DEVELOPMENT OF A RED-LIGHT VIOLATION INDEX FOR SIGNALIZED INTERSECTIONS IN THE DISTRICT OF COLUMBIA

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11. Abstract

The installation of Red-Light Cameras (RLCs) is often based on frequencies of Red Light Violations at signalized intersections. Since frequencies could be influenced by geometrical features of intersecting roadways and overall vehicular volumes (or exposure) there is doubt about their appropriateness use in making decisions regarding the installation of RLCs. Inappropriate installation could result in unintended consequences such as increasing the frequency of some types of crashes. In order to eliminate the potential for bias with the use of frequencies as a means of deciding which intersections may need RLCs, a Red-Light Violation Index (RLVI) is introduced, for dense urban environments.

There is no red-light violation or red light crash threshold in the District of Columbia above which red light cameras should be considered for installation. In this research, a model for background or base RLVI was established which could assist engineers in determining the expected potential for red light running at intersections based on engineering properties, without the use of red-light running frequencies or crash records. A RLVI probabilistic regression model was developed based on five intersection independent variables: vehicles per hour green, lane configuration, clearance distance, duration of green and posted speed limit. The results showed statistically significant regression model with an R^2 of 81%, at 5% level of significance.

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EXECUTIVE SUMMARY

Between 1999 and 2010, the District of Columbia installed red-light cameras (RLC) fifty-two signalized intersections with the aim of curbing red light violations. There was no minimum criterion of red light violation (RLV) or red light crash threshold beyond which RLC should be installed in the District. In undertaking this research, a baseline red-light violation condition, termed red-light violation index (RLVI), is developed for assisting engineers in determining the background potential for red light running at intersections in the District based on engineering properties, without the use of citations or crash records was established. To achieve this, a red-light violation was first defined as event in which any uninterrupted vehicle, after entering an intersection, fails to clear the intersection before the onset of the red interval. A regression model was developed for the red-light violation index using five independent engineering variables: vehicles per hour green, lane configuration, intersection width, duration of green, and posted speed limit.

Eighteen (18) intersections were earmarked for this research. Two-hour video data was obtained at the intersections from which the same independent variables were extracted. The other independent variables were obtained during field visits. The data was compiled and organized for statistical analysis. The inferences from the statistical analysis were based on 5% level of significance.

The results of the analysis of variance (ANOVA) showed that 81% of the variance was explained by these variables, and the model was found to be statistically significant at 5% level of significance. The literature suggests that engineering and human factors variables are equal contributors to red-light-running, however the model developed in this research suggests a particularly high correlation using engineering variables exclusively. This could suggest that the contribution of the human factors variables were reasonably explained by the engineering variables, or that human factors variables have little impact on red-light-running in the District.

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1.0 BACKGROUND

Between 1999 and 2010, the Metropolitan Police Department installed approximately 50 Red-Light Cameras (RLCs) in the District of Columbia (DC). The installations were in response to a perceived high rate of red-light violations at intersections, and a need mitigate the red-light violation (RLV) problem. There is no basis established in the District of Columbia for determining when the RLV experience of an intersection is beyond expectation. A set of criteria is essential to enable the City to objectively prioritize the implementation of strategies for reducing RLV, including engineering and public awareness programs. Several measures are documented in the general literature on red-light running issues. They include the number of violations per certain volume of vehicles, the number of violations per unit time, the number of violations per cycle, as well as complex algorithms for calculating a RLV rate.

A fundamental concern about using the volume-based RLV rate for categorizing the status of RLV of intersections is that motorists who never had a chance to violate (those who crossed on green or amber, and those who never got to the stop line) are included in the factors used in characterizing the RLV status of intersection approaches. In addition, some agencies use the number of RLV citations or RLV crashes in characterizing RLV status, although most RLVs are not recorded and are excluded from crash reports. Further, RLV per unit time period ignores traffic exposure. There is, therefore, the need for a method for establishing the RLV status of intersections. Thus a Red-Light Violation Index (RLVI) is established in this research. The method for obtaining the RLVI of an intersection should be easy to understand, and measureable from field observations. Most agencies do not routinely monitor trends in RLV at critical intersections to determine whether implemented treatments are successful. The RLVI developed serves as a basis for estimating the minimal level of RLV for typical intersections in the City. Knowledge of the background RLV status has two purposes:

1. It enables the District Department of Transportation (DDOT) to establish change via monitoring intersections and comparing values, and
2. It provides a basis for comparing the status with a RLV threshold, i.e. the RLVI.

The extent to which observed RLV status exceeds the standard could be used as a basis for installing RLR cameras at intersections.

2.0 RESEARCH OBJECTIVES

This research explores the relationship between signalized intersection-related variables and RLV, and develops a model that could estimate the background violation potential for intersections within DC. A major portion of the effort would be geared towards determining whether or not a statistically significant, probabilistic model could be developed to determine the background violation potential as a function of standard intersection-related variables such as "duration of green". Thus, the objectives of this research are itemized as follows:

1. To develop a model to generate a background violation probability, the red-light violation index (RLVI), for urban intersections within DC, with emphasis on variables that could be observed in the field.
2. To determine the effect of vehicles per hour green, lane configuration, intersection width, duration of green and posted speed limit, on the background violation rate.
3. To develop a process for determining the need for RLCs.

A fundamental premise of this research is that all signalized intersections would experience some RLVs, the majority of which are not documented, and that there is a background level of RLVs that could be established for intersections.

3.0 LITERATURE REVIEW

3.1 Introduction

Red-light running (RLR) has been a problem for many decades, which dates back to the time when the first modern traffic signals were used in Ohio to control the movement of vehicles and to lower the accident frequency in Cleveland [1]. Since then, departments of transportation (DOTs), and their equivalent agencies around the world, have been implementing diverse methods, including improvements in signal timing, and implementation of RLCs, in order to reduce Red-Light Violations (RLV).

The United States Department of Transportation (USDOT) has approached the problem of red-light-running from two avenues: the Federal Highway Administration (FHWA) addresses the quality of traffic engineering infrastructure and systems for mitigating RLR, and the National Highway Traffic Safety Administration (NHTSA), which looks at the effects of driver inattention, and related human factors on RLR [2].

In terms of countermeasures, the solution to RLR primarily falls into two broad categories: enforcement countermeasures and engineering countermeasures [3]. Enforcement countermeasures involve encouraging drivers to adhere to the traffic laws through use of citations and fines, while engineering countermeasures are geared toward improving driver awareness of traffic signals or reducing the potential of drivers running the red light. Engineering countermeasures hold greater promise than those which involve enforcement, including the legal and political challenges of automated enforcement [3].

In a 1999 citywide survey conducted in the District of Columbia, residents identified unsafe driving, including running red-lights and stop signs, as their number one public safety concern [4]. Since then RLCs have been implemented throughout the District of Columbia, and evaluation statistics indicated a net decrease of 75% in violations captured across the respective intersections at which RLCs were installed [5]. However, various studies across the world have challenged the overall effectiveness of RLCs once implemented, given documented costs to the agency, increased collisions of another kind, and challenges by violators who are cited. In light of this, several hold the view that violations may be corrected by other means, based on an assessment of red-light running and crash potential of an intersection. Such assessments, must confirm a problem of RLVs so that appropriate intervention, if necessary, could be prescribed.

3.2 The Red Light Violation Problem

Pietrucha, Opiela, Knoblauch, and Crigler (1990) performed a study on motorist compliance with Traffic Control Devices (TCDs), including stop signs and traffic signals [6]. Of the 120 drivers surveyed, 38% reported having run a red light at some point in their driving careers, and 18% of these drivers reported doing so at least once a week [6]. For chronic violators, that is those who received a certain number of violation points, 54% reported running red lights, with 24% reporting doing so on a weekly basis. Forty six percent (46%) reported personal reasons for running red lights; i.e. “being in a hurry” [6].

In 1998, it was estimated that 750 deaths and more than 260,000 injuries were caused every year by red-light running in the United States [7]. There were 1,698,000 crossing-path crashes in 1999 out of an estimated 6,271,000 crashes of all types. Therefore, crossing-path crashes accounted for approximately 27% of all crashes [7]. In 2000, there were 1,667,000 crossing-path crashes out of an estimated 6,389,000 crashes (26%). Analysis of this data showed that left-turn crashes made up the majority (about 52%) of crossing-path crashes. The next type was straight crossing-path crash types (30-35%), then right-turn (about 6%) and unknown (7-11%). These incidents resulted in approximately 56% Property Damage Only (PDO) crashes, followed by 39% injury crashes (including fatalities) [8].

Ragland and Zabyshny (2003) reported that crossing-path crashes accounted for 25% of all crashes and 45% of crashes at intersections [9]. They also observed different patterns of crossing-path crashes based on the type of intersection and an over-representation of older drivers in crossing path crashes.

Campbell, Smith, and Najm (2004) reported that signal or stop-sign violations accounted for approximately 20% of the fatal crashes occurring at intersections [10]. Failure to yield to the right-of-way was also an important factor in fatal crashes, representing 13% of fatal crashes occurring at signalized intersections.

An analysis of 156 sites across the US revealed that of the 79,055 vehicles observed, there were 688 violations [8]. The most common maneuver was straight crossing-path (364), followed by left turns (210) and then right turns (114). A 2007 report by the NHTSA suggested that intersection crossing path crashes account for approximately 25% of all police-reported crashes in the United States each year [8]. They also account for 27% of all crash-related delays and over $47 billion in costs.

3.3 Factors Related to Red-Light Running

The general literature indicates that several factors contribute to RLR. Some factors have been found to be present regardless of the intersection being studied, while other factors appear to be unique to a particular jurisdiction. Where factors are common, there have been noted differences on the impact of these factors in a particular jurisdiction. These factors and their descriptive statistics related to RLR are presented in this section.

Factors contributing to red light running include vehicle characteristics, intersection design and operation, weather, and driver behavior [11]. Vehicle characteristics may be linked to inappropriate signal timing, since vehicle characteristics are factored into any traffic signal design. Deficiencies in traffic signal design and the geometrical configuration of signalized intersections may contribute to unintended RLR behavior. Inadequate signal timing, for example, could affect reaction and stopping times, and lead to motorist confusion. Given the variations in intersections' characteristics, an engineering study should always be done to determine whether such factors increase the level of probability or of potential RLR [11].

