MODELLING DRIVERS ABERRANT RESPONSIVENESS TO YELLOW INTERVAL: CASE STUDY OF DURBAN SIGNALIZED INTERSECTIONS

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ABSTRACT

The paper explored the extent of drivers' aberrant responsiveness to yellow intervals at signalized intersections in Durban, South Africa. A signalized intersection primary light pole located at the stop-line has three different kinds of lights; green, yellow and red. It's a given that red means stop, green means go and yellow means when you enter the intersection during the entire yellow interval, it is permitted to proceed and clear the intersection safely, however in a situation where you can neither enter nor be in the intersection on red, you must stop upon receiving the yellow interval. At the onset of yellow, action taken is at driver's discretion; probably explaining why drivers' aberrant responsiveness is prevalent at signalized intersections. In a stochastic study carried out at four selected signalized intersections in Durban, a binary logistic model was used to estimate the probability of red-light running given; speed at a distance from stop line (51m, 70m) and acceleration variables. The results showed that for both the distances; 51m and 70m, the probabilities of red-light running were quite low at low speeds and increased with increase in both speed and acceleration. In the 51m distance, the aberrant behaviour was observed on average in the last second of the 3 second yellow interval. In the 70m case however, the behaviour was observed in the first 1.5 seconds. The paper concluded that driver's aberrant responsiveness during yellow interval emanates from the absence of prescribed speed boundary information before the traffic stop lights.

Keywords: Red-light running, yellow time, permissive laws.

1. INTRODUCTION

Safety is one of the key considerations in any Engineering facility's design, and this includes roads. Despite this, road crashes have been a big challenge leading to substantial loss of life and warranting people to spend many resources. In South Africa, according to the state of road safety report released in 2018, the number of fatalities from road crashes decreased from 11 676 in 2016 to 11 437 in 2017 (TRMC, 2017). However, the national road crash statistics from the year 2000 to 2017 showed an upward trend. The status report also indicated the causes of the road crashes where more than 90% was attributed to human error, including 1.5% attributed to disregard of traffic lights. In one of the intersections sites used for this study, in 2018 alone, there were reported 149 incidents, including one fatality.

A signalized intersection primary light pole is located at the stop-line and has three different kinds of lights; green, yellow and red. Red and green signify a commanding message; red for stop and green for go. However, when the light is yellow, it is up to the driver's discretion to react. These drivers' uncertain reactions to yellow could lead to red-light violations (red-light running), right-angle crashes and even rear-end collisions in case of abrupt braking.

Some studies have argued that red-light violations result from poorly or improperly timed yellow period, which then manifests in a driver's predicament to stop abruptly or proceed to run the red light (Gazis et al., 1959). A study conducted in the United States showed that approximately 93 per cent of drivers believe that red-light running (RLR) is unacceptable if the driver can stop safely, and one-third admitted that they have run and still will run the red-light if they cannot stop safely (Jahangiri et al., 2016).

The problem of yellow lights persists since the late 1950s till today even though extensive studies have been done. Past studies have acknowledged a dilemma zone and solutions fronted on dealing with it, yet the problem persists. This paper investigated the problem from the engineering design aspect. Generally, in transportation planning, road marking and other traffic messages are used to provide drivers with information on what to expect as they travel through the network. Information about speed humps ahead, intersections ahead, speed limits and even camera enforced speed limits are provided to drivers while giving them the distance to react and demarcate where the action is to be taken. With the yellow interval at signalized intersections, the decision is left to driver discretion without adequate information, or when provided (in case of countdown timers), it still leaves too much to driver judgement. The rest of this paper is structured as follows: section 2 reviewed past literature on the topic, section 3 contains the methodology. Results and discussions are in section 4, followed by conclusions and recommendations in section 5.

