8)	17% (6)	0% (2)

Red light camera can encourage more vehicles at different speeds & locations to take the stop decision

Spillover impacts are observed at the downstream intersection. Drivers at the downstream intersection are more likely to choose the stop decision compared to those at the upstream intersection.

US301 (Ineffective site): % drivers take the "stop" decision

N=470

US 301		Vehicle speed at the onset of Yellow (MPH)						
RLC		<35	35~45	45~55	**55~65**	65~75	75~85	>85
Vehicle's distance-to-stop-line at the onset of yellow (feet)	**<200**	0% (2)	0% (1)	0% (3)	**0% (10)**	0% (14)	0% (2)	0% (1)
	200 ~ 300		100% (1)	0% (4)	**33% (6)**	0% (10)		0% (1)
	300 ~ 400			67% (3)	**38% (13)**	55% (11)	100% (1)	0% (1)
	400 ~ 500			89% (9)	**79% (19)**	63% (16)	100% (1)	
	500 ~ 600			85% (13)	**100% (9)**	100% (7)	100% (3)	50% (2)
	600 ~ 700			100% (4)	**94% (18)**	100% (20)	100% (4)	100% (1)
	>700	Only 1 vehicle choose to pass			**100% (9)**	100% (8)	100% (2)	

The spillover impacts of RLC at the ineffective set is less significant.

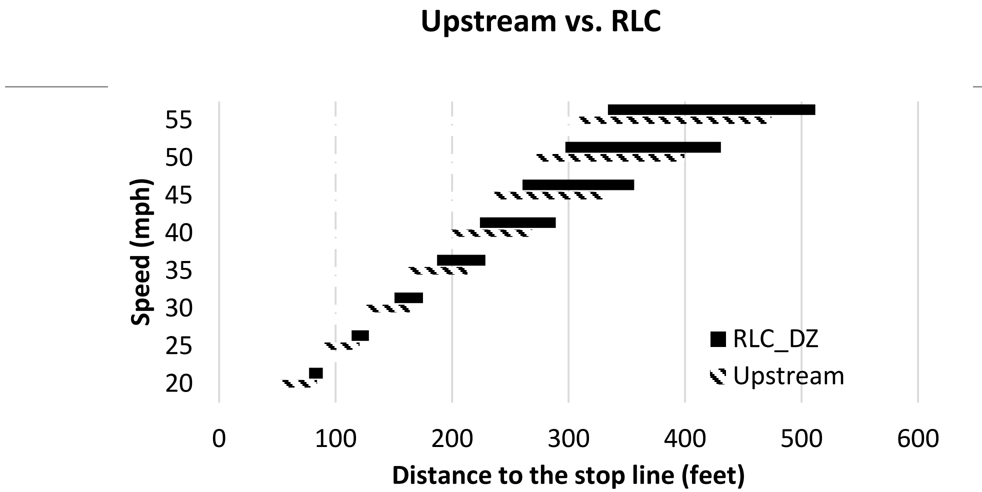
US 301		Vehicle speed at the onset of Yellow (MPH)					
% (RLC – Upstream)		<35	35~45	45~55	55~65	65~75	75~85
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<200						
	200 ~ 300			-50%	**33%**		
	300 ~ 400			21%	**25%**	**55%**	
	400 ~ 500			17%	**8%**	**34%**	
	500 ~ 600			-15%	0%	**20%**	
	600 ~ 700			0%	-6%	0%	0%
	>700				0%	0%	0%

US 301		Vehicle speed at the onset of Yellow (MPH)					
Down vs. Upstream		<35	35~45	45~55	55~65	65~75	75~85
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<200						
	200 ~ 300			**-50%**	0%		
	300 ~ 400			**-14%**	37%	0%	
	400 ~ 500		0%	**29%**	**-5%**	**-29%**	
	500 ~ 600		0%	**0%**	**-33%**	**20%**	
	600 ~ 700			**0%**	0%	0%	0%
	>700						

RLC **encourages** vehicles to take the **stop decision** at the RLC intersection
Especially for drivers at **higher approaching speeds**

Vehicles far away from intersection always choose to stop (no data)