In a study by Grubb (1992) on the *"Individual differences and driver response to highway Intersections,"* a pedal response error analysis revealed higher error rates for older drivers, females, and people scoring higher for the anxiety trait and history of accident involvement [12]. Age accounted for the largest amount of variance in the speed of response, and heart-rate activity. For both sexes, the age group with the highest crash involvement rate was 15-19 years. The age group with the lowest rate for males was 55-64 years and 25-54 years for females. A comparison of involvement rates and likelihoods by age and sex shows that older women have a low likelihood but a high rate of accidents. Older women tend to drive fewer miles, but are disproportionately involved in more crashes per mile.

Wang and Knipling (1994) found that most crossing-path crashes (98%) involved at least one passenger car [13]. They also found that crash involvement rates were highest for younger drivers (15 to 19), second highest for older drivers (75+) and lowest for middle-aged drivers (25-64). Slightly fewer than 75% of crashes occurred on non-divided highways, fewer than 25% on divided highways, and the remainder on one-way roadways. Approximately half of the crashes occurred on 1 or 2-lane roadways, with about 15% occurring on roadways with 5 or more lanes. About 30% of the crashes occurred on roads where the posted speed limits were 35 mph or less, that is, in urban environments. Drivers 65 and older were charged with failure to yield twice as often as drivers aged 25 to 64, relative to their involvement in a collision.

Time of day appears to have an impact on red-light violation probability [14]. Wang and Knipling, (1994) found that twice as many crossing-path crashes occurred in the afternoon through evening traffic peak (3:30 pm to 6:30 pm) than during the morning peak (6:31 am to 9:30 am), with the highest number of crashes occurring on Fridays and the least on Sundays [13]. Research has suggested that during peak hours, increased traffic volumes and congestion may influence the number of motorists running red lights, especially if signal timing is not adequate [17,18]. Weather was discounted as a predictor of RLR, although obscured visibility was considered a major factor in red-light running [18]. With respect to human factors, aggressive driving, distracted driving (use of cellular phones, conversations with vehicle occupants) and driving through unfamiliar territories were key contributors to RLR [18]. When considering infrastructure, appropriate yellow times for an intersection were identified as essential to arrest violation problems, as shorter yellow times were found to increase the probability of a RLV [18].

Porter and England (2000) conducted a study to provide data on the characteristics of red-light runners. They attempted to address the issue of drivers with the potential to violate by identifying participants as those that were last to cross the stop intersection bar prior to the onset of opposing traffic [19]. Only drivers crossing straight paths or making left turns were included. Of the 5,112 observed signal cycles, 1,798 involved at least one red-light runner (35.2%).

Najm, Smith, and Smith (2001), reported that left turns accounted for 47.2% of violation-related crashes, while straight crossing path (vehicles proceeding straight through the intersection), accounted for 29.9% [20]. About 75% of these crashes occurred at intersections, 41.6% of which were at signalized intersections, 36.3% at stop-controlled intersections, and 22.1% at intersections with no controls or other types of controls.

A study by Porter and Berry (2001) analyzed the findings of a telephone survey to determine self-reported tendencies in red-light running. A sample of 880 licensed drivers was used to explore attitudes regarding the following areas:

(a) The prevalence of violation and how driver characteristics can be used to predict it

(b) The effect of passengers on likelihood of violation

(c) The impact of frustration on violation behavior

(d) The role of consequences in decision-making

(e) Ideas to reduce red-light running

The results indicated that 20% of the participants had run at least one red light in the last 10 intersections they had crossed [19]. The only variable that significantly predicted violation behavior was age group, with the youngest group (18 to 25), having the highest rate. The study found that 10.9% of the respondents had been involved in a crash, and the majority, 98.8% believed red-light running to be dangerous, while 79.8% believed it was a problem [19].

A 2002 study (Bonnesson, J., Zimmerman, K., Brewer, M.) of 10 intersections with RLC for at least 10,018 cycles in Texas showed that for observations of 586 vehicles running the red light, 84 were trucks and 502 were passenger cars [3]. In terms of the percentage of truck drivers, 86% violated the red light while 38% of passenger cars did so. The study concluded that Texas truck drivers were twice as likely to run a red light as their passenger counterparts.

Yan, Radwan, and Birriel (2005), found that the risk of red-light running crashes were related to seven environmental factors - number of lanes, crash time, weather, highway character, day of week, urban/rural, and speed limit; four driver factors - driver age, alcohol/drug use, physical defect; and driver residence, and the type of vehicle [21]. Several of these factors were shown to modulate the effects of other factors, i.e. exhibit an interaction with other factors.

Zimmerman and Bonneson (2005) discussed 63 crossing-path crashes at a signalized intersection where a red-light violation was a factor. They found that violations occurring more than 5 seconds into the time-into-red tend to be exclusively straight crossing-path crashes, whereas violations occurring fewer than the 5 seconds into time-into-red tend to be exclusively left turn approach (LTAP) crashes [22].

A 2006 NHTSA report indicated that a decrease in red light running was found to be associated with the following factors: [3]

- A decrease in approach flow rate
- An increase in yellow duration
- A decrease in speed
- An increase in clearance path length (i.e. a wider intersection)
- A decrease in platoon density, and
- The addition of signal head back plates.

To combat the problem of violations, when they are suspected to be frequent, the NHTSA report recommended the following actions:

- Confirm the extent of the problem through the computation of the expected frequency of red-light running for the subject location (either by the number of violations per 1000 vehicles, or number of violators per 100 cycles).
- Compute a "ranking index" that indicates whether the site is truly a problem location [3].

An analysis of red light violations at 11 study intersections in Sacramento, California, revealed that most red light running occurred during the day from 7 am to 7 pm, with highest counts between 2 pm and 2:59 pm and the general afternoon peak [23]. Speeding did not appear to be an issue as more than half (56%) of vehicles were traveling at or below the posted speed limit. Approximately 94% of the red-light violations occurred within 2 seconds after the onset of the red light, and only 3 % after 5 seconds from the onset of the red light [23, 24]. Drivers under 30 years of age were more likely to run red lights than drivers in other age groups. Older drivers had a higher probability of running a red light when the elapsed time since the onset of red light was more than 2 seconds, compared to younger drivers [24].

It should be noted that crashes caused by running red lights are more deadly and damaging than other types of crashes at signalized intersections [14]. Studies show that the number of RLVs does not necessarily correlate to the number of crashes caused by same [14]

3.4 Agency Approach to Resolving Red-Light Running

Given that a range of factors can lead to excessive RLV, the type of countermeasures and the degree to which they have been employed have understandably been varied. An assortment of countermeasures have been developed and implemented over time with varying degrees of effectiveness. A number of jurisdictions have taken the additional step of studying the effects of these countermeasures over time in order to determine their levels of effectiveness. This section gives a synopsis of the various approaches adopted by various states, locales and agencies, including some statistics on the reduction of RLR and RLR-related crashes. The effects of these countermeasures are discussed in further detail in the subsequent section.

Red light cameras have been in operation in Victoria, Australia since 1983 [16]. However, in 1993, New York City became the first major US City to implement a red-light photo enforcement program [25]. After 3 years of photo enforcement, and an average conviction rate of 85%, red light violations at photo enforced locations in New York City reduced by nearly 60% [7, 25].

Crash or accident reduction factors (CRFs or ARFs) provide a quick way of estimating crash reductions associated with highway safety improvements, and are used by many states and local jurisdictions in deciding whether to implement specific treatments and/or to quickly determine the costs and benefits of selected alternatives [26]. Arising out of the analysis of CRFs and ARFs are accident modification factors (AMFs) which are then implemented by the respective agencies, and may include such items as improvements to intersection geometry and signal timing.

Red light cameras in the United States have been applied inconsistently and, at times incorrectly, suggesting no methodical approach to assessing the need [11]. Research has shown that engineering improvements [27, 28], safety education and increased enforcement by law enforcement officers [29, 30] can significantly improve red-light running behavior. Advance Vehicle Detection Systems could be considered in order to extend green times for the end of a platoon. The authors recommended that unwarranted Traffic Signals should be considered for removal as they also contribute to the increased risk of red light running [31].

Research has shown that driver error due to inattention at intersections, inaccurate detection or interpretation of the signal status, poor estimation of time for action associated with signal status, lack of detection of cross traffic, and problematic visual obstructions contribute to crashes at intersections [7]. NHTSA has been seeking to utilize ITS technology to generate an in-vehicle intersection Collision Avoidance-Violation (ICAV) system that would warn drivers approaching intersections, regarding whether they were in danger of running a stop sign or red light. In the agency's 2007 Intersection Collision Avoidance-Violation project [8], the approach adopted was to transmit messages through the implementation of a Driver Vehicle Interface (DVI), using visual, audio or haptic warnings. The aim would be to provide an alert to drivers at a predetermined distance from the intersection, if there is a danger of running the red light. The system was expected work by the placement of a detector upstream of the intersection that computed the speed of a vehicle at a certain time during the green signal phase. A computer program would then determine whether or not there is a danger of that vehicle getting into the dilemma zone (the section of an intersection approach where a driver is uncertain as to whether he/she can safely stop or proceed through the intersection), and issue an alert to the driver prior to arriving at the intersection [31].

Bonnesson and Zimmerman (2002) developed an analytical procedure for determining excessive RLV [32]. The research was limited in its application to:

- Drivers traveling straight through the intersection (as opposed to turning).
- Urban or suburban intersections
- Red-light running that is perceived by the driver as being "unavoidable". This condition is realized when drivers believe that they are unable to safely stop, and consciously run the red indication, or is unaware of the need to stop. In contrast, an "avoidable" red-running event is committed by a driver who believes that it is possible to safely stop but decides it is in his or her best interest to run the red indication.

The research method involved analysis after identifying an issue of RLV, and making an assessment of whether it is excessive or not. Researchers suggested that the method could be used for left and right turns, and for rural intersections, with reasonable accuracy [32].

The FHWA and the Institute of Transportation Engineers (ITE) produced a list of engineering countermeasures to reduce red-light running (McGee et al., 2003) [33]. They suggested that while intentional violators will likely be most affected by law enforcement countermeasures, unintentional violations can be addressed, in part, by engineering countermeasures such as the following:

- Improving signal visibility
- Improving signal conspicuity
- Increasing likelihood of stopping (e.g. make it easier for the driver to stop)
- Addressing intentional violations
- Eliminating the need to stop

3.5 Red-Light Violation Prediction Models for Countermeasure Implementation

While most agencies appeared to apply various methods for addressing their RLV problem, others have gone a step further to develop models to predict RLV problems prior to prescribing a treatment. The premise for these models is the theory that all intersections experience some levels of violations. Therefore, prescribing RLV countermeasures for an intersection should be based on whether the observed violation rate is higher than what should be expected due to intersection characteristics. Regression models were developed, based on observed RLVs and other factors, are used to predict the potential at for RLVs signalized intersections.