2. LITERATURE REVIEW

In South Africa the law states that *when a vehicle enters the intersection during the entire yellow interval, it is permitted to proceed and clear the intersection safety, however in a situation where the vehicle can neither enter nor be in the intersection on red, it must stop upon receiving the yellow interval* (SARTSM 2012). The South Africa Road Traffic Signal Manual prescribes 3s yellow interval for speed ≤ 60km/h; at 70km/h 3.5s yellow interval and at 80km/h 4s yellow interval computed with these equations:

$$Yellow = t_y + \frac{1}{2}\left[\frac{v}{A_y + g.{}^{G}/_{100}}\right] \qquad (1)$$

$$All - red = t_r + \frac{1}{2}\left[\frac{v}{A_r + g.{}^{G}/_{100}}\right] + \frac{W}{v} - Yellow \qquad (2)$$

Where: t_y, t_r~Reaction time (0.75s for yellow, 1s for all-red); v ~posted speed

A_y, A_r - Deceleration rates (3.7m/s^2 for yellow, 3.0m/s^2 for all-red)
g - Gravitational acceleration constant
G - Gradient on approach to signal
W - Clearance width or intersection width

These equations are subject to reaction time and deceleration rate variations. Reaction time for drivers varies between 0.75s and 3s as contained in many studies, whilst the deceleration rate is between 0m/s^2 to 1m/s^2 using extreme values. These variabilities would call to question the reliability of prescribed yellow interval times in SARTSM 2012. It’s worth noting that Koonce (2008) in the calculation of yellow time used a perception reaction time of 1.0 seconds and a deceleration of 3.0m/s^2. According to Williams and

Retting (1996) a comfortable deceleration rate of one third (1/3) of gravitational acceleration ($3.27 m/s^2$) was recommended. Highway Capacity Manual-HCM (2016) recommends 2s driver reaction time whilst TRL (2008) suggested reaction time between 0.85s and 1.2s reaction times. Some accident reconstruction specialists use 1.5s. A controlled study in 2000 (IEA2000) found 2.3s to be an average driver reaction brake time.

Reaction time can be computed from the relationship between reaction distance and vehicle speed, thus suggesting the emphasis should be placed on reaction distance and vehicle speed whilst reaction time becomes a mere function. Deceleration is a function of road pavement friction relative to gravitational force. Since friction values vary from 0 to 1, then deceleration will vary from 0 to $9.8 m/s^2$ suggesting that given a good road pavement with friction of 0.5 under dry weather and clear visibility conditions, the computed deceleration rate is $4.9 m/s^2$. Therefore it is correct to assume that the deceleration rates presented in equations 1 and 2 operate under poor pavement friction conditions. When drivers are keenly alerted often in case where traffic activities are very intense, reaction time may vary from 0.5-1.0s, however the general reaction time is around 1-3s. If the driver's reaction time varies from 1s to 3s, an average of 2s often used by AASHTO (2018), under dry weather and clear visibility conditions Overseas Road Note 6 (1988) is acceptable. It clear from previous studies that the exact values of reaction time are generally difficult to determine mainly because of the impossibility of knowing exactly the start time of reaction.

Traffic signals are man-made systems subject to flaws, misinterpretation, and mismanagement. The South African Road Traffic Signal Manual-SARTSM (2012) defines traffic signals as "*one of the most common and widely accepted forms of traffic control and affect the daily lives of virtually all road users. Traffic signals can be very effective in improving traffic flow and facilitating access".* However, traffic signals can also pose significant danger to road users when installed and timed inappropriately. When drivers are confronted by a poorly timed yellow signal light, they are faced with a predicament of stopping safely when too close to the stop line or proceeding straight when far from the stop line. As defined in SARTSM (2012), the most noted minimum requirements to appropriate installation of traffic signals are: (a) *Speed limit – the approach speed at signalised intersections must not exceed 80km/h*; (b) *Visibility requirements – traffic signal faces must be clearly visible as drivers approach the traffic signal.* What is missing in the installation requirements is communication of these basic requirements to drivers approaching the signalised intersection. This is what the study intend to assess.

Yellow and all red intervals provide safety between the servicing of different phases (Kyte & Tribelhorn, 2014). The duration of the intervals must be long enough so that a driver on the intersection approach is able to; safely come to a stop or clear the intersection before conflicting traffic begins to enter. According to previous studies (Li et al., 2016), a driver may find themselves in one of four points during this period. The points include a "cannot go" region, a "cannot stop" region, a "dilemma zone" and an "option zone". The concept of dilemma zone was first proposed by (Gazis et al., 1959) in what is referred to as the GHM model. Figure 1 below illustrates the location of the above dilemma zone dimensions for a typical four-legged intersection. In the dilemma zone, a driver can neither stop safely nor pass safely and as such the driver may decelerate or accelerate unsafely (beyond values already mentioned in equations 3 and 4). In the option zone, a driver either stops before the stop-line or clears the intersection safely during yellow. Problems arise when different drivers faced with the above conditions make conflicting decisions. This could cause rear end collisions or red light running all of which are unsafe for intersection usage.