MD 650 (Effective): Dilemma Zone Distribution



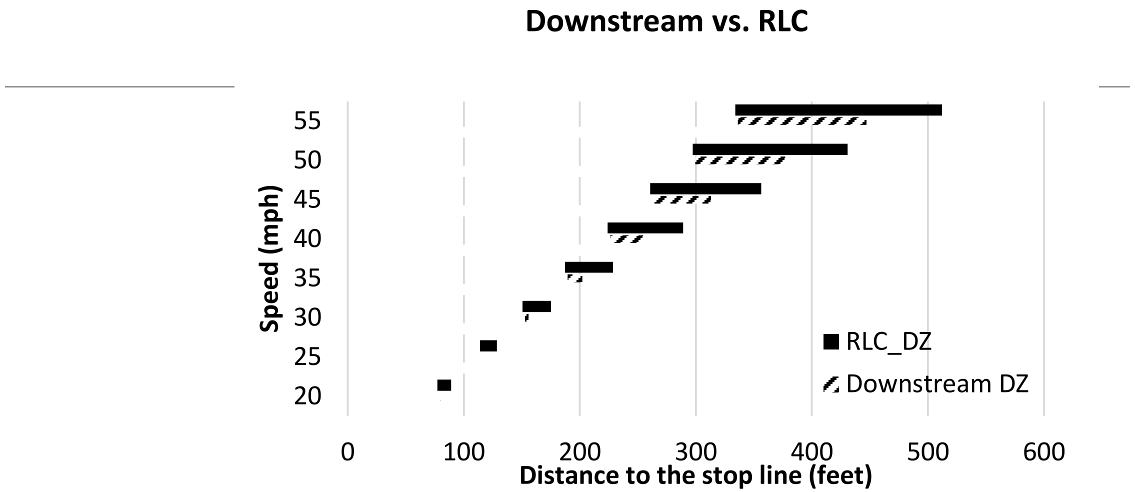
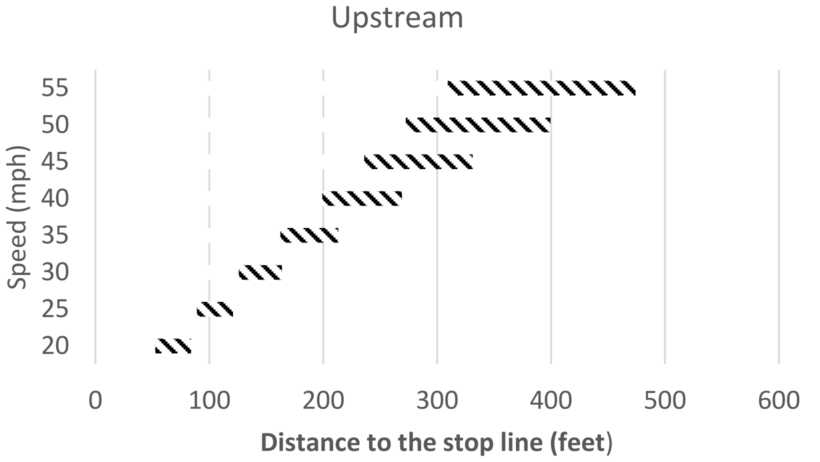
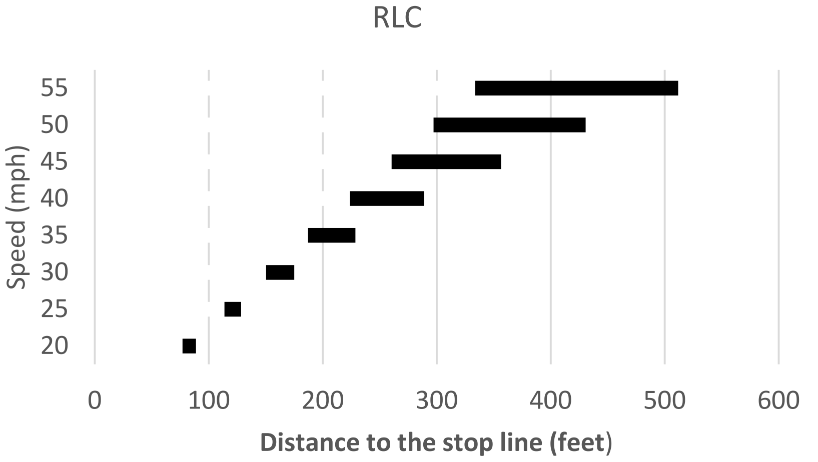
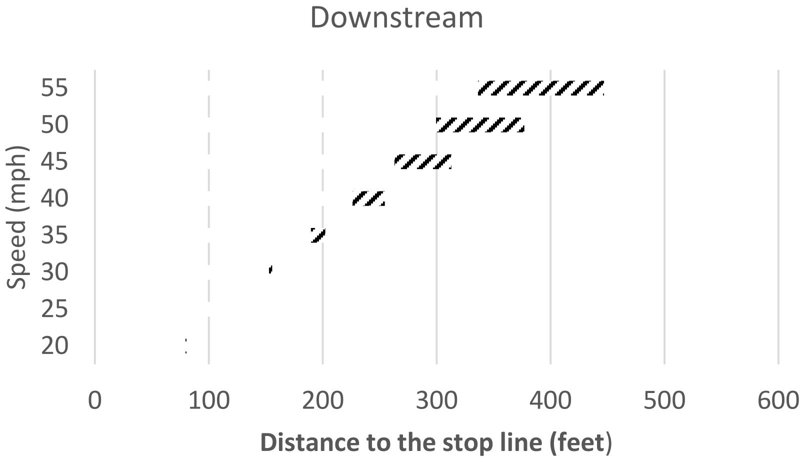


