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Empirical Observations of Red Light Running at Arterial Signalized Intersection

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Abstract

Red Light Running (RLR) has become an increasely national safety issue at signalized intersections. Significant efforts have been made to understand the RLR related driver behaviors and develop countermeasures to reduce RLR and its related crashes. At high speed intersections, it has been well shown that drivers caught in dilemma zone is an important reason of RLR. While at arterial intersections, there are still needs to further investigate RLR related driver behaviors. We carried out our research at a well-designed arterial intersection (speed limit 35 mph to 30 mph, approach dependent) and collected data using multiple discrete point sensors at different distances-to-intersection from multiple approaches. Empirical data showed that for over 90% of the RLRs, the drivers were not trapped in dilemma zone at yellow onset. Instead, they could have stopped safely and comfortably. Further analysis of the empirical data showed that over 60% of the RLR were with a headway less than 3 seconds, or belonged to a platoon. The average headway of RLR vehicles were 10% less than that of vehicles going through yellow. The findings were used in the development of an all-red interval extension system for intersection collision avoidance.

Index Terms

Red-light running, dilemma zone, driver behaviors, option zone

I. Introducion

A. Red-Light Running

Red-light-running (RLR) is an increasing major national safety issue at signalized intersections. In 2004, 2.5 million or 40% of all police-reported crashes in the United States occurred at or near intersections [1]. Of these intersection-related crashes 22.5% were fatal and 46% resulted in injury. The RLR aspect of this problem is known and serious [1–3], as approximately 20% of all intersection crashes occur due to signal violation crashes [3].

Significant efforts, span from enforcement to engineering countermeasures, have been taken to counteract the issue caused by RLR. It is vitally important to understand how RLR and its related crashes happened and upon the investigation of RLR related driver behaviors to build engineering countermeasure systems to reduce RLR and RLR caused crashes, which motivates the research reported in this paper. The research is part of the U.S. Department of Transportation (DOT) initiated Collaborative Intersection Collision Avoidance System CICAS program (Signalized Left Turn Assistance −SLTA and Traffic Signal Adaptation − TSA) conducted under the auspices of the University of California, Berkeley effort[4–6].

B. Red Light Running and Arterial Intersections

The dilemma zones are widely believed to contribute to the RLR behavior. As defined in ITE hand book [7], a dilemma zone is the zone , in which a vehicle approaching an signalized intersection at yellow onset can neither safely / comfortably stop before the stop bar nor clear the intersection safely (equivalently enter the intersection before red onset). This is the classical definition of dilemma zone which is associated with the signal timing [8], and thus is also called yellow time dilemma zone [9].

Denote the duration of the yellow phase as Y, the average perceptive reaction time (PRT) as δ and the speed of the vehicle as $v(t)$, a simple kinematics formulation of the dilemma zone [9] is that when the distance of the vehicle $x(t)$ satisfies both

$$x(t) > Y \cdot v(t), \tag{1}$$

and

$$x(t) < \delta \cdot v(t) + \frac{v^2}{2a}, \tag{2}$$

where "a" is the acceleration rate to stop safely / comfortable.

Note that in the definition, we assume that the vehicle do not accelerate to proceed through the intersection, and this is based on our observations from field intersection (see later sections of this paper). Actually if the vehicle accelerates to proceed, it may be able to clear the intersection even if it is in the dilemma zone defined in (1) and (2). This simple form of dilemma zone makes it more general (covering more vehicles) and static [9, 10].

More recent studies have named the yellow time dilemma zone "Type I dilemma zone", while a second type, "Type II dilemma zone" or the option zone is introduced. It is defined defined as the zone in which 90% and 10% of the drivers at yellow onset would stop. There are also some other definitions of the option zone, which are relatively easier to deal with. Researches show that the option zone typically is between 2s to 5s in terms of time-to-intersection of the vehicles at yellow onset. Figure 1 illustrates two types of dilemma zones in terms of the speed and distance to intersection at yellow onset. It is clearly seen that the two types of dilemma zones are not independent. Without loss of generality, the option zone is more commonly seen than the type I zone.