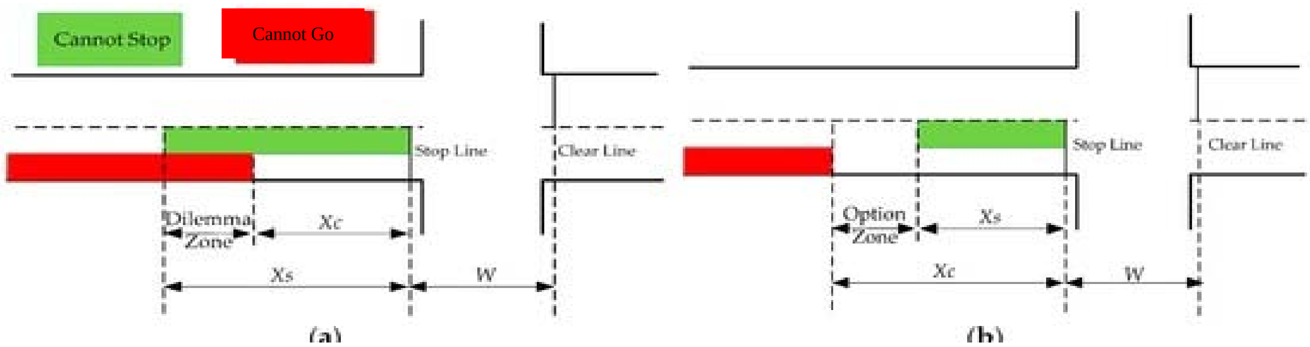

Figure 1: Typical dilemma zone and option zone

Just like reaction time and yellow intervals, there is no clear agreement on the dilemma zone and option zone definition and demarcation. Some studies have also defined dilemma zone as Type I and II. (Si et al., 2007) stated that the dilemma zone and option zone are fundamentally different. According to their study, the dilemma zone can be eliminated by appropriate yellow and red clearance times, however, the option zone always exists because of varied decisions made by drivers depending on approach speed. The research focus on these zones has been aimed at trying to understand the phenomenon of red light running especially the unintentional one. Though there is no clear agreement of definitions, what is agreed is that as a result of yellow interval, there is a zone on the intersection approach created and driver behaviour in that zone is partly what contributes to observed aberrant behaviour. One of the ways that dilemma zone has been dealt with over the years has been to determine appropriate values for both yellow time and all red clearance interval. (Jahangiri et al., 2016) Jahangiri et al. (2016) identified time to intersection, distance to intersection, speed at onset of yellow and vehicle acceleration as contributory factors to red light running (RLR). Other studies have also considered driver characteristics like age, gender, driver aggressiveness, cell phone use among others all in a bid to explain driver behavior during yellow and how that relates to red light violations. In a bid to solve these issues (Elmitiny et al., 2010) undertook a study using observational data in a form of videos and observed driver behavior at signalized intersection, the finding was that there was a positive relationship between vehicle speed and RLR. In a bid to reduce red-light running some measures have been undertaken. For example, law enforcement using cameras was shown to reduce RLR frequency (Martinez & Porter, 2006) and (Ko et al., 2017). It was then concluded that motorists were approximately 3.4 times more prone to RLR when cameras were removed as compared to cameras being present. However, the reduction of RLR by camera law enforcement resolved the issue of RLR but introduced occurrence of rear-end collisions (Shin & Washington, 2007).

It can be concluded that drivers are not aware of the existence of all these zones and therefore do not have adequate information to make safe decisions (Zhang et al., 2014). Also, these zones are quite dynamic depending on the model parameters. Measures like Count down timers (Zhaosheng et al., 2014) have also been found not to offer much relief because of driver competition and perception especially among risk averse drivers to judge the time left and attempt at all costs to cross the stop-line. This study looked at the problem from the aspect of decisions made by drivers from the zones induced by yellow time under the prevailing speed limit with a view to highlight the differing decisions made. This was made under the proposition that getting drivers to behave in a certain uniform way at the onset of yellow by clearing marking out boundaries on the intersection approach and providing necessary information may help reduce the red-light running behaviour and associated incidents.

