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

Sung Yoon Park, Ph.D. Candidate
Directed by Professor Gang-Len Chang
Department of Civil and Environmental Engineering
University of Maryland, College Park
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%

**Side-Swap**
- 11.7%
- Source: http://www.insurancefraud.org/scam-alerts-staged-crash.htm

**Pedestrians/cyclist**
- 2%
Majority of the Intersection Accidents

Vehicles running on the red phase

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
  - **Reactivity** 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 1 to 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)

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<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

<table>
<thead>
<tr>
<th></th>
<th>Field</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed @ 1050 ft (mph)</strong></td>
<td>57.4 (9.7)</td>
<td>59.68 (7.5)</td>
</tr>
<tr>
<td><strong>Speed @ 650 ft (mph)</strong></td>
<td>39.9 (8.2)</td>
<td>41.8 (8.1)</td>
</tr>
<tr>
<td><strong>Speed @ 400 ft (mph)</strong></td>
<td>38.6 (11.4)</td>
<td>42 (9.4)</td>
</tr>
<tr>
<td><strong>Speed @ 200 ft (mph)</strong></td>
<td>31.3 (14.5)</td>
<td>32.8 (14.2)</td>
</tr>
</tbody>
</table>

**Deceleration rate (ft/s²)**
- Passenger car / truck: -9.3(3.5)/-7.5(2.12) vs -9.7(5.4)

**Acceleration rate (ft/s²)**
- Passenger car / truck: 3.6(3.1)/3.5(2.4) vs 3.05(2.6)

The simulator has been calibrated with field data for spatial distribution of speeds and acceleration/deceleration rates.

### Introduction

**DZPS (System-I)**

**Pre-deployment Process**

**System-II**

**Field Data Evaluation**

**Conclusion and Future Study**
# Calibration Results

## Driver Responses to the Yellow Phase

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

<table>
<thead>
<tr>
<th>Speed of vehicle on set of yellow</th>
<th>Location of vehicle from stop line onset of yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 - 100 ft</td>
</tr>
<tr>
<td></td>
<td>Field</td>
</tr>
<tr>
<td>30-40 mph</td>
<td>100%</td>
</tr>
<tr>
<td>40-50 mph</td>
<td>100%</td>
</tr>
<tr>
<td>50-60 mph</td>
<td>100%</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>MOE</th>
<th>No Control</th>
<th>Default</th>
<th>Algorithm-I (Individual based)</th>
<th>Algorithm-II (Zone based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red-light running (RLR) rate</td>
<td>8.9</td>
<td>8.9</td>
<td>9.5</td>
<td>9.1</td>
</tr>
<tr>
<td>(# of RLR vehs / 100 cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension call rate</td>
<td>-</td>
<td>52</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>(extension calls / 100 cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>False alarm rate</td>
<td>-</td>
<td>47%</td>
<td>21%</td>
<td>16%</td>
</tr>
<tr>
<td>(false alarm frequency / cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detection rate</td>
<td>-</td>
<td>56%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>(# of protected RLR vehs / total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of RLR vehs )^4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

Introduction

DZPS (System-I)

Pre-deployment Process

System-II

Field Data Evaluation

Conclusion and Future Study

All-red extension for red light running vehicle to clear the intersection

In-cabinet PC

All-red Extension

Queue Evolution Module

Advisory Speed Module

Gap Out Prediction Module

SPaT Information

Vehicle Speed and Locations

Signal Controller

Microwave sensor

Detection Zone

Advisory Speed limit for safe stop and progression

VMS updates

Safe Stop

Advisory Speed Limit 25 MPH

Progression

Advisory Speed Limit 40 MPH

No Control

Speed Limit 55 MPH

Detection zone range

Recommended location of VMS
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 for Yellow and All-Red Phases

1. Calculate the Advisory Speed for Safe Stop
2. Provide All-Red Extension If Necessary
3. Update Advisory Speed
Control Actions (during yellow and red phases)

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

Control Actions Red Phases

1. Calculate Queue Length
2. Calculate Start of the Green Phase
3. Can Vehicles Progress with Min_Speed?
   - Yes: Calculate the Advisory Speed for Progression
   - No: Calculate the Advisory Speed for Safe Stop
4. Update Advisory Speed

During the end of red phases
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 the Green Phase

1. Calculate Queue clearance time and End of Green Phase
   - If Queue Clearance time > 0, then:
     - If Can vehicles Progress? (Yes), then:
       - Calculate Advisory Speed for Progression
     - Otherwise, Set Advisory Speed as Speed Limit
   - Otherwise, Set Advisory Speed as Speed Limit

2. If Is Remaining End of Green greater than Travel Time to Intersection? (Yes), then:
   - Calculate Advisory Speed for Safe Stop
   - Update Advisory Speed

