# Investigating Positive and Negative Utilities of Red Light Cameras through a Binary Probit Analysis

by

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## ABSTRACT

Driver behavior at intersections equipped with a Red Light Camera (RLC) is influenced by many factors, including the fear of being fined for crossing the intersection during the red signal. This behavioral change may lead to the tendency of stopping at the intersection at the onset of the yellow interval. The following scenarios may arise due to this tendency: (1) the stopped driver may have a rear-end collision by a fast approaching vehicle; (2) the excessive "safe" stoppage by vehicles during the yellow interval may reduce the intersection capacity, thereby increasing congestion; and (3) the safe stoppage during yellow interval may result in reduced intersection related accidents, thereby improving intersection safety. While the first two scenarios can be seen as disutilities (or negative measures) associated with the real intent of RLCs the third scenario is the only utility (or positive measure) that is ideally considered as the basis for RLC installation.

With increasing number of RLCs along busy intersections with the standard assumption of scenario 3 above while the possibilities of scenarios 1 and 2 cannot be ruled out, it is important to thoroughly investigate positive` and negative aspects of a RLC. This can be achieved by collecting reasonably sufficient relevant field data at intersections with and without RLCs and developing a binary choice model to analyze the driver's dilemma (or indecision) of stop and/or go during the yellow interval. The existence of an indecision zone or Dilemma Zone (DZ) can be estimated using dilemma zone curves developed from the probability of stopping vs. distance from stop bar at the onset of the yellow interval. The construction of dilemma zones can help understand the driver behavioral characteristics contributing to positive and negative aspects of RLCs. In this paper, using field data from Baltimore at 10 intersection pairs with and without RLCs that have similar geometric and traffic characteristics, we develop a binary probit choice model to examine driver behavior at RLCs. The results indicate that the negative utilities of RLCs may outweigh their positive utilities.

Key-Words: Red Light Camera, Driver Behavior, Dilemma Zone, Red Light Running. Binary Choice Models

## INTRODUCTION

Modeling driver behavior at traffic intersections has been widely studied over the last 50 years, primarily due to the safety and congestion impacts as they relate to driver behavior. Usually driver faces a dilemma of either crossing or stopping at a signalized traffic intersection when the signal turns yellow. Many previous studies (Sheffi and Mahmassani 1981; Weldegiorgis and Jha 2009a&b) have attempted to model driver behavior at intersections of various characteristics, such as high speed railroad crossings and those with a red light camera. This paper is motivated by the safety and congestion consequences at intersections with red light cameras. A growing number of red light cameras (RLCs) have been installed at intersections over the last 10 years, primarily with the objectives of enhancing safety and fining red light violators. Ideally, safety seems to be the primary purpose of installing RLCs, but not enough attention is directed towards resulting congestion or accumulated revenues that may be considered as a disutility to society..

The dilemma zone is often used to describe the time or space, where some drivers may decide to proceed through a signalized intersection while others may decide to stop at the onset of a yellow indication. Incorrect driver decisions can lead to rear-end crashes if a driver decides to stop when he or she should have proceeded. Such decisions can also lead to right-angle crashes with oncoming side-street traffic if a driver continues to proceed along mainline whereas he or she should have stopped. Driver decision within a dilemma zone may vary as a function of the driver's perception-reaction time, driver's acceptable deceleration rate, and driver's time to intersection at the instant when the yellow indication is introduced (Chang et al. 1985, Rakha et al. 2008). Previous research during the past several decades has investigated various characteristics of driver behavior in the dilemma zone related to highway safety (Gates et al. 2007, Hurwitz et al. 2011, Zimmerman et al. 2004, Zhang et al. 2010, Archer and Young 2009, Archer and Young 2010, Young and Archer 2009).

