TRANSPORTATION LETTERS, 2017
https://doi.org/10.1080/19427867.2017.1336860

Evaluation of Red Clearance Extension designs with Hardware-in-the-Loop simulation

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ABSTRACT
Advances in signal controller software and hardware are introducing new safety-enhancing functions to the signal engineer's toolbox. Hardware-in-the-Loop (HITL) simulation can evaluate alternative timing parameters, detection strategies, and intersection geometries in a safe and cost-effective manner. Red Clearance Extension (RCE) is one design alternative that can be evaluated by HITL simulation. RCE operates by predicting Red Light Running vehicles and dynamically increasing red clearance interval duration to reduce crash probability. In this study, HITL simulation was used to evaluate four alternative RCE detection strategies. Novel code was developed in R to visualize output in Enhanced Time-Space Diagrams (ETSDs). RLR vehicles triggered the highest rate of correct RCE events when the downstream detection alternative was used. However, the ETSDs showed that RCE events triggered by smart upstream speed-conditional detection alternatives at 125, 215, and 475 ft provided greater safety for vehicles with no significant increase to intersection delay incurred.

KEYWORDS
Red Clearance Extension; Hardware-in-the-Loop; detection strategy; Red Light Running; Enhanced Time-Space Diagrams

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 (FHWA 2014a). In 2013, the National Highway Traffic Safety Administration's Fatality Analysis Reporting System reported 697 deaths caused by RLR crashes (National Coalition for Safer Roads 2014a). An estimated 127,000 people are injured each year due to RLR (FHWA 2014b).

Various countermeasures have been proposed to mitigate factors contributing to RLR, but few of these countermeasures address RLR by implementing additional protection when a RLR vehicle is detected. Red Clearance Extension (RCE) is a 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 (see Manual on Uniform Traffic Control Devices, Section 4D.26.11 (FHWA 2009)).

RCE systems have been adopted by transportation agencies of different scales. North Carolina Department of Transportation developed and implemented a dynamic all-red extension system. Nine systems have been implemented across North Carolina since 2011 (Simpson, Harrison, and Troy 2017). The Maryland State Highway Administration has also implemented a dynamic dilemma zone system at one intersection in Maryland (Chang et al. 2013). Currently, the Oregon Department of Transportation (ODOT) runs NWS Voyage™ software on many of their roadside traffic signal controllers and this software has the ability to trigger a RCE (Northwest Signal Supply, Inc 2012). The City of Portland has implemented RCE systems at eight different intersections between 2005 and 2009 (Olson 2012) using the same software.

Although a variety of RCE systems have been designed and field tested, research is needed to determine the best practices for detecting and predicting RLR vehicles and for extending the red clearance interval. RCE designs commonly include two elements, a RLR prediction strategy and a vehicle detection strategy. This paper presents two alternative RCE designs, (1) The Downstream Detection (DD) system, and (2) The Smart Upstream Speed-Conditional Detection (SUSCD) system. These two designs differ from one another both in relation to their RLR prediction algorithms and vehicle detection strategies. In the DD system, RLR events are predicted based on the presence of a vehicle at the detector during the second half of yellow or red clearance interval. This is conceptually different from the SUSCD systems which predict RLR events based on the instantaneous speed of vehicles at a pair of detectors during the aforementioned period. The DD system employs a single inductive loop detector downstream of the stop line while the SUSCD system uses a pair of inductive loop detectors upstream of the stop line. In addition to differences in RLR prediction strategies, the SUSCD systems also perform differently based on the upstream locations of the detector pairs. In this study, three different locations: 125, 215, and 475 ft upstream from stop line are considered for the SUSCD systems.

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 micro-simulation 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

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framework are novel and transferable to other intersection evaluations (see Apendix Table A1 for a complete list of abbreviations).

Literature review

As a form of dilemma zone protection, RCE attempts to mitigate the problem of unintentional RLR, which can occur when a driver cannot decide or does not notice whether to stop or go at the onset of a circular yellow indication. The goal of a successful RCE system is to detect a vehicle approaching an intersection near the onset of the circular yellow indication and to predict if that vehicle will be a RLR. If a RLR vehicle is predicted, then a call is placed to the traffic controller to extend the red clearance interval, thus giving the vehicle additional time to clear the intersection before releasing opposing traffic.

This literature review is divided into three subsections. The first two sections focus on RLR predictive models and vehicle detection strategies, which as discussed before are important elements of any RCE system. The third section focuses on HITL simulation which was used to analyze the performance of alternative RCE systems.

RLR predictive models

To predict whether a vehicle will require a RCE, various predictive models have been applied. Predictions have been made on the basis of the arrival time at the stop line (including car-following information to predict stop vs. go behavior) (Wang et al. 2012), bivariate stop-go models (Zhang et al. 2009), least-squares support vector machine models (Chen et al. 2014), multistep zonal classification (Gates 2007), identification of vehicle presence in a multi-segment detection zone (Awadallah 2013), and stopping-speed prediction algorithms (Xu 2009).

In a recent study, Chang et al. (2013) used minimum speed boundaries for vehicles approaching an isolated intersection with a posted speed limit of 55 mph at the onset of the red clearance interval to determine the need for a RCE. Vehicles detected within 500 ft of the stop line traveling faster than 56 mph at the beginning of the red interval would trigger a RCE, the duration of which would be calculated from the vehicle's speed and distance from the stop line. Vehicles traveling faster than 67 mph at distances between 500 and 875 ft would also trigger a RCE. Detection for the RCE began within 3 s of onset and was updated every 0.1 s until termination of the red clearance interval. As the end of the red clearance interval approached, a final decision was made on whether a RCE was required.

Vehicle detection for RCE

The vehicle detection design for a RCE system is unique as compared to other vehicle detection applications at signalized intersections. Various vehicle detection methods are currently available, including inductive loops (Olson 2012), video (Yung and Lai 2001), radar (Zaheri and Abbas 2015), thermal camera (Iwasaki, Misumi, and Nakamiya 2013), magnetometer (Haoui, Kavaler, and Varaiya 2008), and microwave (Medina and Benekohal 2014), each with different characteristics (see Mimbela and Klein 2000 for an evaluation of vehicle detection methods in intelligent transportation systems).