The Red-Light-Running Handbook, developed by Bonnesson and Zimmerman (2004) for the Texas Department of Transportation, suggests guidelines for identifying and treating locations that have an unusually large number of red-light violations or related crashes. Separate guidelines are presented for the treatment of red-light problems at individual intersections and within entire cities [34]. The method employed the Texas Red-light-running Evaluation and Analysis Tool, (TREAT), to identify problems of red-light-related safety based on crash data for an intersection, approach or jurisdiction and comparing it with the average annual crash frequency of similar intersection approaches. If the subject approach had significantly more crashes than similar approaches, then it was identified as having potential benefit from treatment. For a local intersection, it was based on the observed frequency of red-light violations [34]. TREAT was developed using prediction equations calibrated from data for intersections located in urban areas. Therefore the procedure is most applicable to drivers travelling through the intersection (no turns) and urban and suburban intersections. Data for evaluating the RLV problem, according to the TREAT method, includes the following:

1. *Traffic Characteristics: Volume, 85th percentile approach speed, heavy-vehicle percentage.*
2. *Traffic Control: Posted speed limit.*
3. *Signal Operation: Signal cycle length, green phase duration, multi-loop advance detection, approach control mode, left-turn phasing.*
4. *Motorist information: Signal visibility, signal conspicuity, advance warning signs.*
5. *Traffic Operation: Approach delay, signal coordination.*
6. *Geometry: Approach through lanes, approach grade, clearance path length.*
7. *Red-light Violations: Violation analysis time period, through-vehicle violations during study period.*
8. *Crash History: Crash analysis time period, crash distribution.*

The model developed based on those variables was

$$E[R] = Q/C(1/1.26)\ln[1 + e^{(2.47 - 1.26Ye - 0.855Tct + 0.0545HV + 0.0693V85 + 0.451fx - 0.414Bp)}] \qquad [1]$$

where

E[R] = expected violations for the intersection based on eight variables described above.

Q = approach flow rate, veh/h;

C = cycle length, s;

Ye = effective yellow duration due to advance detector operation, s;

Tct = clearance time, s;

HV = heavy-vehicle percentage, %;

V85 = 85th percentile speed, mph;

V50 = 50th percentile speed (.0.89 *V85*), mph;

fx = overflow delay factor;

Bp = presence of back plates on the signal heads, (1 if present, 0 if not present)

An index was then developed as follows:

$$\text{Index} = (E[R/x] - E[R])/\sqrt{(\sigma^2_{R/x} + \sigma^2_R)} \qquad [2]$$

where

E[R/x] = expected violations divided by actual violations,

$\sigma^2_{R/x}$ = standard deviation of E[R/x]

σ^2_R = standard deviation of E[R]

If the index developed was negative, then the intersection would be described as operating at or below the expected RLV frequency. If the index was positive, then the intersection would be operating above the expected RLV frequency, and countermeasures could be recommended based on the degree of positivity. This model has been included in a "Red-Light-Running Handbook" so that engineers may have a framework in which a RLV problem could be identified and treated [34].

Another regression model was developed by Stephen and Lindly (2003) (red light running prediction and analysis) to assist engineers in making a determination of RLR potential at intersections [35]. In that study, violations at 19 intersections across 4 states (Alabama, Texas, Iowa, and California) were analyzed against fourteen engineering variables initially. After ranking the variables based on the amount of variance each one explained, a final model including six variables was developed:

$$\text{Violations per hour} = 3.10 + 1.21AL - 0.520CL + 8.3 \times 10^{-5}ADT + 0.0120AI1 - 2.31AI2 - 0.476AI3 \quad [3]$$

where

AL = number of lanes on the subject approach

CL = number of lanes on the crossing approach

ADT = ADT of subject approach

AI*x* = Approach direction indicator x (the approach direction for the four-legged intersection)

The model was found to be statistically significant at 5% significance level with an R^2 value of 0.805. However, prior to implementing the model in practice, the researchers suggested that the sample sizes be expanded, particularly for the AD*x* variables, to ensure that the model could be applied more broadly.

In reviewing the literature, there has only been one agency/jurisdiction that has developed a statistically significant model for predicting RLV and put it into practice as a formal procedure to be adopted by engineers. Most agencies implement countermeasures, and subsequently conduct studies to determine the effectiveness of these interventions using various regression analysis techniques.

Virginia Law requires that prior to installing RLCs at intersections, an engineering safety analysis must be conducted [36]. The analysis must include, but not be limited to a review of clearance intervals, signal coordination along the corridor, and the condition of other safety features such as lane markings, traffic control signs, etc. The Commonwealth of Virginia's approach is to have a detailed overview of an intersection's physical/engineering properties to determine whether or not they contribute to RLR. If these conditions could be adjusted such that the incidence of RLV is curbed, then approval for red-light running may not be necessary. However, if after such consideration, there is no potential for a reduction in the RLV rate, then RLCs may be approved.

Virginia legislation requires that violation rates be expressed as number of violations per 1,000 vehicles. The legislation also requires that, prior to submitting an intersection for approval of implementation of a RLVC, the jurisdiction should consider the following factors:

(i) The accident rate for the intersection

(ii) The rate of RLV occurring at the intersection (number of violations per number of vehicles)

(iii) The difficulty experienced by law-enforcement officers in patrol cars or on foot in apprehending violators, and

(iv) The ability of law-enforcement officers to apprehend violators safely within a reasonable distance from the violation.

In the District of Columbia, the primary means of controlling red light violation is through enforcement by the use of RLCs [4]. The regulation of traffic is mandated under the DC Official Code, Division VII, Title 50, Subtitle VII, Chapter 22, and Subchapter 5 [37]. The law in the District of Columbia does not provide guidance on the placement of RLCs, as is the case in Virginia, nor does it clearly spell out the operating parameters under which violators could be cited, for example, elapsed time from the onset of the red light from which the violators can be ticketed. Essentially, the placement of cameras at intersections is at the discretion of the Metropolitan Police Department.

3.6 Impact of Various Agency Approaches to Curb Red-Light Running

In the previous section, a number of strategies to curb red-light-running were identified, and statistics were presented on their relative successes. In most cases, the statistics suggested that strategies had a positive effect in reducing the RLV rate in the jurisdictions where they were implemented. However, in other cases, the impact of RLC was less than desired. This section highlights some of these effects in relation to the installation of RLCs.

McGhee et al (2002) summarized research findings from a number of studies on the effect of RLCs on crash occurrence and severity. Based on a comparison of the data, some of the authors were of the opinion that there is no conclusive evidence that suggested that RLCs actually prevent RLR crashes [38]. The researchers found that when rear-end collisions were taken into consideration, there were minute reductions in both property damage only and injury crashes. This meant that there was a significant side-effect associated with the installation of RLCs such that the investment may not return the expected benefits. Compounding this problem is the overestimation of RLV at intersections, where practitioners neglect to adjust for regression to the mean (Retting, Ferguson, and Hakkert, 2002) [39]: If an intersection was selected for RLC installation because the number of RLV was unusually high for a period of time, some reduction in violation frequency could be expected without intervention. Therefore, when comparative studies are undertaken at a future date, they may show that the RLC as having little effect on the overall RLV rate.

The installation of RLC has also led to underestimations of the real problem of RLV at neighboring intersections. McGee and Eccles (2003) found evidence that RLV was reduced at other intersections in close proximity to intersections at which red light cameras were installed [40]. Because the location of RLCs in the community were not immediately known, driver's adopted the same behavior at nearby intersections, irrespective of whether RLCs were present or not. This phenomenon was referred to as the "halo" or "spillover" effect. When surveys were conducted at intersections in close proximity to those where cameras were installed, and the halo or spillover effect was not considered researchers drew erroneous conclusions about the safety characteristics of those intersections [39]. For example, Retting, Williams, Famer, and Feldman (1999) found that there was a 40% reduction in violations at camera sites and 50% reduction at non-camera sites in neighboring Oxnard, California [41]. As such, the conclusion may be drawn that immediately after the installation of cameras, reductions in RLV may occur at intersections in close proximity, thus magnifying the initial benefit. However, this may not reflect the "safety state" at the intersection. Therefore, as drivers become familiar with the location of RLR cameras over time, the initial halo effect may not be sustained and nearby non-camera intersections may revert to their true and higher violation state. Therefore, the cameras' presence may lead to a misdiagnosis of the real problem at those intersections.

From the onset of red-light violation programs, it was realized that red-light enforcement using RLCs is a costly venture. The installation process requires significant coordination among various city departments, including but not limited to the police, municipal court, Public Works, City Attorney, District Attorney, Public Health and Parking and Traffic [7]. In the 1999, the City of San Francisco completed a six month pilot project to install RLCs. Although the pilot project resulted in a reduction in violations by 40%, one of the two vendors participating in the project eventually discontinued its services to the project in the early stages because it was not financially viable. For the pilot project, the vendors owned all equipment and infrastructure required to run the RLC system. Each vendor received $17.50 per citation out of a possible fine of $104 paid by offenders. This was insufficient to cover the cost of acquisition, installation and operating the system. Though this occurred in the late 1990's, it is a problem that is faced by many jurisdictions today – when RLV is reduced, the main source of revenue to run the system is reduced, and so it becomes a challenge for agencies to continue the program [7].

In the District of Columbia, statistics have shown an overall decrease of 75% in total red-light violations during the installation period of 1999 to 2007 [5]. However, a closer inspection of the statistics revealed that in some cases the violation rate remained about the same, or was actually higher. While the reasons for this may be unknown, it lends credence to the literature that the installation of RLCs is not the only solution to the problem of red light running at intersections.

3.7 Summary

Despite the advent of a number of strategies to combat the problem of red light running since 2000, statistics show that crossing-path crashes consistently account for 20-25% of all crashes in the US. Crossing-path crashes associated with red-light running have been shown to account for at least 60% in most cases.

Agencies have experimented with a number of potential remedies to the issue of red-light violations that include the installation of RLRCs, use of ITS technology and engineering improvements, with varying degrees of success. In some cases, the benefit of the intervention was countered by unexpected, negative effects.