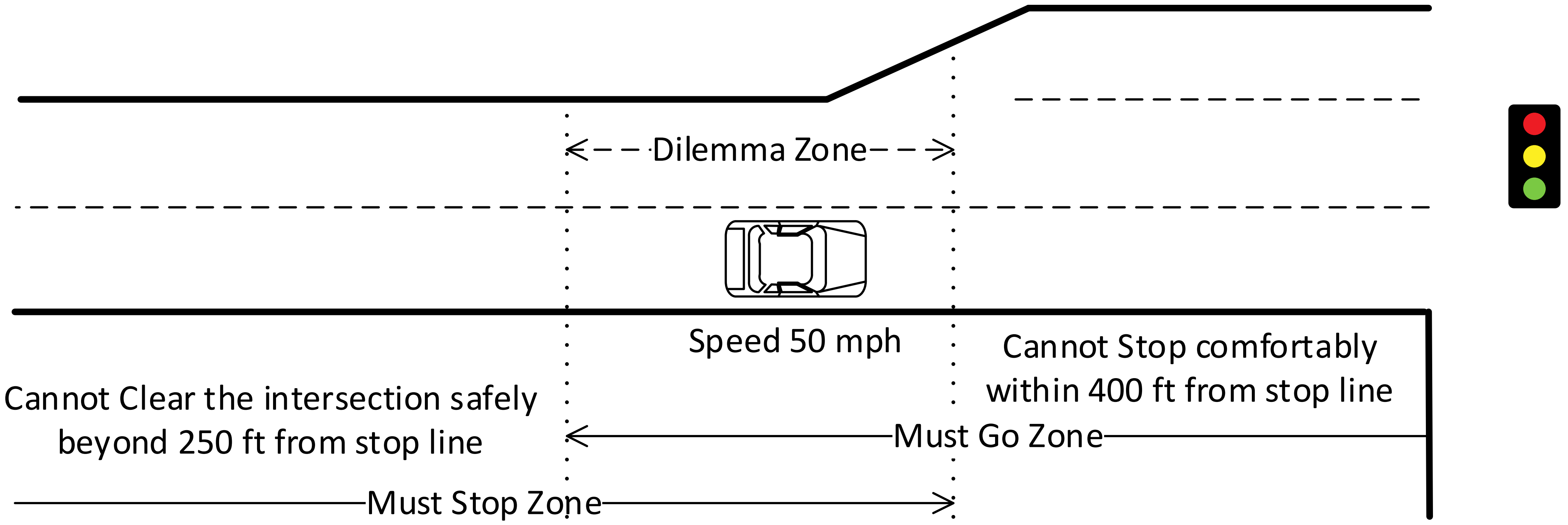
Illustration of the recomputed dilemma zones after the RLC deployment







Dilemma Zone Distribution



Number of vehicles making "inappropriate" decisions (during the yellow phase)

Site	intersection	Choose to stop within their "Must-Go" Zone (rear-end collision)	Choose to pass within their "Must-Stop" Zone (angled crash)	No. of vehicles trapped in DZ	Total No. of vehicles encountering the yellow phase
MD 650 (Effective)	Upstream	0.4% (1)	5.9% (15)	23.7% (60)	253
	RLC	12% (32)	0.7% (2)	6.7% (18)	267
	Downstream	6.1% (12)	2.3% (5)	5.1% (10)	196
US 301 (Ineffective)	Upstream	0.5% (2)	0.9% (4)	**30.1% (131)**	435
	RLC	3.9% (21)	1.3% (7)	**37.4% (202)**	540
	Downstream	2.4% (7)	4.7% (14)	**27.0% (80)**	296

