Evaluation of Red Clearance Extension Systems: An Application of Hardware-in-the-Loop Simulation

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Abstract

Red-light running (RLR) is a safety hazard at signalized intersections throughout the United States. As a form of dilemma zone protection, red clearance extension (RCE) attempts to mitigate the effect of RLR occurrences of through moving vehicles shortly after the termination of a circular yellow indication. Although previous studies have investigated the applicability of RCE systems, there is still an opportunity to improve the detection and prediction of RLR vehicles to refine the procedure of extending the red clearance interval. This study evaluates the performance of four alternative RCE systems including one Downstream Detection (DD) system and three Smart Upstream Speed-Conditional Detection (SUSCD) systems at 125, 215 and 475 ft. upstream from the stop line. A total of 149 hours of video data across five intersections in Oregon were collected and transcribed to investigate RLR events and calibrate simulation models. A Hardware-in-the-Loop (HITL) simulation was developed to model and evaluate the performance of four alternative RCE systems. Findings of this study show that despite minimal variations in the operational performance of the four alternatives, there were notable differences in the accuracy and efficiency measurements. A comparison of RCE systems confirms that, while SUSCD systems are less successful in detecting vehicles with high risk of collision and making correct extensions, they are consistently better at creating highly effective extensions.

Keywords

Red-Light Running; Red Clearance Extension; Hardware-in-the-Loop Simulation.

1. Introduction

Red-light Running (RLR) is a safety hazard at signalized intersections throughout the United States. The Federal Highway Administration (FHWA) reports that there are more than 3 million intersections in the United States alone, at least 300,000 of which are signalized [1]. In 2013, the National Highway Traffic Safety Administration's Fatality Analysis Reporting System reported 697 deaths caused by RLR crashes, according to the National Coalition for Safer Roads [2]. An estimated 127,000 people are injured each year due to RLR [3].

Two categories of countermeasures to prevent RLR are widely employed [4]: enforcement and engineering. Enforcement countermeasures consist of manual or automated enforcement to discourage drivers from disobeying traffic laws by imposing a citation or fine. Enforcement countermeasures are most effective when the driver's decision to run the red light is "avoidable". Engineering countermeasures attempt to prevent drivers from "unavoidable" situations, in which they must decide whether to run or not run the red indication [4, 5].

As a form of dilemma zone protection, red clearance extension (RCE) attempts to mitigate the problem of avoidable or unavoidable RLR, which occurs when a driver cannot decide whether to stop or go at the onset of a circular yellow indication. Dilemma zone protection systems use vehicle detection to reduce driver exposure to the dilemma zone or to offset the impacts of dilemma zone indecision. The goal of a RCE system is to detect a vehicle approaching an intersection near the onset of the circular yellow indication and to predict if the vehicle will either safely stop, safely clear the intersection, or be in the intersection at the end of the red clearance interval. If a RLR vehicle is predicted, then a call is placed to the traffic controller to extend the red clearance interval, giving the vehicle time to clear the intersection before releasing opposing traffic.

Although previous studies have investigated the applicability of RCE systems, there is still an opportunity to improve the detection and prediction of RLR vehicles to refine the procedure of extending the red clearance interval. The present study evaluated the performance of four alternative RCE systems including one Downstream Detection (DD) system and three Smart Upstream Speed-Conditional Detection (SUSCD) systems at 125, 215 and 475 ft. upstream from the stop line. The novelty of this work is twofold. First, a unique Hardware-in-the-Loop (HITL) simulation model which features a RCE module was developed. HITL simulation outputs are processed by a semi-automated R script that enables visualization of real-time microsimulation model outputs through

Enhanced Time Space Diagrams (ETSD). Second, an analysis framework is introduced that enables a systematic comparison between the performance of different detection strategies to quantify the accuracy of RLR prediction and potential to prevent a conflict or crash. The ETSD methodology and the analysis framework are novel and transferable to other intersection evaluations"

2. Literature Review

Engineering countermeasures are disaggregated into three subcategories [4]: motorist information, physical improvements, and signal operation. Motorist information countermeasures provide enhanced signal displays or additional information about the signal ahead. They include pre-yellow signal indications, sight distance improvements, signal visibility improvements, increased signal conspicuity (e.g., backplates), and advanced warning signs. Physical improvement countermeasures aim to improve or solve safety and operation problems through intersection modification. They include removing unnecessary traffic signals, adding capacity through additional traffic lanes, flattening sharp vertical curves, and softening sharp horizontal curves. Signal operation countermeasures involve changing signal timing or phasing. They include improving signal coordination and operation, providing green-light extension systems, and increasing durations of the yellow change and red clearance intervals.

Red clearance extension (RCE) is an engineering countermeasure that provides additional intersection protection by extending the red clearance (all-red) interval if a RLR vehicle is detected, allowing the RLR vehicle to safely clear the conflict zone with opposing traffic (see Manual on Uniform Traffic Control Devices, Section 4D.26.11 [6]). RCE systems have been adopted by transportation agencies of different scales. The North Carolina Department of Transportation developed and implemented a dynamic all-red extension system. Nine systems have been implemented across North Carolina since 2011 [7]. The Maryland State Highway Administration has also implemented a dynamic dilemma zone system at one intersection in Maryland [8]. Currently, the Oregon Department of Transportation (ODOT) runs Voyage™ software on many of their roadside traffic signal controllers. This software has the ability to trigger a RCE [9]. The City of Portland has implemented RCE systems at eight different intersections between 2005 and 2009 [10] using the Voyage™ software. The present paper evaluated the performance of four different RCE systems using Hardware-In-The-Loop (HITL) simulation, which enables direct application of a simulation model for operational analysis purposes.

