A conceptual framework for dynamic extension of the red clearance interval as a countermeasure for red-light-running

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ABSTRACT

This manuscript describes the development and evaluation of a conceptual framework for real-time operation of dynamic on-demand extension of the red clearance interval as a countermeasure for red-light-running. The framework includes a decision process for determining, based on the real-time status of vehicles arriving at the intersection, when extension of the red clearance interval should occur and the duration of each extension. A zonal classification scheme was devised to assess whether an approaching vehicle requires additional time to safely clear the intersection based on the remaining phase time, type of vehicle, current speed, and current distance from the intersection. Expected performance of the conceptual framework was evaluated through modeling of replicated field operations using vehicular event data collected as part of this research. The results showed highly accurate classification of red-light-running vehicles needing additional clearance time and relatively few false extension calls from stopping vehicles, thereby minimizing the expected impacts to signal and traffic operations. Based on the recommended parameters, extension calls were predicted to occur once every 26.5 cycles. Assuming a 90 s cycle, 1.5 extensions per hour were expected per approach, with an estimated extension time of 2.30 s/h. Although field implementation was not performed, it is anticipated that long-term reductions in targeted red-light-running conflicts and crashes will likely occur if red clearance interval extension systems are implemented at locations where start-up delay on the conflicting approach is generally minimal, such as intersections with lag left-turn phasing.

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1. Background and objectives

Red-light-running (RLR) at signalized intersections is a serious safety problem in the United States, contributing to right-angle, left turn head-on, and rear end crashes. Enforcement strategies (human and automated) are often used to reduce the occurrence of red-light-running by imposing the threat of a citation. However, enforcement is only effective in deterring RLR events where the driver could safely stop in time, but instead chooses to proceed through the intersection. Enforcement strategies will not reduce RLR events where the driver entered the intersection shortly after the red, but was either unable or unaware of the need to stop. Such events are more effectively treated by engineering countermeasures, including traffic signal phase extension systems.

Various detection and control strategies have been developed and implemented to provide on-demand extension of the traffic signal phase timings upon the detection of vehicles that will not likely clear the intersection prior to the start of the next conflicting phase. Such systems utilize one or more sensors to detect vehicular characteristics, such as speed, location, and classification, and include algorithms to predict when approaching vehicles will not likely clear the intersection prior to the impending conflicting green phase. Detection of a probable RLR event will inform the signal controller to extend a particular interval for either a preset or calculated amount of time. Until recently, the majority of such systems have been designed to estimate the optimal time to end the green interval based on consideration of both of RLR prevention and delay to vehicles waiting on other approaches (Kronborg and Davidsson, 1993; Bonneson et al., 2002a; Zimmerman, 2003; Middleton et al., 2011; Du et al., 2012). These systems have typically utilized point-detection from in-pavement loop sensors or side-firing microwave or radar, which afford a single predictive measurement of intersection arrival times at the intersection. Prior to 2009, implementation of red clearance extension systems in the United States was prohibited by the Manual on...
Uniform Traffic Control Devices (2003, 2009), as red clearance intervals were required to be of a preset fixed time (2003). However, the 2009 MUTCD included language allowing for on-demand extension of the red clearance interval on a cycle-by-cycle basis (2009). Such provisions, coupled with further advancements in vehicular detection technology, have facilitated development and testing of systems for extension of the red clearance interval (Zhang et al., 2011; Wang et al., 2012; Park et al., 2015), including for use within a connected vehicle environment (Chen et al., 2013).

Extension of the red-clearance interval relies on the ability to obtain and analyze dynamic, real-time data for vehicles on the subject approach, including speed, distance, and classification, and send the appropriate message to the traffic signal controller. Recent advancements in radar-based vehicular detection technology allows for real-time tracking of the trajectories for multiple vehicles approaching an intersection, which is relayed to the corresponding extension controller several times per second. A decision algorithm programmed into the extension controller software instantaneously analyzes the trajectory information based on a pre-programmed set of operating procedures and parameters. Fig. 1 depicts a basic schematic of the detection and control process for an interval extension system using radar detection.

An interval extension call is placed to the signal controller only if the algorithm determines that an oncoming vehicle can neither comfortably stop nor safely clear the intersection prior to the start of the conflicting green phase. The duration of the interval extension is based on the time needed for the vehicle to clear the intersection before the onset of the conflicting green, and is updated dynamically as the status of the approaching vehicle(s) changes. Fig. 2 displays a basic time diagram of the extension process for the red clearance interval.