3. Otherwise, Set Advisory Speed as Speed Limit
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

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Scenarios</th>
<th>Base Case</th>
<th>All-Red Extension Only (System-I)</th>
<th>All-Red Extension and Advisory Speed (System-II)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.66 (0.76)</td>
<td>0.66 (0.77)</td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>Average number of hard-braking</td>
<td>892 (792)</td>
<td>862 (770)</td>
<td></td>
</tr>
<tr>
<td>vehicles per cycle</td>
<td>Total number of vehicles in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dilemma zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The average number of red-light</td>
<td>0.11 (0.094)</td>
<td>0.11 (0.097)</td>
<td></td>
</tr>
<tr>
<td>running vehicles per cycle (RLR /</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cycle)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Detection rate for red-light</td>
<td>-(-)</td>
<td>100% (100%)</td>
<td></td>
</tr>
<tr>
<td>running vehicles</td>
<td></td>
<td></td>
<td>100% (100%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100% (100%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100% (100%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100% (100%)</td>
<td></td>
</tr>
</tbody>
</table>

- **Average number of hard-braking vehicles per cycle:**
  - Base Case: 0.66
  - All-Red Extension Only: 0.66
  - 100% compliance: 0.15
  - 50% compliance: 0.24
  - 25% compliance: 0.29

- **Total number of vehicles in dilemma zones:**
  - Base Case: 892
  - All-Red Extension Only: 862
  - 100% compliance: 540
  - 50% compliance: 702
  - 25% compliance: 790

- **The average number of red-light running vehicles per cycle (RLR / cycle):**
  - Base Case: 0.11
  - All-Red Extension Only: 0.11
  - 100% compliance: 0.06
  - 50% compliance: 0.08
  - 25% compliance: 0.09

- **Detection rate for red-light running vehicles:**
  - Base Case: -(-)
  - 100% (100%) compliance: 100%
  - 50% (100%) compliance: 100%
  - 25% (100%) compliance: 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

<table>
<thead>
<tr>
<th>MOEs</th>
<th>Scenarios</th>
<th>Base Case</th>
<th>All-Red Extension Only (System-I)</th>
<th>All-Red Extension and Advisory Speed (System-II)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100% compliance</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td><strong>Scenarios</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average number of stops per cycle</td>
<td></td>
<td>6.4 (6.4)</td>
<td>6.5 (6)</td>
<td>4.2 (4.5)</td>
</tr>
<tr>
<td>Average stopped delay for all vehicles per cycle (second)</td>
<td></td>
<td>45.7 (76)</td>
<td>48.6 (77)</td>
<td>38.0 (54)</td>
</tr>
<tr>
<td>Average fuel consumption per cycle (Gallon)</td>
<td></td>
<td>0.239 (0.24)</td>
<td>0.226 (0.022)</td>
<td>0.13 (0.14)</td>
</tr>
<tr>
<td>False alarm rate for the all-red extension</td>
<td></td>
<td>- (-)</td>
<td>14% (16%)</td>
<td>5% (4%)</td>
</tr>
</tbody>
</table>
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)

- 7 crashes potentially related to dilemma zone decisions for 3 years (side-angle crashes)
- 3 injuries
Field Data Collection (before deployment)

- 3 video camcorders: 900 ft, 500 ft, and 200 ft
- 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 sensor 1:
    - 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

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Veh ID</th>
<th>Speed</th>
<th>Location</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/14/2016</td>
<td>57:56.5</td>
<td>28168</td>
<td>49</td>
<td>465</td>
<td>Green</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>57:56.7</td>
<td>28168</td>
<td>49</td>
<td>455</td>
<td>Yellow</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>57:56.9</td>
<td>28168</td>
<td>49</td>
<td>445</td>
<td>Yellow</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>57:57.0</td>
<td>28168</td>
<td>49</td>
<td>430</td>
<td>Yellow</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>57:57.2</td>
<td>28168</td>
<td>49</td>
<td>420</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Veh ID</th>
<th>Speed</th>
<th>Location</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/14/2016</td>
<td>58:01.5</td>
<td>28168</td>
<td>46</td>
<td>120</td>
<td>Yellow</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>58:01.7</td>
<td>28168</td>
<td>46</td>
<td>115</td>
<td>Red</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>58:01.8</td>
<td>28168</td>
<td>46</td>
<td>105</td>
<td>Red</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>58:02.0</td>
<td>28168</td>
<td>46</td>
<td>90</td>
<td>Red</td>
</tr>
<tr>
<td>10/14/2016</td>
<td>58:02.2</td>
<td>28168</td>
<td>45</td>
<td>80</td>
<td>Red</td>
</tr>
</tbody>
</table>
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.