3. Hardware-in-the-Loop (HITL) Simulation

Advances in signal controller software and hardware are introducing many new features and functions to the signal engineer's proverbial toolbox. In the context of signal timing, microscopic simulation models can be thought of as a sophisticated evaluation tool. Advances in technology allow direct linkages between simulation models and actual signal controllers, known as HITL simulation [11].

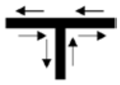
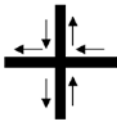
A HITL simulation platform includes three components: 1) a Controller Interface Device (CID), 2) a software interface module to provide the linkage between the CID and a microscopic simulation program, and 3) a microscopic simulation engine that is responsible for moving vehicles through a defined network [12]. In the HITL simulation process, traffic flow characteristics, signal timing plans, geometric aspects, and detection strategies are coded into the microsimulation model. Running the model, calls from simulation are transferred to the external controller device, which operates as it would in the field. The controller then processes the calls using its own internal signal timing and phasing plan to set signal indications. The signal displays are passed back to the simulation model to which simulated traffic responds. This HITL simulation approach is particularly effective for modeling advanced controller features such as transit signal priority and railroad preemption, because these features are controller software specific [11].

HITL simulation using VISSIM offers a unique tool to test different configurations of timing parameters, detections strategies, and intersection geometries in a safe and cost effective manner. Additionally, HITL simulation provides a test of the actual, field ready, signal controller hardware and software, which can be critical for gaining buy-in from stakeholders and decision makers. HITL simulation has been used to investigate a variety of transportation engineering topics [13, 14] including research related to traffic control systems [15, 16].

4. Data Collection

Eleven possible sites were suggested by ODOT staff based on a history of RLR-related crashes, presence of RLR cameras, or use of RCE systems. To determine the best data collection sites for this study, the characteristics of the suggested sites were analyzed and additional data were collected, consistent with recommendations from literature [17]. Finally, five distinct sites, with one intersection per site, were selected for field data collection (Table 1).

Table 1: Summary of selected sites

Site	City, State	Intersection	Geometry	RLR Camera	RCE System	Area Type	Speed Limit (MPH)	Coordination
A (Beta)	Corvallis, OR	OR-99W at Circle Blvd.		N	N	Urban	50	Y
B	Salem, OR	OR-99E at Broadway		N	N	Urban	45	N
C	Woodburn, OR	OR-99E at Mt. Hood		Y	N	Suburban	35	Y
D	Unincorporated Multnomah County, OR	US30 at Cornelius Pass Rd.		N	Y	Rural	55	N
E	Beaverton, OR	US26WB at 185th		N	N	Suburban	45	Y

Sites were located in various geographic areas to aid in the collection of driver behavior from different regions in Oregon, which is necessary for designing a RCE system that can be widely adopted. Site A in Corvallis was selected as the Beta test site due to its proximity to Oregon State University (OSU). Field data collection procedures were tested at Site A to ensure that the desired measures could be effectively collected. Video data were collected by installing digital cameras on telescoping poles at each of the test sites for 1 business week (typically installed on Monday and removed on Friday). Digital video of intersection operations was collected between 7:00 AM and 7:00 PM on Tuesday, Wednesday, and Thursday. Mondays and Fridays were excluded to avoid bias from weekend travel, as weekend travel behavior and traffic characteristics are expected to be substantially different from those of weekdays [18]. Distance measurements on the major and minor approaches were collected at each test site. In addition to collecting video data and measuring distances in the field, spot speed measurements were collected using a light detection and ranging (LIDAR) speed gun. ODOT provided signal timings and plan drawings for all five site intersections, as well as RCE logs for Site D.

Distance measurements on the major and minor approaches made in the field were overlaid on video data. Satellite images and intersection plan drawings were used to verify field measurements. *Paint.net*, a free image-editing software, was employed to make “transparent” images, which were used as distance overlays in the video-reduction process. Data reduction was completed by using *VirtualDub*, a free video-capture/processing utility software that allows captured video data to be viewed frame-by-frame with a video timestamp displayed to the millisecond. *CountCams* were set to record at a rate of 10 frames per second (i.e., accuracy of 0.1 second). The *Image Overlay Utility* program was used to display transparent images with distance markings over the video files. Figure 1 summarizes the process of setting up the raw video footage to be transcribed.

In total, 252 h of video data were collected across all five intersections. File errors and equipment tampering reduced this total to 234 h of usable data (Table 2). Due to the position of the cameras, some mainline vehicles were occluded from view resulting in a higher number of minor street vehicles to be analyzed.

5. Methodology

Collected data were used to calibrate a HITL simulation model. The intersection at Site D was the ideal candidate for additional modeling because it currently operates a RCE system and is overrepresented by RLR events. The intersection at Site D currently operates with a 2070 controller and NWS Voyage™ firmware. This intersection uses the NWS Voyage™ RCE function on through movements along major approaches (NW- and SE-bound on US30) and the left-turn movement on the minor approach (NE-bound on Cornelius Pass Rd). RCE events are triggered by loop detectors located downstream from the stop line. A model of Site D (US30–Cornelius Pass) intersection was developed by using VISSIM 6 (Figure 2). The following field data were used to create the VISSIM model:

- Link alignments and length were taken from scaled aerial images.
- Detector locations were matched to those shown in design drawings.