Detector placement

Detector placement is an important consideration in the development of a RCE system because accuracy rates depend on where detection occurs in relation to the vehicle trajectory and the distance from the stop line. The closer a vehicle is to the stop line, the more accurately its stop vs. go behavior can be detected (Wang et al. 2012). One trade-off in placing static vehicle presence detectors very close to the stop line is that fewer RLR vehicles will be correctly detected, as these vehicles maybe braking and stopping on approach to the traffic signal stop line after the onset of the red clearance interval (Wang et al. 2012).

Detection system

Each prediction algorithm for RLR vehicle detection uses different variables to calculate whether a vehicle will be in the intersection during the red clearance interval. Variables requiring measurement are important in determining the appropriate detection system, as some systems are better suited for certain measurement types. For example, Wang et al. (2012) recorded the time of a vehicle arriving at an advance loop (200 ft upstream of stop line) and the time when vehicle presence call was made by the presence detector (60 ft upstream of stop line) and Gates (2007) used RADAR due to its near real-time measurement of speed, distance, and vehicle classification. The City of Portland's RCE systems use in-pavement inductive loop detectors, downstream of the stop line, to trigger a RCE during the last half of the yellow change interval and the red clearance interval (Olson 2012). The goal of this detector placement is to detect vehicles that enter the intersection in order to reduce the False Positive rate.

Detection evaluation

A method for evaluating the effectiveness of a RCE is needed to differentiate alternative detector placement and operation. One approach for evaluating RLR prediction models is Detection Theory in which missing errors (False Negative) and false alarm errors (False Positive) are important error types in RLR prediction (Wang et al. 2012). Missing errors occur when a vehicle is predicted to stop, but instead runs the red light without the additional safety benefit of RCE (Zhang et al. 2009). False alarm errors occur when a vehicle is predicted to run the red light, but it instead stops at the stop line, thereby increasing intersection delay by adding additional time to the cycle without progressing vehicles (Zhang et al. 2009).

Hardware-in-the-Loop (HITL) simulation concept

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 (Bullock et al. 2004; National Cooperative Highway Research Program (NCHRP) 2015). 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.

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 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 (National Cooperative Highway Research Program (NCHRP) 2015).

HITL simulation has been used to investigate a variety of transportation engineering topics (Donoughe et al. 2011; Hu et al. 2016; Luo et al. 2016), including research related to traffic control systems (Yun, Best, and Park 2008; So, Lee, and Park 2013). 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. For example, Xu (2009) generated a stopping-speed prediction algorithm using VISSIM, an ASC/3 Controller, MATLAB, and the Advanced Traffic Analysis Center Controller Interface Device (CID) as components of a HITL simulation. The author concluded that 150 ft upstream of stop line is the most appropriate position to locate the red extension detector while speed limit is 60 mph.

Method

Data collection

Guided by the results of the literature review, a field study was designed to investigate factors contributing to RLR in Oregon, with the goals of calibrating a HITL simulation study and improving RCE system designs. Eleven possible sites were initially considered based on a history of RLR-related crashes, presence of RLR cameras, or use of RCE systems. To determine the best data collection site for this study, characteristics of the selected sites were analyzed and additional data were collected, consistent with recommendations from McGee et al. (2012), presented in Table 1.

According to traffic volume, frequency of cycles, operational speed, and most importantly frequency of RLR events, the intersection of US30 and Cornelius Pass Road in Multnomah County, OR, were selected for further data collection. Figure 1 shows an aerial image of the selected site along with the speed distribution and latency of RLR vehicles on the major approaches. Latency is considered as the

Table 1. Site selection factors adopted from McGee et al. (2012).

Factor	Categories
Speed limit	≤ 40 mph, 45 mph, or≥ 50 mph
Area type	Urban (downtown),Suburban, or Rural (outside of incorporated area)
Intersection clearing width (from stop line to far curb)	≤ 48 ft, 48–72 ft, 72–96 ft, 96–120 ft, or ≥ 120 ft
Proximity to upstream signal	No upstream signal within 0.5 mi, or Upstream signal within 0.5 mi
Cycle length	< 90 s, 90–120 s, 120–180 s, or > 180 s
Yellow change interval duration	≤ 4.0 s, 4.1–4.5 s, 4.6–5.0 s, or ≥ 5.1 s
Red clearance interval duration	None, < 1.0–2.0 s, 2.1–3.0 s, or > 3.0 s
Opposing left-turn signalization	Protected only, Permissive only, Protected-permissive (leading left-turn), Permissive-protected (lagging left-turn), or None/prohibited
Approach grade	Level (between −3% and +3%), Upgrade (greater than +3%), or Downgrade (greater than −3%)
Existence of red-light camera enforcement	Camera enforcement at the intersection, or No camera enforcement program within jurisdiction
Time of day for sampling	Weekday peak (7–9 AM, 4–6 PM), Weekday lunch (11 AM–1 PM), Weekday off-peak (all other weekday times), or Weekend periods
Vehicle type	Passenger vehicle, Motorcycle, Bus, Recreational vehicle, Single-unit truck, or Multiunit truck