Dynamic extension of the red clearance interval is a relatively new concept with only limited implementation. Furthermore, the operating parameters and procedures have not been broadly researched, and little is known about the potential impacts on safety, traffic operations, and signal operations. It was hypothesized that a properly defined dynamic red clearance interval extension system with appropriately specified operating parameters may potentially reduce conflicts and crashes caused by red-light running events, while having only minimal impacts on traffic operations and signal operations. The primary objective of this research was to develop and evaluate a conceptual framework describing the procedures and operating parameters for real-time extension of the red clearance interval, including determination of when to provide extension of the red clearance interval based on real-time vehicle trajectory data for vehicles approaching at the end of the signal phase, and the duration of such an extension.

2. Interval extension process

2.1. General concepts

The primary objective of a red extension algorithm is to identify vehicles approaching at the end of the phase vehicles that may potentially commit a red-light-running event and extend the red clearance interval in real-time based on the maximum necessary amount of time needed for all potential red-light-running vehicles to clear. The basic flow of information for this process is shown in the following flowchart (Fig. 3).

2.2. Event classification

The detection procedure for interval extension is described as a means of classifying approaching vehicles into respective zones, based on whether it is predicted that a vehicle will:

- Stop prior to entering the intersection (Zone 1);
- Clear the intersection prior to the start of the conflicting green phase (Zone 3); or
- Not clear the intersection prior to the start of the conflicting green phase and also not stop prior to entering the intersection (Zone 2).

Fig. 1. Basic detection and control for radar-based interval extension system.

Fig. 2. Time diagram for extension of red clearance interval.

Obtain speed and distance information for each approaching vehicle in the detection range.

For each detected vehicle, estimate the deceleration rate that would be necessary to stop.

Compare each estimated deceleration rate to a threshold rate, selected based on speed, vehicle type and duration of the yellow interval.

For vehicles with estimated deceleration rates that exceed the threshold, determine the maximum time to clear the intersection.

If the maximum clearing time is greater than the time remaining until the start of the next conflicting green phase, then extend the red clearance interval by the difference between the maximum time to clear and the time remaining in the phase.

**Fig. 3.** Conceptual process for extension of the red clearance interval.

A zonal classification diagram for an intersection approach is shown in **Fig. 4**.

As the time remaining in the phase decreases, the slope of the clearing threshold line increases, thereby increasing the size of Zone 2 while decreasing the size of Zone 3. The size of Zone 2 reaches a maximum at the start of the conflicting green, at which point no clearing time remains. The size of Zone 1 (the stopping zone) is based on the threshold deceleration rate selected by the detection algorithm based on the vehicle type and approach speed.

Determination of the threshold deceleration rate is described in greater detail in subsequent sections. Vehicles in Zone 2 possess the greatest potential need for extension of the red clearance interval. One of three potential outcomes will occur when a vehicle is classified in Zone 2:

- **Outcome 1**: the subject vehicle accelerates, enters the intersection, and clears the intersection prior to the onset of the conflicting green.
- **Outcome 2**: the subject vehicle stops, using a deceleration rate greater than the threshold.
- **Outcome 3**: the subject vehicle enters the intersection but does not clear the intersection prior to the onset of the conflicting green.

Outcomes 1 and 2 would represent false extension calls, as extended clearance time is ultimately unnecessary. Outcome 3 is the target RLR event that a red clearance extension system is designed to treat. Outcome 3 may occur from anywhere within Zone 2, although most of the later-entry and potentially more dangerous RLR events originate from the upstream region of Zone 2. Outcome 3 is also much more difficult to detect because RLR vehicles initially possess the speed and positioning characteristics similar to those of a stopping vehicle, but ultimately proceed through the intersection. This event detection ambiguity for Zone 2 vehicles is illustrated in **Fig. 5** based on field data collected from five intersections in Wisconsin.

**2.3. Operating parameters**

The interval extension algorithm must provide accurate classification of vehicles requiring extension and ensure that such vehicles are provided with sufficient extended red clearance time. It is also important to minimize unnecessary extensions, such as false-calls from stopping or turning vehicles, to reduce both vehicular delay on adjacent approaches and impacts on signal operations. The specific parameters specified herein include:

- Boundary condition between Zones 2 and 3 (clearing threshold);
- Boundary condition between Zones 1 and 2 (stopping threshold);
- Time-into-phase for system initialization;
- Minimum speed threshold for false-call prevention; and
- Duration of red clearance extension.