- Vehicle turning movement volumes for passenger cars and heavy vehicles were determined from video data collected at the intersection during weekday PM peak hours.
- LIDAR-measured speed profiles were used to calibrate speed distributions along US30. Speed profiles on Cornelius Pass Road were estimated.

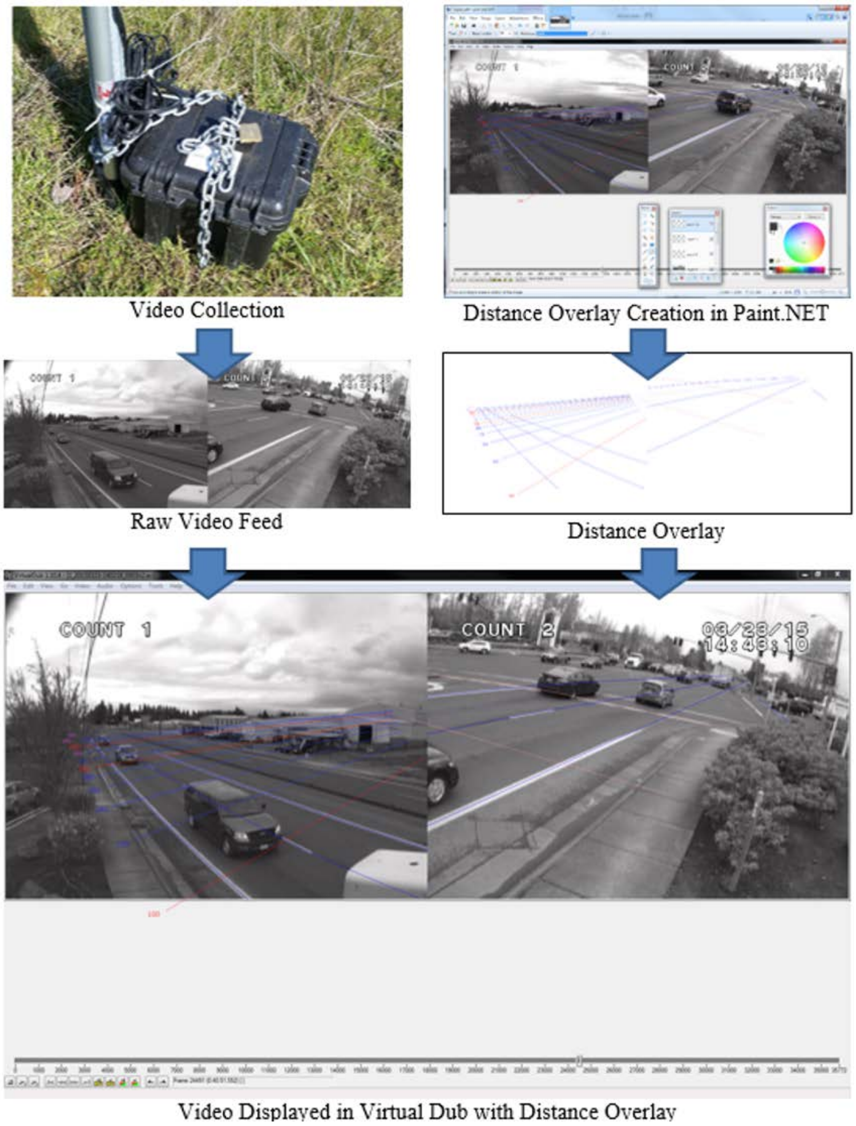


Figure 1: Data transcription process.

Table 2: Summary of collected data

Site	Hours Recorded (Usable)	Hours Transcribed	Vehicles per day (Major)	Vehicles per day (Minor)	Cycles per day	RLR events per day
A	72 (71)	47	N: 844 S: 640	W: 925 E: 1035	390	N: 3 S: 3
B	36	23	1141	697	372	0
C	72	36	N: 625 S: 571	W: 401 E: 779	403	N: 1 S: 0
D	36	24	984	1439	844	24
E	36 (19)	19	1350	2180	501	5
Total	252 (234)	149	6155	7456	2510	36