One of the measures to reduce crashes in dilemma zone considers installation of RLCs at signalized intersections along urban arterials. The principal motivation of installing RLCs is to reduce Red Light Running (RLR) behavior in an effort to improve intersection safety. The use of RLCs for the enforcement of RLR at signalized intersection is becoming widespread in the United States (Weldegiorgis and Jha 2009a). Driver behavior at intersections equipped with a RLC is influenced by many factors, including the fear of being fined for crossing the intersection during the red signal. This behavioral change may lead to three possible scenarios that may impact intersection safety and congestion: (1) the sudden stop decision can lead to rear-end crashes; (2) the excessive "safe" stoppage by vehicles during the yellow interval may reduce the intersection capacity, thereby increasing congestion; and (3) the safe stoppage during yellow interval may result in reduced intersection related accidents, thereby improving intersection safety. While the first two scenarios can be seen as disutilities (or negative measures) associated with the real intent of RLCs the third scenario is the only utility (or positive measure) that is ideally considered as the basis for RLC installation. With increasing number of RLCs along urban intersections with the standard assumption of scenario 3 above, while the possibilities of scenarios 1 and 2 cannot be ruled out, it is important to develop a scientific framework to investigate aspects of utilities and disutilities associated with a RLC.

According to the Insurance Institute for Highway Safety (IIHS), in 2009 RLR crashes caused 676 fatalities and 130,000 estimated injuries (IIHS 2011). Although the primary reason for using RLCs is to reduce RLR accidents, we cannot ignore their potential in bringing significantly higher revenues to jurisdictions and RLC vendors through fines for crossing at red light. A significantly higher amount of such revenues may be considered a loss to the society and may impact the quality of life of communities. After the camera installation if accident reduction is not so significant or there has been an increase in the total number of accidents over successive years then obviously RLCs can be viewed as revenue generators. Another issue at RLC intersections is that in order to avoid RLR related traffic citations some drivers may decide to stop even in situations when there is enough time to cross the intersection. This may result in an increase in rear-end crashes at RLC intersections. Another related issue is that fearing rear-end crashes motorists in leading vehicles are sometimes forced to run red lights because they cannot stop due to another vehicle closely following them.

# LITERATURE REVIEW

Many studies reported that dilemma and option zones existing upstream of intersections at the onset of the yellow signal are associated with larger variability in the drivers' stop/go decisions (Mahael and Prashker 1987, Elmitiny et al. 2010, Zimmerman et al. 2004). When the driver is going at a speed lower than the speed limit an option zone is created, i.e., an area where the driver can stop or cross successfully. When a driver is traveling higher than the speed limit a dilemma zone is created, i.e., the driver can neither stop without slamming on the brakes or cross safely without running the red light (Papaioannou 2007). When vehicles are located in an option zone, drivers can either easily stop before the stop line or successfully clear the intersection before the onset of the red signal. The option zones' existence may contribute to rear-end conflicts due to the variability of the drivers' stop/go decisions. On the other hand, drivers who are in a dilemma zone can neither stop, nor cross the stop line before the signal turns red. Therefore, the dilemma zone's existence may result in both rear-end conflicts and RLR violations. The probability for drivers' stop/go decisions was modeled as a function of the space or potential time (gap) from the stop line using the logistic regression (logit) technique (Newton et al. 1997, Yan et al. 2009). A longer indecision zone indicates a larger variability in drivers' stop/go decision and higher rear-end crash (Sheffi and Mahmassani 1981). Typically, the total number of vehicles in the dilemma zone has been used as a surrogate measure for safety at rural high speed intersections. Dilemma zone was initially defined as the area where the driver can neither stop comfortably nor clear safely on the onset of yellow. This approach (Gazis et al., 1960; May, 1968) uses deterministic design values such as perception reaction time, comfortable deceleration rate, length of yellow interval etc., to determine the location of dilemma zone. There have been several attempts to ascertain the dilemma zone boundaries (Rakha et al. 2007, Olson 1962, Sheffi and Mahmassani 1981). In recent years, several studies (Porter and England 2000, Retting et al. 2002, Datta et al. 2000, Schattler et al. 2003, Gates et al. 2007, Gates and Noyce 2010, Retting et al. 2008a, Retting et al. 2008b, Retting 2010, Yan et al. 2005) have been undertaken in connection with RLCs and RLR incidents. Most of those studies mainly discuss the advantage of using RLCs qualitatively, such as reducing accidents or documenting installation guidelines for RLCs. None of the studies investigated the effects of RLCs on driver behavior during the yellow interval.