Variables affecting the probability of red-light running are several in number, and the impact of these variables can be affected by location of the problem area and driver demographics. However, the literature has consistently identified the following as key variables in the scheme of violations:

1. Age – Younger drivers (generally under 30) and older drivers (over 65) were highly represented in red-light violation citations and intersection related crashes. Middle aged drivers (between 30 and 65) had the lowest rate.
2. Intersection properties – Geometrics, road cross-section, signal timing and protected versus permitted left-turns were a few of the significant factors cited as potential problem areas at intersections. How well these are designed for the local conditions plays a significant role in the violation rate.
3. Traffic volumes – Heavier traffic volumes could be associated with higher violation rates. Evidence of this can be observed during peak hours, where several sources identified heavier traffic during peak hours with higher violation rates.
4. Time – Time of the day and day of the week also play a role in RLV rates. Researchers have identified the afternoon peak period as the time when most red-light violations occur. This is also related to the previous point on increased traffic volume. Drivers were also more likely to violate the traffic signal on a Friday and least likely on a Sunday.
5. Driver Behavior – Approximately 40% of red-light violators are considered intentional violators. The majority of intentional violators commit the offence for personal reasons, for example, "being in a hurry". Another 40% could be considered as unintentional violators, since the reason for their violations attributed primarily to distracted driving.
6. Countermeasures – The impact of countermeasures, such as RLCs at intersections within close proximity to typically problematic intersections, have been shown to reduce red-light running behavior significantly at those intersections.

One of the most popular mitigation strategies for red-light violation is the RLRC. After initial success in reducing red-light violations, the problem of increased rear-end collisions at intersections occurred. This was attributed to an increase in unexpected stop maneuvers at intersections by drivers fearing citations for RLRV. Due to this outcome one researcher concluded that the net benefit of the introduction of RLRC's, was only 7%. Agencies that rely on the revenue from RLC programs for the capital investments, operation and maintenance experience a diminishing return from fines as the numbers of RLVs decrease.

Agencies across the US have recognized the need for rating intersections in terms of their accident potential, in order to prescribe appropriate remedial actions. In some cases, agencies have attempted to adopt, the same methods developed by other state agencies for assessing RLV and accident potential at intersections. However, due to jurisdictional peculiarities, this approach has been met with limited success.

For the most part the decision process adopted by agencies for selecting intersections for RLC based on a post-hoc analysis of events at intersections. This procedure does not facilitate safety evaluations for recently built intersections or intersections being designed, where little or no relevant data exists. For a typical intersection crashes due to RLV are rare events and it would take several years to compile an adequate sample of such crashes for developing reliable crash models.. Research on general models for predicting crashes has not been successful, despite the need. There is an opportunity for models that are especially developed for particular localities.

A number of agencies categorize their RLV as a rate expressed as function of the number of violators per number of vehicles crossing an intersection. However, that measure does not give the practitioner a clear picture of the problem at intersections. Since RLV is also a behavioral matter, its extent should be judged by considering only drivers who have the opportunity to violate the signal. In the denominator of the ratio, there are drivers who would not have the opportunity to violate the red because of their position in the approaching traffic. By including all motorists in developing a violation rate (e.g., violations per 1000 vehicles), the value of the resulting measure is clouded. The closest that the general literature came to resolve the confusion is by the use of the ratio developed from cycles with violation and cycles without violations, which is the probability of a signal cycle with a RLV. The behavioral measure that is directly associated with drivers is the probability that drivers would violate the red signal, which is the ratio of violators divided by those with the opportunity to violate.

As the general literature suggests, there are numerous factors that contribute to RLV. All signals would be violated by at least one driver; this includes unintentional violations. Thus there is always a background level of violation. Apart from a select few studies, the general literature is silent on this matter and whether intersection safety improvement could be measured via observed changes in the expected or background status. This research investigates the background red light violation probability (i.e. the red light violation index) and its use in measuring intersection safety from the perspective of compliance with traffic signals.

A Red Light Violation Index (RLVI) for the District of Columbia is essential for the following reasons:

1. There exists no scientific basis for measuring driver compliance with traffic signals and the effect of RLV countermeasures. Given that the predominant countermeasure is RLC deployment, inappropriate or over-treatment of an intersection can lead to issues of excessive costs to the agency, and unnecessary legal wrangling.
2. Though methods have been developed by various agencies across the US to rate intersections' the red-light violation condition, such methods have been shown to be non-transferrable across state boundaries. Peculiarities such as driver characteristics by region, road design characteristics, record keeping by state police departments and a host of other parameters affect the outcome of the various methods. Therefore, an index developed specifically for a state, jurisdiction or metropolitan area is essential in order to generate accurate results for violation indices.
3. Once the violation index has been developed for the District of Columbia, the law governing the regulation of traffic should be amended to include parameters for implementing RLV countermeasures at intersections, similar to the approach by the Virginia legislature.

4.0 RESEARCH METHODOLOGY

Several jurisdictions across the world quantify red light violation rates as a function of the number of violators compared to the gross number of vehicles crossing the intersection. However, a statistic that may be more appropriate for agencies attempting to determine the RLV potential at an intersection would be the number of violators compared with the number of drivers with the opportunity to violate the red light: i.e. the red light violation probability (RLVP). Vehicles with the potential to violate the red light would be those that are at the intersection at start of the red interval, and whose drivers must then decide whether to proceed or stop. Further, the vehicles behind the first vehicle in this queue, will only have the opportunity to violate the red light, if the first vehicle proceeds through the intersection, or if the lane adjacent to the first vehicle in the queue is vacant. For all other vehicles, the freedom to violate is very restricted by the presence of other vehicles. The goal of this research, is therefore to generate a Red Light Violation Index (RLVI) for intersections within the District of Columbia, using the latter criteria for determining the potential for such an occurrence.

"Opportunity to run red lights is a function of what time during the signal cycle the vehicle approaches the intersection and whether the road is clear ahead of the vehicle. Obviously, those who approach and proceed through the green interval did not have an opportunity to violate. In addition, those who arrived after the light had turned red and with a stationary vehicle in the same lane directly ahead of them (especially when the adjacent lanes were also full) had no opportunity to violate either".[6]

5.0 ESTABLISHING RED-LIGHT VIOLATION PROBABILITY MODEL

5.1 Selection of Variables Related to RLV

From the literature it was determined that a number of variables could have an effect on RLV. These range from human factors such as driver age and ability, to engineering properties, such as intersection geometry and lane characteristics. Only the engineering variables highlighted in the literature that would likely have the most significant impact on red light running, as well as those for which the data collection exercise can be reasonably managed, were selected for study in order to develop a background violation index for specific types of intersections. These variables are listed and described below:

5.1.1 Vehicles per Hour Green of Approach: Vehicles per hour of green interval of approach is defined as the number of vehicles served by the green interval for the approach to the intersection under study. It includes all the vehicles crossing the stop bar on green, and excludes those vehicles that are considered violators under the definition. This variable was chosen on the theory that the percentage of vehicles utilized by the green compared to the actual number of vehicles traversing the intersection in a given cycle, may lead drivers to run the red light. The literature suggests that this variable directly correlates with RLV at urban intersections.

5.1.2 Lane Configuration: This variable relates to the number and type of lanes at the intersection approach, as well as the number of turns. Each through lane at an intersection was given a code of 1, and each turning lane was given a code of 0.5. The values were summed for the total of each type of lane which was used in the analysis. For example, an intersection with two through lanes and one turning lane, would be assigned a code of 2.5 (one for each through lane and 0.5 for the turning lane, which sums up to 2.5). The literature suggests that the number of approach lanes plays a role in RLV as well as the type (straight or turning lanes). Therefore, a combination of these variables is used as an independent variable in this model.

5.1.3 Clearance Distance: The longitudinal distance from the approach intersection's stop bar to the opposing stop bar was used as a variable in the analysis. The literature suggests that the wider the intersection, the less likely a motorist would run a red light, assuming signal timing and all other variables were constant.

5.1.4 Duration of Green: The duration of green refers to the actual green time allocated to an approach at each intersection. The duration of green affects the queue build up at an intersection which impacts the potential of red light running.

5.2.1 Characteristics of Intersections

The selected intersections are located in an urban environment, in Washington DC. All intersections were signalized, with a cycle length of 120 seconds and an amber interval of 4 seconds. The majority of intersections were controlled by two phases, however, there were a few exceptions, where some intersections were controlled by a third phase. This phase arrangement arose due to the presence of exclusive left-turn lanes at those intersections, and the need for protected-permissive phasing. The intersections were either 3- or 4-leg configurations, and were mostly equipped with pedestrian countdown timers. The pedestrian phases operated with the through phase of each intersection, and there were no situations where pedestrian-only phases existed. The number and configuration of lanes varied from single, shared lanes, to multiple, shared and exclusive lanes. The number of lanes for the respective intersections is displayed in Table 1, while the configuration (number, shared/exclusive) is as described in section 5.1.2.

The intersections were generally free of congestion, with the green interval largely underutilized. There were no queues, and so delays were mostly due to signal timing, or the occasional blockage at the departure side of the intersection, where vehicles may have been parked, or other temporary obstructions existed. In the case of the latter, heavy vehicles, particularly buses, were present in the traffic stream, with stops varying between the near and far sides of the intersections. Buses accounted for the majority of "heavy" vehicles, and associated effects on the traffic stream. While there were other trucks present, their impacts were negligible, given that they were not stopping within the area of influence of the respective intersections. Pedestrian impact on the through and left-turning movements was negligible, however, there was some observed delay experienced by right turning vehicles at some locations. A summary of the key characteristics of the intersections are included in Table 1.