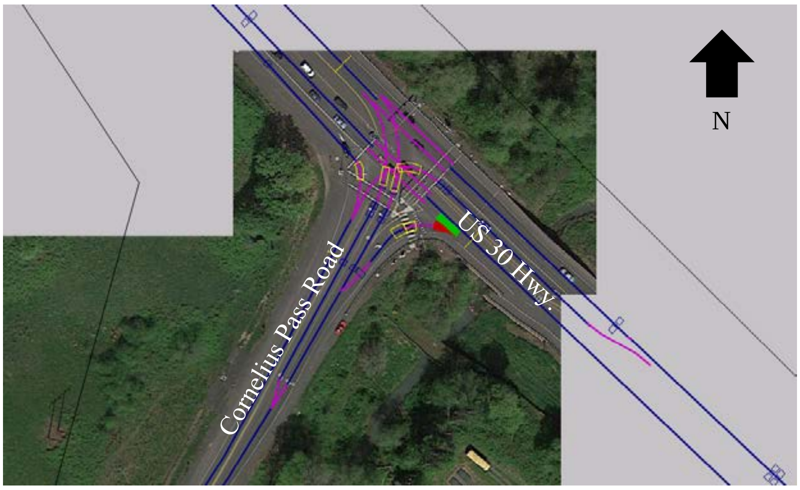


Figure 2: VISSIM model of the selected site

Signal heads were programed with 90% compliance, to simulate RLR (Each vehicle in the system has a 10% chance of disobedience when presented with the circular red indication). However, due to car following rules, the resultant RLR events are close to 1%. HITL was used to control the traffic signal in the VISSIM microsimulation (Figure 3). Actuations from simulated detectors were used to create inputs for a physical signal controller, which, in turn, was used to operate the simulated signals. ODOT provided the NWS Voyage^{TM} BIN file containing the existing signal timing at the selected intersection. The file was loaded and run on an Econolite 2070 ATC controller. The NWS Voyage^{TM} Software Operating Manual [9] provided details on the use and programing of the RCE feature in the Voyage^{TM} firmware. Specifically, the red clearance interval can be extended based on the presence of a late-arriving call, if the call occurs during the last 50% of the yellow change interval or any time during the red clearance interval. The programmable value for the RCE timer ranges from 0 to 25.5 seconds. The RCE feature can be disabled based on time-of-day operations. A McCain-NIATT CID was used to communicate between the signal controller and the computer running the VISSIM microsimulation. Four scenarios were evaluated, with 30 runs of an 80-min simulation (15-min seeding period, 60-min evaluation, 5-min cooldown). Data for the HITL microsimulations were collected from three main sources:

- Direct VISSIM outputs included the position data for each vehicle (.FZP file) and the chronologically sorted signal changes (.LSA file) from the microsimulation, both at a resolution of 0.1 seconds.
- VISSIM nodal analysis provided data for the total and stop delays, collected from a single node surrounding the simulated intersection.
- Signal controller logs (NWS VoyageTM RCE logs) recorded the beginning and end of each RCE event with a resolution of 1 second.

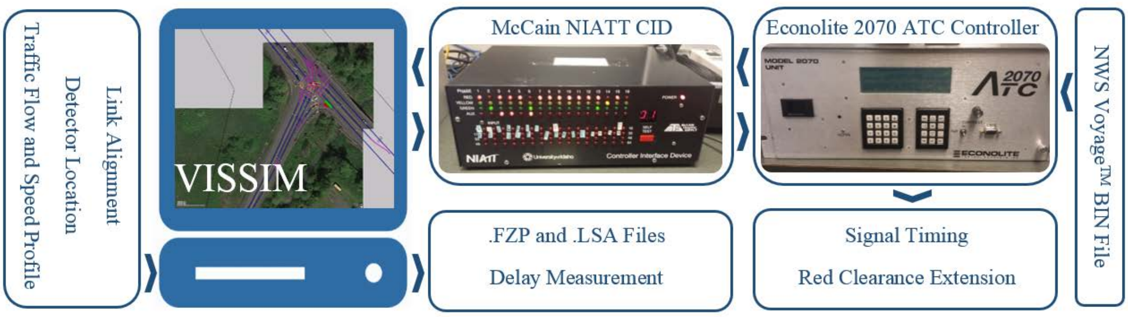


Figure 3: Hardware-in-the-Loop (HITL) simulation

Two detection strategies for triggering RCE were considered. Downstream Detection (DD), which is currently in place at the intersection, and Smart Upstream Speed-Conditional Detection (SUSCD):

- Downstream Detection (DD): DD involves a single in-pavement loop detector (per lane) located downstream from the stop line (Figure 4a). If the downstream detector is active during the second half of the yellow change interval or a typical red clearance interval, then a RCE will be triggered.

- Smart Upstream Speed-Conditional Detection (SUSCD): SUSCD uses a pair of in-pavement loop detectors (per lane) located upstream from the stop line (Figure 4b). Using programmable logic in NWS Voyage™, the two loops are used to differentiate vehicles at higher vs. lower speeds. If a higher speed vehicle is detected during the second half of the yellow change interval or typical red clearance interval, then a RCE will be triggered.

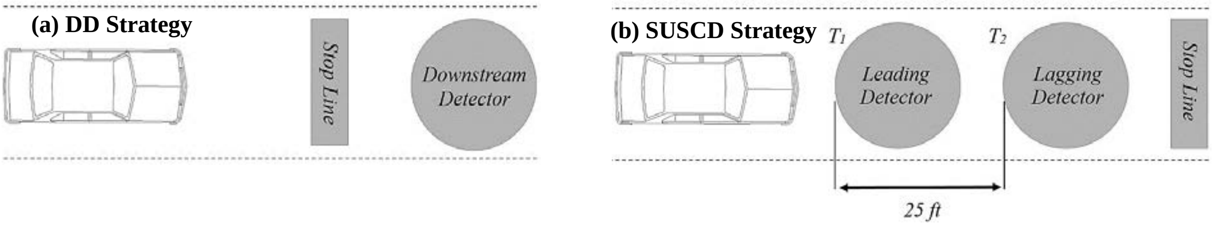


Figure 4: Detection strategies

A diagram of the SUSCD is included in Figure 4b. A timer starts counting down when a vehicle first actuates the leading detector (T_1). If the lagging detector is actuated before the timer reaches zero (T_2), then a call is placed to the RCE detector. By adjusting the value that the timer counts down from, the minimum speed needed to trigger the RCE can be increased or decreased. A short distance (25 ft.) between two detectors (from leading edge to leading edge) was used, to reduce the possibility that two vehicles would occupy the SUSCD setup at the same time. Table 3 describes the logical programming used by NWS Voyage™ to operate the SUSCD setup for a single lane of traffic. SUSCD on multiple lanes was accomplished by repeating these steps while updating the timer, latch, and detector input numbers.