The safety problems have traditionally been solved using dilemma zone protection and a number of studies provided numerous solutions as described in the earlier section. However, dilemma zone protection tends to be associated with an increasing chance of running the phase to its maximum allowable duration (i.e., max-out). At max-out, any dilemma zone protection that has been provided ceases, and any number of vehicles may be in the dilemma zone, thus creating the safety problem the system was meant to prevent. RLCs can have an adverse effect on traffic delay on red-light violation. One of the study in Texas observed that the violations increased in a predictable manner with an increase in V/C ratio. Red-light violations are minimal when the volume-to-capacity ratio is in the range of 0.6 to 0.7 (Bonneson et al. 2004b). Volume-to-capacity ratios below this range result in an increase in violations due primarily to shorter cycle lengths. Volume-to-capacity ratios above this range resulted in an increase in violations due primarily to an increase in delay. These findings imply that cycle length can be adjusted to reduce violations; however, the nature of the adjustment will depend on the volume-to-capacity ratio (Bonneson et al. 2004a).

Modeling driver behavior in presence of RLCs and within dilemma (or indecision) zone is complex as drivers in the queue continue to enter the intersection for several seconds after the onset of red. Logically, some drivers are motivated to run the red out of a desire to avoid the delay associated with waiting for the next green indication. In some instances, changes to the signal phasing can improve this situation (Bonneson et al. 2003). Green extension is one of the measures deployed at high speed signalized intersections to reduce the number of red light violations and rear end crashes. The green phase of the high speed approach is extended until there is no vehicle in the dilemma zone (Sharma et al. 2011).

Weldegiorgis and Jha (2009a&b) studied driver behavior changes on intersection capacity and length of dilemma zone due to the presence of a RLC. They found that the presence of RLCs influence some drivers to stop at the intersection during the yellow interval. As a result the capacity of a RLC monitored intersection is lower than that of a non RLC intersection. The Maryland State Highway Administration (SHA) performed evaluation of 41 RLC intersections using before and after accident data (SHA 2002). The results for major type of accidents from this study are summarized below:

- 6% increase in total accidents
- 100% decrease in fatal accidents
- 13% decrease in injury accidents
- 26% increase in property damage only accidents
- 21% decrease in right angle crashes
- 40% increase in rear end accidents
- 65% increase in sideswipe accidents
- 25% decrease in left turn accidents

The large body of literature suggests that the presence of RLCs have an impact on both safety and capacity (thereby performance of traffic operation). The combined effect of safety and capacity at RLC operated traffic intersections in the dilemma zone is not addressed in the literature.

## RESEARCH OBJECTIVES

The objectives of our research are twofold: first to provide a theoretical framework for quantifying a tradeoff between highway safety and capacity in dilemma zones for urban signalized intersections consisting of RLCs; second to demonstrate the application of the developed framework in an urban area with real world data.

## METHODOLOGY

The methodology is based upon drivers' behavioral analysis at RLC equipped intersections to estimate the length and location of the dilemma zone (Sheffi and Mahmassani 1981). While the zone boundaries can be estimated deterministically using standard equations for "minimum stopping distance" and "clearing distance" with the approach speed and the width of the intersection using typical values of acceleration and deceleration rates, in this paper we develop a binary probit model to estimate the parameters where the dilemma zone boundaries are estimated using the probability of stopping and speeding.

