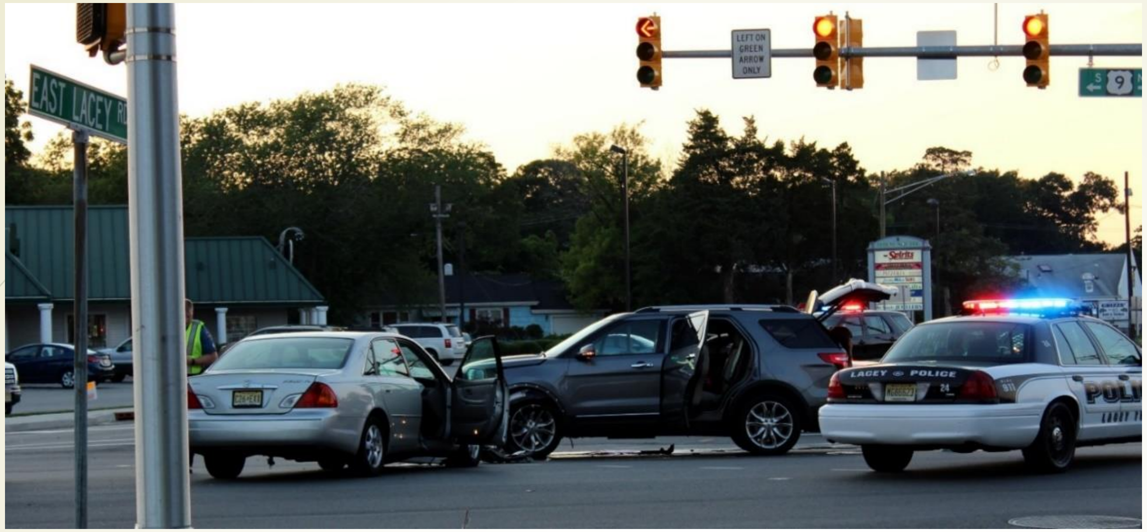

Design, Deployment, and Evaluation of the Dilemma Zone Protection System

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Types of the Intersection Accidents?

(Source: U.S. Department of Transportation, National Highway Traffic Safety Administration.)

Rear-End

32.4%

Source: http://crownheights.info/accidents/page/4/

Side-angle

21.2%

Source: https://www.autobody-review.com/shop/10162/david-maus-collision-center/article/3180/steering-clear-of-the-yellow-light-trap

Side-Swap

11.7%

Source: http://www.insurancefraud.org/scam-alerts-staged-crash.htm

Pedestrians/cyclist

2%

Source: http://www.dailymail.co.uk/news/article-3335035/So-wrong-time-Cyclist-colliding-pedestrian-sparks-new-debate-taxi-video-divided-internet.html

Majority of the Intersection Accidents

Vehicles running on the red phase

-OR-

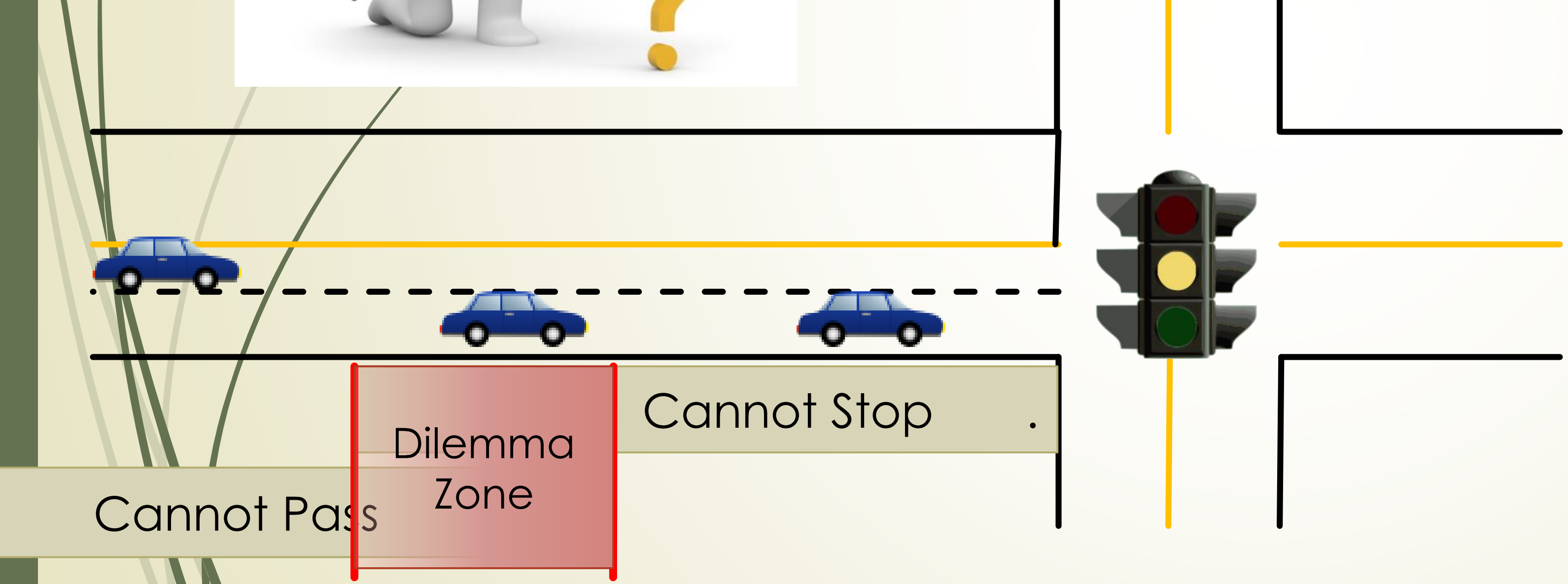
53.6%

Vehicles making hard breaking at the intersection

Source: http://www.sheepsheadbites.com/2012/09/while-dot-studies-another-accident-on-bedford-avenue-and-emmons-avenue/v

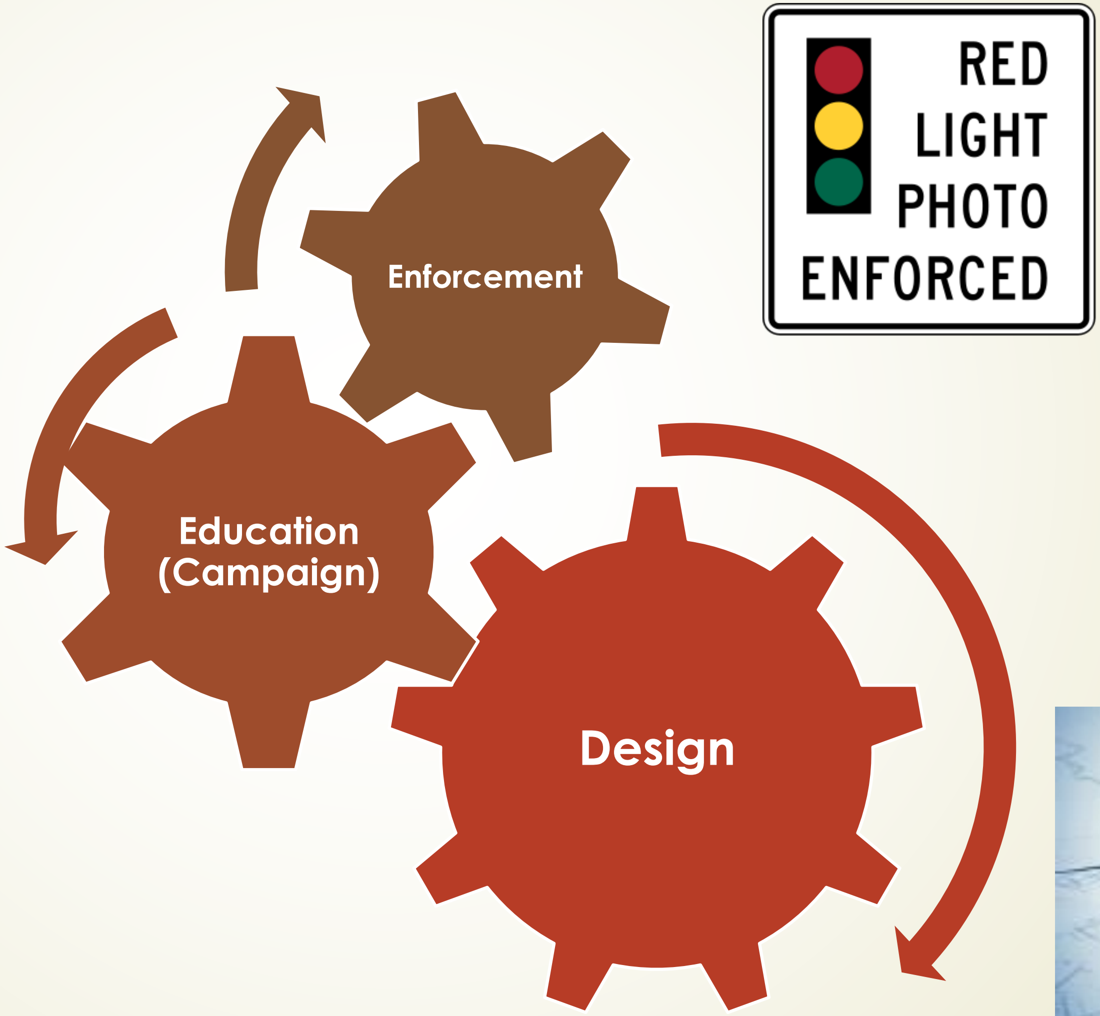
Source: http://crownheights.info/accidents/page/4/

Contributing Factors to Intersection Accidents ?



- **Potential contributors to Dilemma Zone related accidents**
  - **Insufficient duration of the yellow phase**
  - **Aggressiveness of drivers**
    - **High speed**
  - **Short sight distance**
  - **Driver's characteristics**
    - **PRT, age, gender**
  - **Deceleration rate of vehicles**

How to Prevent Accidents?



Challenges from the Design Perspective

- How to improve intersection safety from both preventive and reactive perspectives to minimize both rear-end collisions and side-angle crashes?
- How to consider the tradeoff between intersection safety and operational efficiency?
- How to best use hardware and software devices for intersection dilemma zone to reduce signal delay and improve progression?