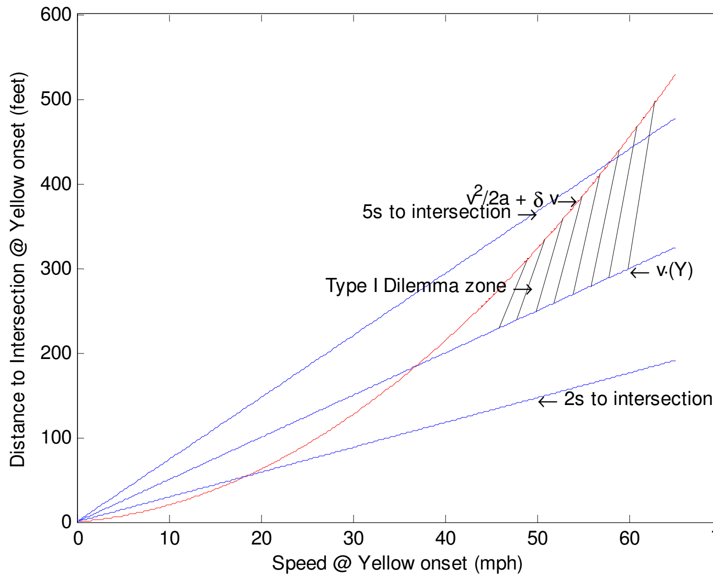

Fig. 1. Dilemma Zones (Yellow Interval = 4sec, $a = 0.3g$

For high speed intersections, RLRs are typically associated with dilemma-zone (type I) problems, as reported by Sheffi and Mahmassani [11]. The isolated, high speed intersections usually feature smoother traffic and drivers tend to exceed the speed limit more frequently. From the definition of the (type I) dilemma zone as well as from Figure 1, it is clear that drivers are more likely to be trapped in dilemma zone when the speed is high, especially when it is higher than posted speed limit (intersection yellow intervals are designed to eliminate the dilemma zone, at least to some extent, for vehicles at posted speed limit[8, 9]). The dilemma zone protection system, such as (dynamic) green extension systems are proven to be effective in reducing RLR at high speed isolated intersections.

At typical arterial intersections, the situation is different. California, for example, has state arterial roads with speed limit mostly at 30 mph to 35 mph. For intersections at such roads, it is much less likely for the vehicles to encounter the dilemma zone. Earlier studies showed some relevant results of RLR behavior at arterial intersections. Gate, Noyce et al in a recent research observed one to two days of videos recorded using commercial cameras at two low speed intersection at Madison, Wisconsin area. Manual review of these video showed that necessary deceleration rate for over 85% of the RLR vehicles to stop was less than 12.7ft^2, which is a safe deceleration rate [12].

Observations of those different driver behaviors are interesting. An important subject to investigate into is how these observations could help to predict RLR and its related hazards. And it motivated the current research, which via field data collection and analysis, tried to:

- collect high quality RLR data at typical arterial intersection;
- learn RLR related driver behavior at arterial intersection when posted speed limits are lower (such as 30 mph, 35 mph).

The research performed here focused on empirical observations from infrastructure based sensors, which would provide speeds of each individual vehicles at different distances-to-intersection. The sensors we used were emulated speed loops of Autoscope (R) cameras. The characteristics of each individual driver, however, were not available during the study.

This research tried to get the following specific results related to RLRs at arterial intersections.

- Basic Statistics of RLR, as opposed to those first to stop vehicles and go through yellow vehicles;
- Distances and speeds at Yellow onset, to learn whether or not drivers were trapped in the dilemma zone; and
- Headways of RLR, as opposed to first-to-stop vehicles and go through yellow vehicles.

Our primary method was to compare the observed empirical statistics of RLR vehicles with those first-to-stop vehicles and go-through yellow vehicles to form reasonable conclusion on the RLR related driver behaviors.

II. Data Collection and Processing

A. Field Setup and Configuration of Point Detectors

Field data are collected using the Autoscope cameras. Nine cameras are installed at three approaches of an arterial intersection (Page Mill Road and El Camino Real, Caltrans State Route 82) in the San Francisco Bay Are. We note that the signal phase and timing setting of this intersection fully conforms to the ITE standard. Three cameras are installed for each approach, covering respectively the exit area, stop area and advance area. We summarize the configurations into Table I. Raw video data were also recorded to serve as ground truth of the engineering data. Part of the video clips were manually reviewed to verify the RLR events.

Data were collected during May 14th, 2008 to June 21st, 2008.

As can be seen in Table I, multiple virtual speed loops are placed at advance area of difference approaches to monitor the violation and also at stop area to get the conflict entry time behaviors.