## DATA COLLECTION AND ANALYSIS

The data is collected for 10 paired urban intersections in Baltimore, Maryland. The paired intersections consisted of RLCs and non-RLCs (Weldegiorgis and Jha 2009a). The non-RLC intersections are located on the same street either in the upstream or downstream of the corresponding RLC. The data collected can be broadly classified into three categories: (1) highway geometry, (2) traffic volume and pedestrian activity, (3) traffic signal timing, and (4) highway safety. The summary of the data is presented in Table 1. The crash reduction percentage represents the savings (or increase) in crashes over one year during which the average number of vehicles stopped during the yellow and number of RLRs in successive months is recorded. The posted speed, number of lanes (surrogate for capacity), and signal timing data for these locations are collected and shown in Table 1.

**Table 1.** Statistical Analysis of the Data

| Attribute | Max | Min | Avg | SD |
|---|---|---|---|---|
| RLC ( 1=Yes, 0=No) | 1 | 0 | 0.5 | 0.512989 |
| Crash Reduction Percentage | 5 | -15 | -5.65 | 5.769931 |
| Average Vehicles Stopped | 6 | 1 | 3.2 | 1.880649 |
| Number of RLR | 115 | 72 | 94.35 | 11.83338 |
| Posted Speed | 40 | 25 | 35.5 | 4.261208 |
| Number of Lanes | 6 | 2 | 3.9 | 0.967906 |
| Green Time | 60 | 40 | 51.85 | 6.123939 |
| Yellow Time | 5 | 3 | 3.9 | 0.640723 |
| All Red Time | 2 | 0 | 1.25 | 0.850696 |
| Cycle Length | 120 | 90 | 107.75 | 9.797287 |

## MODEL FORMULATION

Let $T_{in}$ be a linear function that determines discrete outcome I for observation n, such that

$$T_{in} = \beta_i X_{in} + \varepsilon_{in} \tag{1}$$

where $\beta_i$ is the vector of estimable parameters for discrete outcome $i$ and $X_{in}$is the vector of observable characteristics that determine discrete outcomes for observation $n$. $\varepsilon_{in}$ is the disturbance term to support the unexplained effects of Equation 1 (Washington et al. 2011). The estimable model of discrete outcomes with $I$ denoting all possible outcomes for observation $n$ and $P_n(i)$ being the probability of observation n having discrete outcome $i$ ($i \, \varepsilon \, I$).

$$P_n(i) = P(T_{in} \geq T_{In}) \forall\, I \neq i \tag{2}$$

Alternatively,

$$P_n(i) = P(\beta_i X_{in} + \varepsilon_{in} \geq \beta_I X_{In} + \varepsilon_{In}) \;\; \forall\, I \neq i \tag{3}$$

or

$$P_n(i) = P(\beta_i X_{in} - \beta_I X_{In} \geq \varepsilon_{In} - \varepsilon_{in}) \;\; \forall\, I \neq i \tag{4}$$

The error term is assumed to be normally distributed. In case of two outcomes, the binary probit (outcome as 1, and 0) model takes the following form:

$$P_n(1) = P(\beta_1 X_{1n} - \beta_0 X_{0n} \geq \varepsilon_{0n} - \varepsilon_{1n}) \tag{5}$$

$\varepsilon_{0n} - \varepsilon_{1n}$ is normally distributed with mean as 0 and variances as $\sigma_1^2 + \sigma_1^2 - \sigma_{12}$. The standardized cumulative normal distribution becomes:

$$P_n(1) = \emptyset\left(\frac{\beta_1 X_{1n} - \beta_0 X_{0n}}{\sigma}\right) \tag{6}$$

The parameter vector $\beta$ can be estimated using maximum likelihood method. The likelihood function can be defined as:

$$L = \prod_{n=1}^{N} \prod_{i=1}^{I} P(i)^{\delta_{in}} \tag{7}$$

where $\delta_{in}$ is equal to one if observed discrete outcome for observation n is I, and zero otherwise (Washington et al. 2011).