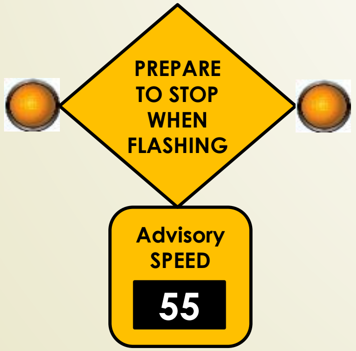
Research Objectives

- Design, deploy, and evaluate a dilemma zone protection system for high-speed suburban intersections
  - Proactively slow down approaching vehicles
  - Reactively prevent side-street vehicles from crashing with red-light running vehicles

Functional Requirements for the DZPS

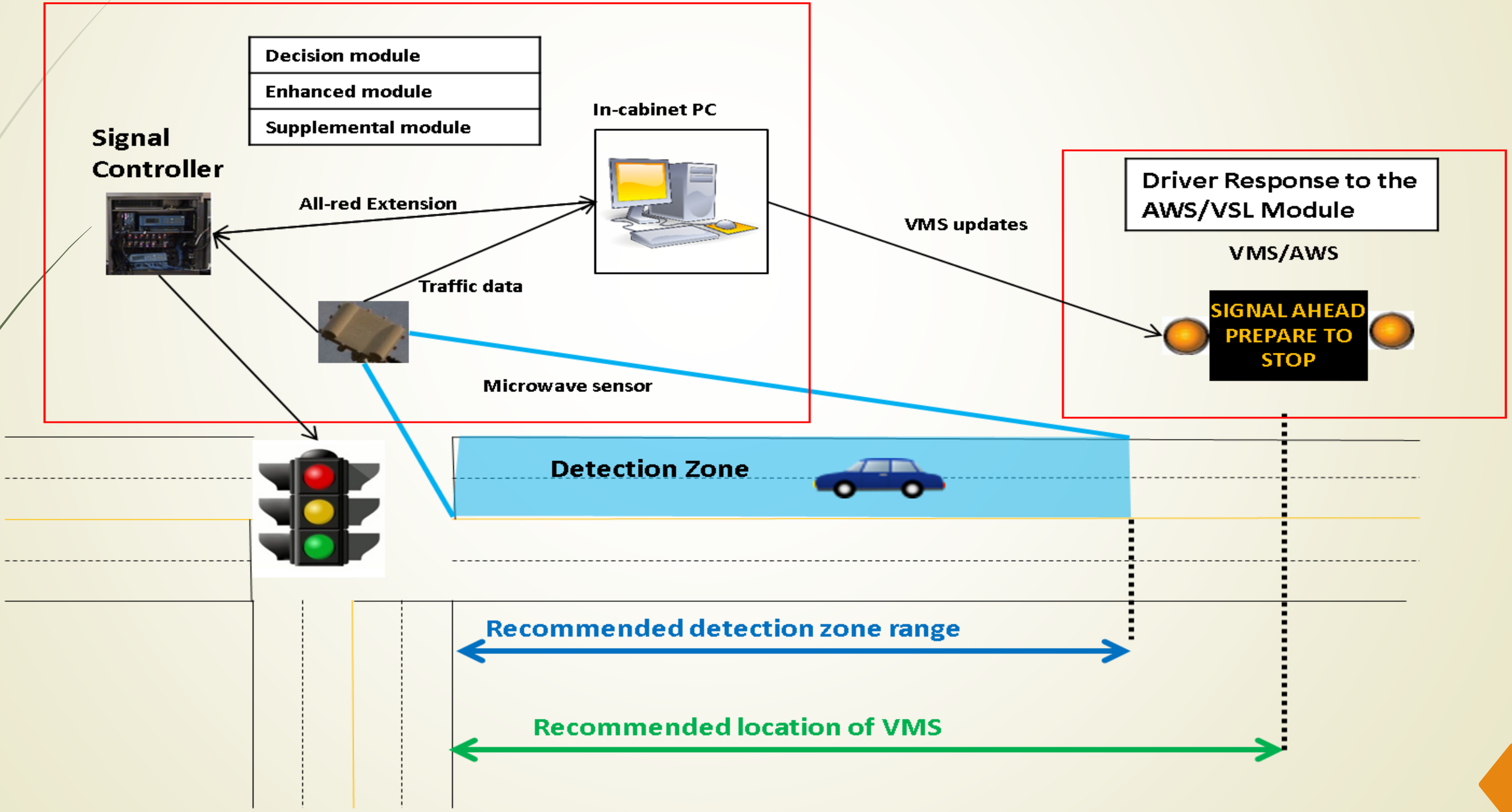
- Provide **Real-time** traffic information within a monitoring zone **(tracking each individual vehicle's speed and location)**
- **Identify** potential red-light running vehicles
  - Predict a driver's reaction to the yellow phase
- Extend an **all-red phase** to identified red-light running vehicles
  - Reactive control strategies to prevent aggressive drivers from side-angle crash
- Provide **advanced warning message** to approaching vehicles
  - Proactive control strategies to slowdown speeds of approaching vehicles

Proposed Key Components of the DZPS



- **Wide-range traffic monitoring sensors**
  - Provide speeds and locations of all vehicles within the monitoring zone
  - Update the traffic data at the interval of every 0.1 seconds
- **Signal Controller**
  - Signal Controller with an all-red extension function
- **In-cabinet Computer**
  - Receives traffic data from sensors and signal controller to execute all-red extension or to activate AWS/VSL
- **AWS/VSL**
  - Provide information on the signal status or downstream intersection conditions

System-I: All-Red Extension with Advanced Warning Signs/Variable Message Signs



Key Tasks for the System-I Design

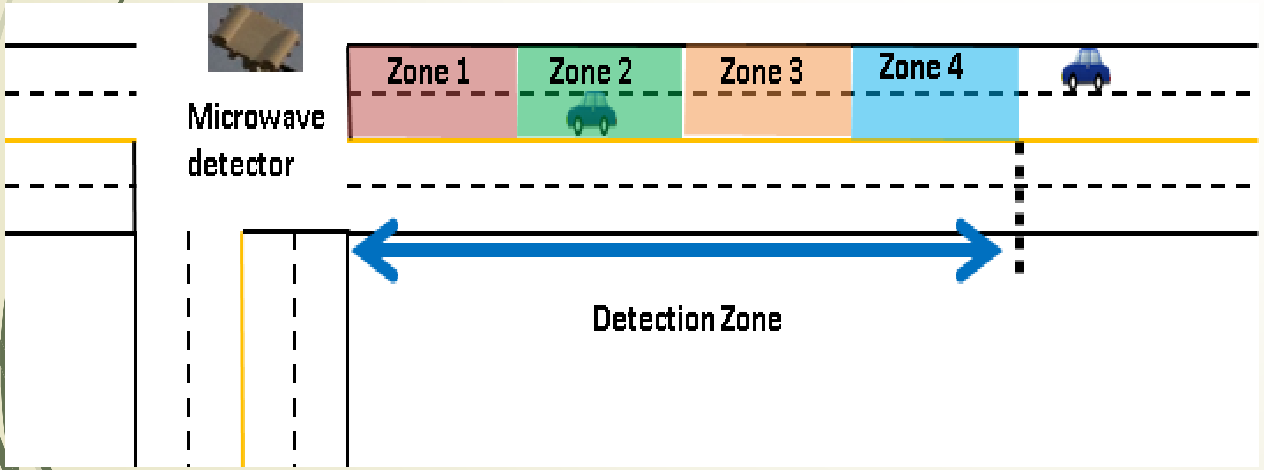
- Develop an **all-red extension algorithm**
  - **Identify** potential-red light running vehicles
- **Pre-deployment** analysis
  - Develop a **simulation platform**
  - Analyze potential **issues**
  - Evaluate the **system performance**
- **Post-deployment** analysis
  - Analyze **field data**
  - Evaluate **system performance**

All-Red Extension Algorithm 1 (individual-based)

- **Step 1**
  Identify which vehicles are trapped in their respective dilemma zones based on their speeds and locations detected by the deployed wide-range sensors
- **Step 2**
  Calculate the required clearance time for each vehicle trapped in its DZ to pass the intersection
- **Step 3**
  Estimate the probability for vehicles identified in step 1to take the passing decision
- **Step 4**
  Identify vehicles with a passing probability greater than the preset threshold
- **Step 5**
  Find the maximum required clearance time among all vehicles identified from step 4
- **Step 6**
  Compute the all-red extension based on the maximum clearance time calculated from step 5
- **Step 7**
  Onset of the red phase, identify vehicles cannot stop safely, and
  Compare all-red extension duration and update if necessary

All-Red Extension Algorithm 2 (Zone Based)

- Compute the **optimal duration of all-red extension,** from a macroscopic perspective, based on the **spatial-temporal** evolution of vehicles in the monitoring zone
- **Reduce the potential false alarm rate** (unnecessary all-red extension)



<Critical relations btw neighboring traffic zones>

- ***The decision of a following vehicle will be affected by the decision of leading vehicles***
- ***If 1) vehicles in the leading zone(s) decide to stop at the intersection***
  AND
  2) the vehicles travelling on the leading zone(s) occupy both lanes
- ***Then the following vehicles are more likely to select the "stop" decision***

Pre-Deployment Assessment

- **Purpose:**
  - **Identify issues prior to the field deployment**
- **Tasks:**
  - Collect **field data**
  - Develop a **simulation platform for experimental analysis**
  - Validate an **all-red extension algorithm**
  - Identify potential issues

Simulation Platform?

- **Evaluate** the effectiveness prior to the deployment
- **Identify** potential deployment issues
- **Validate** of the developed algorithms
- **Provide data** for experimental analysis
- **Cost effective**
- **Ensure the success of the deployed DZPS**

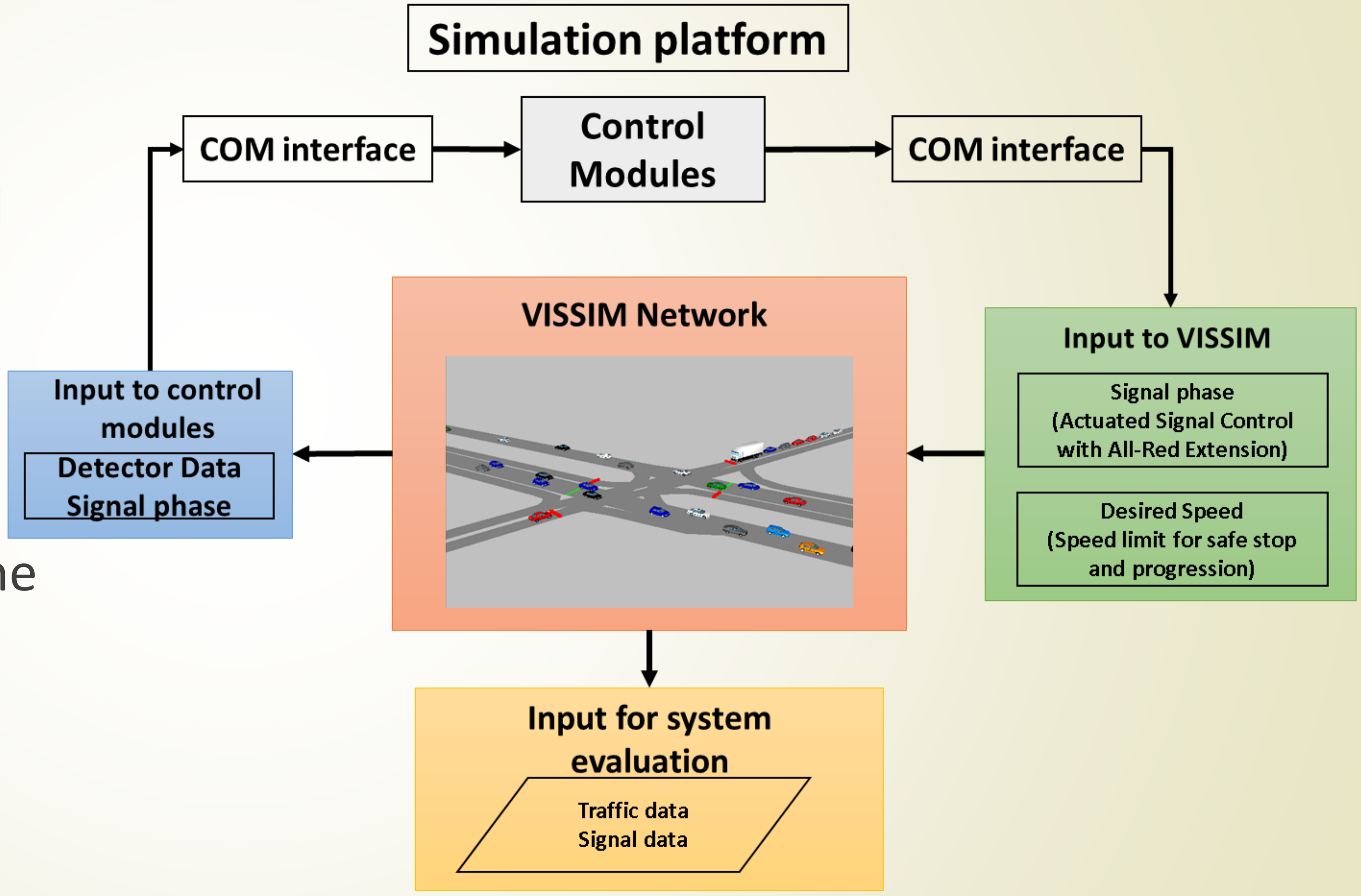
Challenges for Developing the Simulation Platform

- How to **replicate** the driving behaviors?
- How to **implement** drivers' responses to the yellow phase in the simulator?
- How to **replicate** the functions of a wide-range traffic monitoring sensor?
- How to **simulate** the impacts of the VMS/VSL/AWS on drivers?
- How to **simulate** the operations of an all-red extension?
- How to **predict** the gap-out timing?