Fig. 2. Google Earth Snapshot of the Field Intersection

Results of the configurations of the emulated speed loops at the field intersection are summarized in Table I. We note that "distance" indicates the distance of sensor from the stop bar to upstream direction (in feet). When less than zero, it indicates a sensor inside the intersection.

B. Sensor Calibration

A Nissan Infinity FX45 probe vehicle equipped with GPS and data computer is used for calibration. For each run and for every approach, the engineering data obtained from the Autoscope speed loops are processed to generate the vehicle trajectories. The tracking and data association procedure helps to reduce the occasional missed-call / false-call problems of video camera based vehicle detectors [13]. The Autoscope measured speed is then compared to the wheel speed recorded by the computer on-board vehicle. Results show that for most associated trajectories, the measurement from Autoscope speed loops present speed error lower than 10% (c.f. Figure 3). It can also be seen that the error of the speed loop is random and can therefore be viewed as an independently-distributed error which is simply added to the variance of the observation vector (c.f. Figure 4).

TABLE I

CONFIGURATION OF THE FIELD INTERSECTION

Page Mill rd. at El Camino Real			
	East bound	West bound	South bound
Lanes (recorded)	2	1	2
Speed Limit (mph)	30	35	35
Average Speed (mph)	30	35	35
90% speed less than (mph)	45	45	40
Yellow Duration (s)	4	4	4
All-red Interval (s)		0.5	
# Speed Loops (Exit)/ Lane	1	1	1
# Speed Loops (advance) / Lane	3	3	3
# Speed Loops (stop / conflict entry) / Lane	3	3	2
95% RLR time-into-red less than (s)	2.5s	2.5s	2.5s
Description of the approach	0.15 Mile from upstream intersection	No upstream intersection for More than 0.7 mile upstream	0.25 mile from upstream intersection, main street

TABLE II

CONFIGURATIONS OF THE AUTOSCOPE VIRTUAL LOOPS

Page Mill rd. at El Camino Real : Sensor Configurations			
	East bound	West bound	South bound
Average Speed of RLR	30 mph	35 mph	38 mph
Min distance requirement	90 feet	110 ft	110 ft
$d(k_1)$ **and** $d(k_2)$	97,120	139,190	120,195
Locations of All Speed Loops	-110, -15, 0, 15, 40, 63, 97, 120, 190	-110, -15, 0, 20, 40, 95, 139, 190	-120, -30, 0, 30, 90, 120, 195

C. Data Processing

The stored engineering data from emulated speed loops of Autoscope included the speed, time-stamp (accuracy up to 33ms) as well as the real-time status of the signal phase. The discrete sensors reports were associated using a Multiple-Hypothesis-Tracking (MHT) algorithm to build full trajectories of each vehicle (proceeding through the intersection or (first-to) stopping at the intersection) [4]. For