3. METHODOLOGY

Traffic and individual vehicle data were collected on four-legged intersections in the city of Durban (eThekwini Municipality) and set up in four different site cases. The intersections were selected to meet the criteria: be within the eThekwini municipality in Durban, be four-legged with two or more lanes on the major road and have a clear and adequate safe stopping sight distance. Four sites were selected. The data collected was only for daytime and dry conditions. Data collection was done for three weeks considering weekday traffic. The speed limit for all selected sites was 60km/h and as such two points were chosen to collect data. The first point was 51m from the intersection stop-line, this was because with a speed of 60km/h (16.67m/s) with yellow interval time of 3s equal 51m as the distance covered during yellow time. The second distance considered a speed of 70km/h (60km/h +10km/h) and for this speed the South Africa manual notes that the yellow time should be 3.5s, this (70km/h= 19.44m/s x 3.5s) gave 68m approximated to 70m. For all sites the safe stopping site distance (SSD) calculated using a perception reaction time of 1s and deceleration of 3.7m/s^2 was 87.9m, the 70m point considered therefore also falls within the dilemma zone.

Traffic videos were used where traffic volume was obtained by observing and manually counting the vehicles. Individual vehicle data (speed, acceleration and time to intersection) was extracted using a traffic data extractor software. From the software, vehicle speed was extracted at the 51m,70m as well as stop-line for those involved in RLR. The software also recorded time when the vehicle passed the designated points, and this was used to obtain the acceleration and deceleration values. Intersection geometry data was obtained through field data collection and Google Earth. Traffic signal information (cycle length and yellow time) was obtained from the eThekwini transport authority and confirmed through observation and timing on the videos. From initial data and analysis on all selected sites, vehicle composition showed above 90% personal cars and a decision was thus made to concentrate on those and as such vehicle type was not included in model estimations. The data extracted was then used to estimate a logistic regression model for each of the site. The choice to fit the logistic curve was because, the outcome is more probabilistic than deterministic, and this better fit the red-light running phenomenon. The probability may be defined in equation (3) or (4) by (Gates, et al., 2007) and (Li, 2011): Expressed as;

$$P_i = \frac{1}{1+e^{-Z_i}} \tag{3}$$

Where Z is the utility function, it can be computed with;

$$Z_i = \alpha + \beta X_{i+\dots\dots}\beta X_{n\dots} \tag{4}$$

where P_i is the RLR probability for the ith driver choosing RLR; Z_i is the utility function that is a summation of intercept coefficient (α) plus vectors of factors considered; β is the coefficient of each vector parameter considered; and X_i is the vector of independent variables (speed and acceleration) considered.

4. RESULTS AND DISCUSSIONS

A step by step approach was used to analyze the data and obtain results. The data obtained was speed at the two points; 70m and 51m as well as at the stop-line and along with acceleration/deceleration. Driver action in form of 1 for red-light running and 0 for those that stopped was also recorded. The data obtained was then used to estimate binary logit model for all the sites and for the two points per site. The utility model equations are presented in Table 1.

Table 1: Model equations for all sites at 51m and 70m

Site	Model Equation- 51m	R^2	Model equation -70m	R^2
1	Z_{151}= -15.373+0.962v+0.2935α	0.74	Z_{170}= -13.407+1.646v+14.624α	0.74
2	Z_{251}= -36.714+2.732v+10.610α	0.58	Z_{270}= -29.546+3.274v+18.544α	0.74
3	Z_{351}= -2.142+0.1621v+1.543α	0.67	Z_{370}= -11.185+0.953v+4.457α	0.71
4	Z_{451}= -40. 461+3.157v+23.540α	0.74	Z_{470}= -10.097+0.813+2.327α	0.72

Where the subscripts *i* represents the site number, *x* the distance from the stop-line, *v* the speed at the designated distance and *α* is deceleration. *β* represents the coefficient of each vector parameter considered. Note that R^2 values for all model equations are above the 0.5 mark, indicating the parameters used fit the model estimated. Further analysis with the model equations for better interpretation of the results was done by plotting out the results on graphs.