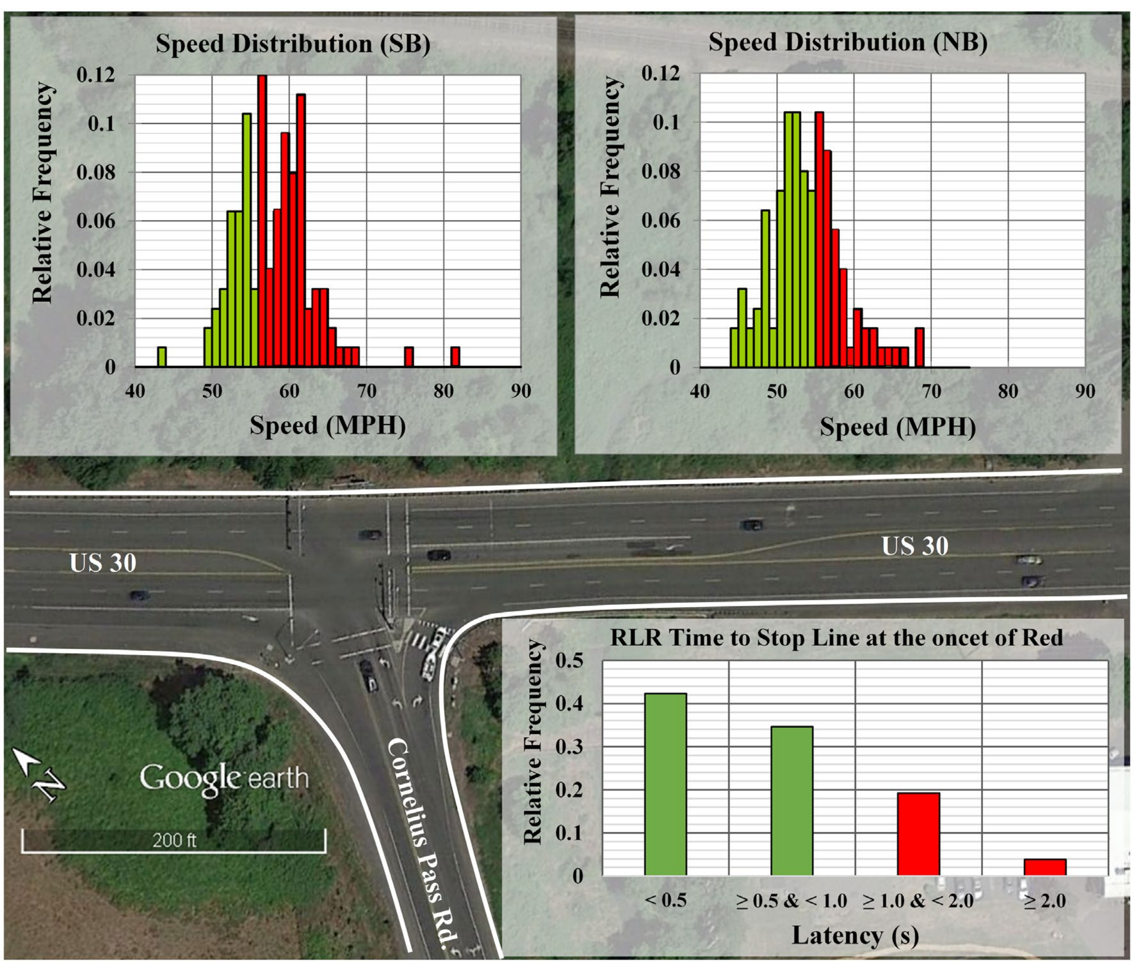

Figure 1. Selected site with speed distribution and latency on major approach.

time to stop line at the onset of circular red indication for a RLR vehicle. Visual inspection of Figure 1 reveals that speeding is a common violation on the major approaches. Inspection of latency distribution also reveals that about 23% of RLR vehicles attempt to run red light 1 s after the onset of circular red indication.

Field data collection procedures were tested at a beta site (located in Corvallis, OR) to ensure that the desired measures could be effectively collected. Video data were collected by installing digital cameras on telescoping poles, programmed to record between 7:00 AM and 7:00 PM on Tuesday, Wednesday, and Thursday. Monday and Friday 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 (Agarwal 2004; Javid 2017). ODOT provided signal timings and plan drawings, as well as RCE logs for the selected intersection for days that the research team collected video data.

In total, 36 h of video data were collected, 24 h of which were transcribed, using a standard transcription process. During 844 observed cycles, data related to 984 vehicles on major approach and 1439 vehicles on minor approach were recorded, including 24 RLR and 1 near miss event. The following field data were used to create and calibrate the HITL simulation 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;
- RADAR-measured speed profiles were used to calibrate speed distributions along major approach. Speed profiles on minor approach were estimated; and
- Signal heads were programmed with 90% compliance to simulate RLR (each vehicle in the system has a 10% chance of disobedience when presented with the red indication). However, due to car following rules, the resultant RLR events are close to 1%.

Simulation process

A microsimulation analysis of different detection strategies used to trigger RCEs was conducted. Specifically, VISSIM microsimulation software with HITL with a 2070 controller and NWS Voyage™ software was used to analyze detection strategies at the selected intersection of US30 with Cornelius Pass Road. This intersection currently uses a RCE function on through movements along major approach (US30) and left-turn movement on minor approach (Cornelius Pass Road). RCE events are triggered by loop detectors located downstream from the stop line. Figure 2 shows methodological framework along with the components of our simulation process.