Table 1: Intersection Characteristics

Intersection	Intersection Name	No. of Legs	Observed Approach	No. of lanes		Parking		Pedestrian Traffic	Heavy Vehicles
				Near Side	Far Side	Near Side	Far Side		
1	New Mexico Avenue @ Westover Place NW	3	SB	1	1	No	No	No	Yes
2	Pennsylvania Avenue @ 8th Street SE	4	WB	4	4	Yes	No	Yes	Yes
3	North Capitol Street @ H Street	4	NB	3	3	Yes	Yes	Yes	Yes
4	Wisconsin Avenue @ Western Avenue NW	4	NB	3	3	Yes	No	Yes	Yes
5	Michigan Avenue @ 7th Street NE	4	EB	2	2	No	No	Yes	Yes
6	MLK Junior Avenue @ Malcolm X Avenue SE	4	NB	2	2	No	Yes	Yes	Yes
7	South Capitol Street @ Atlantic Street SE	4	SB	3	2	No	No	Yes	Yes
8	Connecticut Avenue @ Newark Street	4	SB	3	3	No	No	Yes	Yes
9	14th Street @ U Street NW	4	NB	3	3	No	Yes	Yes	Yes
10	Connecticut Avenue @ Devonshire NW	3	SB	3	3	No	Yes	Yes	Yes
11	Benning Road @ 32nd Street NE	3	EB	4	4	No	No	No	No
12	13th Street NW @ N Street NW	4	SB	3	3	Yes	Yes	Yes	Yes
13	13th Street NE @ Maryland Avenue NE	4	NB	2	2	Yes	Yes	Yes	No
14	6th Street SE @ Constitution Avenue	4	NB	2	2	Yes	Yes	Yes	No
15	34th Street @ Benning Road N	4	WB	5	4	No	No	Yes	Yes
16	K Street NE @ 7th Street NE	4	EB	2	2	Yes	Yes	Yes	Yes
17	Franklin Street NE @ 14th Street NE	4	WB	2	2	No	Yes	Yes	Yes
18	North Capitol Street NE @ Gallatin Street	4	NB	3	3	No	Yes	Yes	Yes

5.2.2 Data Compilation and Reduction

Data was collected at one approach of the 18 intersections using a video camera, for a 2 hour duration, during the morning off-peak period, between 10:00 am and 12 noon where the potential for red light running is high. The off-peak periods were deliberately selected in this research in order to minimize RLVs that are associated with poor traffic operating conditions. The selection of the approach for video-taping was based on volume and having adequate vantage location for positioning the video team and cameras. The video playback was used to extract the information for vehicles per hour of green (V), duration of green (G), intersection width (W), and lane configuration (L). The posted speed limit was on the approaches, were obtained during site visits. The intersections and data extracted are summarized in Table 2.

Table 2: List of Intersections and Extracted Data

Intersection	VPHG*	Green	Clearance distance	Approach Lane Configuration	Posted Speed Limit
1	319	66	92	2.5	25
2	657	59	90	3.5	30
3	586	49	121	4.0	25
4	593	34	130	2.5	30
5	536	52	143	3.0	25
6	341	51	103	3.0	25
7	536	64	90	2.5	30
8	1014	63	100	4.0	25
9	659	40	113	3.0	25
10	817	61	85	4.0	25
11	693	66	68	5.0	30
12	382	55	102	2.5	25
13	196	26	118	2.0	25
14	308	55	122	1.5	25
15	900	67	68	4.5	15
16	180	24	72	1.5	15
17	158	46	70	1.5	25
18	727	72	66	3.5	25

5.3 Regression Model

To develop the RLVI, each of these independent variables will be tested against the dependent variable, red light violation probability (RLVP) to determine the degree of correlation. This was conducted using Microsoft EXCEL and SPSS. After a series of data transformations, the following generalized regression model was deemed to be adequate:

$$(RLVI) = \beta\ (G, V^{-1}, W, W^2, L, \log(L), S) + \varepsilon,$$

where

RLVI = Red Light Violation Index, same as the background RLVP

G = Duration of Green

V = Vehicles per Hour Green

W = Clearance Distance

L = Lance Configuration

S = Posted Speed Limit

The constant β is a coefficient of the regression model with an associated error of ε [$\varepsilon \sim N\ (0, \sigma^2)$]. The statistical significance of the regression coefficients were tested at 5% level of significance. Similarly, the overall statistical significance of the regression model for the intersections was tested using the F-test at 5% level of significance. The F-test, tests the significance of the overall model by determining if the variance accounted by the model is reasonably large. If the associated *p*-value of the F-test is less than 5% (0.05), then the regression model is acceptable and that the hypothesis of the non-existence of a relationship between the independent variable and the dependent variable is rejected. In addition, the regression model was checked for homoscedasticity (constant variance) using residual plots, and also checked for normality using the normal probability plots. The residual plots should show the errors randomly distributed about the mean line (zero) or is rectangular, with a concentration of points along the center. In a normal probability plot, if all the data points fall near the line, an assumption of normality is reasonable. Otherwise, the points will curve away from the line, and an assumption of normality is not justified.

For the developed regression model, the coefficient of determination or the R^2 value was reported. This is the amount of variability in the data explained or accounted for by the regression model. It is worth noting that the R^2 value of a regression model will increase with the introduction of a new variable, although the new model may not be necessarily better or superior. Furthermore, if the dependent and independent variables are related in a non-linear fashion, the R^2 value will often be large, although linearity is assumed.

Upon obtaining the regression model, an analysis of the predicted values from the model was compared to the observed probabilities for RLR to determine whether there is a statistically significant difference between the two data sets. This was done using the Kolmogorov-Smirnov (KS) test, which provides a D statistic, indicating the difference between the data sets. If the D statistic is less than the expected D statistic for the sample size, and normality is obtained, then it can be said that there is a goodness of fit between the predicted and observed values for RLV.

The number of vehicles running the amber and the red light were also recorded. Vehicles breaching the amber, and caught in the intersection at the commencement of the red interval were recorded in a separate column labeled “amber/red”. The summary results are presented in Table 3.

Table 3: Observed Violations per Cycle

Intersection	Violation Opportunities	Number of Violations	Violation Probability
1	90	22	0.244
2	127	38	0.299
3	242	110	0.455
4	170	80	0.471
5	130	46	0.354
6	58	29	0.500
7	142	48	0.338
8	43	7	0.163
9	132	73	0.553
10	76	23	0.303
11	284	110	0.387
12	126	4	0.032
13	66	21	0.318
14	22	12	0.545
15	245	74	0.302
16	57	10	0.175
17	64	17	0.266
18	106	46	0.434

The five variables described were then used to develop a regression model, for the RLVI at 95% confidence. The first step involved determining the type of relationship between each independent variable and the dependent variable. The SPSS software was used, and each variable analyzed separately. The "best fit" relationship was determined and used for further analysis. The results of the best fit relationship for each independent variable with the dependent variable a represented in Table 4.

Table 4: Relationships between the Independent Variables and the Dependent Variable

Variable	Relationship
Vehicles Per Hour Green	Inverse, linear
Duration of Green	Cubic
Intersection Width	Quadratic
Lane Configuration	Inverse, linear

6.0 RESULTS

A statistically significant relationship (P = 0.001216) was found between the selected independent variables and the dependent variable, RLV. The resulting regression model is:

$$RLVP = -0.0004807G - 99.91795V^{-1} + 0.3354L - 2.9455\log(L) + 0.0133962W - 6 \times 10^{-5}W^2$$

where G = Duration of Green

V = Vehicles per Hour Green

W= Intersection Width

L = Lane Configuration

RLPP = Red-Light Violation Index (RLVI)

The percentage of variance (R^2) explained by this model was 81%, suggesting that the majority of the causes of red-light-running in the City could be explained by the independent variables. The summary results for the ANOVA are presented in Table 5.

Table 5: Summary Results for ANOVA and Regression Statistics

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	6	0.626318	0.104386	8.641496	0.001216
Residual	12	0.144956	0.01208		
Total	18	0.771275			

Regression Statistics	
Multiple R	0.901142
R Square	0.812056
Adjusted R Square	0.650413
Standard Error	0.109908
Observations	18

The resulting regression model was subjected to the Kolmogorov-Smirnov (KS) test in order to determine the difference, D, between the predicted values generated by the model, and the observed values. The results are summarized in Table 6.

Table 6: Results for KS-test conducted on the Predicted and Observed RLV Data Points

	Data Set 1 – Predicted RLV Probabilities	Data Set 2 – Observed RLV Probabilities
Mean	0.3411	0.3410
Standard Deviation	0.139	0.100
Median	0.3280	0.3229
Third Quartile	0.459	0.428
First Quartile	0.261	0.282
Interquartile Range	0.198	0.146

The results indicate that both sets of data, the predicted and observed values, are normally distributed. Additionally, the D statistic was found to be 0.16667 with p = 0.945. This indicates that there is there is a close fit between the predicted and observed values for RLVI.

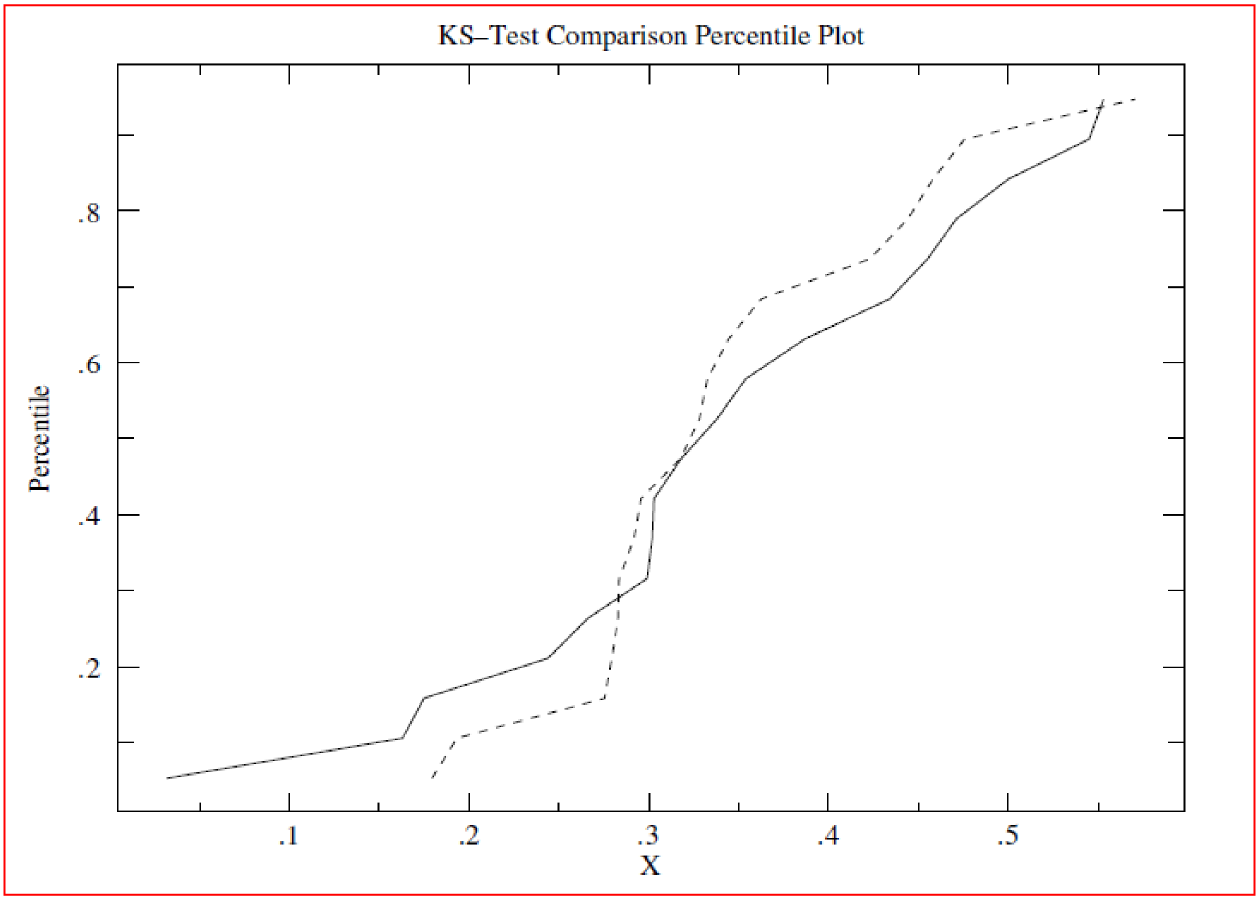

Figure 1: Results of the Kolmogorov-Smirnov Comparison Test

A normal probability plot for the regression model was generated, which produced a straight line graph of approximately 45 degrees, confirming the normality of the distribution. The result is displayed in Figure 2.