Development of the Simulation Platform

Objectives

- Replicate the real-world traffic distributions and driver characteristics
- Integrate all key components of the proposed system into the simulation platform for experimental analysis
- Evaluate the resulting effectiveness on safety improvement



Data flowchart in the Simulation Platform

Embedded Components in the Simulation Platform

Simulation Platform Components

VISSIM Network

- Geometric features
- Traffic flow rate
- Driving behaviors
- Reactions to the yellow signal

Control Module

- Wide-range traffic monitoring sensors
- Advanced warning sign/advisory speed sign
- Response to the AWS/advisory speed sign
- Signal Controller (signal phases, logic, and all-red extension)
- Advisory speed module
- Queue evolution module

Key Calibration Results

Traffic Characteristics

	Field	Simulation
Speed @ **1050** ft (mph)	**57.4** (9.7)	**59.68** (7.5)
Speed @ **650** ft (mph)	**39.9** (8.2)	**41.8** (8.1)
Speed @ **400** ft (mph)	**38.6** (11.4)	**42** (9.4)
Speed @ **200** ft (mph)	**31.3** (14.5)	**32.8** (14.2)
Deceleration rate (ft/s^2) Passenger car / truck	-9.3(3.5)/-7.5(2.12)	-9.7(5.4)
Acceleration rate (ft/s^2) Passenger car / truck	3.6(3.1)/3.5(2.4)	3.05(2.6)

- Simulator has been **calibrated** with field data
  - Spatial distribution of Speeds
  - Acceleration/Deceleration rates

Calibration Results

Driver Responses to the Yellow Phase

<The Percentage of Drivers Taking the “Pass” Decision During a Yellow Phase>

Speed of vehicle on set of yellow	Location of vehicle from stop line onset of yellow									
	0 - 100 ft		100 - 200 ft		200 - 300 ft		300 - 400 ft		400 - 500 ft	
	Field	Final	Field	Final	Field	Final	Field	Final	Field	Final
30-40 mph	100%	100%	86%	61%	21%	21%	2%	0%	0%	0%
40-50 mph	100%	100%	100%	93%	74%	76%	50%	26%	20%	8%
50-60 mph	100%	100%	100%	100%	88%	80%	50%	48%	0%	21%

- Driver responses are close to the field observations
  - 100-400 feet
  - 40-60 mph

Simulation Scenarios

- **Base scenario: No DZPS**
  - Base line for comparing the performance of different DZPS algorithms
- **Scenario 1: Base algorithm**
  - Divide the detection zone into two zones
  - If a vehicle running at the speed greater than 27 mph in the first zone or a vehicle running at the speed greater than 56 mph in the second zone is detected during the all-red phase, then extend the all-red phase.
- **Scenario 2: The Proposed Algorithm-1 (Individual based)**
- **Scenario 3: The Proposed Algorithm-2 (Zone based)**

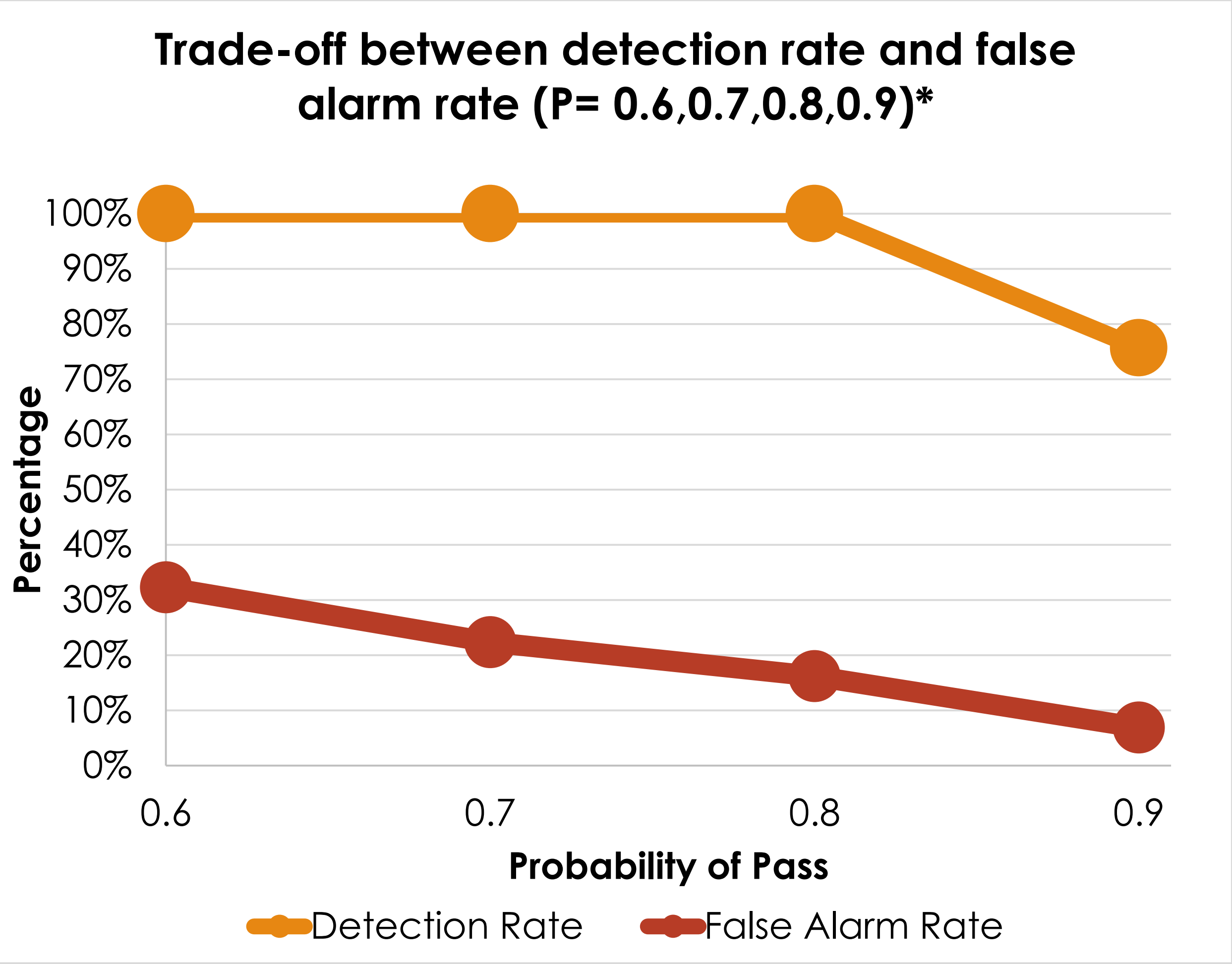
*Each scenario has been simulated 40 hours of simulation

MOEs and Result Analysis

- Algorithm 1 : **100** % detection rate, **21** % false alarm rate
- Algorithm 2: **100** % detection rate, **16** % false alarm rate

MOE	No Control	Default	Algorithm-I (Individual based)	Algorithm-II (Zone based)
Red-light running(RLR) rate (# of RLR vehs / 100 cycle)	8.9	8.9	**9.5**	**9.1**
Extension call rate (extension calls / 100 cycle)	-	52	**30**	**25**
False alarm rate (false alarm frequency/ cycle)	-	47 %	**21 %**	**16 %**
Detection rate (# of protected RLR vehs/ total # of RLR vehs) [4]	-	56%	**100%**	**100%**

Sensitivity Analysis (False Alarm Rate and Detection Rate)

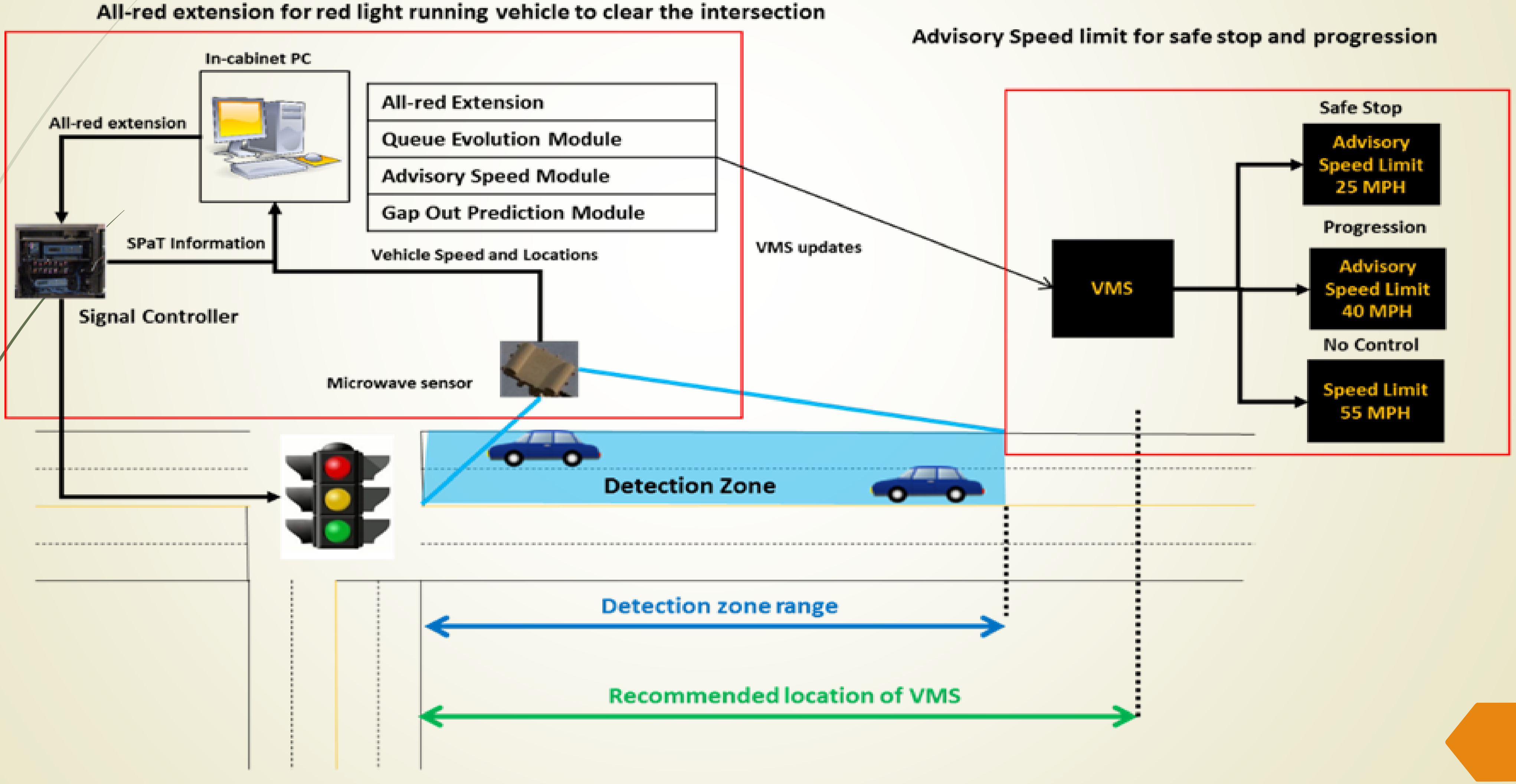


- Trade off between the **false alarm** and **detection rates**
- **Intersection safety is the main objective**
  - P = 0.8 (probability)
  - Detection rate 100%
  - False alarm rate 16%