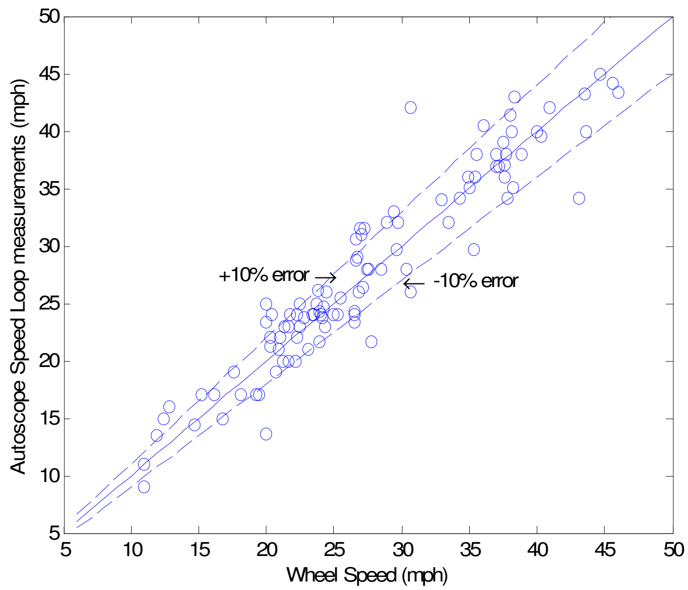

Fig. 3. Comparison of Autoscope Speed and Wheel speed

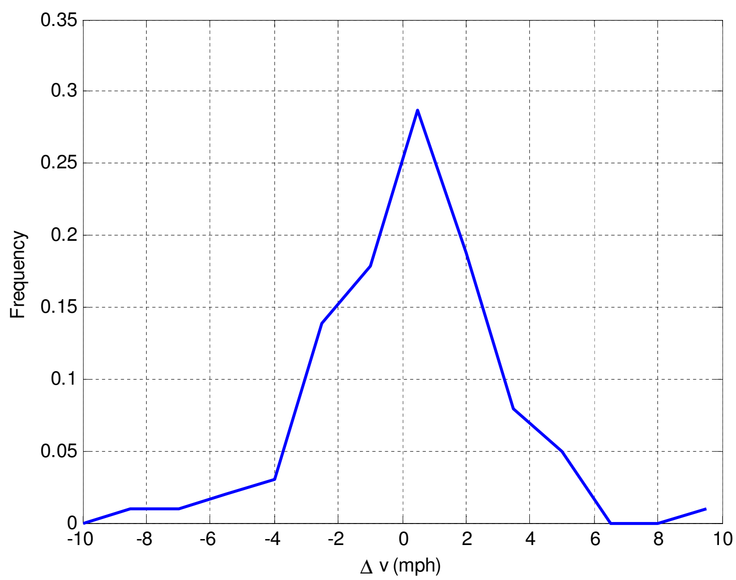

Fig. 4. The empirical distribution of the error of Autoscope speed measurements

each approaching vehicle i, we have a series of speeds

$$\{v_1(i), v_2(i), \ldots, v_K(i)\} \tag{3}$$

and time-stamps

$$\{t_1(i), t_2(i), \ldots, t_K(i)\}, \tag{4}$$

at the following distances to intersection,

$$\{d(1), d(2), \ldots, d(K)\} \tag{5}$$

where K is the total number of discrete emulated speed loops for each lane. To simplify the expressions, the time stamps were all referenced to the time of yellow onset of the recorded cycle.

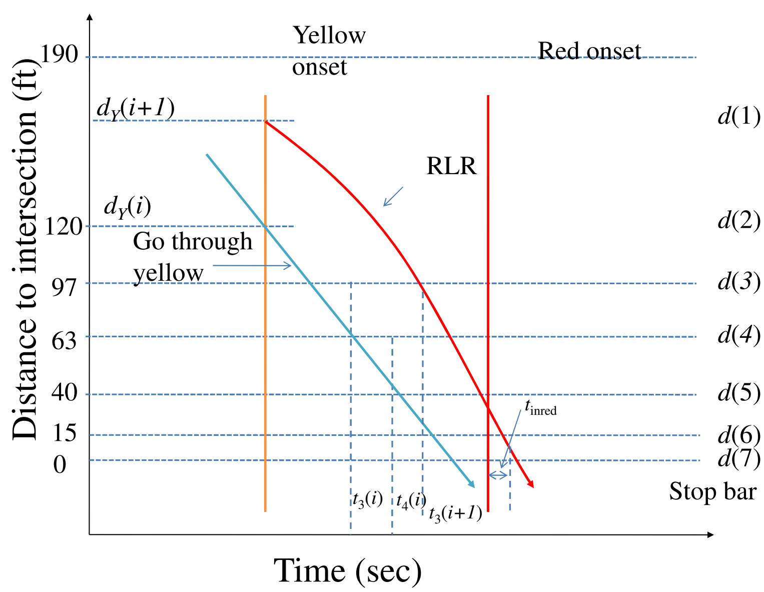

Fig. 5. Time space diagram

Interesting samples of all these trajectories were three categories, to include the first-to-stop vehicles, the going through yellow vehicles and the RLR vehicles. The observed trajectories were further processed and only the above three interesting types of data were extracted.

We also excluded all the samples when the above mentioned vehicles were moving very slowly due to heavy traffic. In such scenarios, vehicles might experience stopping-then-going maneuver which is difficult to track. We put a lower speed limit of 10 mph, average speed above which is our interesting case. During our field observation period for over one month, we did not see any RLR case with speed lower than 10mph. The numbers of total interesting samples collected in the field observations were tabulated in Table III.