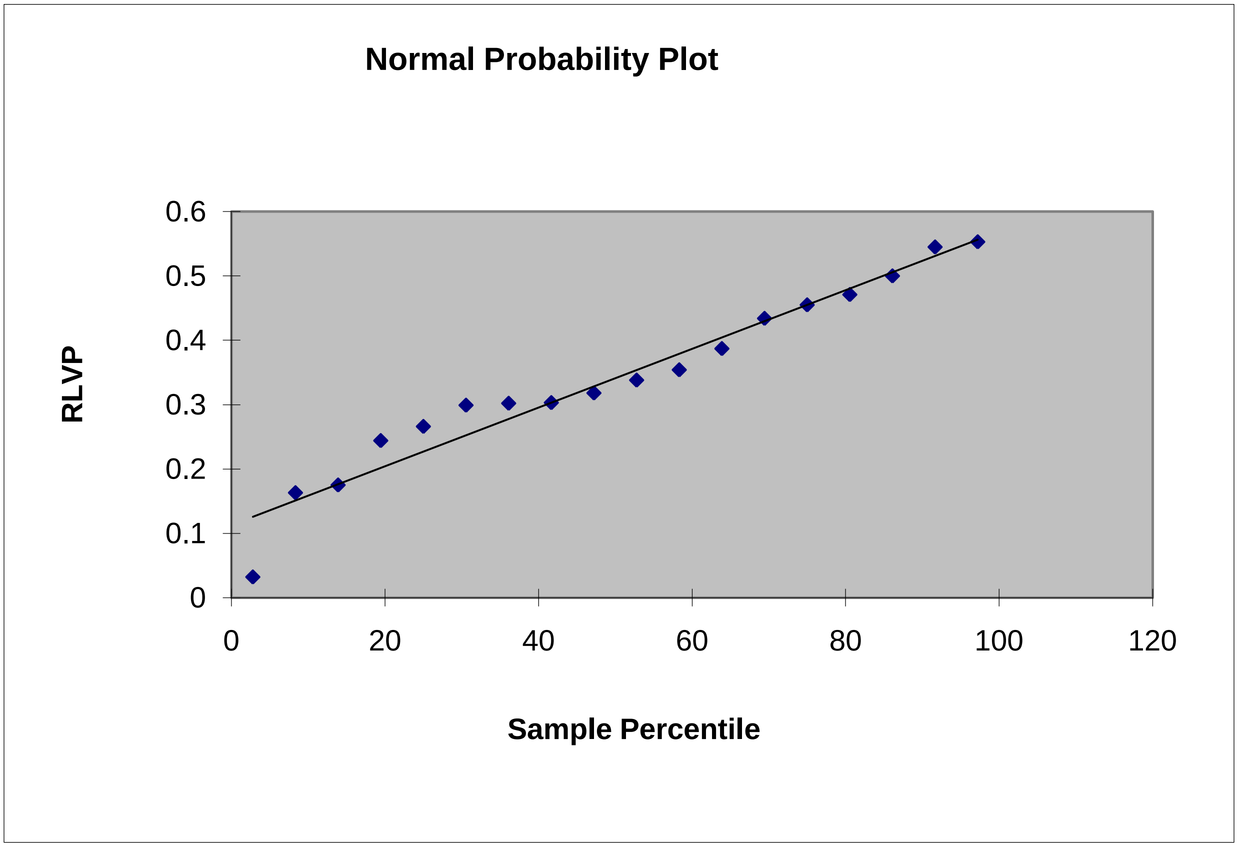

Figure 2: Normal Probability Plot of RLVP vs Sample Percentile

7.0 DISCUSSION OF RESULTS

The results showed that for the 18 intersection studied, the relationship between the RLVI, and the independent variables (vehicles per hour green, duration of green, intersection width, lane configuration, and posted speed limit) was statistically significant at 95% confidence interval. The amount of variance explained by independent variables amounted to 81%.

The results of the ANOVA indicated that none of the variables, on their own, had a statistically significant impact on red light running. However, the interaction among the variables was strong enough to render the overall model statistically significant. This means that although none of the variables could predict RLVP individually, their combined effect was large enough to achieve reliably estimates.

The results of the Kolmogorov-Smirnov (KS) test revealed that the data points for the predicted and observed RLVs were normally distributed, and closely matched each other. The D statistic was obtained to be 0.1667 with p = 0.945, suggesting that there was no statistical difference between the observed and predicted RLVP values. A comparison of the means for both data sets found respectively to be statistically equal. The mean for the predicted and observed values are 0.3411 and 0.3410 with corresponding standard deviations of 0.139 and 0.100.

The literature suggested that human factors variables also (such as driver age, gender, etc.) play a significant role in red-light-running and related crashes. Although only engineering factors were considered in this model, they also directly impact driver behaviors at intersections. Consider the engineering variable "duration of green" and the human factors variable "age" as an example. Given the findings in the literature that suggest young people between the ages of 16 and 25 are most likely to run a red light when compared to the 25-64 or the 64+ age group, then it may be reasonable to assume that if the duration of green at an intersection is inadequate, a young person may be more likely to run the red light than an older counterpart when faced with the same situation. In other words, there may be a strong correlation between two independent variables that can be predictors for red light running.

8.0 CONCLUSIONS

The analysis show that the intersection-related variables: vehicles per hour green, duration of green, intersection width, lane configuration, and posted speed limit, are strong predictors of red-light running in the District of Columbia. Given that the percentage of variance explained by the model was as high as 81%, it means that modifications to the engineering properties studied in this research may lead to a significant reduction in red-light-running in the District.

Although the literature suggests that human factors variables play a significant role in red-light running, the experience in the District of Columbia is that intersection engineering factors could be used to account for the incidence of red-light-running. The potential exists that since the driver-related behavior the variables have a strong correlation with the engineering variables, the model may be accounting for their effect. The RVVI expressed in the model presented on page 33 of this report demonstrates, with only 18 intersections, that a reliable model for characterizing the level of RLV for at-grade intersections is achievable. The developed model is applicable to the types of intersections studied in this research. The model has broad practical appeal since it relies on engineering factors that are easily obtained and available. The research advances the state of knowledge on the question of what benchmark could be used to determine the effectiveness of RLV projects and programs.

9.0 RECOMMENDATIONS

While statistical significance was obtained at 95% confidence interval and a high R^2 value was also obtained for the model. Only eighteen intersections were earmarked for this study. Thus, additional data will be needed to substantiate and validate the model. In addition, instead of using the video data for 2-hour duration, an extended duration of 5 hours could be obtained. This will enable a much larger sample and a applicable to both peak and off-peak conditions.

Prior to full application of the model, a validation exercise should be undertaken, where data is collected at several test intersections. The predicted values generated could then be compared to observed RLVI to determine the model is validity.

As stated in the literature, the causes of red light violations can be vary significantly as one goes from one jurisdiction to the other. Therefore, care should be taken in applying this model in other jurisdictions, and to intersections that are vastly different from these used in this study..

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APPENDIX 1: PRELIMINARY APPLICATION PROCEDURE

There may be a number of reasons why an intersection's approach(es) may be considered for evaluation to determine whether a problem of excessive RLV exists. Complaints from within the community, crash records, and/or police citations for errant drivers may all be compelling reasons. Prior to proposing any form of treatment, e.g. installation of RLRCs, an assessment must be made as to whether the level of violations is typical, above or below average for the intersection and the District, based on its engineering properties. To this end, the following procedure is proposed.

1. *Data collection*

   Once an intersection has been identified for evaluation, the first step in the evaluation process would be data collection. The data to be collected will be gathered from historical sources and from field visits to the intersections. Historical sources include any as-built drawings or condition diagrams for the intersection(s) where clearance distances, lane configuration and posted speed limits may be obtained. If such records are unavailable, site visits may be used as much as possible to obtain the data, including VPHG and the duration of green. The field visit would require 2 technicians to gather the data accurately. The *VPHG* may be obtained by recording the number of vehicles that cross the approach stop bar on the green (crossings on any of the clearance intervals are not included) for a one hour duration. The *duration of green* may be recorded at random intervals to ensure that the timing remains consistent while VPHG is recorded. Any changes must be recorded to ensure an accurate estimate of the VPHG for the intersection.

2. *Data Entry and Analysis*

   The data will be entered and presented in the format presented in Table 7 below.

Table 7: Sample Data Collection Sheet

Intersection	Intersection Name	VPHG	Green	Clearance distance	Approach Lane Configuration	Posted Speed Limit
1						
2…						
n						

This information will applied to the model, and the returning RLVI value generated will then be compared to the violation probability based on observations at the intersection. This comparison will show whether the intersection is experiencing violations above or below its expected violation rate. Secondly, the results will be compared against the mean violation rate of 0.341 for the District of Columbia, to determine whether the intersection's RLV characteristic is typical or atypical for the DC area.

3. *Agency Response*

   Upon completion of the analysis, if it is determined that the intersections' RLV characteristic is below the mean for DC, plus or minus three standard deviations, no further analysis will be undertaken for the intersection. If, however, the results are above the mean, a detailed study of potential causes may be undertaken, including but not limited to review of the signal timing, duration of the green and/or clearance intervals, approach lane configuration and posted speed limit.