Enhancements of System-I to System-II

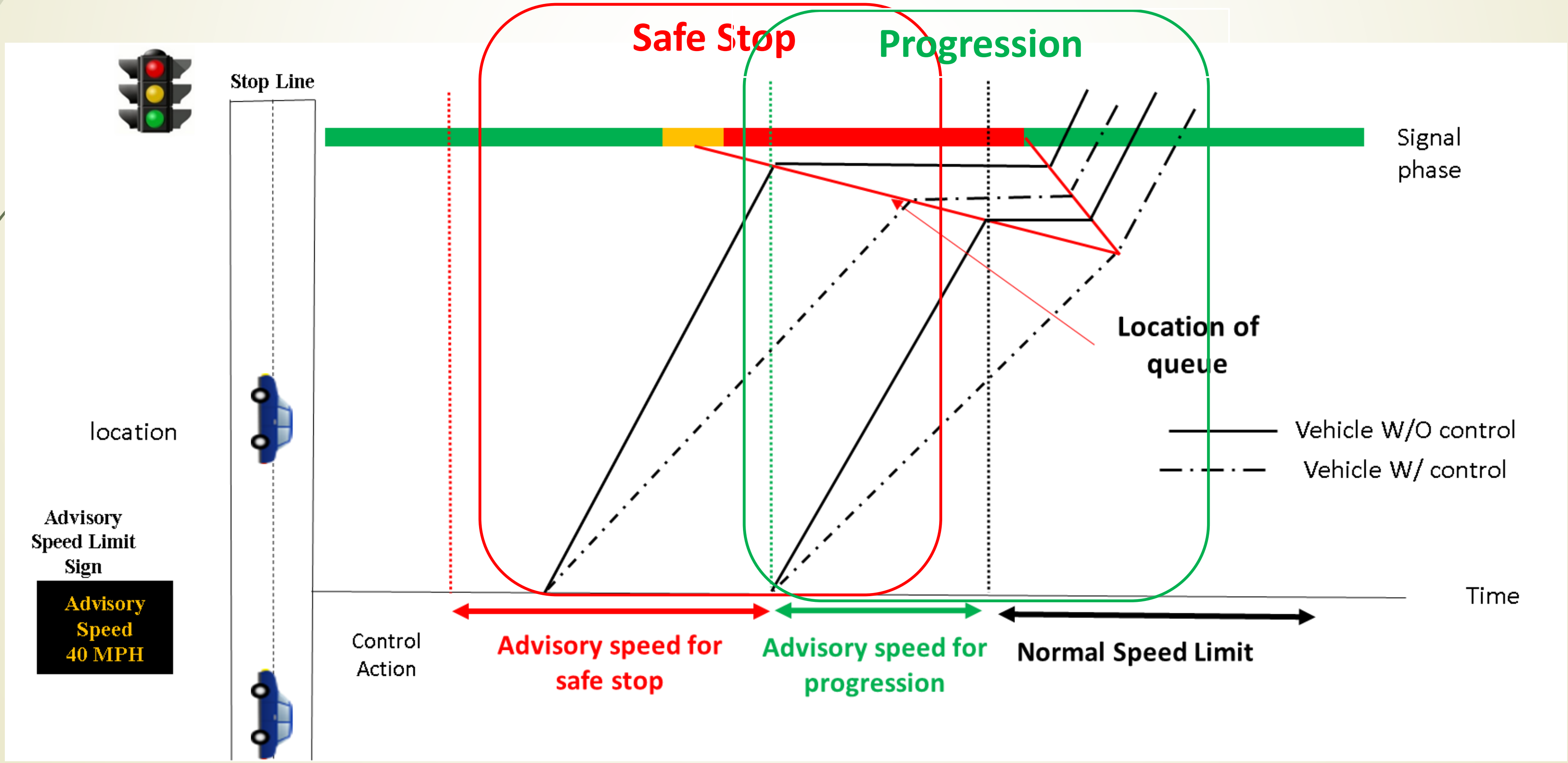
- How to fully utilize existing hardware?
- Can the "warning message" be replaced with an advisory speed?
- Can Safety and mobility be currently improved?
- How to compute the advisory speed?
- Can the "advisory speed" be displayed in advance under the actuated signal control?
  - Development of a gap-out prediction methodology

System-II: An Integrated Intersection Control System for Both Safety and Operational Efficiency



Variable Advisory Speed

- **Provide advisory speed for:**
  - Safe stop to vehicles during the yellow and red phase
  - Progression to vehicles at the end of the red phase or beginning of a green phase

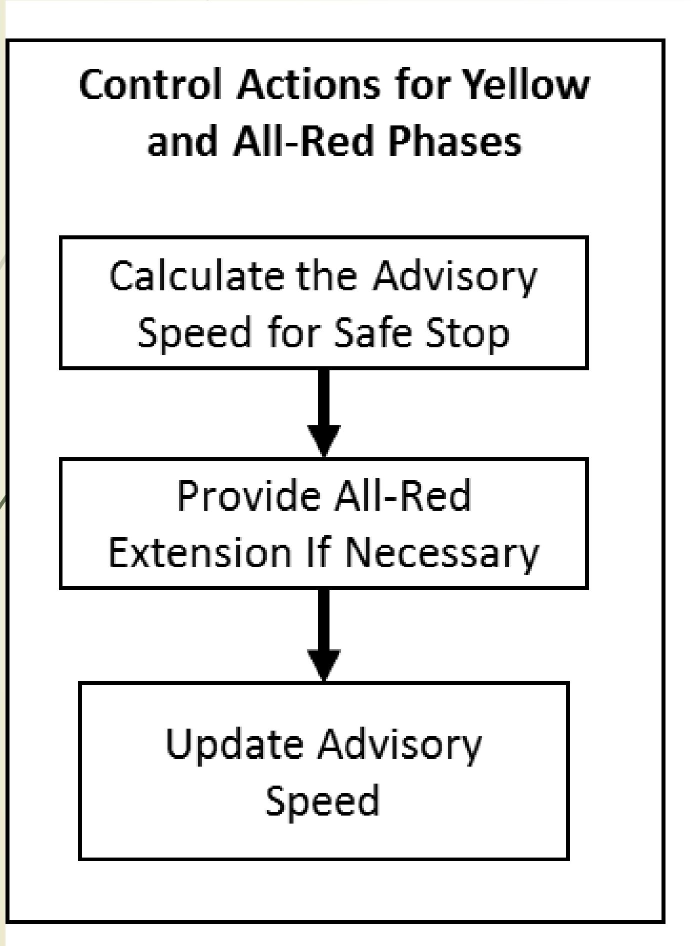


Gap-out Prediction Strategies

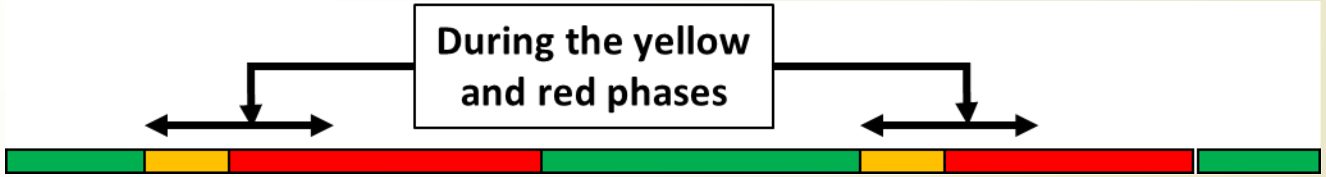
- To estimate the gap-out timing for an **actuated signal control**
- To provide **advisory speeds** for vehicles either arriving at the start or the end of the green (progression and safe stop)

- **Step 1**
  - Calculate the Avg acceleration rate
  - Calculate the current trajectory
- **Step 2**
  - Check for potential conflicts with the leading vehicle
- **Step 3**
  - Estimated the ETA time
- **Step 4**
  - Determine the green termination time by compared with a min green and a max green

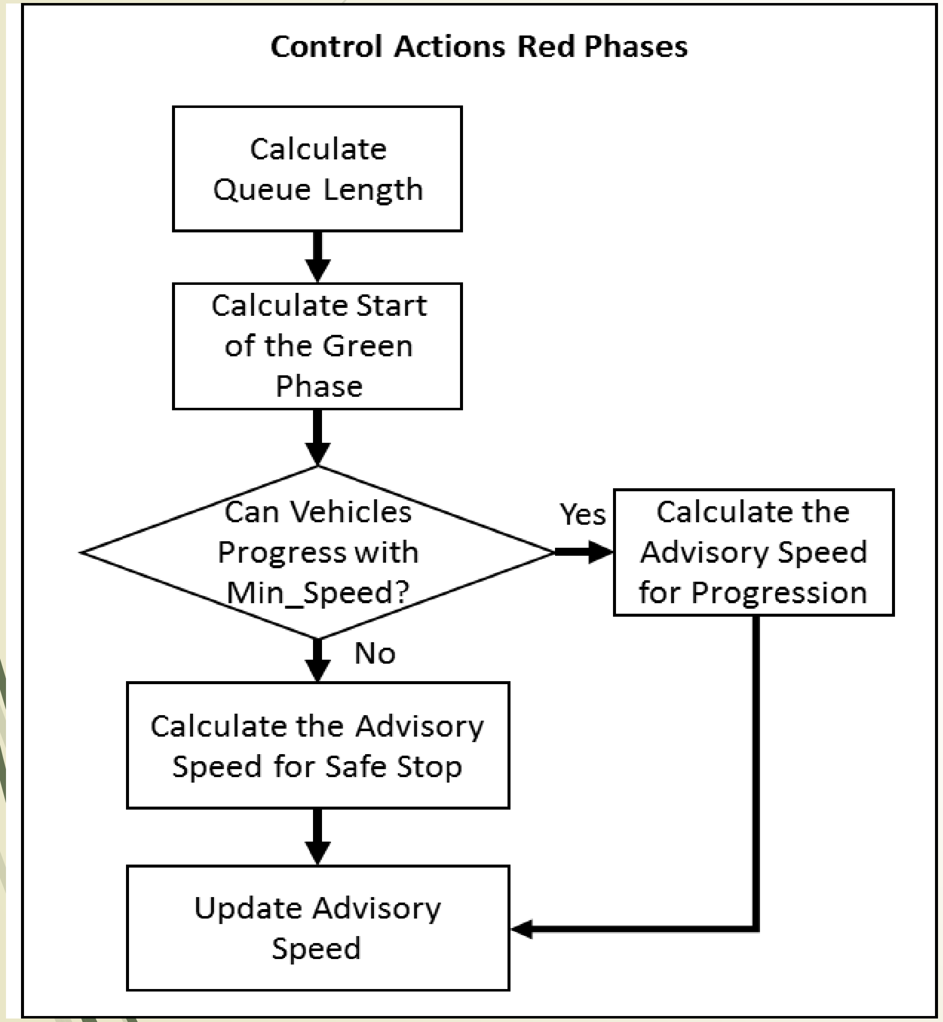
Control Actions (during yellow and red phases)



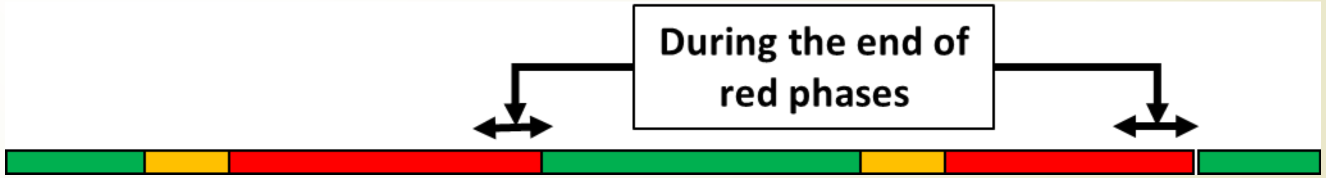
- Case 1: Arriving at the yellow and all-red phases
  - Advisory speed for safe stop
  - All-red extension