- ***More vehicles in the ineffective*** RLC intersection ***trapped in the dilemma zone***, compared to the effective RLC intersection
- Some vehicles at the RLC intersection ***choose to "Stop" within their "Must-go" zone***. Such inappropriate decisions **may result in potential rear-end crashes**

Observing drivers taking the “passing” decision during the yellow phase -1

- **MD650 (Effective site): (N = 270, 7 Red-Light-Running Vehicles)**
  - **2.69%** cross the stop line after the onset of the all-red phase (***vs. 3.8% at ineffective site***)
  - 15.77% cross the stop line within 1 second prior to the all-red phase
  - 36.15% cross the stop line within 2 seconds prior to the all-red phase
- **US301 (Ineffective site): (N = 79, 3 Red-Light-Running Vehicles)**
  - **3.8%** cross the stop line after the onset of the all-red phase
  - 15.19% cross the stop line within 1 second prior to the all-red phase
  - 39.24% cross the stop line within 2 seconds prior to the all-red phase

Observing drivers taking the "passing" decision during the yellow phase -2

- **For those drivers decide to pass the intersection after encountering a yellow phase at US301 (ineffective site)**
- **Upstream: (N=76)**
  - **9.21%** after the onset of the all-red phase (7 Red-Light-Running vehicles)
  - **31.58%** within 1 second prior to the all-red phase
- **RLC: (N=79) – *reduce the red-light-running percentage (3.8% vs. 9.21%)***
  - **3.8%** cross after the onset of the all-red phase (3 Red-Light-Running vehicles)
  - **15.19%** cross within 1 second prior to the all-red phase
- **Downstream: (N=28) – spillover impact exists (3.57% vs. 9.21%)**
  - **3.57%** cross after the onset of all-red phase (**1** Red-Light-Running vehicles)
  - **17.86%** cross within 1 second prior to the all-red phase

Residual impacts can be observed from the percentage of red-light-running vehicles

Observing drivers taking the “passing” decision during the yellow phase -3

- **For those drivers decide to pass after encountering a yellow phase at MD650 (effective site)**
- **Upstream: (N=163)**
  - **3.07%** after the onset of the all-red phase (5 Red-Light-Running vehicles)
  - **17.18%** within 1 second prior to the all-red phase
- **RLC: (N=270) *reduce the red-light-running percentage* (3.07% vs. 2.69%)**
  - **2.69%** after the onset of the all-red phase (7 Red-Light-Running vehicles)
  - **15.77%** within 1 second prior to the all-red phase
- **Downstream: (N=146) spillover impact exists (3.07% vs. 2.74%)**
  - **2.74%** after the onset of all-red phase (4 Red-Light-Running vehicles)
  - **15.75%** within 1 second prior to the all-red phase

Residual impact can be observed from the percentage of red-light-running vehicles

Research findings: Positive impacts

- RLC's effectiveness and evidences of spillover effects

- **Reduce** the percentage of **aggressive driving behaviors** at the RLC and its downstream intersections;
- Pressure more drivers to **reduce their speeds** when **passing the RLC** and its downstream intersections during the yellow phase;
- **Encourage more drivers** under the same conditions to take **the "stop" decision** during the yellow phase at the RLC and its downstream intersections; and
- **Decrease** the percentage of **red-light-running vehicles** and the aggressive passing action of drivers (i.e., entering the intersection one second ahead of the all-red phase) at the RLC and its downstream intersections.

Research findings: Negative impacts
- May increase rear-end collisions at some RLC sites?

- May cause some drivers to make improper decisions such as taking a "stop" decision in the "must-go" zone, or exercising the "passing" action in the "must stop" zone; and
- Increase the percentage of drivers in the "must go" zone to take the "stop" action when compared with the same statistics observed at RLC's upstream and downstream intersections.
  - Making the "stop" decision at the "must-go" zone. (12% at MD650; 3.9% at US301)
  - The percentage of drivers taking such wrong decisions at the RLC intersection (e.g., 12% at MD650) is higher than that at the upstream (0.4%) and downstream intersections (6.1%)

Research findings:

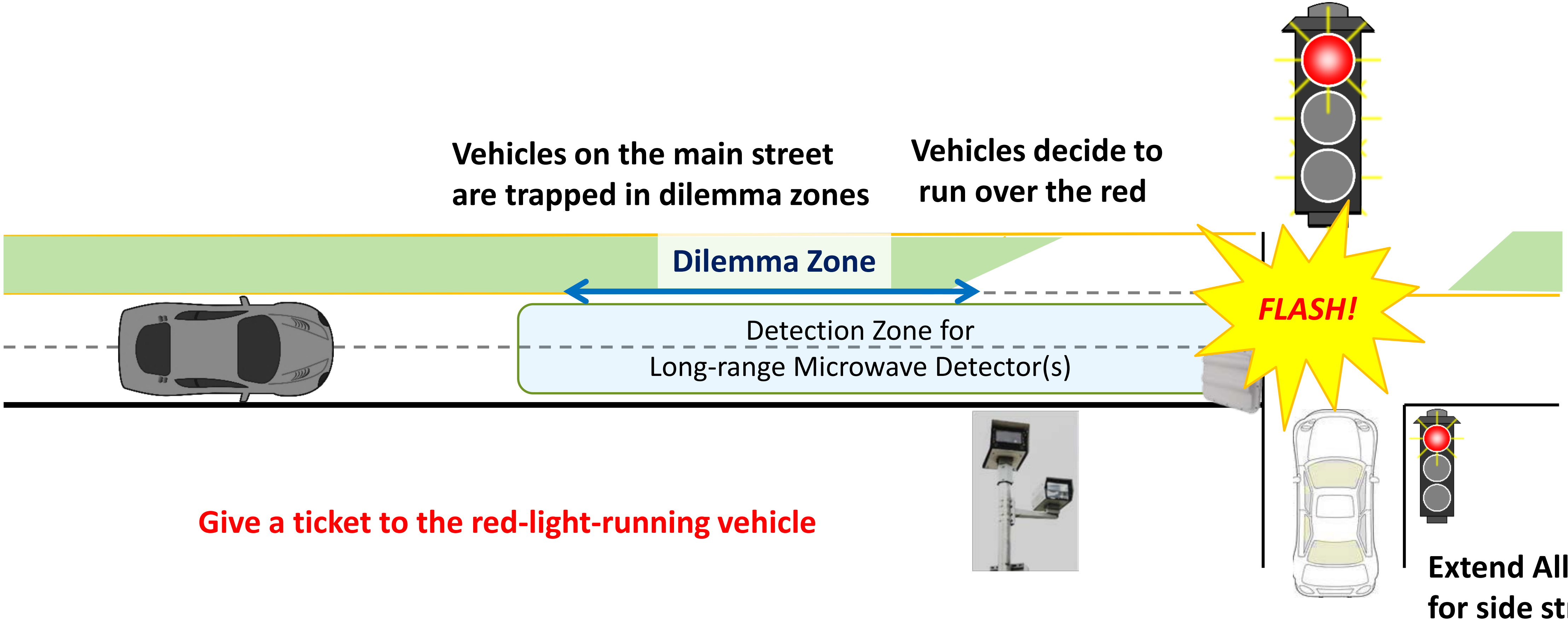
- Compare the RLC effective with ineffective intersections

- Much lower percentage of aggressive drivers (e.g., 9.62% vs. 39.81%);
- A higher percentage of drivers reducing the speed when passing the intersection;
- More significant "spillover" impacts, especially on the percentage of drivers taking the "stop" decision under the same conditions;
- Lower percentage of drivers trapped in the dilemma zone; and
- Relatively low percentage of red-light-running drivers.

Recommendations:

- More empirical observations to have definitive findings and for developing the operational guidelines.
- Need a more effective design to prevent the rear-end collisions.

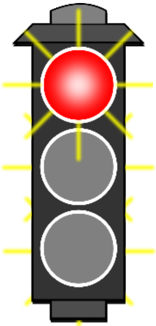
Design 1: Red-Light Camera with Dilemma Zone Protection System: **Reduce** angled crashes