**2.3.1. Boundary condition between Zones 2 and 3 (clearing threshold)**

The clearing threshold line displayed in **Fig. 4** represents the boundary between Zones 2 and 3. The position of the clearing threshold is dependent on a combination of the width of the

**Fig. 5.** Comparison of travel times for red-light-running, first-to-stop, and last-to-go vehicles at the start of yellow. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)
intersection and the time remaining until the start of the next green phase. The slope of the line continuously increases as the time remaining in the phase approaches zero and has infinite slope (i.e., vertical) at the end of the red clearance interval (i.e., start of conflicting green phase).

The slope of the clearing threshold line is given as follows:

$$\text{slope} = \frac{1}{1.467 \times TTG}$$  \hspace{1cm} (1)

where

$$\text{slope} = \text{slope of the time remaining line (mph/ft)},$$

$$\text{TTG} = \text{time remaining until start of conflicting green phase (s),}$$

$$1.467 = \text{conversion from miles per hour to feet per second (fps/mph)}.$$  

The x-intercept of the clearing threshold line is represented by the total distance needed for a vehicle to clear the intersection. The total clearing distance of the intersection is equal to the intersection width from the stop line to the far-edge of the furthest lane plus the assumed vehicle length, as shown in Eq. (2):

$$x_{-}\text{intercept} = d_{\text{clearing}} = - (w + L)$$  \hspace{1cm} (2)

where

$$d_{\text{clearing}} = \text{total intersection clearing distance (ft)},$$

$$w = \text{intersection width (ft)},$$

$$L = \text{assumed length of vehicle [e.g., 25 ft for passenger vehicle, 75 ft for semi-trailer]}.$$  

### 2.3.2. Boundary condition between Zones 1 and 2 (stopping threshold)

The boundary between Zones 1 and 2 (i.e., stopping vehicles vs. vehicles that potentially require extended red clearance time) is represented by a threshold deceleration rate. Assuming adequate radar-detection capabilities, the threshold deceleration rates may be determined in real-time by the detection algorithm. To that end, threshold deceleration rates were derived from a logistic regression model for classification of first-to-stop vs. last-to-go events using a set of estimable parameters for which real-time data are available from the radar sensor. These parameters included: travel time to the intersection at yellow onset, type of vehicle (passenger vehicle or heavy vehicle), and duration of the yellow interval. The logistic regression model was calibrated using data collected from five intersections in Wisconsin, and was specified as follows (Gates, 2007):

$$\ln \left( \frac{\pi_{\text{go-thru}}}{\pi_{\text{stop}}} \right) = -20.747 - 0.262x_{\text{trav time (s)}} + 11.689x_{\text{yellow(s)}} - 1.271x_{\text{veh type}}$$  \hspace{1cm} (3)

where

$$\pi_{\text{go-thru}} = \text{probability of vehicle going through the intersection in response to the yellow indication},$$

$$\pi_{\text{stop}} = \text{probability of vehicle stopping in response to the yellow indication},$$

$$x_{\text{trav time (s)}} = \text{travel time to the intersection stop bar at the onset of the yellow interval (s)},$$

$$x_{\text{yellow(s)}} = \text{total duration of yellow interval (s)},$$

$$x_{\text{veh type}} = 1 \text{ for passenger vehicle, 0 for heavy vehicle}.$$  

### Tables 1 and 2: Threshold deceleration rates for passenger and heavy vehicles

#### Table 1: Threshold deceleration rates for passenger vehicles

<table>
<thead>
<tr>
<th>$P(Go)$</th>
<th>Yellow interval (s)</th>
<th>Threshold deceleration rate equation Predicted from logistic regression model (ft/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.163v + 0.764$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.153v + 0.927$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.153v + 0.671$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.154v + 0.277$</td>
</tr>
<tr>
<td>0.05</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.183v + 0.934$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.166v + 1.243$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.164v + 0.927$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.167v + 0.334$</td>
</tr>
<tr>
<td>0.10</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.193v + 1.034$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.176v + 1.263$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.171v + 1.051$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.177v + 0.324$</td>
</tr>
<tr>
<td>0.20</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.206v + 1.250$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.187v + 1.486$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.182v + 1.113$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.187v + 0.384$</td>
</tr>
<tr>
<td>0.50</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.240v + 1.800$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.209v + 2.036$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.201v + 1.571$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.211v + 0.464$</td>
</tr>
<tr>
<td>0.75</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.289v + 2.590$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.235v + 2.836$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.225v + 2.029$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.240v + 0.609$</td>
</tr>
</tbody>
</table>

Note: $d_{\text{threshold}}$ = estimated threshold deceleration rate; $v$ = vehicular approach speed obtained from sensor.