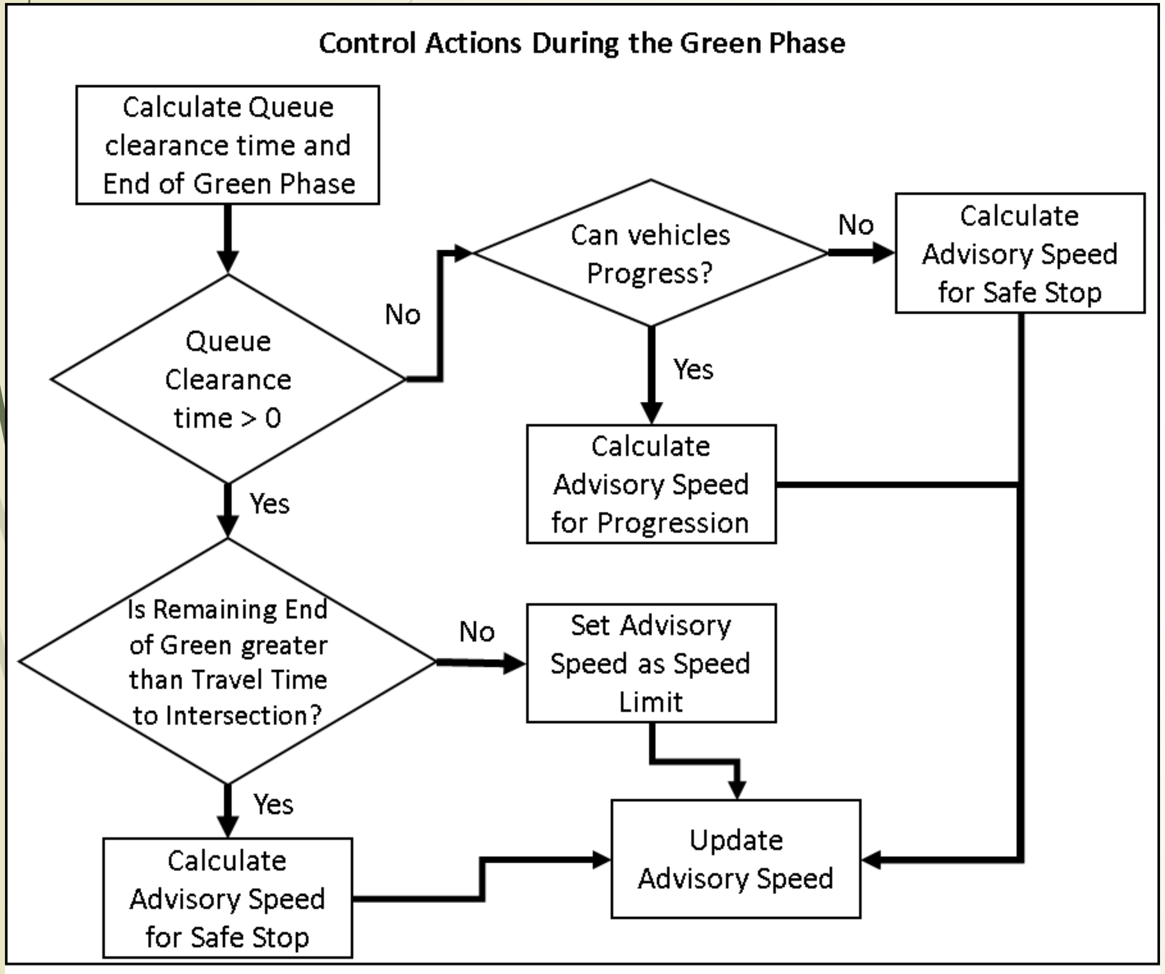
Control Actions (during yellow and red phases)



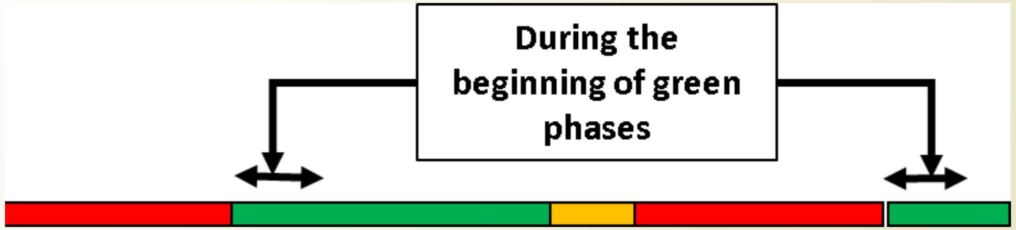
- Case 2: Arriving at the end of a red phase
  - Advisory speed for progression



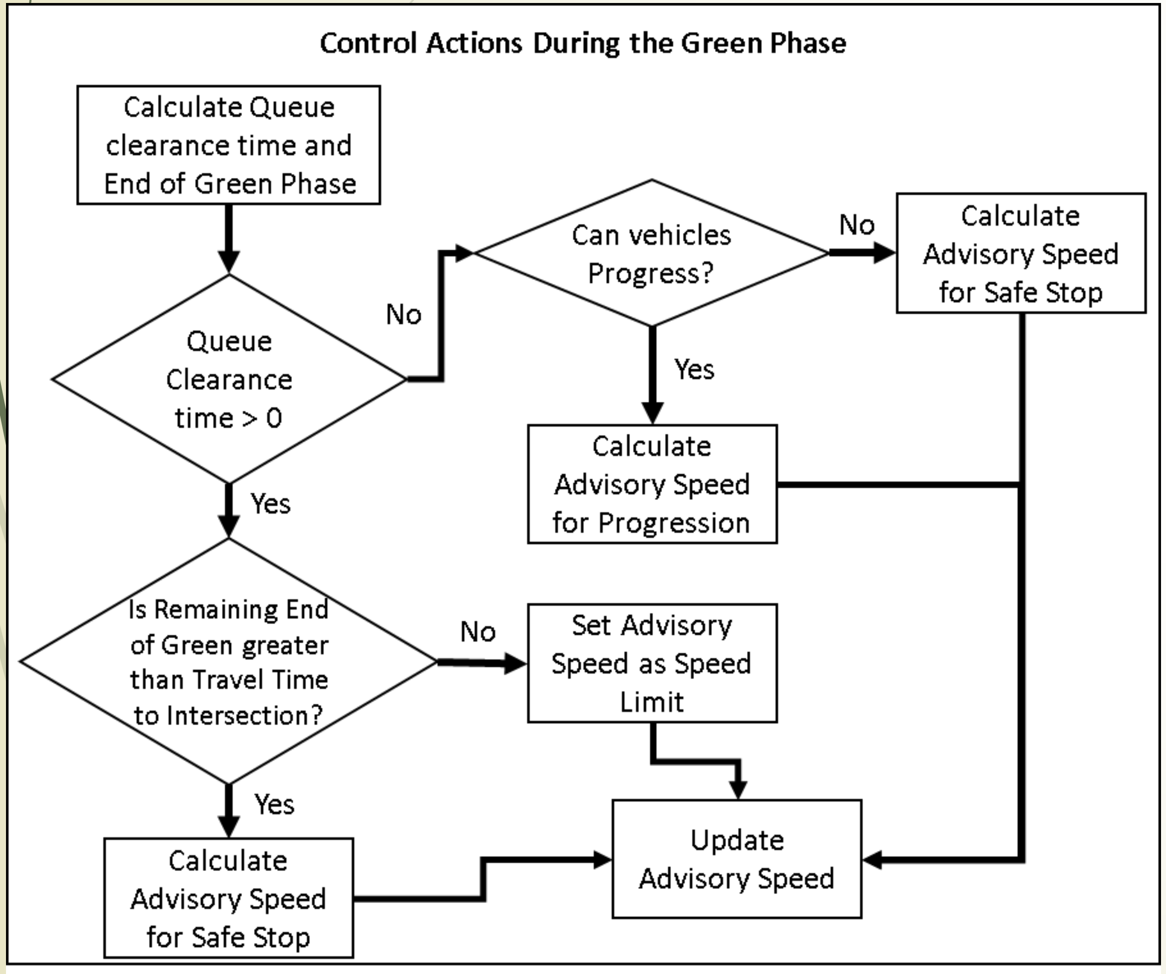
Control Actions (during green phases)



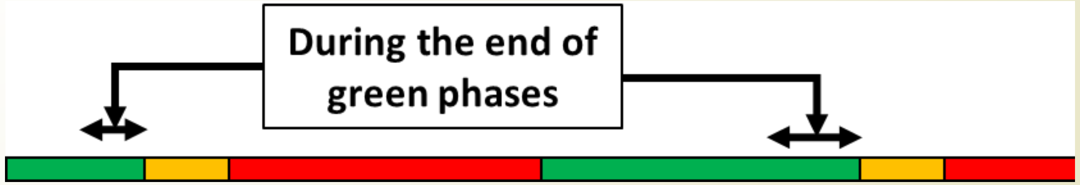
- Case 1: Arriving at the beginning of a green phase and encounter the stop queue
  - Advisory speed for progression



Control Actions (during green phases)



- Case 2: : Arriving at the end of a green phase and encounter the yellow and red phases
  - Advisory speed for safe stop



Experimental Scenarios for simulation analysis

- **Base scenario:**
  - Without any proactive/reactive protection system
- **Scenario 1: System-I only**
- **Scenario 2: System-II**
  - Scenario 2-1: Set the driver compliance rate to 100%.
  - Scenario 2-2: Set the driver compliance rate to 50%.
  - Scenario 2-3: Set the driver compliance rate to 25%.

Result Analysis

- **MOEs for Safety:**
  - Average number of hard-braking vehicles per cycle
  - Total number of vehicles in dilemma zones
  - The average number of red-light running vehicles per cycle (RLR / cycle)
  - Detection rate for red-light running vehicles