TABLE III

INTERESTING SAMPLES

Page Mill rd. at El Camino Real			
	East Bound	West Bound	South Bound
RLR Occurrence	61	35	22
First-to-Stop Occurrences	912	419	1627
Go through Yellow Occurrences	4318	1718	3005

III. EMPIRICAL OBSERVATIONS

This section summarizes an analysis of the empirical observations of the RLR. Specifically the analysis compared the RLR statistics obtained to the other two closely related vehicle maneuvers, first-to-stop and going through yellow. We examined the following issues, to include (1) the statistics of the speeds and acceleration; (2) the distances and speeds of interesting vehicles at yellow onset; and (3) headway distributions at advanced area. The first issue helped to understand how the RLR vehicles generally proceed through the intersection. The seconds issue helped to identify if the RLR drivers were trapped in the dilemma zone at the time of yellow onset. A comparison of the RLR trajectories with going other trajectories also revealed possibilities of RLR like inattentiveness of the driver and deliberate running, etc. We studied the third issue to further identify the driver behaviors of RLR vehicles' interaction with leading vehicles. Summary of the variables used in the samples are provided in Table I, Table II and Table III.

A. Statistics of Speeds and Accelerations

During the field observation, 118 vehicles were found to run the red light. We first get the running speed of red light violator i, which is the speed at stop bar, or

$$\text{running speed} = v_K(i), \text{when } i \text{ is a RLRer.} \tag{6}$$

K is the index of the stop-bar speed loop.

The observed statistics of running speed were compared to the speed of the yellow through and the results are shown in Table IV. It can be seen that the RLR vehicles do have a slightly higher average speed than the vehicles going through yellow, while the differences are not significant though. And when compared the running speeds to the posted speed limit (c.f. Table I), it is also observed that running speeds are at or around the posted speed limits. For West Bound and South Bound where the posted speed limits are higher, we do find the running speed also higher than East Bound where the posted speed limit is 5 mph lower.

TABLE IV

SPEED STATISTICS OF RLR

Page Mill rd. at El Camino Real			
	East Bound	West Bound	South Bound
Average RLR Speed	30 mph	35 mph	35 mph
85% of RLR speed less than	38 mph	42 mph	43 mph
Average Going-through-Yellow Speed	28 mph	33 mph	34 mph
85% of Going-through-Yellow Speed less than	35 mph	40 mph	42 mph

Average speed and the acceleration rate of the RLR vehicles are also compared to the other two kinds of maneuvers. The acceleration is calculated using the speed difference at two discrete locations close to intersection (such that most drivers would have already made their decisions to go or not)

$$\bar{a}(i) = \frac{v_{k_2}(i) - v_{k_1}(i)}{t_{k_2}(i) - t_{k_1}(i)}, \tag{7}$$

where k_1 and k_2 are set to the indexes of the 60 ft and 90 ft sensors, and the average speed of a running vehicle is formulated as

$$\bar{v}(i) = \left(v_{k_1}(i) + v_{k_2}(i)\right)/2. \tag{8}$$

Results are summarized in Table V. We would like to further group the RLR and going-through-yellow maneuvers as going-through maneuvers as opposed to the first-to-stop maneuvers. The vehicles proceeded through the intersections were observed, in average, to move at constant speed. While there is a significant difference in the acceleration for go-through and first-to stop maneuvers, as expected. We note that the running speed distribution (average to standard deviation ratio) shows good agreement with the finding reported by Bonneson, et al in [14].

TABLE V

AVERAGE SPEED AND ACCELERATION (EAST BOUND)

	average speed $\bar{v}(i)$	standard deviation of $\bar{v}(i)$	acceleration $\bar{a}(i)$	standard deviation of $\bar{a}(i)$
RLR	30 mph	7.4	0.1 m/s^2	1.9 m/s^2
Go through Yellow	28 mph	7.5 mph	0.1 m/s^2	2.1 m/s^2
First-to Stop	20 mph	8.2	-2.1 m/s^2	2.4 m/s^2

B. Distances and Speeds at the Time of Yellow Onset

The distances and speeds of the observed interesting vehicles trajectories are of vital importance to understand the driver behavior. The dilemma zone (and the option zone) theory tells if the driver was able to pass the intersection safely or stop safely. The information of which zone the RLR drivers were in or were not in at the time of yellow onset could distinguish the have-to-run / because-of-speeding behavior with inattentive / deliberate running.