## RESULTS AND INTERPRETATION

The binary probit model is solved using open source library Generalized Linear Model (GLM) in R. The model results are presented in Table 2. The continuous variables, i.e., number of RLR, number of lanes, and yellow time are found to be significant. The signs of the estimates appear reasonable and intuitive. The number of RLR is inversely related to the RLCs which show the number of RLR is reduced by enforcing RLCs at urban intersections. This observation is expected as the driver behavior is affected by enforcement of RLCs. The likelihood of number of RLRs decreases with installation of RLCs at urban signalized intersections. Similarly, number of lanes is also inversely related to the RLCs, whereas yellow time is directly proportional to RLCs over non-RLCs. The estimation results show that with one unit increase in number of RLR the probability of its occurrence at RLC decreases by 17.89 percent. The model shows that the probability of RLR on urban intersections equipped with RLCs is lower than that of non-RLCs. As the number of lanes increase or with an increase in capacity at urban intersections, the probability of installation of RLCs is lower than non-RLCs. Similarly, longer yellow intervals are expected at RLC locations.

**Table 2**: Binary Probit Model Results

| Attribute | Coefficient | Std Error | z-value |
|---|---|---|---|
| Constant | 15.13423** | 7.01409 | 2.158 |
| Number of RLR | -0.17899** | 0.07971 | -2.245 |
| Number of Lanes | -0.65604* | 0.48298 | -1.358 |
| Yellow Time | 1.12849* | 0.70585 | 1.599 |

Note: **: 95 Percent Level of Significance, *: 90 Percent Level of Significance
Null deviance: 27.726 on 19 degrees of freedom, Residual deviance: 14.715 on 16 degrees of freedom

Finally the estimates from Table 2 are used to compute the utility of 10 paired intersections. The utility values of the 10 intersections are presented in Figure 1. Each curve represents 10 data points denoting 10 study area intersections. Two series are shown in Figure 1: one for RLCs and another for non-RLCs. The utilities for urban signalized intersections at RLCs are higher than those of non-RLC counterparts. Figure 1 suggests that for given attributes shown in Table 1, the utilities of intersections with RLCs are higher than those of non-RLCs.