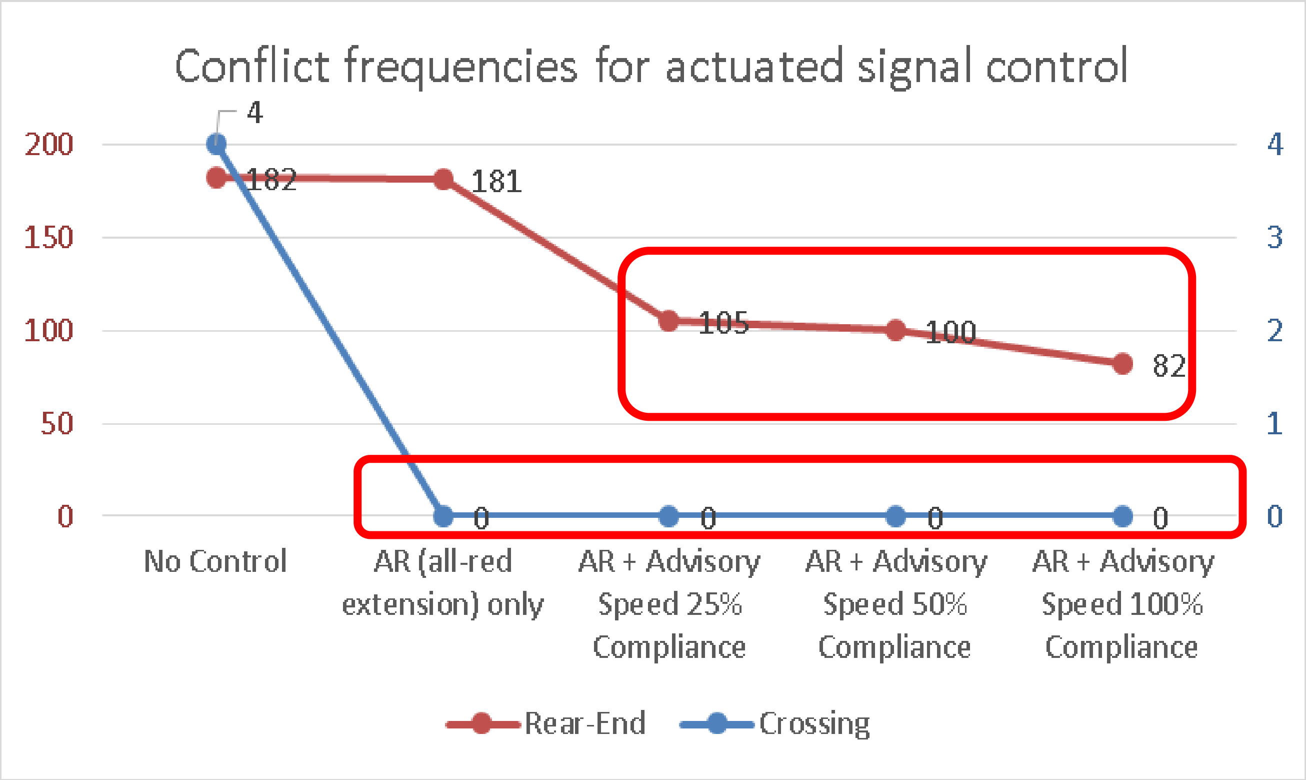
MOEs \ Scenarios		Base Case	All-Red Extension Only (System-I)	All-Red Extension and Advisory Speed (System-II)		
				100% compliance	50% compliance	25% compliance
Safety	Average number of hard-braking vehicles per cycle	0.66 (0.76)	0.66 (0.77)	0.15 (0.18)	0.24 (0.21)	0.29 (0.26)
Safety	Total number of vehicles in dilemma zone	892 (792)	862 (770)	540 (525)	702 (596)	790 (622)
Safety	The average number of red-light running vehicles per cycle (RLR / cycle)	0.11 (0.094)	0.11 (0.097)	0.06 (0.064)	0.08 (0.08)	0.09 (0.087)
Safety	**Detection rate for red-light running vehicles**	**-(-)**	**100% (100%)**	**100% (100%)**	**100% (100%)**	**100% (100%)**

Result Analysis

- **MOEs for Mobility:**
  - The average number of stops per cycle
  - The total stopped delay per cycle
  - The fuel consumption
  - The false alarm rate for the all-red extension protection

Scenarios / MOEs		Base Case	All-Red Extension Only (System-I)	All-Red Extension and Advisory Speed (System-II)		
				100% compliance	50% compliance	25% compliance
Mobility	Average number of stops per cycle	6.4 (6.4)	6.5 (6)	4.2 (4.5)	4.5 (5.1)	4.6 (6.89)
	Average stopped delay for all vehicles per cycle (second)	45.7 (76)	48.6 (77)	38.0 (54)	40.5 (59)	42.1 (63)
	Average fuel consumption per cycle (Gallon)	0.239 (0.24)	0.226 (0.022)	0.13 (0.14)	0.16 (0.15)	0.167 (0.17)
	False alarm rate for the all-red extension	**- (-)**	**14% (16%)**	**5% (4%)**	**10% (7%)**	**12% (7%)**

Further Analysis on Safety - Conflict Frequency Analysis



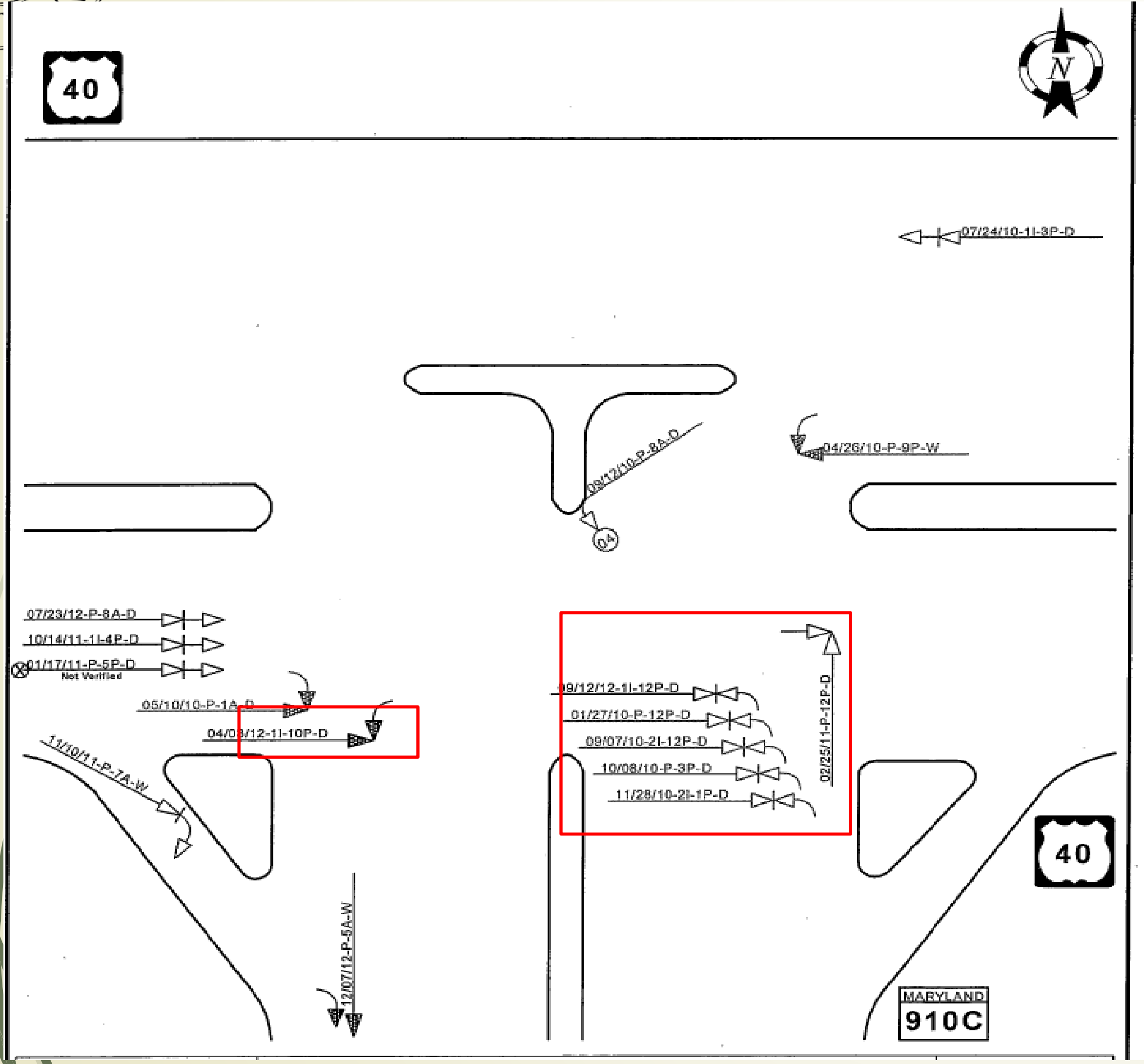
- SSAM (Surrogate Safety Assessment Model)
  - Based on the simulation vehicle data
  - Side-angle, rear-end conflicts
- **Potential side-angle crashes are eliminated**
- **Potential rear-end crashes are reduced with an advisory sign**

Post-Deployment Evaluation for System-I

Location Overview

- US 40@ Western Maryland Parkway
  - 4 -lanes divided highway (US 40), 3 approach lanes for Western Maryland Parkway (2-left, 1-right)
  - Isolated intersection
  - 55 mph speed limit
  - Ramp from I-81 for eastbound
  - 5% HV

Accident History (2011-2013)



Accident history diagram

- 7 crashes potentially related to dilemma zone decisions for 3 years (side-angle crashes)
- 3 injuries

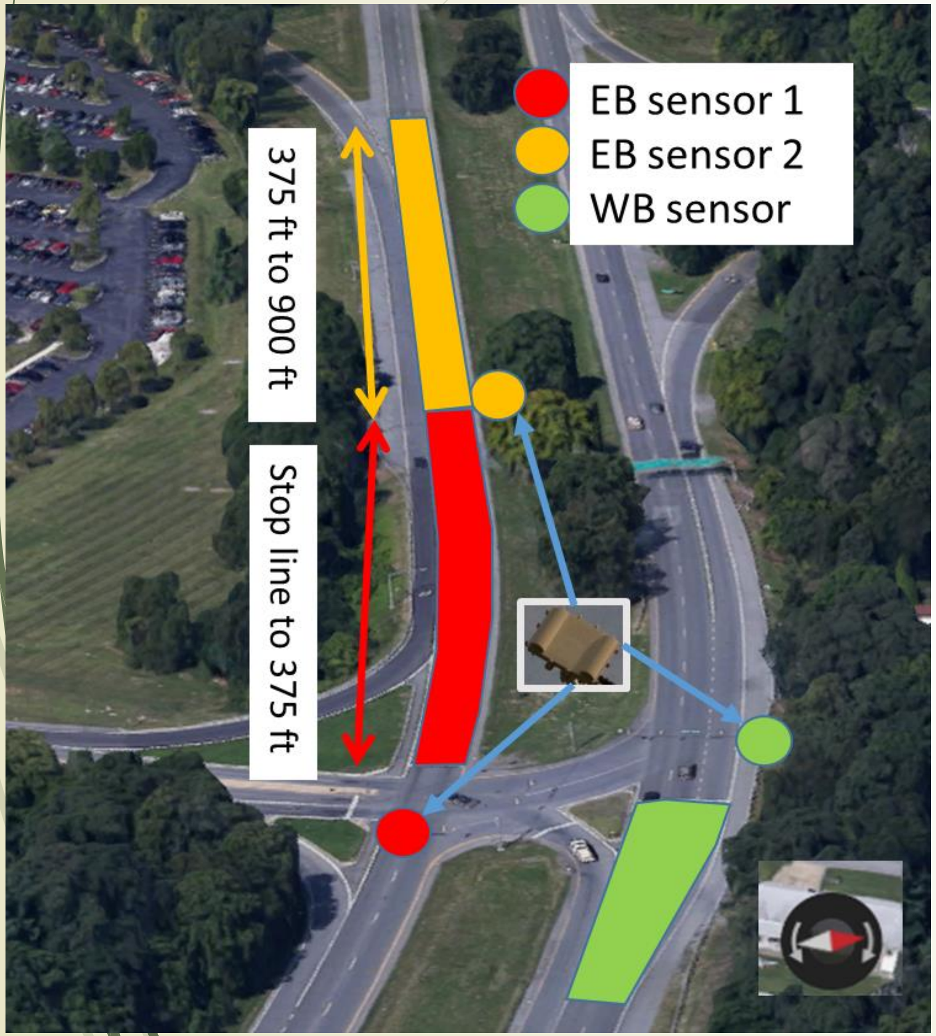
Field Data Collection (before deployment)

900 ft video capture

signal video capture

- 3 video camcorders : 900 ft, 500 ft, and 200ft
- 1 camcorder for monitoring the stop line and the signal
- Data Collection Period: Oct 10th 2014
- Data Processing
  - **Spatial distribution of speeds**
  - **Driver's decision at the onset of the yellow phase**

Field Deployment of the System



- **Two sensors** on EB on US 40
  - EB sensor1:
    - Green Extension, **All-red Extension**
  - EB sensor 2:
    - **All-red Extension**
- **One sensor** on WB on US 40
  - WB sensor:
    - Green Extension