4.1 The 51m Distance

Results of the probability of red-light running versus speed where the acceleration/ deceleration was assumed to be constant are presented below in Figure 2. At the 51m point, at lower speeds like 12.5m/s the probability of red-light running is low and this increases as speed increases. The increase follows a similar trend for all the sites considered. It should be noted that the cases were observed over the 3s yellow interval. The time elapsing between the start of the yellow interval and the actual time the vehicle passed the 51m distance was also recorded. For site 1 for example the average speed for vehicles that were involved in red-light violations was 19.19m/s, the average acceleration was 2.7m/s^2 and the time from onset of yellow was about 1.76s. For those that stopped, time elapsed was 2.04s. This helps to explain why at high speeds the probability of red-light running was still high. For site 3 the average speed for those involved in red-light running was 18.87m/s and the average acceleration was 2.74m/s2 and time elapsed from yellow onset about 1.12s, while those that stopped about 2.12s. These differences in average speed, acceleration and time from onset of yellow when vehicles pass the marked point could be the reason there is some difference in the observed behaviour indicated by the graph.

To put the results into further perspective, a 3D plot was done to incorporate the acceleration and speed into the probabilities of red light running and the results are represented below in the Figure 3. These highlight the differences between the sites as noted above. It is also worth noting that site 1 and 2 have a cycle time of 120s while site 3 and site 4 have 100s, which adds further to the difference in observed behaviour.