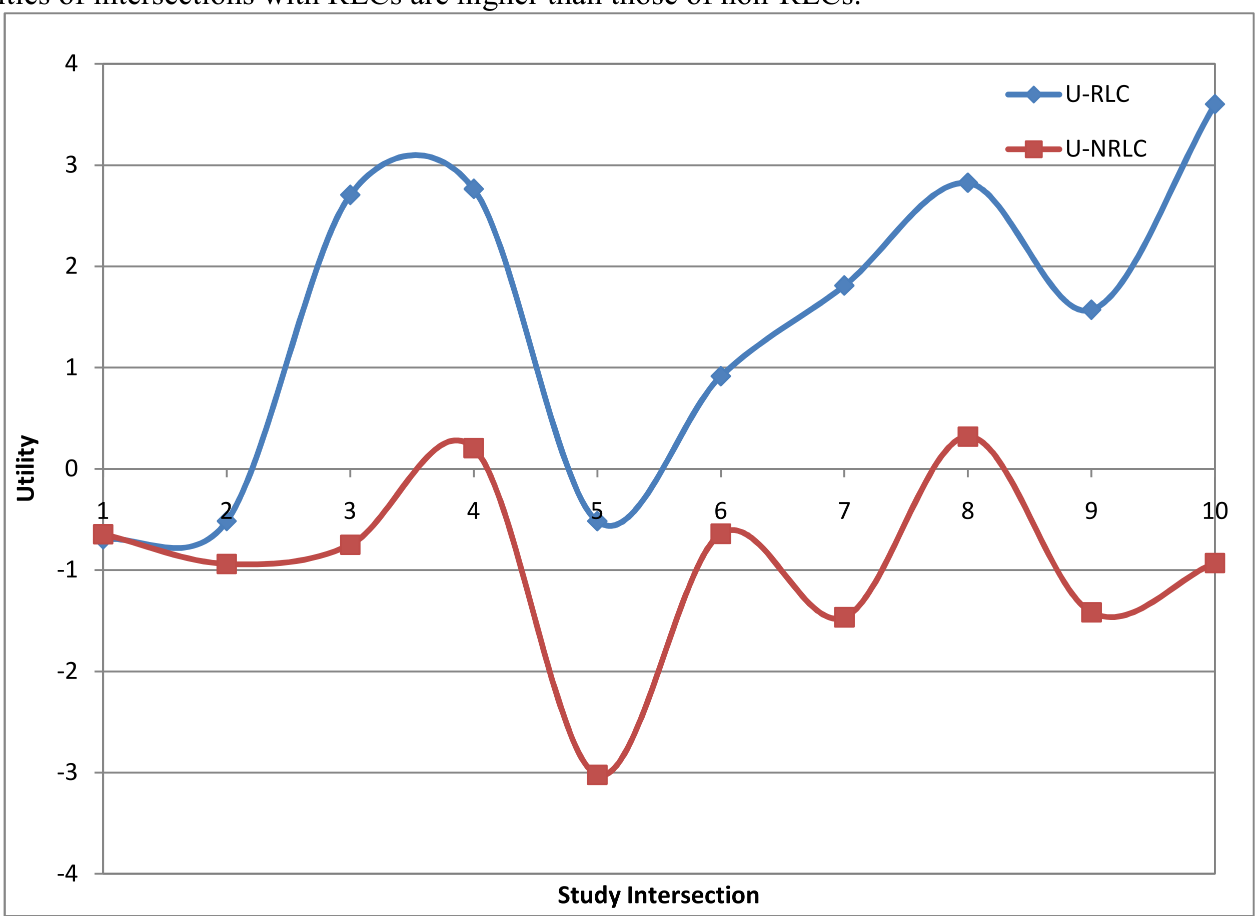


**Figure 1:** Utility of Study Intersections with RLCs and Non-RLCs.

Weldegiorgis (2009) computed the mean and standard deviation using data collected at the ten RLC and non RLC intersection pairs. Then using a similar approach used by Sheffi and Mahmassani (1981) at high-speed signalized intersections the dilemma zone plots for the ten RLC and non RLC intersection pairs can be developed using Equation (8). The parameters used for the normal distribution and dilemma zone curve computations are shown in Table 3.

$$P_{stop}(D) = \Phi\left(\frac{\frac{D_i}{V} - \mu}{\sigma}\right) \tag{8}$$

where:

$P_{stop}(D)$ = probability of stopping during yellow;

$\Phi(\bullet)$= standard cumulative normal function;

$D_i$= the distance to the stop line, feet;

$V$ = the posted speed limit at the intersection, ft/sec;