The distances and speeds at the yellow onset were not directly reported by the discrete sensors, since they were configured to report vehicle speed at given locations, not given time. The distances and speeds at the yellow onset were obtained using the following interpolation method.

We denote the speed of vehicle i at yellow onset as $v_Y(i)$ and the corresponding distance as $d_Y(i)$. The time of yellow onset is denoted as t_{yon}. The distances at t_{yon} is obtained using

$$d_Y(i) = \begin{cases} \dfrac{d(k_2) - d(k_1)}{t_{k_2}(i) - t_{k_1}(i)} \cdot \left(t_{yon} - t_{k-1}(i)\right), & \text{when} t_{k_1}(i) < t_{yon} < t_{k_2}(i) \\ d(1) + (t_1(i) - t_{yon}) \cdot v_1(i), & \text{when} t_1(i) > t_{yon} \end{cases}, \tag{9}$$

and $v_Y(i)$ in a similar way,

$$v_Y(i) = \begin{cases} \dfrac{v_{k_2}(i) - v_{k_1}(i)}{t_{k_2}(i) - t_{k_1}(i)} \cdot \left(t_{yon} - t_{k-1}(i)\right), & \text{when} t_{k_1}(i) < t_{yon} < t_{k_2}(i) \\ v_1(i), & \text{when} t_1(i) > t_{yon} \end{cases}. \tag{10}$$

In (9) and (10), when at the time of yellow onset t_{yon}, the interesting vehicle i has not yet arrived at the first advanced detector, or $t_1(i) > t_{yon}$, we assume that the vehicle moved at constant speed from where it was at yellow onset to the first detector. If the interesting vehicle i has already passed the first detector at the time of yellow onset, then it must be between two of our detectors, say k_1 and k_2. The distance and speed are calculated using the interpolation of the speeds and distances at detector k_1 and k_2.

The statistics from the interesting samples with respect to (9 and (10) are summarized in Table VI and illustrated in Figure 6-8.

The parameters used in the dilemma zone definition (1) and (2) are

$$\delta = 1.0s, \tag{11}$$

$$a = 0.3g, \text{and} \tag{12}$$

time-to-intersection from 2s to 5s for option zone.

TABLE VI

STATISTICS OF DISTANCES AND SPEEDS AT YELLOW ONSET

Page Mill rd. at El Camino Real			
	East Bound	West Bound	South Bound
Number of RLR samples	61	35	22
Number in dilemma zone	6 (10%)	1 (3%)	2 (9%)
Could Have Stopped Safely	52(85%)	31 (88%)	14 (64%)
Observed Decelerate-then-go	9 (14%)	4 (11%)	7 (32%)
Go through Yellow Samples	4318	1718	3005
Would have violated signal if not accelerated	431 (10%)	52 (3%)	241 (8%)

IV. CONCLUSION

The empirical observations of Red Light Running vehicles were obtained using multiple emulated speed loops from the Autoscope cameras. We installed nine cameras at one typical arterial intersection in the San Francisco Bay area to cover three approaches of that intersection. Over one month of data were collected and among which we selected the RLR , first-to-stop samples and go-through yellow samples. Statistics of different interesting samples were obtained, to include the speeds and acceleration distributions, the distances and speeds at the time of yellow onset and the headway distributions. We addressed the RLR related behaviors by a comparison study of the above-mentioned statistics to the other two interesting maneuvers. The statistics showed that the going-through yellow and RLR vehicles were in average moving at constant speed. Over 90% of the RLR drivers were not trapped in the dilemma zone at the time of yellow onset. It was also observed that a certain amount of RLR trajectories featured decelerate-after-yellow then accelerate-to-go behaviors. The headway analysis showed that in average