Table 3: NWS Voyage™ logical programing

Step	Command	Logic Description	Function for SUSCD setup and notes
1	209	Set a Latch if Test is True	Set a latch when a vehicle first actuates the lead detector
2	1	Latch Number (Latch #1)	
3	22	Test if Input is Active	
4	106	Input Number (Leading Detector #14)	
5	208	Load a Timer if Test is True	Load a timer when the latch is not set. Decrement the timer when the latch is set.
6	1	Timer # (Time #1)	
7	0.4	Timer Value (0.4 seconds)	
8	24	NOT	
9	26	Test if a Latch is Set	
10	1	Latch #	
11	210	Reset a Latch if Test is True	Reset the latch when the timer decrements to 0.0 s.
12	1	Latch Number (Latch #1)	
13	24	NOT	
14	27	Test if Timer is Reset/Decrementing	
15	1	Timer # (Time #1)	
16	209	Set a Latch if Test is True	Set a second latch when a vehicle first actuates the lagging detector. This function is not strictly needed to operate the SUSCD setup. However, using this latch makes calibration easier when viewing the latch status in the Voyage Internal Logic Menu.
17	5	Latch Number (Latch #5)	
18	22	Test if Input is Active	
19	107	Input Number (Lagging Detector #15)	
20	210	Reset a Latch if Test is True	Reset the latch when the vehicle no longer actuates the lagging detector. This function is not strictly needed to operate the SUSCD setup. However, using this latch makes calibration easier when viewing the latch status in the Voyage Internal Logic Menu.
21	5	Latch Number (Latch #5)	
22	24	NOT	
23	22	Test if Input is Active	
24	107	Input Number (Lagging Detector #15)	
25	206	Turn On an Input if Conditions are Met	Place a call on the Red Extension Detector when the two latches are active at the same time. As with standard detection for RCE, if this call is placed during the second half of the yellow or during the normal all red, a RCE will be triggered.
26	231	Input Number (Voyage Red Extension Detector #52)	
27	26	Test if a Latch is Set	
28	1	Latch Number (Latch #1)	
29	20	AND	
30	26	Test if a Latch is Set	
31	5	Latch Number (Latch #5)	

Detector positions for SUSCD systems were initially considered based on the reviewed literature. Dilemma zone protection is one of the goals of a RCE system. Dilemma zone indecision boundaries are assumed to be located 2.5 and 5.5 seconds from stop bar [4]. Considering the average 85th percentile speed on both main approaches (59.2 mph), two scenarios were initially developed for detector placement, one located 215 ft. (corresponding to almost 2.5 seconds) and the other 475 ft. (corresponding to almost 5.5 seconds) upstream of the stop bar. However, detector placement closer to stop lines has been found to minimize both missed RLR vehicles and false alarms [19]. As such, three additional locations, 75 ft., 100 ft., and 125 ft. upstream of stop bar were preliminary evaluated. The initial inspection of the extensions produced by each of these detector locations indicated that 125 ft. upstream of the stop line produced the most effective extensions. Therefore, a third full scenario using an SUSCD detector 125 ft. upstream of stop line was evaluated.

Useful outputs were collected from the .LSA files, .FZP files, and RCE logs. RCE data from the .LSA files (0.1 second frequency) matched data from the lower resolution Voyage™ RCE logs (1.0 second frequency). Therefore, the higher resolution .LSA files were used for extension events. The data sets were large enough to necessitate the development of an efficient data reduction procedure. Code was created in R, a statistical software package, to partially automate the data reduction procedure.

Enhanced Time Space Diagrams (ETSDs) were developed for each experimental scenario. In these diagrams, trajectories of the front and rear bumpers of vehicles were plotted against signal status, intersection geometry, and detector locations for cycles that included a RCE (Figure 5). ETSDs were used to analyze the performance of detection strategies.

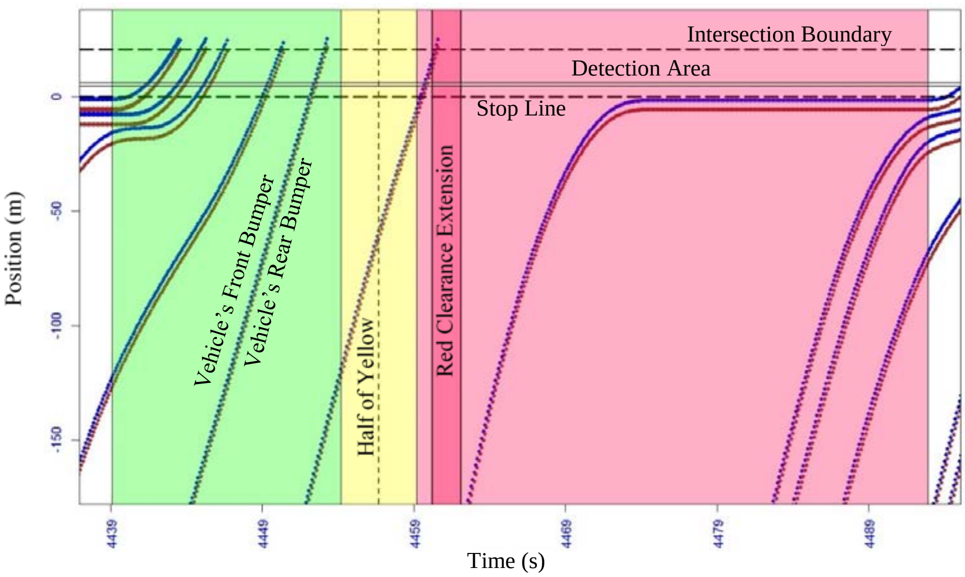


Figure 5: Example of an ETSD showing a RLR event with DD strategy that triggered a RCE