Design 2: Red-Light Camera with Dilemma Zone Advisory System

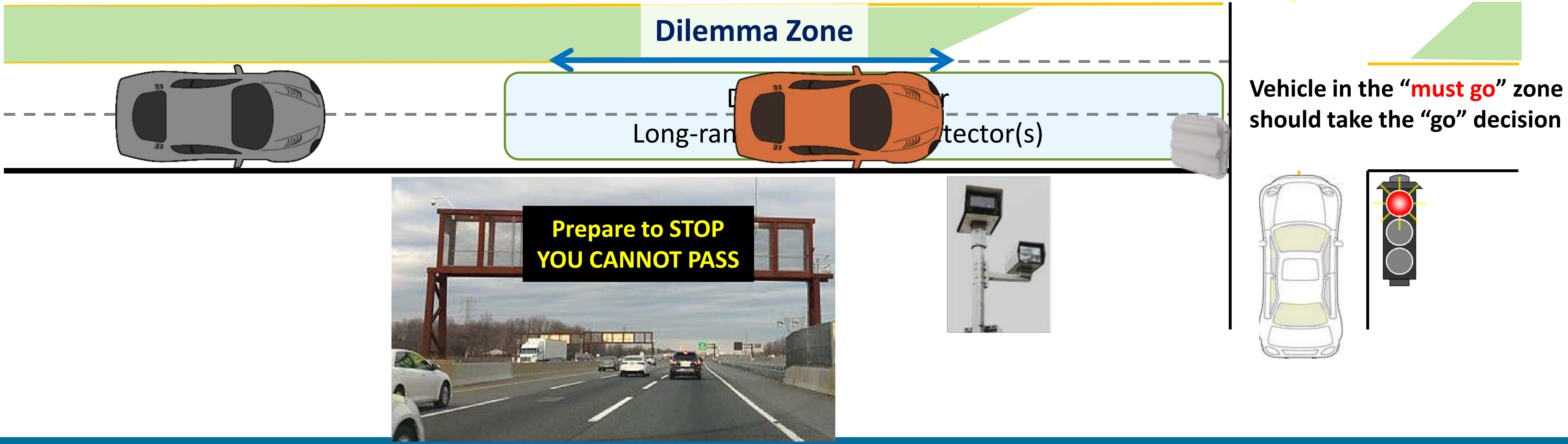
Dilemma Zone Advisory System

- **Reduce** both angled and rear-ended crashes



Vehicles encountering a yellow phase

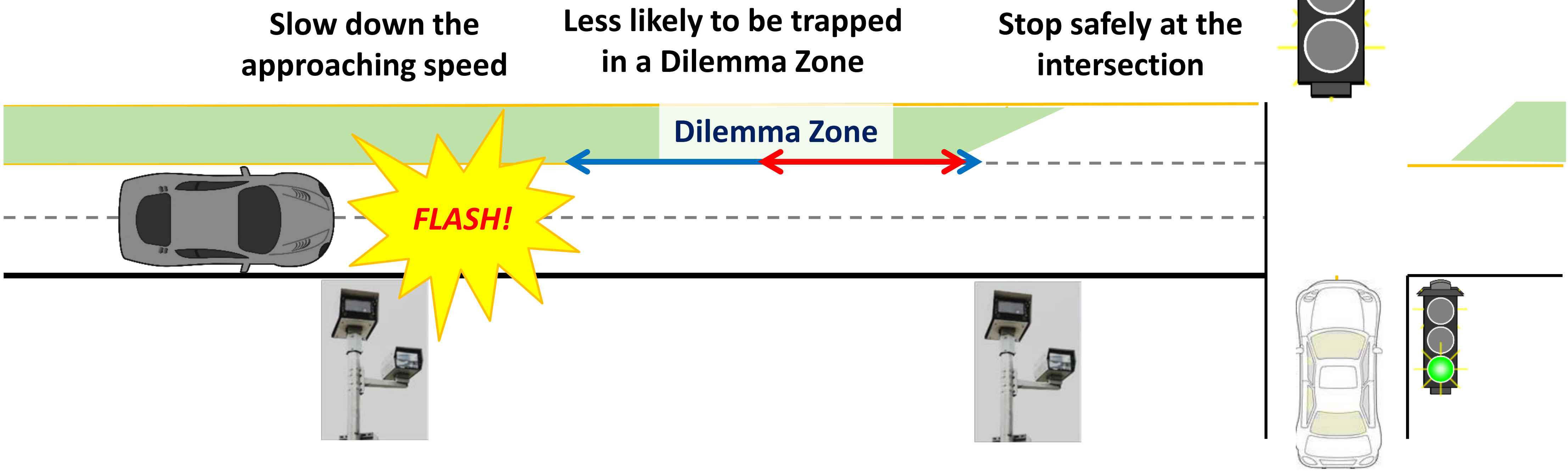
Advise vehicles in "must-stop" zone to take the "stop" decision



Design 3: Red-Light Camera with Automated Speed Enforcement

RLC with Automated Speed Enforcement

- **Reduce** both **angled** and **rear-ended** crashes



Design 4: Red-Light Camera with Dilemma Zone Protection System and Variable Message Sign

Dilemma Zone Protection System with Variable Message Sign

- **Reduce** both **angled** and **rear-ended** crashes
- Promote **progression** through the intersection