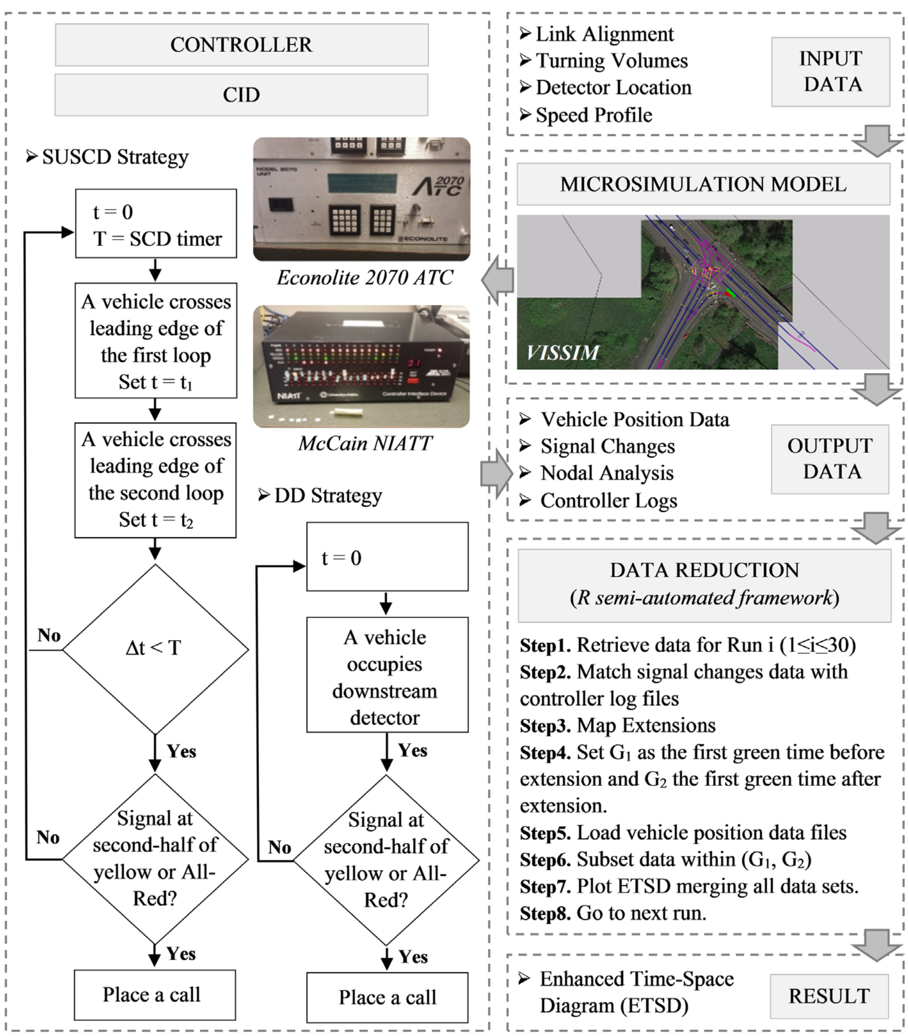

Figure 2. Hardware-in-the-Loop simulation process.

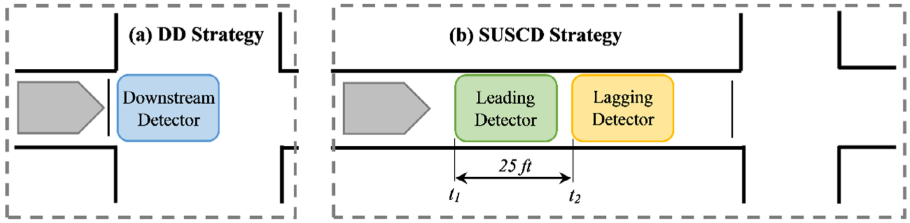

Figure 3. Detection strategies.

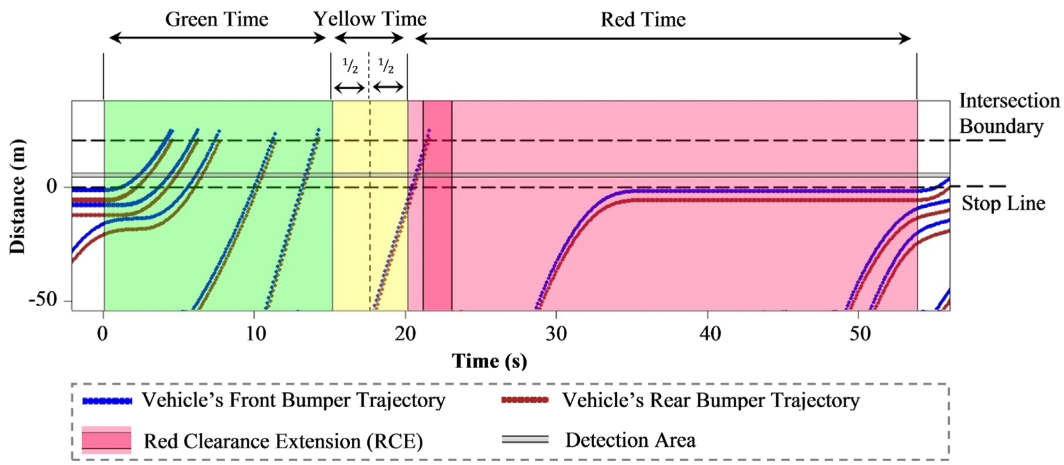

Figure 4. Example of an ETSD showing a RLR event with DD that triggered a RCE.

HITL was used to control the traffic signal in the microsimulation model (Figure 2). 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 a BIN file containing the existing signal timing at the intersection. The file was loaded and run on a 2070 controller. The NWS Voyage™ Software Operating Manual (Northwest Signal Supply, Inc 2012) provided details on the use and programming of the RCE feature. Specifically, the red clearance interval can be extended based on the presence of a late-arriving call at a specified detector, if the call occurs during the second half 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 s. 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 microsimulation model.

As is shown on Figure 2, two detection strategies for triggering RCE were considered:

- Downstream Detection (DD) which involves a single in-pavement loop detector (per lane) located downstream from the stop line (Figure 3(a)). 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) which uses a pair of in-pavement loop detectors (per lane) located upstream from the stop line (Figure 3(b)). Using programmable logic in controller device, the two loops were 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.

A diagram of the SUSCD is included in Figure 2 and Figure 3(b). 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.

Data for the HITL microsimulations were collected from three main sources.

- Direct microsimulation model outputs included the position data for each vehicle and the chronologically sorted signal changes both at a resolution of 0.1 s.
- Microsimulation analysis provided data for the total and stop delays, collected from a single node surrounding the simulated intersection.
- Signal controller logs recorded the beginning and end of each RCE event with a resolution of 1 s.

For the purpose of data reduction, useful outputs were collected from the signal changes data, vehicle positions, and controller RCE logs. RCE data from signal changes (0.1 s frequency) matched data from the lower resolution controller logs (1.0 s frequency). Therefore, the higher resolution signal changes 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. The stepwise procedure is summarized in Figure 2.

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 4). ETSDs were used to analyze the performance of detection strategies.

Experimental scenarios

Scenarios were created using single decision model for driver behavior at the onset of the circular yellow indications with compliance rate of 90% (PTV 2013). Four scenarios were evaluated, with 30 runs of an 80-min simulation. Simulation runs included 15-min seeding period (the time between the start of the simulation and when the network has necessary number of vehicles in the system for the representative time period), 60-min evaluation, and 5-min cooldown (the time between the end of the evaluation and when the network is flush out). Table 2 summarizes the characteristics of final experimental scenarios.