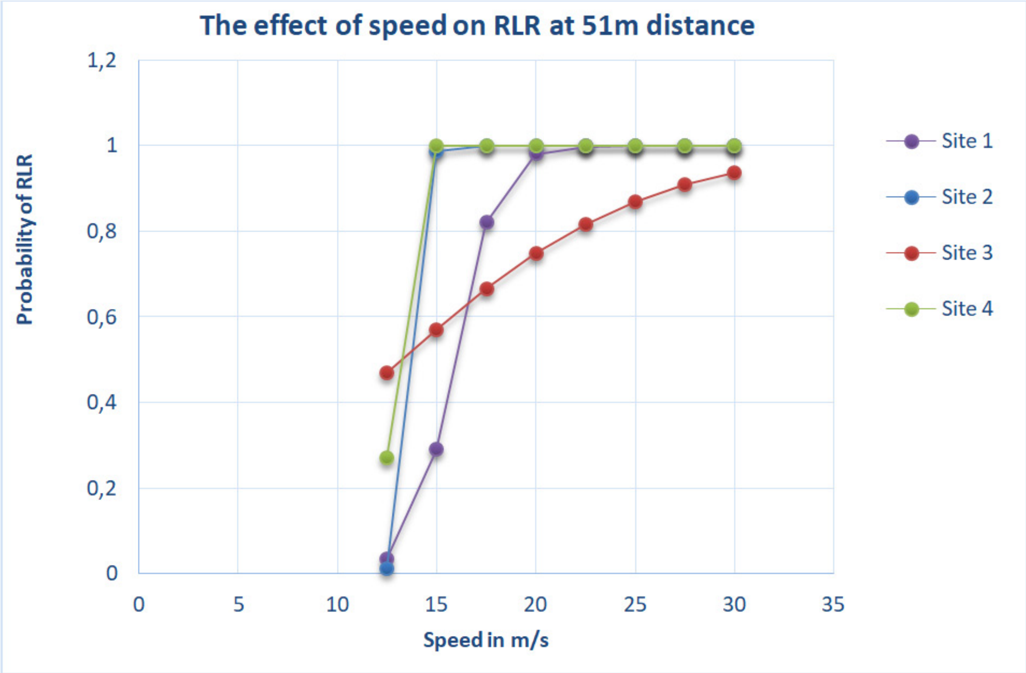

Figure 2: Effect of Speed on RLR at 51m distance for all sites

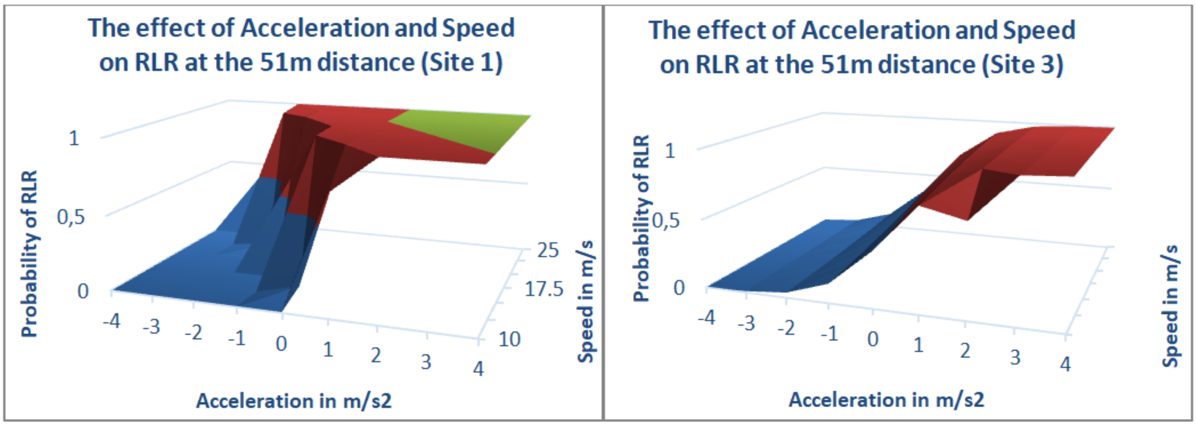

Figure 3: Effect of Acceleration and speed on RLR at 51m distance

4.2 The 70m Distance

The same analysis done for the 51m distance was repeated at the 70m distance. For the graph of red-light running at different speeds given zero acceleration the results are presented in the graph below. As compared to the 51m point, at this distance the probabilities are all above 0.5 even at lower speeds because its further away from the stop-line. Sites 1 and 2 are closely related as are sites 3 and 4. The differences as was the case for the 51m distance are attributed to the differences in driver behaviour observed. For site 1; the average speed for red light running vehicles was 15.83m/s, acceleration 1.75m/s^2 and for those stopping -2.38m/s^2. The time elapsing from start of yellow for the red-light violating vehicles was 0.63s and for those that stopped was 1.54s.

For site 3, average speed for red-light violations was 16.71m/s and an acceleration of 1.40m/s^2 while for stopping average acceleration was -2.42m/s^2. The average time from the start of yellow for red-light violations was 1.23s and that for stopping was 1.65s. As compared to the 51m distance, at this point the driver behaviour was observed within the first 1.5s of the yellow time.

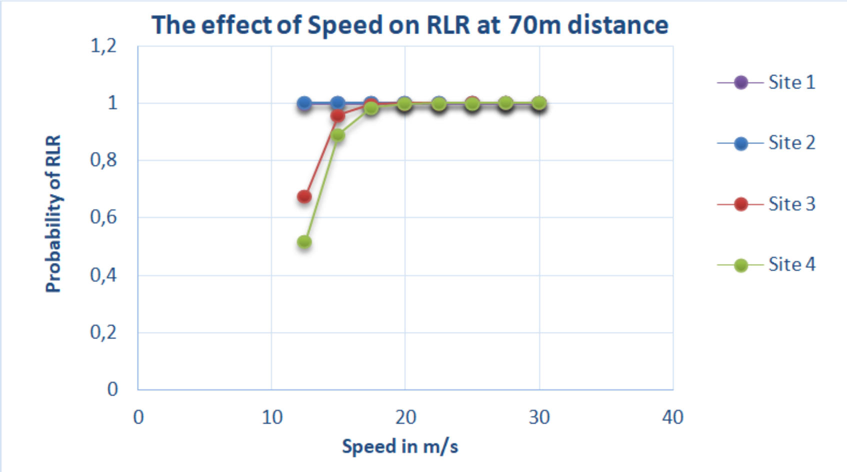

Figure 4: Effect of speed on RLR at 70m distance

On average it can be noted the average speeds at this point are lower compared to the 51m point. This could be attributed to the fact that at 70m may be around the point the decision to either accelerate to pass or decelerate to stop is made and as such by the time they get to 51m the speed is already higher on average. Secondly the time elapsing from start of yellow when the decisions are made is also lower in this case. For those who go on to violate the red light, they pass the point within the first second (0.63s, 1.23s), the decision to stop was also on average made before elapse of 2 seconds from onset of yellow. The 3D plot for this also helps to further highlight the slight difference between the sites.