#### Table 2: Threshold deceleration rates for heavy vehicles

<table>
<thead>
<tr>
<th>$P(Go)$</th>
<th>Yellow interval (s)</th>
<th>Threshold deceleration rate equation Predicted from logistic regression model (ft/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.151v + 0.614$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.146v + 0.687$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.143v + 0.591$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.143v + 0.244$</td>
</tr>
<tr>
<td>0.05</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.165v + 0.776$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.155v + 0.959$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.151v + 0.809$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.155v + 0.241$</td>
</tr>
<tr>
<td>0.10</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.172v + 0.870$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.160v + 1.043$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.158v + 0.817$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.162v + 0.253$</td>
</tr>
<tr>
<td>0.20</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.183v + 0.894$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.169v + 1.149$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.165v + 0.894$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.170v + 0.297$</td>
</tr>
<tr>
<td>0.50</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.203v + 1.234$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.185v + 1.421$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.180v + 1.137$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.185v + 0.374$</td>
</tr>
<tr>
<td>0.75</td>
<td>3.5</td>
<td>$d_{\text{threshold}} = 0.228v + 1.607$</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>$d_{\text{threshold}} = 0.201v + 1.866$</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>$d_{\text{threshold}} = 0.196v + 1.353$</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>$d_{\text{threshold}} = 0.203v + 0.451$</td>
</tr>
</tbody>
</table>

Note: $d_{\text{threshold}}$ = estimated threshold deceleration rate; $v$ = vehicular approach speed obtained from sensor.

extensions serves two primary purposes. First, the static red clearance interval allows for system initialization to occur after the yellow time has expired, which greatly reduces the potential for false extension calls from stopping vehicles that have not begun to decelerate. Second, use of a static red clearance interval reserves the use of extended red clearance time for vehicles that are not otherwise protected by the static red clearance interval, thereby reducing the number of extension calls and subsequent operational impacts. In other words, the use of a static red clearance interval would allow for normal signal operation to occur unless a red-light-running vehicle was detected which exhibited a predicted clearing time greater than that provided by the static red clearance time. In this way, the extended red clearance interval can be considered as an emergency measure, only to be utilized when absolutely necessary. The duration of the static red clearance interval should be determined based on established policy or practice for the particular jurisdiction.

2.3.4. Minimum speed threshold to reduce false calls

The greatest challenge of the zonal classification process involves distinguishing between late-arriving stopping vehicles and RLR vehicles, as these groups often display similar speed and location characteristics at the start of the red clearance interval. In many cases, it is nearly impossible to distinguish between stopping vehicles and RLR vehicles (i.e., Zone 1 vs. Zone 2) based solely on the threshold deceleration rate. Thus, it was determined that an additional differentiation process was necessary to reduce the number of false extension calls from stopping vehicles without compromising the prediction accuracy of RLR vehicles needing extension.

The most effective method for reducing the rate of false extension calls from stopping vehicles, while maintaining a minimal rate of missed RLR events, was to include a minimum speed threshold in the decision process. Vehicles with speeds below this minimum speed threshold would be classified into Zone 0. Calibration showed that false calls were minimized and missed calls were held to zero if the minimum speed threshold was specified according to the following procedure:

For \( t = 0 \) to \( T \), where \( T \) equals the preprogrammed static red clearance time,

\[
\text{Lev}_{\text{min}} = v_{\text{mean}} - 2\sigma_v - \sigma_v \frac{t}{\sqrt{T}}
\]

where

- \( v_{\text{min}} \) = minimum speed for red clearance extension (mph),
- \( v_{\text{mean}} \) = mean speed of non-platooned vehicles (mph),
- \( \sigma_v \) = standard deviation of speed (mph),
- \( t \) = time after start of red clearance interval (s),
- \( T \) = static red clearance interval duration (s).