Key deployment Activities

- Check the sensor's functions
  - Validate the speed and location of approaching vehicles with sensor data
  - Checked whether or not the sensor sending proper calls to the signal controller
- Using camcorders record to measure signal timings
- Identify if there are all-red extension calls from the recorded video
- Identify red-light running vehicles
- Compare all-red extensions and red-light running vehicles to identify missed calls, false alarm, and correct calls

Field Data Collection after Deployment

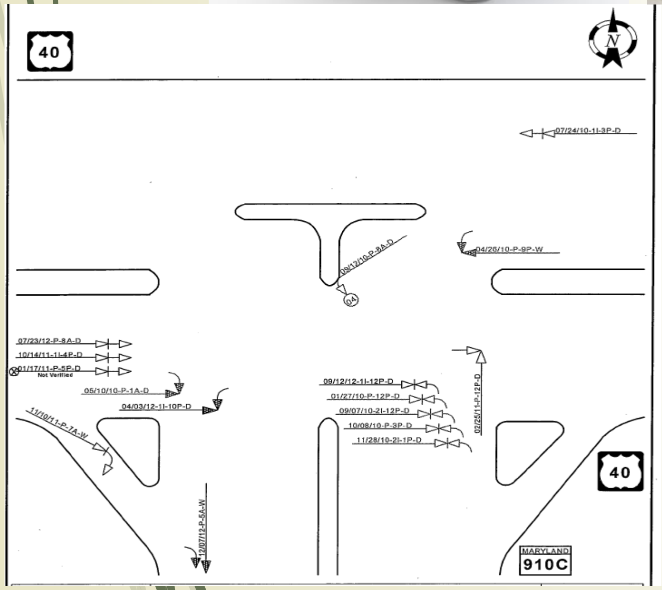
Date	Time	Veh ID	Speed	Location	Signal
10/14/2016	57:56.5	28168	49	465	Green
10/14/2016	57:56.7	28168	49	455	Yellow
10/14/2016	57:56.9	28168	49	445	Yellow
10/14/2016	57:57.0	28168	49	430	Yellow
10/14/2016	57:57.2	28168	49	420	Yellow

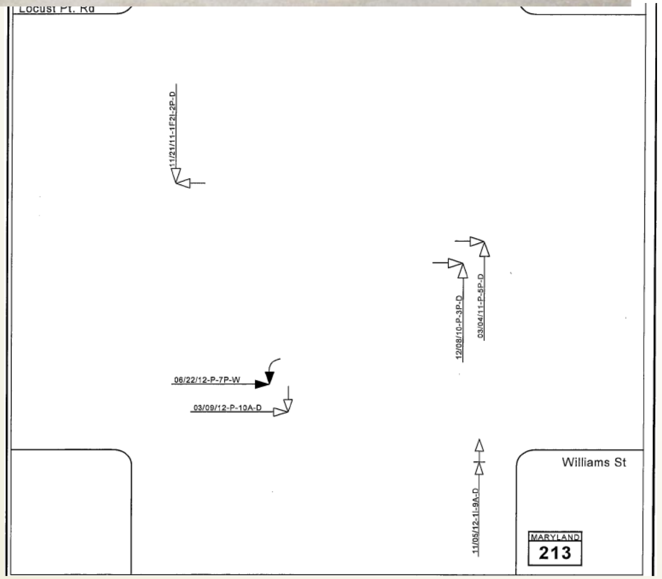
⋮

10/14/2016	58:01.5	28168	46	120	Yellow
10/14/2016	58:01.7	28168	46	115	Red
10/14/2016	58:01.8	28168	46	105	Red
10/14/2016	58:02.0	28168	46	90	Red
10/14/2016	58:02.2	28168	45	80	Red

- **Signal timings** (camcorders)
- **Traffic speeds and locations** (sensors)
- **Decisions of drivers during the yellow phase**
- **System's performance**

Evaluation of the Short-Term Impacts





- Due to the Stochastic nature of accidents
- Purposes:
  - To evaluate the effectiveness of the system's
    - Impacts on driver behaviors and traffic conditions
    - The performance of DZPS with respect to preventing side-angle accidents.

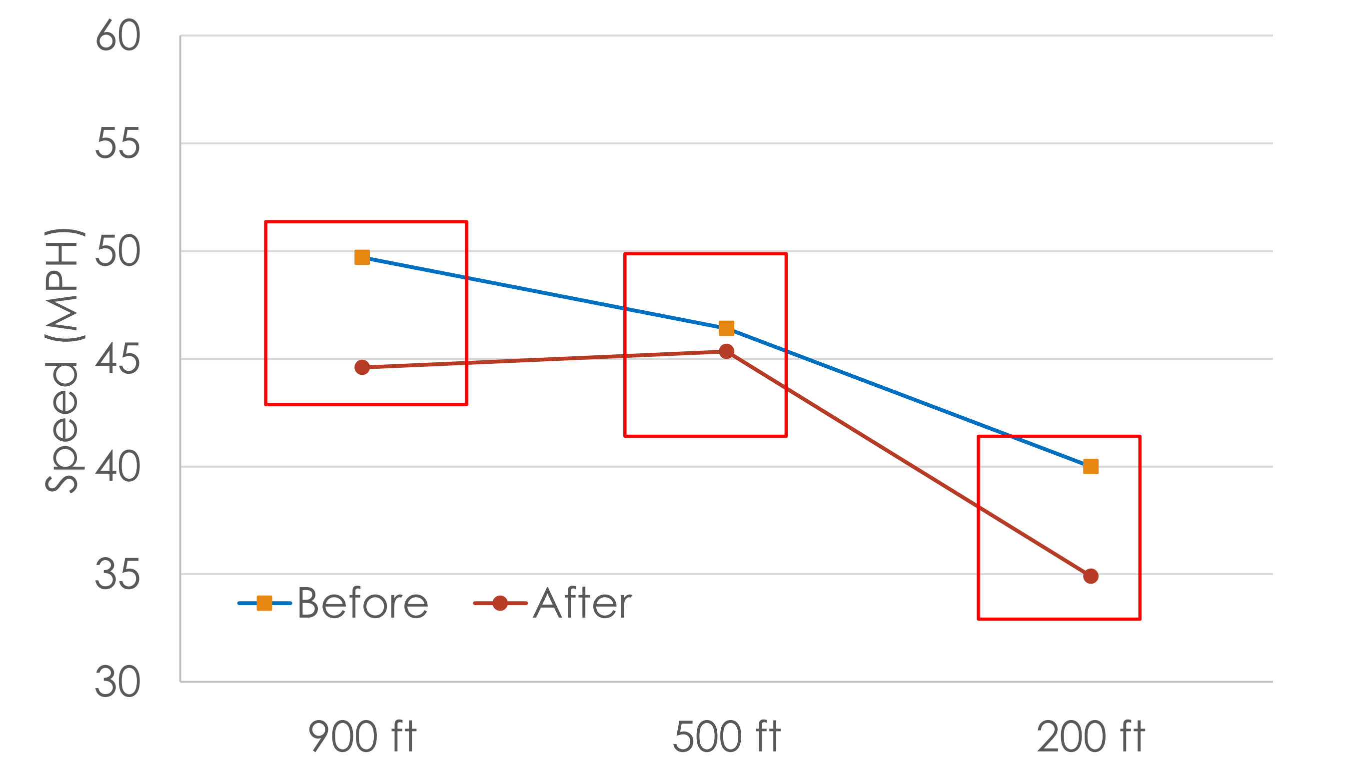
Impacts by the Roadside Sensors?

Roadside Sensors

- Impacts on the traffic?
  - Change in the Speed?
  - Change in acceleration/deceleration rates?
  - Change on decisions of drivers during the yellow phase?

Impacts on Traffic Flow Speed

- Average speed reduced at 900 feet and 200 feet
- Not very significant reduction at 500 feet

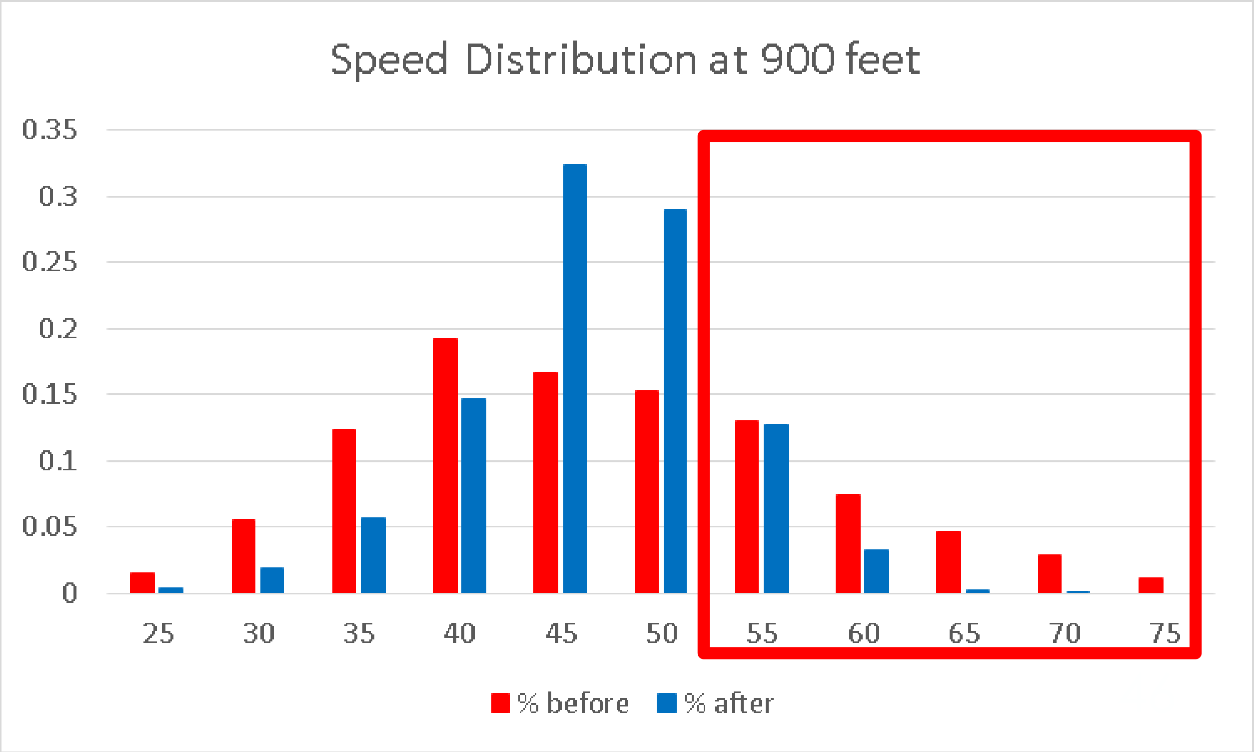


Location		900 ft	500 ft	200 ft
Avg Spd	Before	49.7	46.4	40
	After	44.6	45.33	34.9