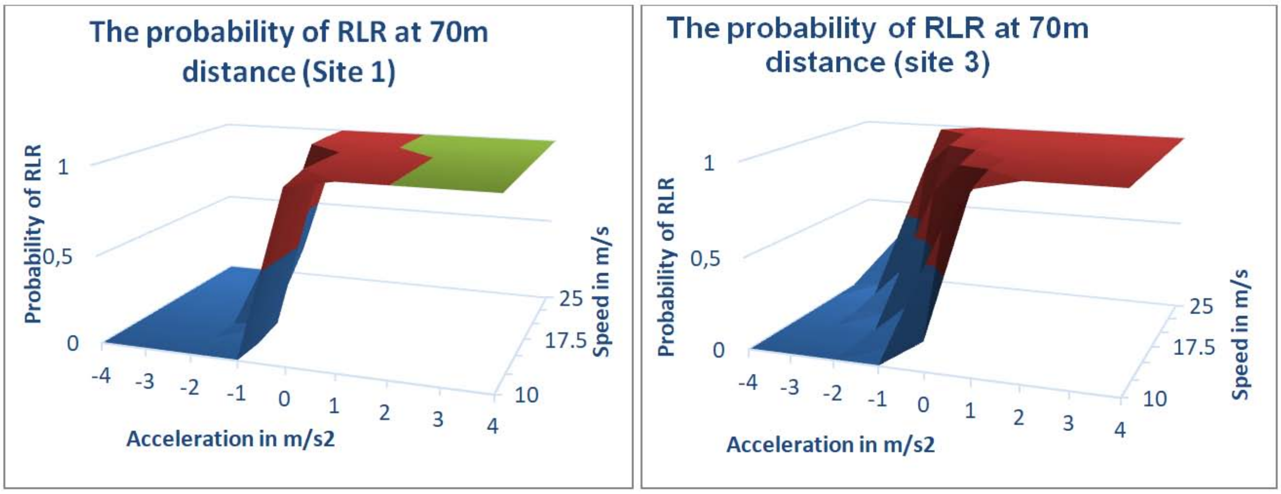

Figure 5: Effect of speed and acceleration on probability of RLR at 70m distance

From all the above presented results, right from the onset of the yellow time, depending on where the driver is positioned, different decisions are made, and it is these decisions that lead to the cases of red-light violations that were noted here. It was also noted that there was quite a variation in the recorded speed, most being above the speed limit of the sites (60km/h/16.67m/s). Further it can be concluded from the above that the decision to either stop or attempt to go through the stop-line was made upstream of the intersection stop-line. In all the cases however it can be noted that the safest decision to be made would been to slow down and stop.

Past literature quoted in section 2 mentioned some of the mitigation measures that have worked to reduce red-light violations red camera enforcement was among them. But this enforcement works best for those who blatantly violate red light. For those who are caught in dilemma and other zones who are involved in unintentional red-light running this may not work as it is neither a possible nor safe. If, however this enforcement could be provided upstream in form of a camera enforced speed limit with clear boundary demarcation, it may help to guide drivers during the yellow interval. The yellow interval would still mean warning and give discretion to the driver to choose action but by enforcing a speed limit in a clearly demarcated way the drivers would be limited in their action to only one decision; to observe the posted speed. If the posted speed therefore is a lower speed limit (for yellow interval) then the drivers would most likely drive slower and stop in time.

5. CONCLUSION AND RECOMMENDATIONS

At both 51m and 70m point from the intersection stop-line, driver decisions made after the onset of yellow interval lead to aberrant driver behaviour. The decision made depends on driver speed and distance and could lead the driver to accelerate or decelerate. In most observed cases, acceleration led to red light violation while deceleration led to safely stopping. The paper concluded that driver's aberrant responsiveness emanates from the absence of prescribed speed boundary information before the traffic stop lights. For further research, there is a need to carry out tests both in simulation and real world by implementing the speed camera enforcement with clear marking on intersection approach zone to determine its effect on actual driver behaviour

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