2.3.5. Interval extension duration

The duration of the red clearance extension is a straightforward computation for Zone 2 classified vehicles, based on the difference between the estimated time to clear the intersection and the time remaining until the onset of the next conflicting green phase. The duration of the extension time is computed as follows:

\[
R_{\text{extended}} = \text{TTC} - \text{TTG}
\]

where

- \( R_{\text{extended}} \) = extended red clearance interval (s),
- TTC = estimate time for vehicle to clear the intersection (s),
- TTG = time until the next conflicting green phase (s).

The duration of the red clearance interval extension time may be increased depending on changes in the status of approaching vehicles as provided by the detection equipment. A maximum refresh frequency of 10 Hz was assumed, as this coincided with the

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refresh rate of a typical radar sensor and is also the resolution of a typical traffic signal controller. The situation will undoubtedly arise where multiple red-light-running vehicles approach the intersection simultaneously, either in the same lane or in different lanes. If multiple vehicles are simultaneously detected in Zone 2, then the maximum time to clear among all simultaneously detected Zone 2 vehicles will be used as the basis for determining the extension time provided. This is a reasonable operational assumption, as modern radar sensors are capable of tracking multiple vehicles simultaneously.

2.4. Interval extension process

A summary of the conceptual zonal event classification procedure and the subsequent red extension process is displayed in the following figure.

3. Performance evaluation

The previous sections established a conceptual framework for the red clearance extension process. The expected performance was evaluated by replicating the classification procedure and conceptual red extension process displayed in Fig. 7 for a sample of vehicle event observations obtained during a field study. Subsequent Poisson modeling was used to estimate the efficacy under various conditions.

\[
\text{For each } n^{th} \text{ vehicle within the detection area, determine current speed } (v_i) \text{ and distance from the stop line } (C_i) \text{ from sensor data.}
\]

Compute the minimum speed threshold for the specific location and phase time:

\[
v_{\text{min}} = v_{\text{max}} \times 360 - \frac{1}{t}
\]

Classify vehicle as ZONE 0

\[
\text{If } v_i > v_{\text{min}} \text{ then}
\]

\[
\text{Yes}
\]

\[
\text{No}
\]

\[
\text{Compute } d_{\text{threshold}} \text{ for the vehicle, based on speed, vehicle type,}
\]

\[
\text{yellow duration, and assumed } P(\text{Go}) \text{ (See Tables 1 & 2).}
\]

\[
\text{If } d_i > d_{\text{threshold}} \text{ then}
\]

\[
\text{Yes}
\]

\[
\text{No}
\]

\[
\text{Compute } TTC \text{ for the vehicle to clear the intersection by computing:}
\]

\[
TTC = \frac{x_i + w_i + \frac{d_i}{v_i}}{v_i}
\]

Classify vehicle as ZONE 1

\[
\text{If } TTC > TTC \text{ then}
\]

\[
\text{No}
\]

\[
\text{Yes}
\]

\[
\text{Classify vehicle as ZONE 2}
\]

\[
\text{Extend red clearance time by:}
\]

\[
S_{\text{extended}} = TTC - TTG
\]

Fig. 7. Classification procedure for conceptual red extension process.

3.1. Data

Relevant data were obtained for 1913 vehicles during nearly 35 total hours of high-definition video recording at five intersections in the greater Madison, Wisconsin area. Each of the study intersections was functionally isolated and not coordinated with other nearby intersections and most vehicular arrivals occurred at random.

The data set included 1520 stopping vehicles, 346 legal-entry go-through vehicles, and 47 red-light-running vehicles obtained from observations of 1372 signal cycles. Heavy vehicles (single unit trucks and semi-trailers) accounted for 133 of the observations, while the remaining 1780 observations were passenger vehicles. The average number of cycles per hour for the total data set was 39.67, or an average cycle duration of 90.73 s. RLR occurred at a rate of 1.36 per hour per approach, which was similar to the rate of 1.13 per hour per approach observed by Bonneson et al. (2002b). The following data were obtained for each of the 1913 vehicles:

- Approach speed at the start of red clearance interval;
- Distance upstream of the stop line at the start of red clearance interval;
- Time that the vehicle reached the stop line;
- Whether the vehicle stopped, went-through legally, or committed a RLR event;
- Vehicle type;
- Duration of yellow and red clearance intervals; and
- Intersection width.