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 s from stop bar (Bonneson et al. 2002). 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 approximately 2.5 s) and the other 475 ft (corresponding to approximately 5.5 s) upstream of stop bar. However, detector placement closer to stop line has been found to minimize both missed RLR vehicles and false alarms (Xu 2009). As such, a preliminary evaluation was made of the SUSCD at three additional locations, 75, 100, and 125 ft upstream of stop bar. The preliminary 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.

Comparison measures

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.

Accuracy measurement

Evaluation of system accuracy was based on the number of correct RCE calls defined as 'Correct Calls' and the number of detected vehicles with a high risk of collision (VHRC) defined as 'Correct Detection'. VHRCs are defined by one of the two conditions: (1) if a vehicle enters intersection late in the yellow change interval, it can be considered a late yellow indication entry (Figure 5a) or (2) if a vehicle enters the intersection during the red indication, it is considered a RLR (Figure 5(b)).

Table 2. Experimental scenarios.

Scenario	Detection strategy	Detector position	Description
1	DD	5 ft. downstream	Signal head compliance rate = 90%, single decision for YLB
2	SUSCD	125 ft. upstream	Signal head compliance rate = 90%, single decision for YLB, SCD timer duration = 0.4 s
3	SUSCD	215 ft. upstream	Signal head compliance rate = 90%, single decision for YLB, SCD timer duration = 0.4 s
4	SUSCD	475 ft. upstream	Signal head compliance rate = 90%, single decision for YLB, SCD timer duration = 0.4 s

*YLB: yellow-light behavior; **SCD: speed-conditional detection.

'Correct Calls' (True Positive) are explicitly defined as RCEs which benefit the VHRC that triggered the RCE as it clears the intersection (Figure 5(c)). If a RCE is triggered by a non-VHRC (Figure 5(d)), 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 (Figure 5(e)), it is also considered an 'Incorrect Call' (False Positive).

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 (Figure 5(f)). However, if a VHRC occupies the detection area during the aforementioned period but a RCE is not triggered, it is an 'undetected' VHRC (Figure 5(g)) or a False Negative. 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 (Figure 5(h)).

Table 3 defines RCE system accuracy measurements in terms of the occurrence of a RCE and a VHRC.

Efficiency measurement

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 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. If a VHRC is downstream of the stop line 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. Based on the position of VHRCs at the onset of red, three levels are defined to measure the efficiency of RCE (Table 4).

Operation measurement

The impact of RCE systems on signal operations was evaluated; the implications on delay (reported as delay per vehicle and stop delay per vehicle) were considered. The microsimulation model considers delay time as the difference between theoretical (optimal, ideal) travel time and actual travel time. Delay per vehicle is calculated as the total delay divided by number of vehicles and stop delay is the average standstill time per vehicle (PTV 2013).

Results

Each of the detection strategies were analyzed for accuracy, efficiency, and operational performance. Table 5 presents accuracy measurements for each of the detection systems over 30 simulation runs.

In this context, a correct call is explicitly defined as RCE which benefits the VHRC that triggered the RCE as it clears the intersection. The DD system correctly detected 130 of 194 VHRCs (67.0% success rate vs. 33.0% False Negative) and correctly triggered 130 of 337 RCE (38.6% success rate – 61.4% False Positive). The SUSCD system at 125 ft correctly detected 114 out of 175 VHRCs (65.1% success rate vs. 34.9% False Negative) and correctly triggered 114 out of 401 RCE (28.4% success rate vs. 71.6% False Positive). The SUSCD system at 215 ft correctly detected 37 out of 160 VHRCs (23.1% success rate vs. 76.9% False Negative) and correctly triggered 37 out of 202 RCE (18.3% success rate vs. 81.7% False Positive). The SUSCD system at 475 ft correctly detected 68 out of 138 VHRCs (49.3% success rate vs. 50.7% False Negative) and correctly triggered 68 out of 803 RCE (8.5% success rate vs. 91.5% False Positive).