It should be noted that this violation probability must form part of a standard traffic safety analysis. That is, this procedure is intended to support an already established traffic safety analysis procedure, such that it becomes part of a standard procedure in conducting safety review at intersections in the City.

APPENDIX 2: DEATAILED RESULTS OF STATISTICAL ANALYSIS

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.966927501
R Square	0.934948792
Adjusted R Square	0.699161351
Standard Error	0.150008163
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	11	2.263915857	0.205811	9.14613927	0.006568057
Residual	7	0.157517143	0.022502		
Total	18	2.421433			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
G	0.01931095	0.024721804	0.78113	0.46032269	-0.039146827	0.077769	-0.03915	0.077769
1/G^2	4247.917392	3586.714168	1.184348	0.2749255	-4233.31391	12729.15	-4233.31	12729.15
1/G^3	-82782.53694	66631.30344	-1.2424	0.2540944	-240340.5329	74775.46	-240341	74775.46
1/V	-116.8922402	82.42393239	-1.41818	0.1990843	-311.7938695	78.00939	-311.794	78.00939
V	-0.000571019	0.00043997	-1.29786	0.23546225	-0.001611382	0.000469	-0.00161	0.000469
W	-0.00197156	0.008368701	-0.23559	0.82049695	-0.021760393	0.017817	-0.02176	0.017817
1/Sqrt W	-31.55194528	29.82464167	-1.05792	0.32522951	-102.0760163	38.97213	-102.076	38.97213
L	0.169414001	0.154056301	1.099689	0.30784288	-0.194871265	0.533699	-0.19487	0.533699
1/L	1.295622162	1.063146225	1.218668	0.26244248	-1.218319185	3.809564	-1.21832	3.809564
1/W	133.6964176	147.2775425	0.907786	0.39416878	-214.5596311	481.9525	-214.56	481.9525
S	-0.002175745	0.012094316	-0.1799	0.86232952	-0.030774257	0.026423	-0.03077	0.026423

RESIDUAL OUTPUT

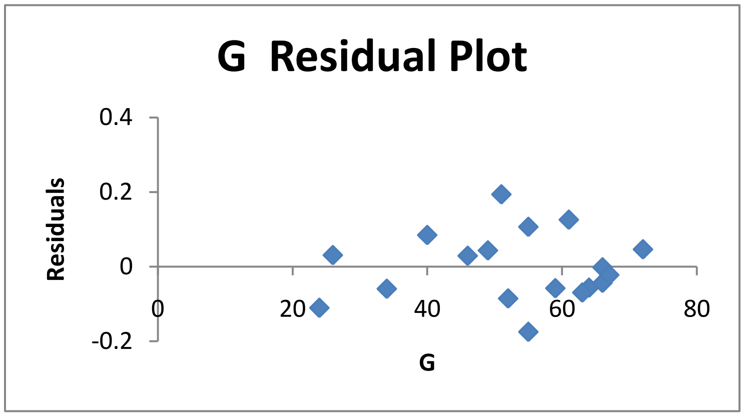
Observation	Predicted RLVP	Residuals	Standard Residuals
1	0.28288956	-0.03888956	-0.41572
2	0.283574111	0.015425889	0.164901
3	0.422912475	0.032087525	0.343011
4	0.570649312	-0.099649312	-1.06524
5	0.362472056	-0.008472056	-0.09057
6	0.32824165	0.17175835	1.836074
7	0.291770639	0.046229361	0.494186
8	0.193285575	-0.030285575	-0.32375
9	0.458162281	0.094837719	1.013803
10	0.275460703	0.027539297	0.294391
11	0.444119452	-0.057119452	-0.6106
12	0.317608734	-0.285608734	-3.05312
13	0.295731388	0.022268612	0.238049
14	0.475650871	0.069349129	0.741333
15	0.344554247	-0.042554247	-0.4549
16	0.179557401	-0.004557401	-0.04872
17	0.279534892	-0.013534892	-0.14469
18	0.33264661	0.10135339	1.083454

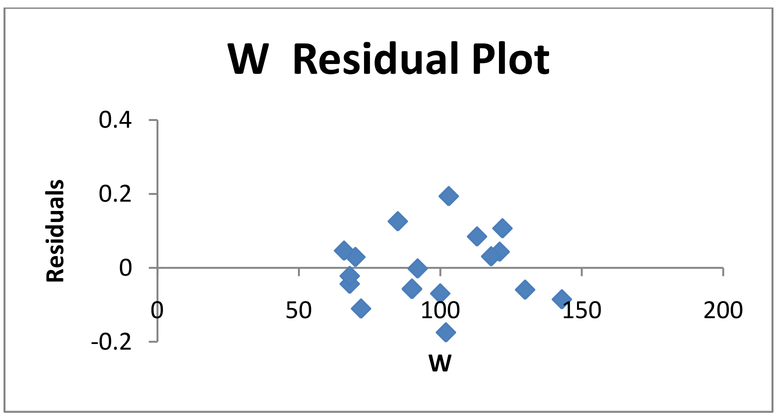
`

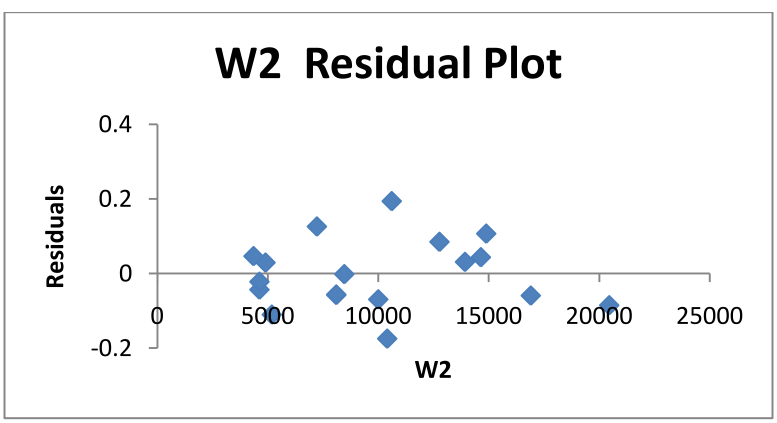
PROBABILITY OUTPUT

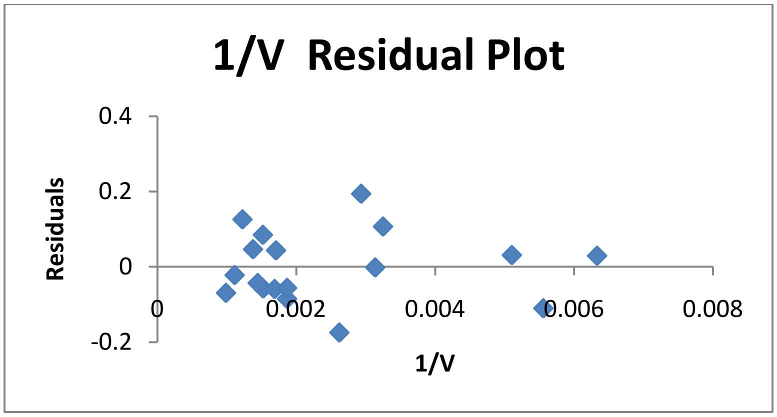
Percentile	RLVP
2.777777778	0.032
8.333333333	0.163
13.88888889	0.175
19.44444444	0.244
25	0.266
30.55555556	0.299
36.11111111	0.302
41.66666667	0.303
47.22222222	0.318
52.77777778	0.338
58.33333333	0.354
63.88888889	0.387
69.44444444	0.434
75	0.455
80.55555556	0.471
86.11111111	0.5
91.66666667	0.545
97.22222222	0.553