In addition, the following data were also estimated based on the data recorded for each vehicle:

- Approach speed at the end of red clearance interval;
- Location at the end of red clearance interval;
- Average deceleration rate necessary for a go-through vehicle to stop at the stop line;
- Time to clear the intersection; and
- Threshold deceleration rate based on specified levels of P(\text{Go}) (see Tables 1 and 2).

3.2. Simulated classification and interval extension

Using the data obtained from the videos, each of the 1913 vehicles was classified into the appropriate zone (i.e., Zone 0, 1, 2, or 3) according to the procedures specified in Fig. 7, thus replicating the design field operation of the interval extension decision process as closely as possible. The vehicle detection area was assumed to exist between the stop line and 500 ft upstream of the stop line, which approximated typical field setup of a radar detection unit. Each vehicle was classified at both the start and end of the static red clearance interval for the intersection based on the speed and location with respect to the intersection stop line. The classification process was replicated for various threshold deceleration rates, which were computed from the logistic regression results (described previously). The following values of P(\text{Go}) were used to determine the deceleration rates for the classification process: 0.01, 0.05, 0.20, 0.50, 0.75.

Assuming a properly operating red clearance extension system, each cycle with at least one vehicular classification into Zone 2 would result in extension of the red clearance interval. Thus, extended red clearance time was computed for any vehicle that was classified in Zone 2 at either the start and/or end of the static red clearance interval. For vehicles classified in Zone 2 at both the start and end of the red clearance interval, the greater of the two computed extension times was reported, thereby representing the
dynamic extension capability of the process. For cases where two or more vehicles requiring extension arrived simultaneously, the extended red clearance time was based on the vehicle with the largest estimated time to clear the intersection.

A series of Poisson curves were developed based on the zonal classification results to allow for prediction of interval extension calls and subsequent extension durations based on variable in operating conditions. The Poisson count distribution for prediction of Zone 2 arrivals per hour is given by Eq. (5):

\[ P(x) = \frac{m^x e^{-m}}{x!} \]  

(6)

where

\( P(x) \) = probability of exactly \( x \) Zone 2 arrivals in a one hour period,

\( m \) = average number of Zone 2 arrivals in a one hour period,

\( x \) = number of vehicular arrivals in a one hour period.

The red clearance extension times for RLR vehicles were also assumed to occur at random and were modeled using the negative exponential distribution. The appropriate form of the negative exponential equation is given as:

\[ P(\text{ARextended} \geq t) = e^{-t/\text{ARextended}} \]  

(7)

where

\( P(\text{ARextended} \geq t) \) = probability of \( \text{ARextended} \) exceeding time \( t \),

\( \text{ARextended} \) = extended red clearance time (s).