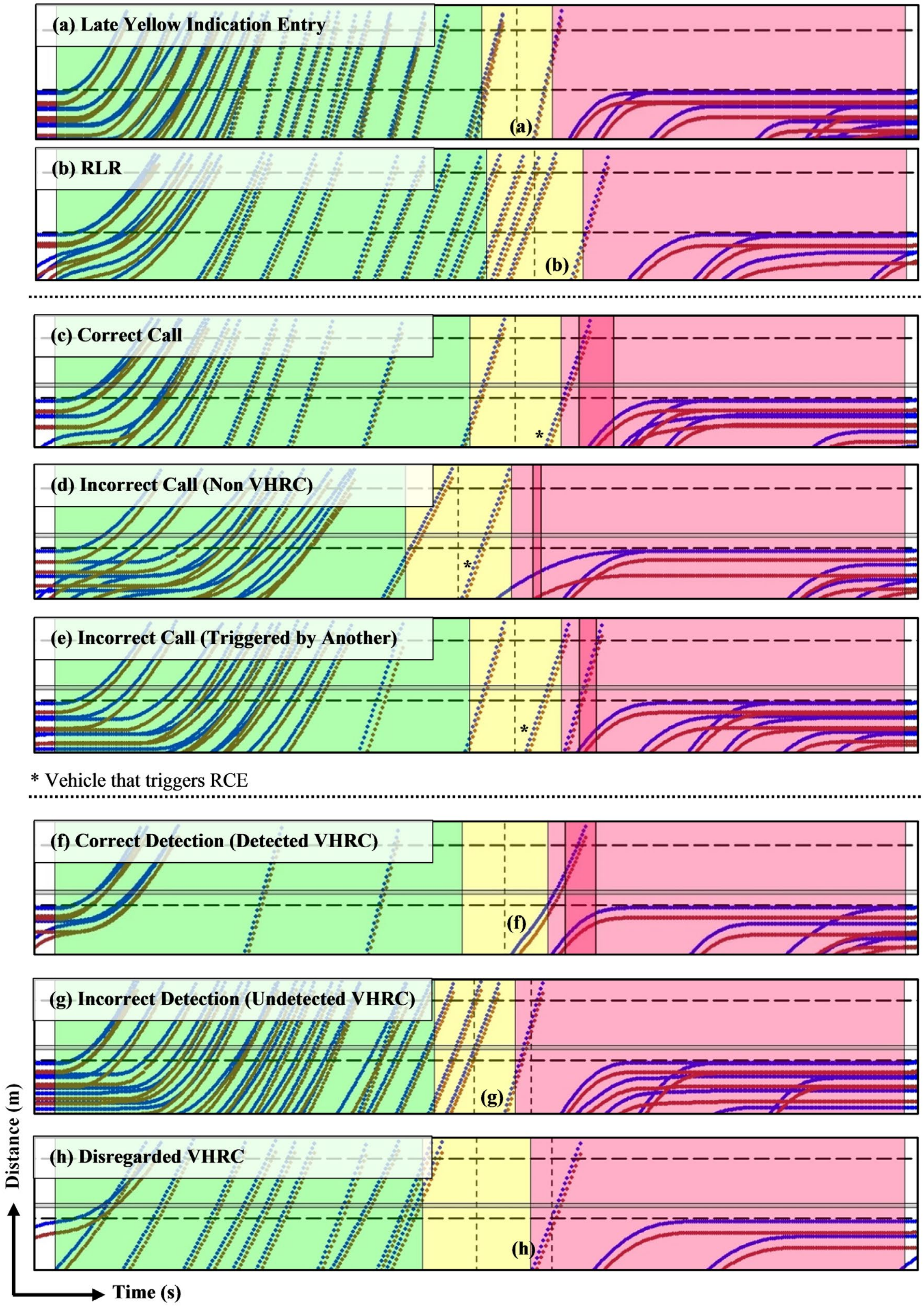

Figure 5. Evaluation of system accuracy specifics.

Using three levels of effectiveness (Table 4), the efficiency of correctly triggered RCE by each of the detection systems was analyzed (Table 6).

The DD system was able to create highly effective or effective extensions in approximately 33% of all cases. The SUSCD systems at 125, 215, and 475 ft were able to create highly effective or effective extensions in 82.5, 100, and 100% of all cases, respectively.

Figure 6 depicts operational characteristics measured as delay per vehicle and stop delay for each of the detection systems, over 30 individual simulation runs. The results of a one-way ANOVA F-test indicated that there was no difference in mean vehicle delay between four detection systems ($F = 2.161$, $p = .101$) but there was an effect of detection strategy on mean stop delay ($F = 4.359$, $p = 007$). Looking at pairwise comparisons, results of Tukey HSD *post hoc* test revealed that mean stop delay was higher for SUSCD at 475 ft compared to DD ($p = .017$), SUSCD at 125 ft ($p = .005$), and SUSCD at 215 ft ($p = .032$). Mean stop delay was not statistically different among DD, SUSCD at 125 ft, and SUSCD at 215 ft.

Table 3. Accuracy measurements.

		Extension	
		Yes	No
VHRC	Yes	A VHRC is detected and a RCE is triggered (True Positive)	A VHRC is not detected and a RCE is not triggered (False Negative)
	No	A RCE is triggered by a non-VHRC (False Positive)	A RCE is not triggered and there is no VHRC (Neutral Cycles or True Negative)

Table 4. Efficiency measurement.

Position	Definition	Crash prevention effectiveness
Upstream of Stop Line	VHRC has not reached the stop line at red onset	Highly effective
At Stop Line	VHRC reached stop line at red onset	Less effective
Downstream of Stop Line	VHRC passed the stop line at red onset	Not effective

Table 5. 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		287		165		735	

Table 6. Efficiency measurements for detection strategies.

	DD	SUSCD at 125 ft.	SUSCD at 215 ft.	SUSCD at 475 ft.
RCE crash prevention effectiveness	Frequency (%)			
Highly effective	23 (17.7%)	86 (75.5%)	36 (97.3%)	68 (100.0%)
Less effective	20 (15.4%)	8 (7.0%)	1 (2.7%)	0 (0.0%)
Not effective	87 (66.9%)	20 (17.5%)	0 (0.0%)	0 (0.0%)

Figure 7 provides an overall 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 (correct 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 calls 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.

From an efficiency standpoint, SUSCD systems outperformed the DD system. While the rate of highly effective RCE 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.

Discussion

Figure 8 shows typical cases of RCE produced by each of the detection systems. By definition, the DD system (Figure 8(a)) calls extensions when a vehicle first occupies the detector downstream of the stop line during the second half of the yellow change 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 red clearance interval. From a safety standpoint, drivers in opposing lanes would be able to see a vehicle in their forward view at the onset of their green. Additionally, the time required for the lead vehicle stopped in a queue to complete the perception–reaction process, accelerate from a stopped position, and reach the near boundary of the conflict zone with the vehicle triggering the extension should also be considered.

Figure 8 parts (b), (c), and (d) show a common RCE event for the SUSCD system at 125, 215, and 475 ft. By definition, in these systems, VHRC are detected based on their instantaneous velocity at 125, 215, and 475 ft upstream of the stop line. The ETSD for SUSCD at 125 and 215 ft demonstrates a VHRC that passes the stop line at the end of