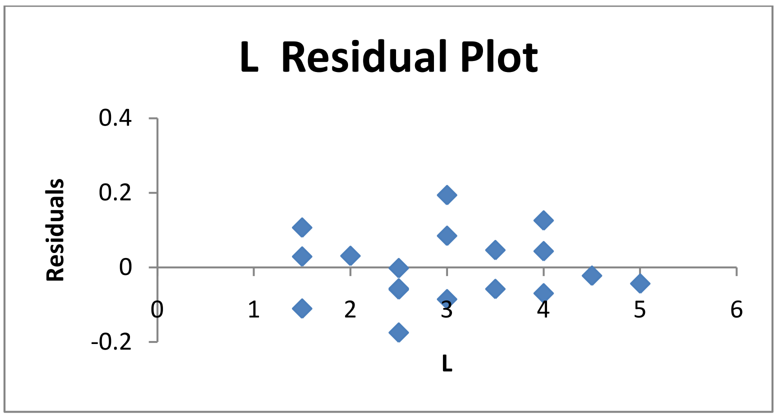
Residual Plots

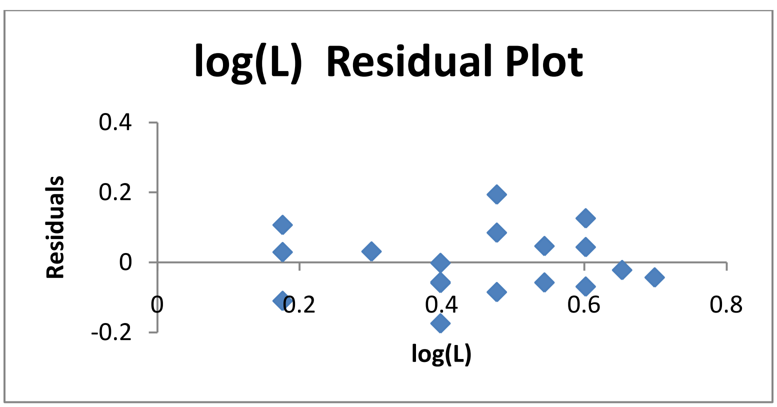




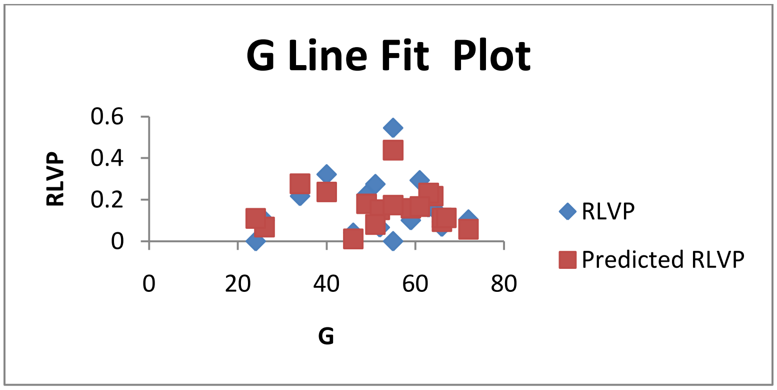


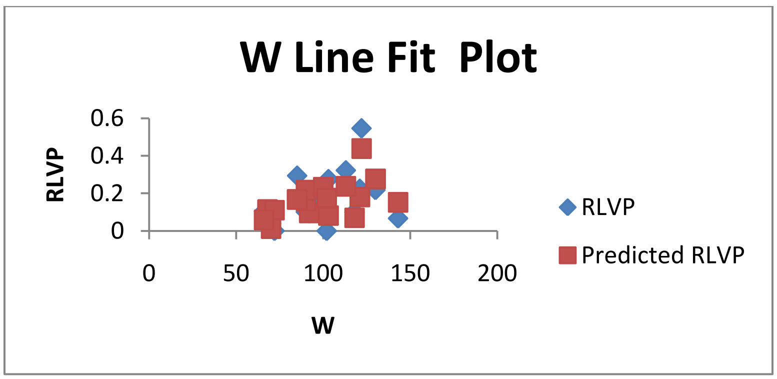

1/V Residual Plot
Residuals
0.4
0.2
0
-0.2
0
0.002
0.004
0.006
0.008
1/V

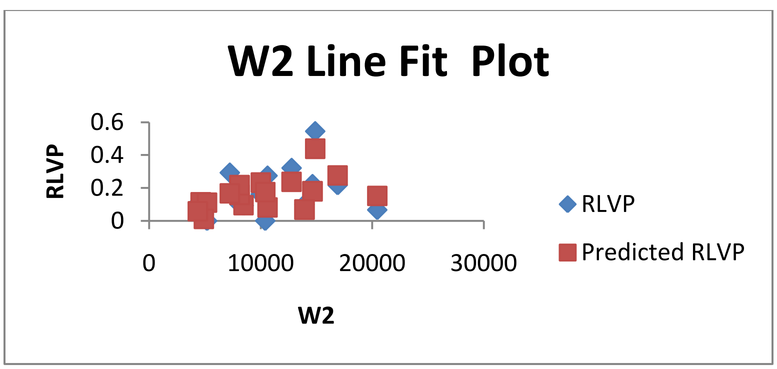

L Residual Plot
Residuals
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
L

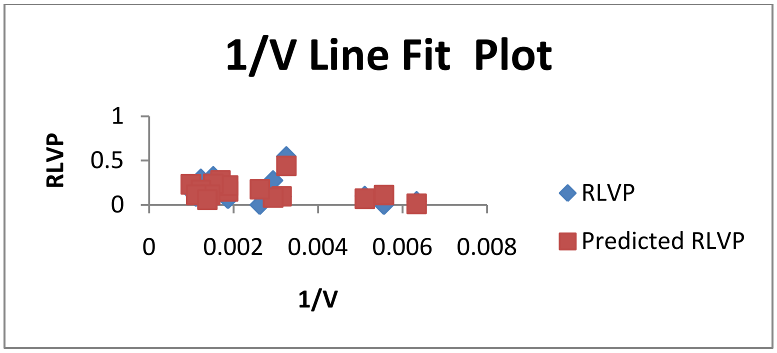

log(L) Residual Plot
Residuals
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
log(L)

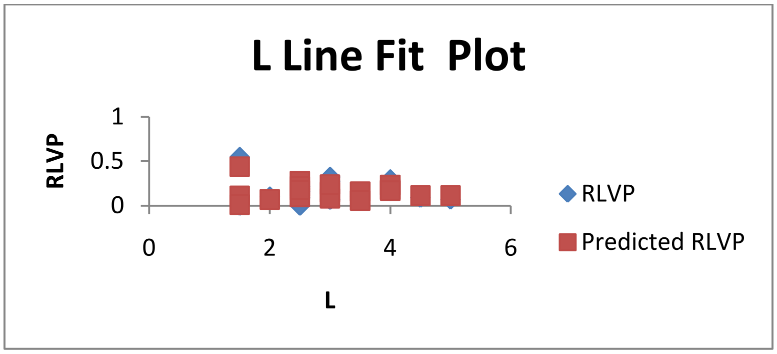
Line Fit Plots

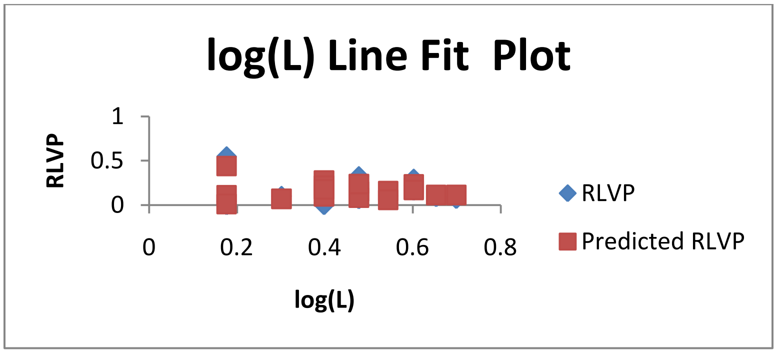







1/V Line Fit Plot
RLVP
1
0.5
0
0
0.002
0.004
0.006
0.008
1/V
RLVP
Predicted RLVP


L Line Fit Plot
RLVP
1
0.5
0
0
2
4
6
L
RLVP
Predicted RLVP


log(L) Line Fit Plot
RLVP
1
0.5
0
0
0.2
0.4
0.6
0.8
log(L)
RLVP
Predicted RLVP

APPENDIX 3: KOLMOGOROV-SMIRNOFF TEST RESULTS

The maximum difference between the cumulative distributions, *D*, is: 0.1667 with a corresponding *P* of: 0.945

Data Set 1:

18 data points were entered
Mean = 0.3411
95% confidence interval for actual Mean: 0.2720 thru 0.4101
Standard Deviation = 0.139
High = 0.553 Low = 3.200E-02
Third Quartile = 0.459 First Quartile = 0.261
Median = 0.3280
Average Absolute Deviation from Median = 0.108
KS finds the data is consistent with a normal distribution: *P*= 0.87 where the normal distribution has mean=
0.3356 and sdev= 0.1668
KS is not particularly happy calling this data log normally distributed: *P*= 0.10 where the log normal
distribution has geometric mean= 0.2881 and multiplicative sdev= 3.006

Items in Data Set 1:

3.200E-02 0.163 0.175 0.244 0.266 0.299 0.302 0.303 0.318 0.338 0.354 0.387 0.434 0.455
0.471 0.500
0.545 0.553

Data Set 2:

18 data points were entered
Mean = 0.3410
95% confidence interval for actual Mean: 0.2913 thru 0.3908
Standard Deviation = 0.100-
High = 0.571 Low = 0.180
Third Quartile = 0.428 First Quartile = 0.282
KS Test: Results http://www.physics.csbsju.edu/cgi-bin/stats/KS-test.n.plot
1 of 2 9/28/2010 1:36 PM
Median = 0.3229
Average Absolute Deviation from Median = 7.444E-02
KS finds the data is consistent with a normal distribution: *P*= 0.51 where the normal distribution has mean=
0.3505 and sdev= 0.1153
KS finds the data is consistent with a log normal distribution: *P*= 0.41 where the log normal distribution has
geometric mean= 0.3279 and multiplicative sdev= 1.431

Items in Data Set 2:

0.180 0.193 0.275 0.280 0.283 0.284 0.292 0.296 0.318 0.328 0.333 0.345 0.362 0.423 0.444
0.458 0.476
0.571

Format:
X Scale Options:
Linear
Log
Y Scale Options:
Linear
Probability
Format:
X Scale Options:
Linear
Log

APPENDIX 4: RAW DATA

Table 1: Vehicles per Hour Green (V), per Intersection

Time Period (mins)	Vehicles per Intersection																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
5	32	65	47	53	45	32	41	132	56	77	63	32	28	21	95	16	19	47
10	28	71	55	55	54	22	55	95	72	53	55	36	20	18	76	8	10	53
15	30	77	58	45	44	39	46	86	56	90	59	35	24	22	77	18	6	50
20	30	55	48	37	39	37	34	82	60	65	65	38	14	27	82	19	11	74
25	23	40	42	47	41	24	47	56	50	59	57	37	9	30	88	8	10	67
30	24	49	54	44	34	23	48	93	60	70	53	40	11	18	44	16	17	69
35	26	48	50	48	45	39	40	85	62	62	61	27	12	23	76	19	21	55
40	25	46	50	48	40	18	29	79	45	73	59	23	12	28	98	16	15	62
45	33	47	49	47	50	16	49	83	48	77	63	33	17	30	69	13	14	65
50	26	65	51	56	51	25	56	88	52	72	56	25	20	28	63	15	13	62
55	22	44	40	58	42	31	49	60	48	50	45	21	16	35	67	20	12	66
60	20	50	42	55	51	35	42	75	50	69	57	35	13	28	65	12	10	57
TOTAL	**319**	**657**	**586**	**593**	**536**	**341**	**536**	**1,014**	**659**	**817**	**693**	**382**	**196**	**308**	**900**	**180**	**158**	**727**

Table 2: Duration of Green for the Intersection Approach

Intersection	Duration of Green (secs)
1	66
2	59
3	49
4	34
5	52
6	51
7	64
8	63
9	40
10	61
11	66
12	55
13	26
14	55
15	67
16	24
17	46
18	72

Table 3: Intersection Widths

Intersection	Intersection Width (ft)
1	92
2	90
3	121
4	130
5	143
6	103
7	90
8	100
9	113
10	85
11	68
12	102
13	118
14	122
15	68
16	72
17	70
18	66

Table 4: Lane Configuration for the Approaches

Intersection	Lane Configuration
1	2.5
2	3.5
3	4.0
4	2.5
5	3.0
6	3.0
7	2.5
8	4.0
9	3.0
10	4.0
11	5.0
12	2.5
13	2.0
14	1.5
15	4.5
16	1.5
17	1.5
18	3.5

Table 5: Posted Speed Limits for the Approaches

Intersection	Posted Speed Limit (mph)
1	25
2	30
3	25
4	30
5	25
6	25
7	30
8	25
9	25
10	25
11	30
12	25
13	25
14	25
15	15
16	15
17	25
18	25