6. Results

This study is novel in the way it uses ETSD from data collected in HITL simulations to evaluate RCE system alternatives. One of the contributions of this paper is the development of a framework that enables a systematic comparison between the visual performance results of different detection strategies. This framework allowed for an analysis of the accuracy, effectiveness, and operations of the four HITL experimental scenarios.

Evaluation of system accuracy was based on the number of correct RCE calls and the number of detected vehicles with a high risk of collision (VHRC). VHRCs are defined by one of two conditions: (1) if a vehicle enters intersection late in the yellow change interval it can be considered a late yellow indication entry or (2) if a vehicle enters the intersection during the red indication it is considered a RLR. "Correct" calls are explicitly defined as RCEs which benefit the VHRC that triggered the RCE as it clears the intersection. If an extension is triggered by a non-VHRC, or if the RCE is triggered by a leading vehicle which does not benefit from the RCE, but a following VHRC then uses that RCE to safely clear intersection, it is also considered an "incorrect" call. Detection accuracy is also limited to those VHRCs which could have triggered the RCE in the system. If a VHRC occupies the detection area during the second half of the yellow change or red clearance interval and it triggers a RCE, it is a "detected" VHRC. However, if a VHRC occupies the detection area during the aforementioned period but a RCE is not triggered, it is an "undetected" VHRC. If a VHRC does not occupy the detection area during the aforementioned period, the RCE system, by design, is not capable of identifying that vehicle. Those vehicles were disregarded for the analysis of accuracy. Table 4 presents accuracy measurements for each of the detection systems over 30 simulation runs.

Table 4: Accuracy measurements for Detection Strategies

		DD		SUSCD at 125 ft.		SUSCD at 215 ft.		SUSCD at 475 ft.	
		Extension		Extension		Extension		Extension	
		Yes	No	Yes	No	Yes	No	Yes	No
VHRC	Yes	130	64	114	61	37	123	68	70
	No	207	4228	287	4063	165	4241	735	3544

The purpose of a RCE system is to provide additional time for a VHRC to clear an intersection. The position and speed of a VHRC at the onset of the red clearance interval contributes to the likelihood of that vehicle safely crossing the intersection. If a VHRC is upstream of the stop line at the onset of the red clearance interval, then the RCE is assisting a RLR to completely clear the intersection (highly effective). If a VHRC is at the stop line or downstream of it at the onset of the red change interval, then the RCE is helping a late runner, which will traverse the greater part of intersection during the normal red clearance interval (less effective and not effective, respectively). Using three levels of effectiveness, the efficiency of correctly triggered RCE by each of the detection systems was analysed (Table 5).

Table 5: Efficiency measurements for Detection Strategies

	DD	SUSCD at 125 ft.	SUSCD at 215 ft.	SUSCD at 475 ft.
RCE Crash Prevention Effectiveness	Frequency (Percentage)			
Highly Effective *(VHRC Prior to Stop Line at Onset of Red)*	23 (17.7%)	86 (75.5%)	36 (97.3%)	68 (100.0%)
Less Effective *(VHRC at Stop Line at Onset of Red)*	20 (15.4%)	8 (7.0%)	1 (2.7%)	0 (0.0%)
Not Effective *(VHRC Beyond Stop Line at Onset of Red)*	87 (66.9%)	20 (17.5%)	0 (0.0%)	0 (0.0%)

The impact of RCE systems on signal operations were evaluated with the implications on delay (reported as delay per vehicle and stop delay per vehicle) and extension duration being considered. Table 6 summarizes descriptive statistics for mean delay (measured as delay per vehicle and stop delay) and mean extension duration for each of the detection systems, over 30 individual simulation runs.

Figure 6 provides a comparison of the accuracy, efficiency and operational measurements for the detection system alternatives. Although there were few variations in the operational performance of the alternatives, there were notable differences in the accuracy and efficiency measurements. Upon visual inspection, the DD system appears to be more successful at creating extensions and identifying VHRCs than the other RCE systems. While the rate of VHRC detection for the DD system was very close to SUSCD at 125 ft., this rate was nearly three times that of the SUSCD system at 215 ft. and 1.3 times that of the SUSCD system at 475 ft. Moreover, the rate of correct extensions in the DD system was close to 1.4 times that of SUSCD at 125 ft., more than double that of the SUSCD system at 215 ft. and about 4.5 times that of the SUSCD system at 475 ft. Therefore, the DD system outperforms the accuracy of the SUSCD alternatives.