Introduction
DZPS (System-I)
Pre-deployment Process
System-II
Field Data Evaluation
Conclusion and Future Study
Impacts by the 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

<table>
<thead>
<tr>
<th>Location</th>
<th>900 ft</th>
<th>500 ft</th>
<th>200 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Spd</td>
<td>Before</td>
<td>49.7</td>
<td>46.4</td>
</tr>
<tr>
<td></td>
<td>After</td>
<td>44.6</td>
<td>45.33</td>
</tr>
</tbody>
</table>

Introduction
DZPS (System-I)
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**Impacts on Traffic Flow Speed**

- 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

<table>
<thead>
<tr>
<th>Speed</th>
<th>Before Frequency</th>
<th>Before Percentage</th>
<th>After Frequency</th>
<th>After Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>14</td>
<td>1%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>70</td>
<td>36</td>
<td>3%</td>
<td>3</td>
<td>0%</td>
</tr>
<tr>
<td>65</td>
<td>58</td>
<td>5%</td>
<td>6</td>
<td>0%</td>
</tr>
<tr>
<td>60</td>
<td>92</td>
<td>7%</td>
<td>94</td>
<td>3%</td>
</tr>
<tr>
<td>55*</td>
<td>160</td>
<td>13%</td>
<td>375</td>
<td>13%</td>
</tr>
<tr>
<td>50</td>
<td>189</td>
<td>15%</td>
<td>850</td>
<td>29%</td>
</tr>
<tr>
<td>45</td>
<td>206</td>
<td>17%</td>
<td>951</td>
<td>32%</td>
</tr>
<tr>
<td>40</td>
<td>236</td>
<td>19%</td>
<td>432</td>
<td>15%</td>
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<tr>
<td>35</td>
<td>153</td>
<td>12%</td>
<td>166</td>
<td>6%</td>
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<tr>
<td>30</td>
<td>68</td>
<td>6%</td>
<td>56</td>
<td>2%</td>
</tr>
<tr>
<td>25</td>
<td>19</td>
<td>2%</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>1231</td>
<td>100%</td>
<td>2943</td>
<td>100%</td>
</tr>
</tbody>
</table>

* Speed limit: 55 MPH
Distribution of the Dilemma Zones

- Deceleration rate
  - Before: $-7.28 \, \text{ft/s}^2$
  - After: $-11.27 \, \text{ft/s}^2$

- 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

<table>
<thead>
<tr>
<th>Location of vehicles from the stop line at the onset of a yellow phase</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 200 ft</td>
<td>100% (100)</td>
<td>94% (32)</td>
</tr>
<tr>
<td>200 - 300 ft</td>
<td>74% (73)</td>
<td>59% (41)</td>
</tr>
<tr>
<td>300 - 400 ft</td>
<td>50% (24)</td>
<td>43% (40)</td>
</tr>
<tr>
<td>400+ ft</td>
<td>20% (5)</td>
<td>5% (59)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed of vehicle on set of yellow (sample size)</th>
<th>Location of vehicles from the stop line at the onset of a yellow phase</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 - 55 mph</td>
<td>0 - 100 ft</td>
<td>100% (78)</td>
<td>100% (78)</td>
</tr>
<tr>
<td></td>
<td>100 - 200 ft</td>
<td>100% (100)</td>
<td>100% (100)</td>
</tr>
<tr>
<td></td>
<td>200 - 300 ft</td>
<td>94% (32)</td>
<td>94% (32)</td>
</tr>
<tr>
<td></td>
<td>300 - 400 ft</td>
<td>74% (73)</td>
<td>74% (73)</td>
</tr>
<tr>
<td></td>
<td>400+ ft</td>
<td>50% (24)</td>
<td>50% (24)</td>
</tr>
<tr>
<td>55+ mph</td>
<td>0 - 100 ft</td>
<td>100% (9)</td>
<td>100% (9)</td>
</tr>
<tr>
<td></td>
<td>100 - 200 ft</td>
<td>100% (20)</td>
<td>100% (20)</td>
</tr>
<tr>
<td></td>
<td>200 - 300 ft</td>
<td>100% (9)</td>
<td>100% (9)</td>
</tr>
<tr>
<td></td>
<td>300 - 400 ft</td>
<td>88% (47)</td>
<td>88% (47)</td>
</tr>
<tr>
<td></td>
<td>400+ ft</td>
<td>91% (22)</td>
<td>91% (22)</td>
</tr>
</tbody>
</table>

Drivers become more conservative

Introduction
DZPS (System-I)
Pre-deployment Process
System-II
Field Data Evaluation
Conclusion and Future Study
Performance Evaluation on Detection and Activation

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

<table>
<thead>
<tr>
<th>MOE</th>
<th>Simulation</th>
<th>Field Operation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection rate (protected RLR)</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>False alarm rate (false alarm / 100 cycle)</td>
<td>21</td>
<td>30</td>
</tr>
</tbody>
</table>
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