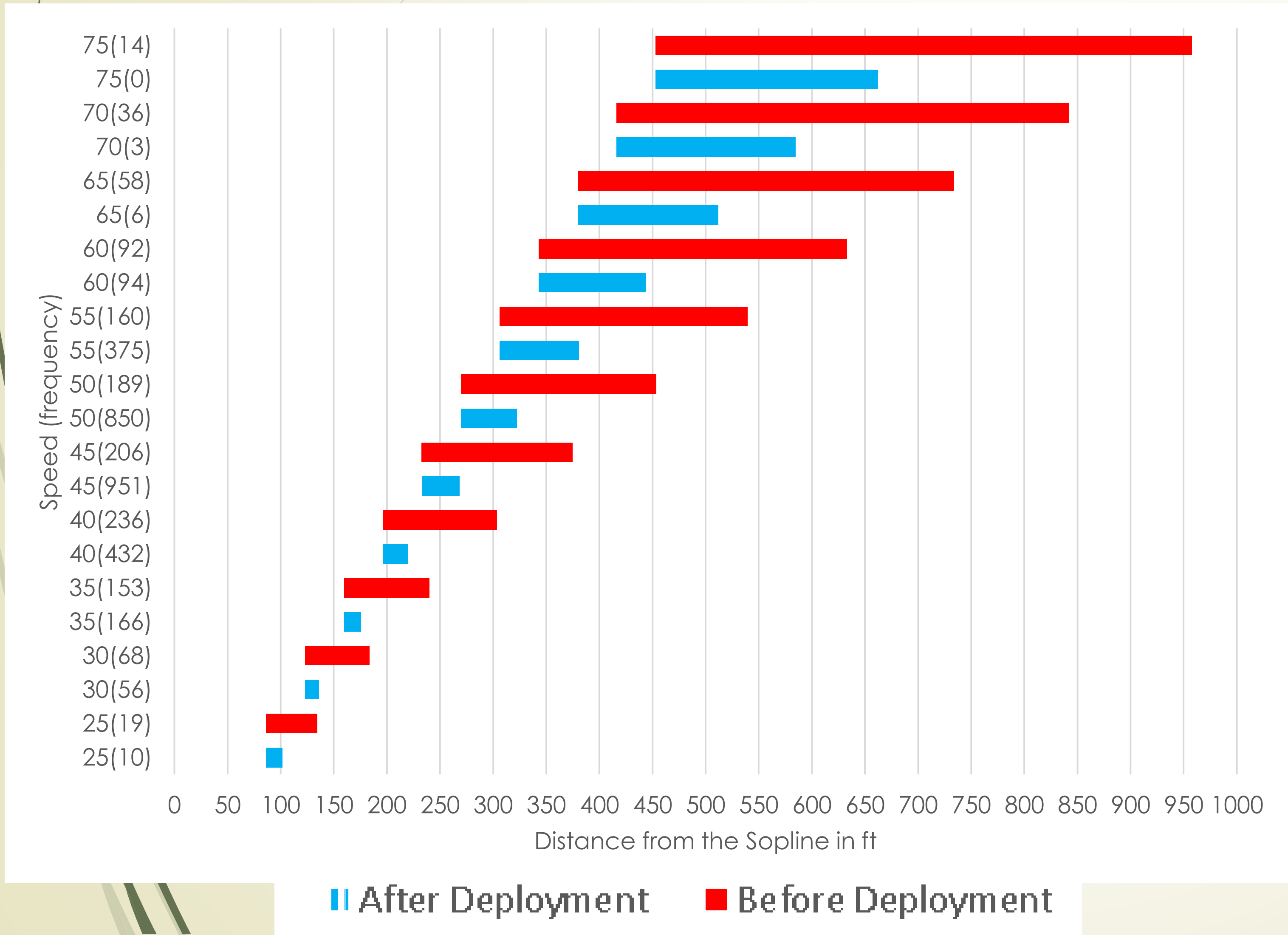
Impacts on Traffic Flow Speed

Speed	Before		After	
	Frequncy	Percentage	Frequncy	Percentage
75	14	1%	0	0%
70	36	3%	3	0%
65	58	5%	6	0%
60	92	7%	94	3%
55*	160	13%	375	13%
50	189	15%	850	29%
45	206	17%	951	32%
40	236	19%	432	15%
35	153	12%	166	6%
30	68	6%	56	2%
25	19	2%	10	0%
Total	1231	100%	2943	100%
* Speed limit: 55 MPH				

- Percentage of the high-speed drivers (above speed limit at 900 feet) reduced from 29 % to 16%
- Vehicles mostly choose to slow down when approaching the intersection



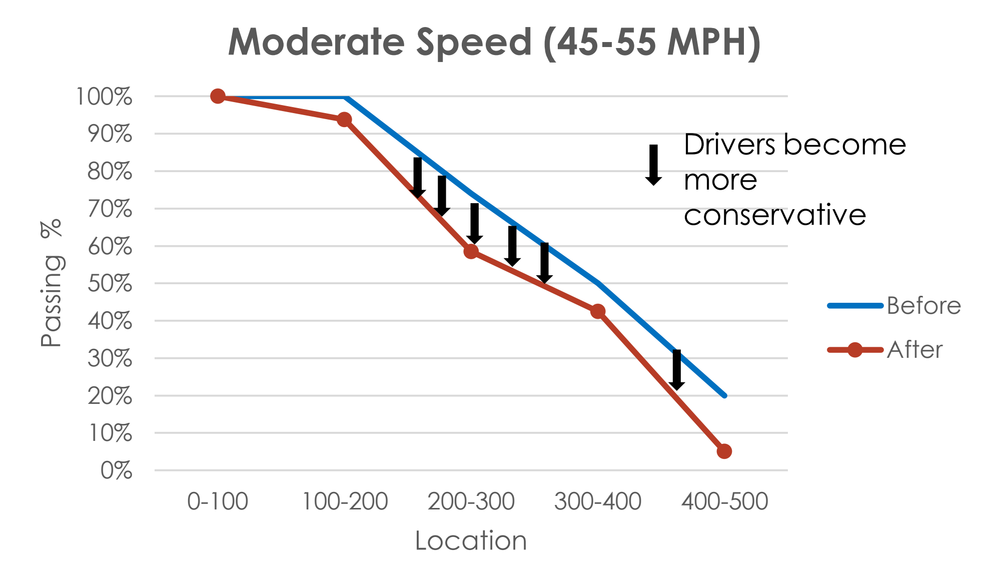
Distribution of the Dilemma Zones

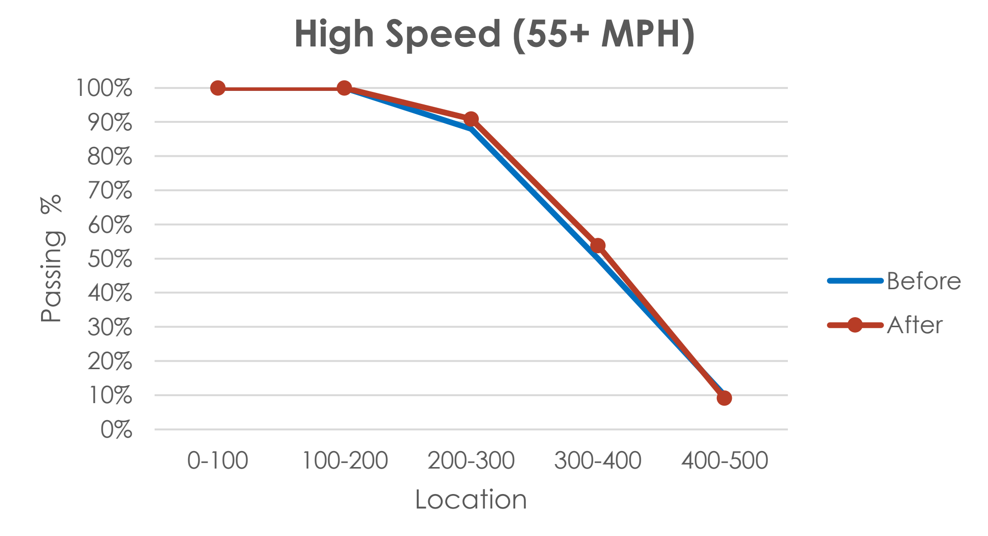


- Deceleration rate
  - Before -7.28 ft/s^2
  - After: -11.27 ft/s^2
- Maximum Length of the DZ
  - Before: 960 feet
  - After: 670 feet
- Distribution of the DZ reduced

Drivers' Decisions During the Yellow Phase

- More drivers at moderate speeds choose "STOP" decisions (below or around speed limit)
- Not significant impact on high-speed drivers





er	100 - 200 ft		200 - 300 ft		300 - 400 ft		400+ ft	
er	Before	After	Before	After	Before	After	Before	After
%)	100% (100)	94% (32)	74% (73)	59% (41)	50% (24)	43% (40)	20% (5)	5% (59)

Speed of vehicle on set of yellow (sample size)	Location of vehicles from the stop line at the onset of a yellow phase									
	0 - 100 ft		100 - 200 ft		200 - 300 ft		300 - 400 ft		400+ ft	
	Before	After	Before	After	Before	After	Before	After	Before	After
45 - 55 mph	100% (78)	100% (24)	100% (100)	94% (32)	74% (73)	59% (41)	50% (24)	43% (40)	20% (5)	5% (59)
55+ mph	100% (9)	100% (7)	100% (20)	100% (9)	88% (47)	91% (22)	50% (16)	54% (13)	10% (20)	9% (44)

Performance Evaluation on Detection and Activation

MOE	Simulation	Field Operation*
Detection rate (protected RLR)	**100%**	**100%**
False alarm rate (false alarm / 100 cycle)	**21**	**30**

- 5 vehicles ran on the red phases
- System provides all-red extension to all such vehicles
- 100% detection rate
- 30% false alarm rate

Summary of Findings from Field Evaluation

- Deployed DZPS can
  - Reduce the average approaching vehicle speed
  - Reduce the percentage of high-speed vehicles
  - Reduce the range of dilemma zones
  - Encourage drivers to take the "stop" action during the yellow phase
- High-Speed vehicles
  - Are more likely to be reduced
  - Side-street vehicles are protected by all-red extensions

Additional Findings from Design and Deployment of DZPS

- A function to track each individual vehicle's speed and location (**Wide-range traffic monitoring sensor**) over a monitoring zone is the **essential input** for the proposed system's computing module
- **Design** of intersection safety issue should be based on behaviors of driving population
- **Field observations** are essential for understanding key factors contributing to accidents
- A set of robust **behavior models** are needed for predicting driver behaviors

Additional Findings from Design and Deployment of DZPS

- The behavior of **aggressive drivers** is **unlikely to change** significantly from the roadside sensor or AWS– justify the need of a reactive control
- To ensure the **success of a system** and to identify **any potential issues**, it is beneficial to have a well-calibrated traffic simulator
- A well-designed all-red extension algorithm can effectively **predict red-light running vehicles** to prevent potential side-crashing accidents
- **Enhancement** of the DZPS for all-red extension to speed harmonization can be implemented with **minimal additional hardware**

Additional Findings from Design and Deployment of DZPS

- An **integrated system** can improve both intersection **safety** and **mobility**
- Effective monitoring of the evolution of intersection **traffic queues** and **gap-out timing** are critical input for computing advisory speed
- Proper display of the **VMS/VSL** can effectively reduce the number of vehicles trapped in the dilemma zone and thereby **reduce number of rear-end and side-angle crashes**
- A higher compliance rate under the displayed message/advisory speed will often result in a **safer** and **more efficient** traffic environment

Future Studies

- Impacts of the **VMS and AWS on driver behaviors**
  - Additional in-depth analysis and development of behavior models to reflect the discrepancies of **driver behaviors under different VMS and AWS**
- Integration of the system with **connected vehicles**
  - Integrate the proposed DZPS under different penetration rates of **connected vehicles** so as to improve the reliability of the system’s operational functions
- More field studies on **the impacts of roadside sensors on the driving behaviors**
  - **The impact of roadside sensor may vary** with different driving populations

Future Studies

- Development **of an intersection safety evaluation function**
  - To promote the deployment of proposed systems from the **cost/benefit perspective**
  - A reliable function with critical data associated with accidents to facilitate short-term performance analyses
- **Long-term analysis** on safety
  - The **learning impacts** (i.e., any changes on short-term impact) of driving populations over time with respect to the roadside sensors or any deployed system deserve further understanding with more field studies.

Questions and Comments?

Thank You