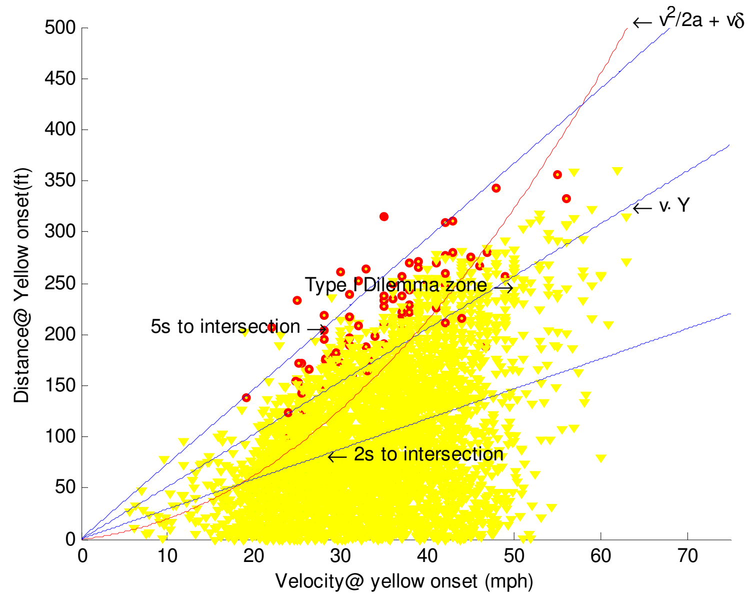

Fig. 6. Distances and Speeds at Yellow Onset (East Bound)

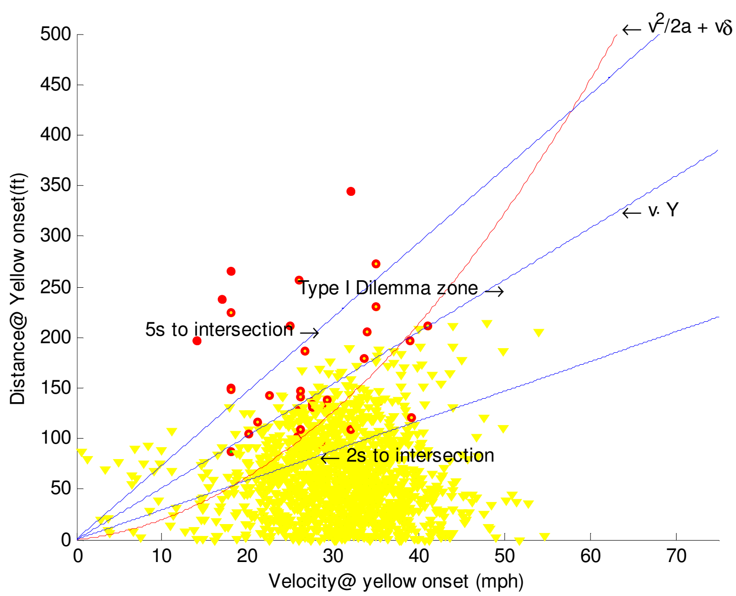

Fig. 7. Distances and Speeds at Yellow Onset (West Bound)

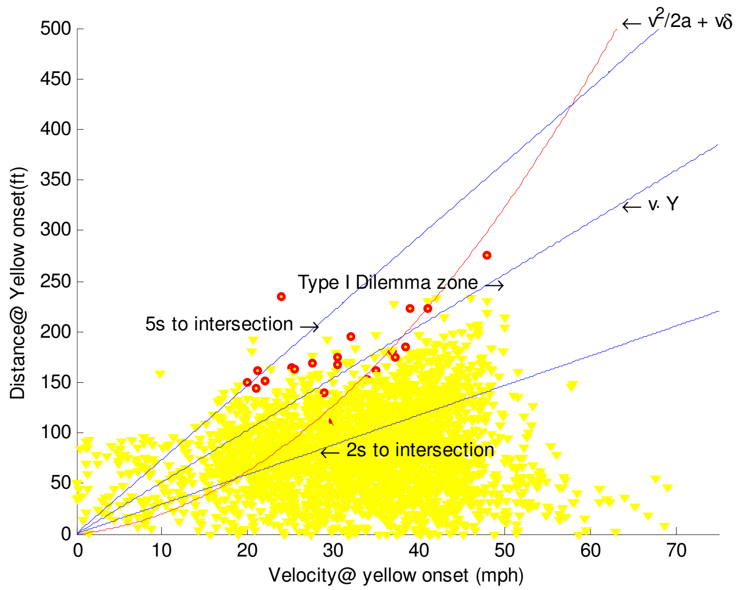

Fig. 8. Distances and Speeds at Yellow Onset (South Bound)

RLR vehicles had an average headway about 10% lower than that of going through yellow group, and over 60% of RLR vehicles had a headway less than 3s. These statistics could help in understanding the behaviors of inattentive violators. Further study at more arterial intersections is necessary to justify the validity of the findings as a general conclusion for arterial intersection.

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