Table 6: Descriptive statistics for delay and extension duration with detection strategies

	DD			SUSCD at 125 ft.			SUSCD at 215 ft.			SUSCD at 475 ft.		
Statistics	Vehicle Delay	Stop Delay	Extension Duration	Vehicle Delay	Stop Delay	Extension Duration	Vehicle Delay	Stop Delay	Extension Duration	Vehicle Delay	Stop Delay	Extension Duration
Min	11.94	4.69	0.10	12.08	4.76	1.60	12.10	4.64	0.10	12.15	4.88	1.20
Mean	13.08	5.35	1.25	13.04	5.32	3.35	13.11	5.38	1.01	13.31	5.58	3.34
Median	13.12	5.34	1.40	12.99	5.35	3.40	13.16	5.40	1.40	13.39	5.58	3.40
Max	13.93	5.93	1.90	13.87	5.94	4.90	13.83	5.85	1.90	14.33	6.13	5.00
SD	0.42	0.26	0.59	0.43	0.26	1.01	0.44	0.26	0.59	0.46	0.28	0.97

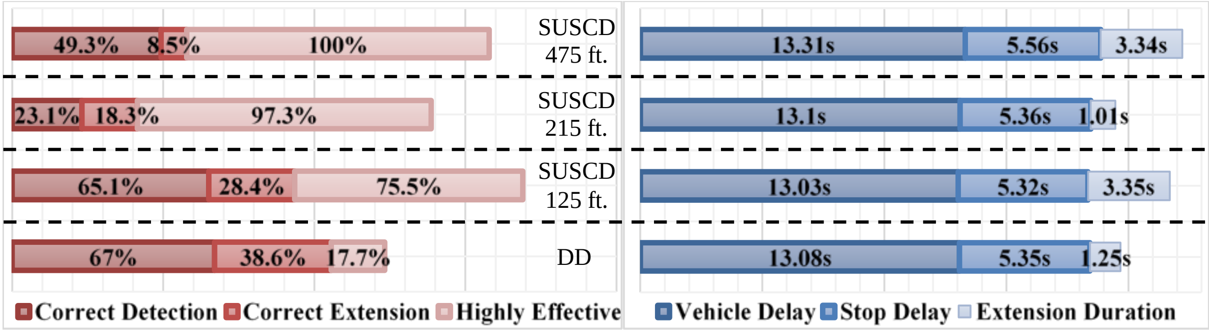
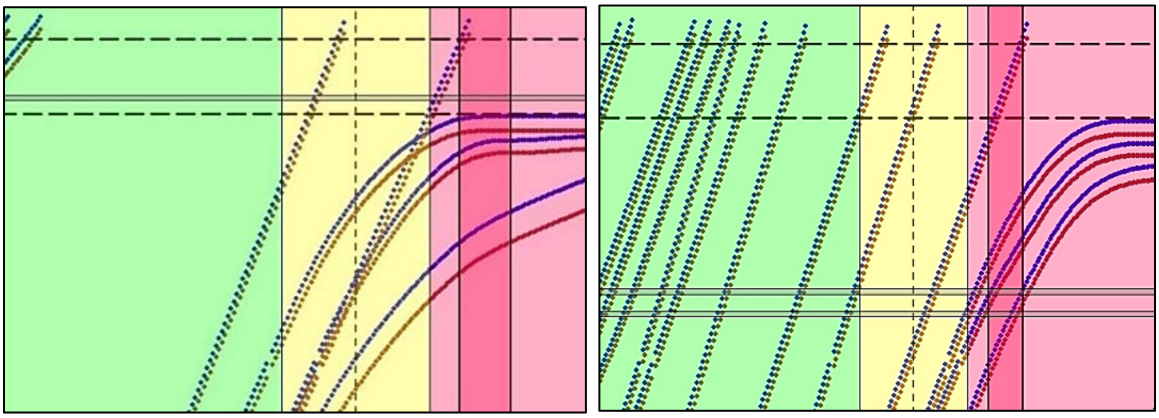


Figure 6: Comparison of accuracy, efficiency and operational measurements in detection systems

From an efficiency standpoint, SUSCD systems outperformed the DD system. While the rate of highly effective correct extensions for the DD system is approximately 18%, this rate is almost 100% for SUSCD systems at 215 and 475 ft. and is 75.5% in SUSCD at 125 ft. This finding necessitated a closer examination of the triggered extensions for each RCE system.

7. Discussion and Conclusion

Figure 7a shows a typical case of RCE produced by the DD system. By definition, the DD system calls extensions when a vehicle first occupies the detector downstream of the stop line during the second half of the yellow or a normal red clearance interval. In other words, a vehicle that triggers an extension could be halfway or further through the intersection at the end of the typical 1-s red clearance interval. From a safety standpoint, drivers in opposing lanes are able to see a vehicle in front of themselves at the onset of their green. Figure 7b shows a common RCE event for the SUSCD system. In these systems, VHRC are detected based on their instantaneous velocity at 125 ft., 215 ft., or 475 ft. upstream of the stop line. The ETSD for SUSCD demonstrates a VHRC that passes the stop line at the end of the 1-s all-red period. With the help of a correct, complete, and precise extension, the VHRC clears the intersection before any conflicting movement can occur.