$\mu$= respective mean time for RLC and NRLC, sec; and

σ = respective standard deviation for RLC and NRLC, sec

**Table 3**: Dilemma Zone Curve Computation for RLC vs. NRLC Intersections

| | RLC | NRLC | RLC | NRLC | RLC | NRLC | RLC | NRLC | RLC | NRLC |
|---|---|---|---|---|---|---|---|---|---|---|
| V (mph) | 25 | | 30 | | 35 | | 40 | | 45 | |
| V (ft/sec) | 36.75 | | 44.1 | | 51.45 | | 58.8 | | 66.15 | |
| µ (sec) | 4.22 | 3.98 | 4.22 | 3.98 | 4.22 | 3.98 | 4.22 | 3.98 | 4.22 | 3.98 |
| σ (sec) | 2.22 | 2.32 | 2.22 | 2.32 | 2.22 | 2.32 | 2.22 | 2.32 | 2.22 | 2.32 |
| D (ft) | F(x) | F(x) | F(x) | F(x) | F(x) | F(x) | F(x) | F(x) | F(x) | F(x) |
| 0 | 0.028657 | 0.043125 | 0.028657 | 0.043125 | 0.028657 | 0.043125 | 0.028657 | 0.043125 | 0.028657 | 0.043125 |
| 50 | 0.098865 | 0.129433 | 0.082236 | 0.109946 | 0.071714 | 0.097379 | 0.064524 | 0.088670 | 0.059330 | 0.082308 |
| 100 | 0.249779 | 0.293691 | 0.189573 | 0.230222 | 0.152590 | 0.190041 | 0.128224 | 0.162935 | 0.111242 | 0.143683 |
| 150 | 0.475151 | 0.517471 | 0.356155 | 0.401520 | 0.278389 | 0.323168 | 0.226088 | 0.268967 | 0.189573 | 0.230222 |
| 200 | 0.709022 | 0.735734 | 0.556444 | 0.594559 | 0.440430 | 0.484058 | 0.356155 | 0.401520 | 0.294945 | 0.340055 |
| 250 | 0.877664 | 0.888139 | 0.743016 | 0.766690 | 0.613279 | 0.647625 | 0.505697 | 0.546614 | 0.421320 | 0.465529 |
| 300 | 0.962154 | 0.964316 | 0.877664 | 0.888139 | 0.765968 | 0.787508 | 0.654433 | 0.685679 | 0.556444 | 0.594559 |
| 350 | 0.991555 | 0.991566 | 0.952945 | 0.955939 | 0.877664 | 0.888139 | 0.782408 | 0.802383 | 0.685251 | 0.713993 |
| 400 | 0.998659 | 0.998540 | 0.985549 | 0.985886 | 0.945327 | 0.949036 | 0.877664 | 0.888139 | 0.794721 | 0.813506 |
| 450 | 0.999850 | 0.999816 | 0.996486 | 0.996350 | 0.979270 | 0.980035 | 0.938999 | 0.943314 | 0.877664 | 0.888139 |
| 500 | 0.999988 | 0.999983 | 0.999328 | 0.999242 | 0.993369 | 0.993307 | 0.973163 | 0.974397 | 0.933692 | 0.938523 |
| 550 | 0.999999 | 0.999999 | 0.999899 | 0.999874 | 0.998218 | 0.998087 | 0.989625 | 0.989728 | 0.967433 | 0.969139 |
| 600 | 1.000000 | 1.000000 | 0.999988 | 0.999983 | 0.999599 | 0.999535 | 0.996486 | 0.996350 | 0.985549 | 0.985886 |

The dilemma zone curves for the study intersections are shown in Figure 2. The curves show that for the same speed, the dilemma zone at RLC intersections is higher than non RLC intersections.

## CONCLUSION AND FUTURE WORKS

As noted in the Introduction section, there has been a surge of RLCs at congested urban intersections, primarily with the aim of penalizing red light runners, in an effort to improve the intersection safety. However, the authors like many driving people strongly feel that most of the RLCs may have been used by city, local, and state transportation agencies as means to collect revenues. In this paper we have tried to introduce the disutilities associated with RLCs and compare those with the widely believed utilities associated with RLCs.

We developed a scientific framework for investigating the positive and negative utilities associated with RLCs using data from 10 intersection pairs in the Baltimore area. The results indicate that, in general, negative utilities outweigh positive utilities of RLCs. Given the fact that excessive revenues generated through fines collected from red light violators may be a burden on the society resulting in degraded quality of life of motorists that frequently travel through RLC intersections, the negative utilities of RLCs should be carefully taken into consideration when deciding for future installations of RLCs. In addition, a routine evaluation of existing RLCs (at least annually) should be performed to investigate their effectiveness using the methodology developed in this study.

In future works, among other things, we can investigate the systemwide capacity reduction in a transportation network due to the existence of a RLC. In addition, if the before and after accident data were available, and amount of fines collected due to RLR violation then we can develop a robust framework to perform a trade-off analysis to examine the safety effectiveness of the RLCs as opposed to the potential of the RLCs as a revenue generator for jurisdictions running the RLC program. Finally, a more comprehensive investigation of RLC utilities and disutilities can be performed by collecting data from different States. This will also reveal the similarities and dissimilarities between driver behavior across various States and jurisdictions.