### Table 3

<table>
<thead>
<tr>
<th>Threshold deceleration rate based on P(\text{Go})</th>
<th>0.01</th>
<th>0.05</th>
<th>0.2</th>
<th>0.5</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of extensions (i.e., Zone 2 Classifications)</td>
<td>225</td>
<td>166</td>
<td>118</td>
<td>81</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>34</td>
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<td></td>
<td>191</td>
<td>132</td>
<td>84</td>
<td>47</td>
<td>18</td>
</tr>
<tr>
<td>Total extension time (s)</td>
<td>957.9</td>
<td>617.6</td>
<td>374.9</td>
<td>203.5</td>
<td>79.3</td>
</tr>
<tr>
<td></td>
<td>29.0</td>
<td>29.0</td>
<td>29.0</td>
<td>29.0</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>928.9</td>
<td>588.6</td>
<td>345.9</td>
<td>174.5</td>
<td>50.2</td>
</tr>
<tr>
<td>Average time per extension (s)</td>
<td>4.26</td>
<td>3.72</td>
<td>3.18</td>
<td>2.51</td>
<td>1.52</td>
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<tr>
<td></td>
<td>0.85</td>
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<tr>
<td></td>
<td>4.86</td>
<td>4.46</td>
<td>4.12</td>
<td>3.71</td>
<td>2.79</td>
</tr>
<tr>
<td>Standard deviation of extension time (s)</td>
<td>1.82</td>
<td>1.81</td>
<td>1.83</td>
<td>1.76</td>
<td>1.27</td>
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<td>0.86</td>
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<tr>
<td></td>
<td>1.15</td>
<td>1.12</td>
<td>1.14</td>
<td>1.16</td>
<td>0.92</td>
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<tr>
<td>Average extension time per cycle (s)</td>
<td>0.70</td>
<td>0.45</td>
<td>0.27</td>
<td>0.15</td>
<td>0.06</td>
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<tr>
<td></td>
<td>0.02</td>
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<tr>
<td></td>
<td>0.68</td>
<td>0.43</td>
<td>0.25</td>
<td>0.13</td>
<td>0.04</td>
</tr>
<tr>
<td>Average extension time per hour (s) (assumes 39.67 cycles/h)</td>
<td>27.62</td>
<td>17.81</td>
<td>10.81</td>
<td>5.87</td>
<td>2.29</td>
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<td>0.84</td>
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<tr>
<td></td>
<td>26.79</td>
<td>16.97</td>
<td>9.97</td>
<td>5.03</td>
<td>1.45</td>
</tr>
<tr>
<td>Average number of cycles between extensions</td>
<td>6.12</td>
<td>8.29</td>
<td>11.66</td>
<td>16.99</td>
<td>26.46</td>
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<td></td>
<td>40.47</td>
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<tr>
<td></td>
<td>7.20</td>
<td>10.42</td>
<td>16.38</td>
<td>29.28</td>
<td>76.44</td>
</tr>
<tr>
<td>Average number of extensions per hour (assumes 39.67 cycles/h)</td>
<td>6.49</td>
<td>4.79</td>
<td>3.40</td>
<td>2.34</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>0.98</td>
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<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>5.51</td>
<td>3.81</td>
<td>2.42</td>
<td>1.36</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*Note: results assume a single implemented approach per intersection.*
$P(Go) = 0.01$ to $P(Go) = 0.75$ did not increase the number of missed extension calls. However, as $P(Go)$ was increased from 0.01 to 0.75, the number of false calls decreased from 191 to 18, while the number of calls from RLR vehicles needing extension remained constant at 34. Similarly, the expected number of false extension calls per hour decreased from 5.51 to 0.52 (assuming the average rate of 39.67 cycles/h) and average extension times dropped from 4.26 s to 1.52 s.

Fig. 8 displays the cumulative Poisson distributions for hourly extension frequency assuming (a) all extension calls and (b) extension calls due to RLR vehicles vs. stopping vehicles (false calls). Fig. 9 displays the negative exponential distributions for (a) total extension time per hour and (b) duration per extension. The predicted red clearance extension times for RLR vehicles only (i.e., excluding false calls) are also shown in Fig. 9b along with the calculated extension durations for the 34 vehicles needing extension. The respective distributions were computed based on $P(Go)$ of 0.01, 0.05, 0.20, 0.50, and 0.75 and assume 39.67 cycles/h, which was the average cycle rate for the field data set.

Figs. 8 and 9 show that, as expected, both the predicted extension frequencies and extension times decreased as $P(Go)$ (and the corresponding threshold deceleration rate) increased due to the reduction in size of Zone 2. The Poisson probability of two or fewer extension calls per hour was approximately 0.05 at $P(Go) = 0.01$ but increased to approximately 0.80 at $P(Go) = 0.75$. The reduction in the predicted extension call frequency was due entirely to the decreasing probability of false calls as the threshold deceleration rate was increased. The probability of a maximum of one false extension call per hour increased dramatically from 0.02 to 0.90 when $P(Go)$ was increased from 0.01 to 0.75. The probability of at least one RLR extension call per hour was constant at 0.62 for all probabilities of a go-through event occurring. The median total extension time per hour was predicted at approximately 19 s and 2 s for $P(Go) = 0.01$ and $P(Go) = 0.75$, respectively. The predicted median duration of a single extension was approximately 3 s for $P(Go) = 0.01$, decreasing to approximately 1 s for $P(Go) = 0.75$.

The probability of misclassifying a RLR vehicle in need of red clearance extension (i.e., a missed call) was also determined. Using the negative exponential distribution, the probability of a missed RLR extension call was found to be very low for all scenarios (i.e., less than 0.001). Using the negative exponential probabilities along with the observed RLR arrival rates, passenger vehicles at $P(Go) = 0.75$ were predicted for fewer than 0.75 missed calls per month and 0.26 per 10,000 cycles. Heavy vehicles were predicted for fewer than 0.30 predicted missed calls per month and 0.04 predicted missed calls per 10,000 cycles at $P(Go) = 0.75$.