(a) DD Strategy **(b) SUSCD Strategy**

Figure 7: Examples of detected VHRC in the DD and SUSCD systems

To judge the appropriateness of each RCE alternative design, both the quantitative and qualitative performances should be considered. A comparison of demonstrated ETSDs confirms that, although SUSCD systems are less successful in detecting VHRC and making correct extensions, they are potentially strong in creating highly effective extensions. For the SUSCD systems, VHRC are detected by a single spot speed measurement made 125 ft., 215 ft. or 475 ft. before the intersection. Although speed is a crucial determinant in identifying VHRC, drivers' decisions to stop or proceed cannot be predicted by using speed alone. SUSCD systems trigger RCE events without observation of RLR. This prognostic trait in SUSCD systems justifies the lower accuracy. SUSCD systems are also different, when compared to each other. The SUSCD system at 125 ft. is the closest to DD system based on the rate of correct extensions (28.4% compared to 38.6%) and correct detection (65.1% compared to 67.0%). However, while this system outperforms the other speed-conditional systems in accuracy, it is less successful in creating highly effective and effective extensions. When comparing the SUSCD systems at 215 ft. and 475 ft., the SUSCD at 215 ft. is more successful at triggering correct extensions (18.3% compared to 8.5%) while the SUSCD at 475 ft. outperforms in the detection of VHRCs (49.3% compared to 23.1%). Looking at the accuracy and efficiency measurements (Figure 6), it appears that placing speed-conditional detectors further upstream of the stop line increases the efficiency of extensions while negatively affecting accuracy. Considering accuracy and efficiency interactively, the SUSCD system at 125 ft. could be considered the optimal solution in implementation of red clearance intervals.

While the results of the present study are considered to be transferable to intersections with similar characteristics, other studies that investigate RCE systems could benefit from this work in several ways. First, the unique HITL simulation platform which features a RCE module could be used to model other detection strategies, detector locations, or a combination of both. Additionally, the HITL simulation outputs could be processed by the developed R script that enables visualization of real-time microsimulation model outputs in a novel and useful form. Further, the analysis framework introduced here could be employed in a similar study to evaluate RCE systems based on ETSDs.

References

1. Federal Highway Administration. (FHWA). *Safety at Signalized Intersections*, U.S. Department of Transportation, Washington, D.C. http://safety.fhwa.dot.gov/intersection/signalized/presentations/sign_int_pps051508/short/index.cfm. Accessed Aug. 21, 2014.
2. Federal Highway Administration. (FHWA). *How Red-Light Running is Defined and How Crash Figures Are Determined*, U.S. Department of Transportation, Washington, D.C. http://safety.fhwa.dot.gov/intersection/redlight/howto/. Accessed July 28, 2014.
3. Federal Highway Administration. (FHWA). *Red-Light Running*, U.S. Department of Transportation, Washington, D.C. http://safety.fhwa.dot.gov/intersection/redlight/. Accessed July 28, 2014.
4. Bonneson, J.A., K.H. Zimmerman, and M. Brewer. *Engineering Countermeasures to Reduce Red-Light-Running.* Report 4027-2. Texas Transportation Institute, College Station, TX, 2002.
5. Institute of Transportation Engineers. (ITE). *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running - An Informational Report.* Publication No. IR-115, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2003.
6. Federal Highway Administration. (FHWA). *Manual on Uniform Traffic Control Devices*, U.S. Department of Transportation, Washington, D.C., 2009.
7. Simpson, C. L., Harrison, M. W., and Troy, S. A. *Pilot Implementation of a Dynamic All-Red Interval at Signalized Intersections in North Carolina-Phase I Evaluation*. Proceeding of the 96th Annual Transportation Research Board Meeting, Paper No. 17-00324). Washington, D.C., 2017.
8. Chang, G.-L., M.L. Franz, Y. Liu, Y. Lu, and R. Tao. *Design and Evaluation of an Intelligent Dilemma-Zone Protection System for a High-Speed Rural Intersection*. In Transportation Research Record: Journal of the Transportation Research Board, 2356, pp. 1-8. 2013.
9. Northwest Signal Supply, Inc. *Voyage Software Operating Manual Version 5.1.0*., 2012.
10. Olson, C.S. *Safety Effectiveness of Red Light Treatments for Red Light Running*. MS Thesis. Portland State University, Portland, OR, 2012.
11. National Cooperative Highway Research Program (NCHRP). *Signal Timing Manual*. 2 Edition, Washington, D.C. 2015.
12. Bullock, D., B. Johnson, R.B. Wells, M. Kyte, and Z. Li. *Hardware-in-the-loop simulation*. Transportation Research Part C: Emerging Technologies, 2004. 12(1), pp. 73-89.
13. Luo, Y., Y. Xiang, K. Cao, and K. Li. *A dynamic automated lane change maneuver based on vehicle-to-vehicle communication*. Transportation Research Part C: Emerging Technologies, 2016, 62, pp. 87-102.
14. Hu, J., Y. Shao, Z. Sun, M. Wang, J. Bared, and P. Huang. *Integrated optimal eco-driving on rolling terrain for hybrid electric vehicle with vehicle-infrastructure communication*. Transportation Research Part C: Emerging Technologies, 2016, 68, pp. 228-244.
15. So, J., J. Lee, and B. Park. *Evaluation of manual traffic-signal control under oversaturated conditions using hardware-in-the-loop simulation*. Journal of Transportation Engineering, 2013, 139, no. 11, pp. 1068-1075.
16. Xu, J. *The Development and Evaluation of a Detection Concept to Extend the Red Clearance by Predicting a Red Light Running Event.* MS Thesis. University of Tennessee, Knoxville, TN, 2009.
17. McGee, H., Sr., K. Moriarty, T. Gates, K. Eccles, R. Retting, and M. Liu. *NCHRP Report 731: Guidelines for Timing Yellow and All-Red Intervals at Signalized Intersections*. Transportation Research Board of the National Academies, Washington, D.C., 2012.
18. Agarwal, A. *A comparison of weekend and weekday travel behavior characteristics in urban areas*. Graduate Theses and Dissertations in University of South Florida. 2004.