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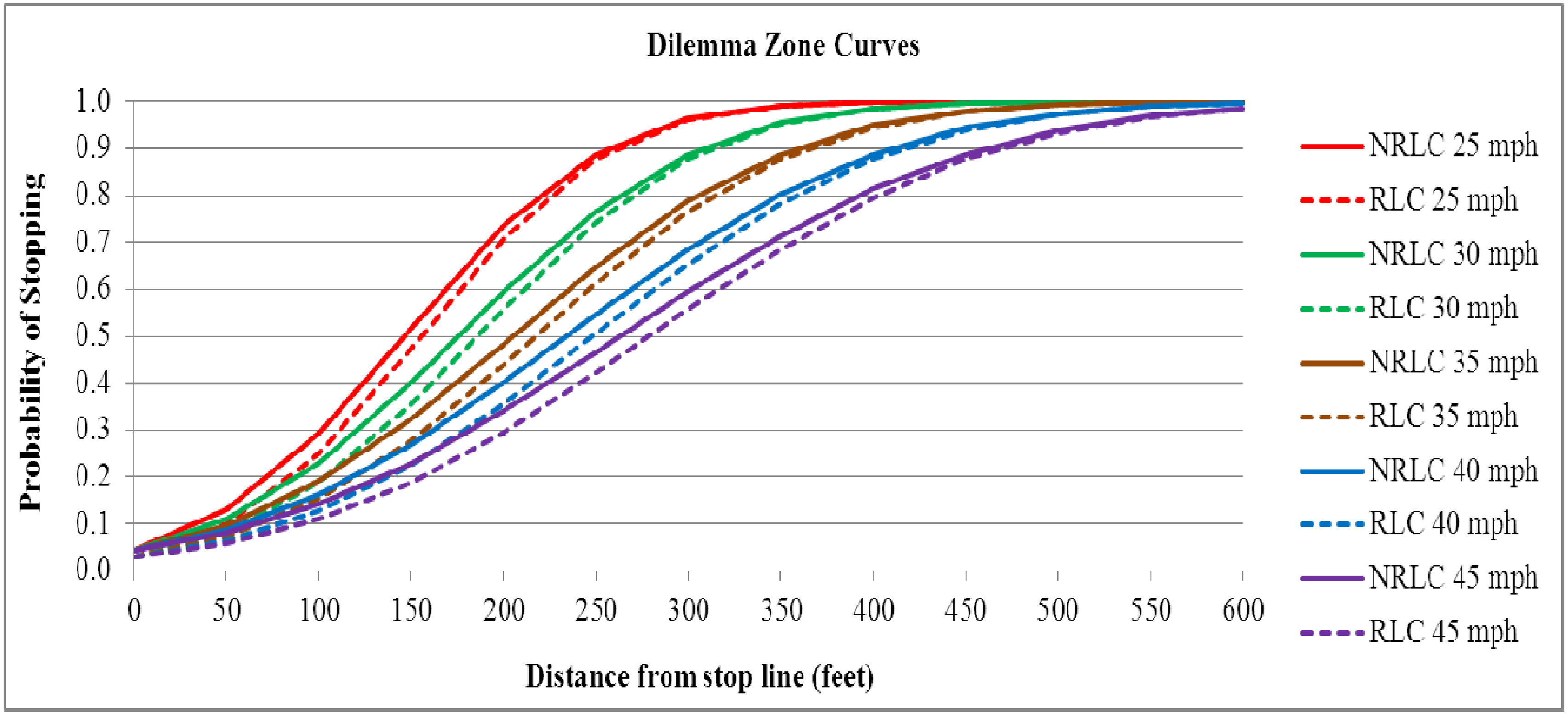


Figure 2: Dilemma Zone Curves RLC vs. NRLC Intersections

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