---

Table 4
Recommended threshold deceleration rates.

<table>
<thead>
<tr>
<th>Yellow interval (s)</th>
<th>Vehicle type</th>
<th>Threshold deceleration rate equation (ft/s²)</th>
<th>Threshold deceleration rate based on approach speed (ft/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>Passenger</td>
<td>( \dot{a}_{\text{threshold}} = 0.289v + 2.590 )</td>
<td>&lt;25 mph: 9.82, 30 mph: 8.40, 35 mph: 9.50, 40 mph: 10.66, 45 mph: 11.82, 50 mph: 12.98, 55 mph: 14.14, 60 mph: 15.27</td>
</tr>
<tr>
<td></td>
<td>Truck/bus</td>
<td>( \dot{a}_{\text{threshold}} = 0.228v + 1.607 )</td>
<td>18.0°</td>
</tr>
<tr>
<td>4.0</td>
<td>Passenger</td>
<td>( \dot{a}_{\text{threshold}} = 0.235v + 2.836 )</td>
<td>8.70, 9.78, 10.92, 12.09, 13.28, 14.48, 15.69, 16.91</td>
</tr>
<tr>
<td></td>
<td>Truck/bus</td>
<td>( \dot{a}_{\text{threshold}} = 0.201v + 1.866 )</td>
<td>6.88, 7.82, 8.80, 9.83, 10.81, 11.86, 12.88, 13.90</td>
</tr>
<tr>
<td>4.5</td>
<td>Passenger</td>
<td>( \dot{a}_{\text{threshold}} = 0.225v + 2.029 )</td>
<td>6.75, 7.69, 8.69, 9.80, 10.94, 12.10, 13.24, 14.40, 15.52</td>
</tr>
<tr>
<td></td>
<td>Truck/bus</td>
<td>( \dot{a}_{\text{threshold}} = 0.196v + 1.353 )</td>
<td>6.26, 7.20, 8.18, 9.14, 10.12, 11.12, 12.13, 13.13</td>
</tr>
<tr>
<td>5.0</td>
<td>Passenger</td>
<td>( \dot{a}_{\text{threshold}} = 0.240v + 0.600 )</td>
<td>6.60, 7.80, 8.99, 10.20, 11.36, 12.53, 13.74, 15.00</td>
</tr>
<tr>
<td></td>
<td>Truck/bus</td>
<td>( \dot{a}_{\text{threshold}} = 0.203v + 0.451 )</td>
<td>5.53, 6.56, 7.55, 8.57, 9.60, 10.61, 11.63, 12.64</td>
</tr>
</tbody>
</table>

Note: \( \dot{a}_{\text{threshold}} \) is estimated threshold deceleration rate derived from logistic regression for \( P(\text{Go}) = 0.75 \); \( v \) = approach speed obtained from sensor (mph).

4. Conclusions and directions for future work

This manuscript describes the development and evaluation of a conceptual framework for real-time operation of dynamic on-demand extension of the red clearance interval as a countermeasure for red-light-running. Expected performance of the conceptual framework was evaluated through modeling of replicated field operations using vehicular event data collected as part of this research. The results showed highly accurate classification of red-light-running vehicles needing additional clearance time and relatively few false extension calls from stopping vehicles, when threshold deceleration rates were specified based on \( P(\text{Go}) = 0.75 \). Thus, it was concluded that maximum classification accuracy and operational efficiency would occur when relatively high threshold deceleration rates were used to distinguish between stopping vehicles and vehicles needing extended intersection clearance time. The recommended threshold deceleration rates for red clearance interval extension are displayed in Table 4. Based on the recommended parameters, extension calls are predicted to occur once every 26.5 cycles. Assuming a 90 s cycle, 1.5 extensions per hour are expected per approach, with an estimated extension time of 2.30 s/h.

Although field implementation was not performed, it is anticipated that a red clearance extension system utilizing the properly calibrated process will likely produce long-term reductions in targeted RLR-related conflicts and crashes, in addition to minimal impacts on signal operations and vehicular delays. However, field installation and evaluation of system performance is necessary before definitive conclusions can be made as to the impacts on safety and operations. The most appropriate locations for implementation include locations where start-up delay on the conflicting approach is generally minimal, such as intersections with lag left-turn phasing, or locations with large truck volumes.

References