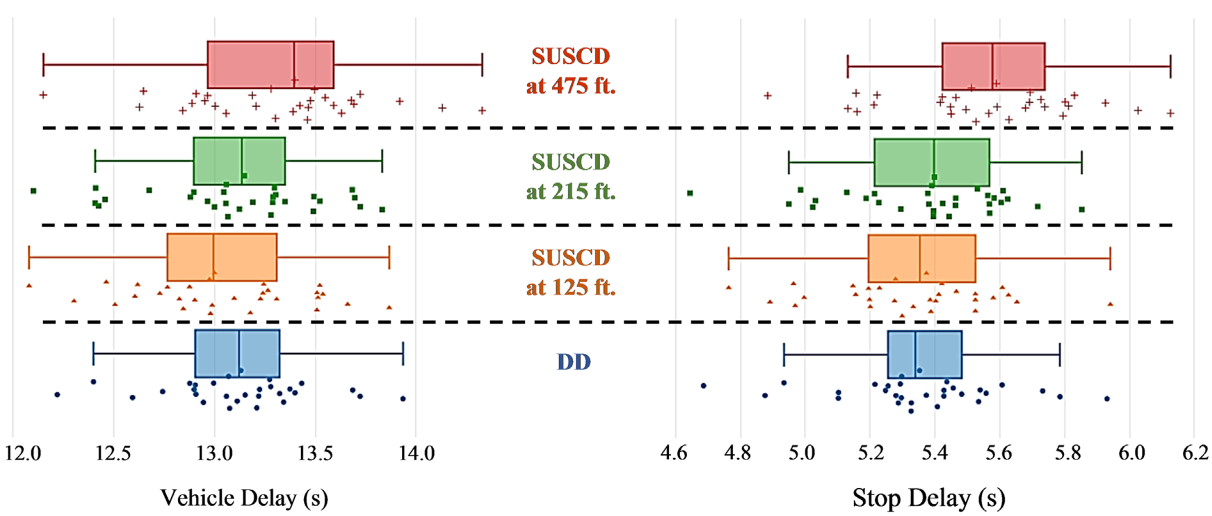

Figure 6. Operational measurements for detection strategies.

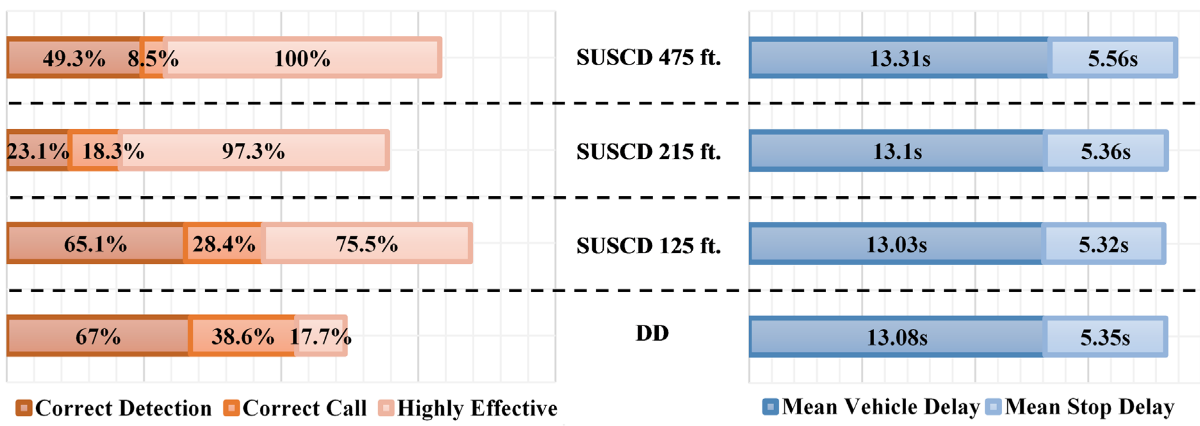

Figure 7. Comparison of accuracy, efficiency, and operational measurements in detection systems.

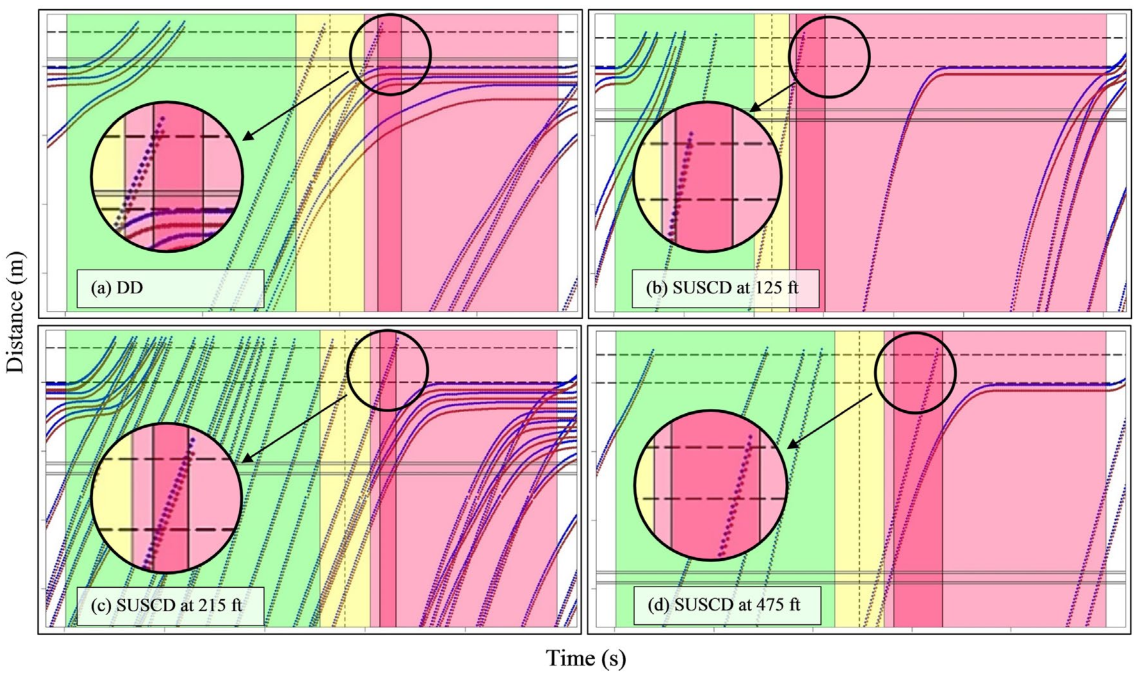

Figure 8. Typical example of a detected VHRC from alternative RCE systems.

the one second red clearance interval; the ETSD for SUSCD at 475 ft demonstrates a VHRC that crosses the stop line long after the onset of red. In all three cases, with the help of a correct, complete, and precise extension, the VHRC clears the intersection before any conflicting movement is provided a green indication.

To judge the appropriateness of each alternative design, both quantitative and qualitative performance should be considered. A comparison of demonstrated ETSDs confirms that, although SUSCD systems are relatively less successful in detecting VHRCs and making correct calls, they produce highly effective extensions more consistently, promoting traffic safety at the signalized intersections. For the SUSCD systems, VHRCs are detected by a single spot speed measurement made 125, 215, or 475 ft before the intersection. Although speed is a crucial determinant in identifying VHRCs, drivers' decisions to stop or proceed cannot be perfectly predicted from instantaneous velocity at point sensors. As such, the SUSCD systems triggered RCE events without observation of RLR. The predictive ability in SUSCD systems justifies the reduced accuracy. Additionally, as the detector is located further away from the stop line, the accuracy of the detection system also decreases (Figure 7). A system based on detectors downstream of the stop line, such as the DD system, is not able to identify VHRCs as depicted in parts (b), (c), and (d) of Figure 8. The highly effective extension rates ranging from 75.5 to 100% with the SUSCD systems, as compared to 17.7% of that in DD system, emphasize this limitation.

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 calls and correct detection. However, while this system outperforms the other speed-conditional systems in accuracy, it is less successful in creating highly effective and effective extensions. Comparing the SUSCD systems at 215 and 475 ft, while the SUSCD at 215 ft is more successful at triggering correct calls, the SUSCD at 475 ft outperforms in the detection of VHRCs. SUSCD at 475 ft creates highest number of extensions among all detection systems. This higher rate of RCE, which are frequently incorrect calls (False Positive), increases the vehicle delay and stop delay as shown in Figure 6.

Looking at the accuracy and efficiency measurements (Figure 7), it appears that placing speed-conditional detectors further upstream of stop line increase the efficiency of extensions while negatively affecting accuracy. Considering accuracy and efficiency interactively, the SUSCD system at 125 ft could be considered as the optimal solution in implementation of RCE with an 85th percentile speed of approximately 60 mph.

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.

Conclusion

In this study, a novel HITL simulation was developed. The field deployed timings of existing signal timing at the US30 and Cornelius Pass Road intersection located in Multnomah County, OR, were loaded and run on a 2070 controller. A CID was used to communicate between the signal controller and the computer running the microsimulation. Within the HITL simulation environment, logic for the SUSCD concept was developed and used to predict RLR vehicles on the approach to a signalized intersection at 125, 215, and 475 ft. This logic could be directly implemented in the field at a traffic signal with a 2070 controller and the NWS Voyage™ operating software. The HITL simulation of the selected site was used as a test bed to evaluate alternative RCE system designs. A semi-automated procedure was coded in R to visualize microsimulation model outputs in ETSDs, in which the trajectories of the front and rear bumpers of vehicles were plotted against the signal changes, intersection geometry, and detector locations, specifically for cycles that included a RCE. The HITL simulation method and the framework for evaluation of alternatives proposed in this study could be employed in similar studies to investigate accuracy, efficiency, and the operational characteristics of alternative RCE systems.

Cursory examination of quantitative results leads to three general observations. (1) The DD alternative and SUSCD at 125 ft provided higher accuracy than the SUSCD system at either 215 or 475 ft (2) All of the SUSCD systems provide higher efficiency than the DD system. (3) The average vehicle delay was relatively small and consistent across all four RCE system alternatives. Detection rates were high for the DD alternative because no prediction was made; the vehicle was already in the intersection when it was detected. Although the SUSCD systems had a higher likelihood of false prediction of a RLR vehicle compared to the DD system, the SUSCD systems introduced the potential for providing more robust RCE. An examination of the ETSDs showed improved relationships between the vehicle trajectories, RCE events, and conflicting movements when the SUSCD systems were used.

Although HITL traffic simulation provides many meaningful advantages, it also requires expensive hardware and software interfaces, as well as uniquely trained staff. Perhaps the most important limitation is the requirement that the simulations take place in real-time. The process of collecting 30 individual runs, an industry standard, for each alternative scenario is very time intensive. Furthermore, 30 new runs must be produced each time the system design or a setting is modified to improve the performance measurements. Finally, the volume and structure of the produced data required substantial programming expertise and staff time to reduce the output data into usable statistics and visualizations.

As with many complex transportation problems, there exist opportunities to continue to advance the state of the practice. The development of RCE systems is no different. Two recommendations are made for future work:

- HITL Simulations of Additional RCE System Designs – The calibrated HITL model and the data analysis code developed for this study could be leveraged to test alternative SUSCD locations and approach speeds to refine the logic of the RLR prediction, thereby improving the overall performance of the system.
- Field Evaluation of Alternative Vehicle Detection Strategies – The in-pavement loop is still widely considered to be the most accurate and commonly implemented vehicle detection strategy. However, a single point sensor has a limitation in the type of traffic data that can be extracted (presence and instantaneous speed) to support a RLR prediction algorithm. Conversely, a wide area detection system, such as that produced by a RADAR sensor, could be used to evaluate the time-to-stop-line, acceleration, or deceleration data for each approaching vehicle. These additional continuous data streams could dramatically improve the performance of a RCE system.

Acknowledgment

This material is based on work supported by the Oregon Department of Transportation under grant number SPR 773. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Oregon Department of Transportation.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Oregon Department of Transportation [grant number SPR 773].

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Appendix 1. Glossary

Table A1. Definition of abbreviations and acronyms.

Abbreviation/Acronym	Definition
CID	Controller Interface Device
DD	Downstream Detection
ETSD	Enhanced Time-Space Diagram
FHWA	Federal Highway Administration
HITL	Hardware-in-the-Loop
ODOT	Oregon Department of Transportation
RCE	Red Clearance Extension
RLR	Red Light Running
SCD	Speed-Conditional Detection
SUSCD	Smart Upstream Speed-Conditional Detection
VHRC	Vehicle with High Risk of Collision
YLB	Yellow-Light Behavior