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Innovative countermeasures for red light running prevention at signalized intersections: a driving simulator study

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ABSTRACT

The change interval, which includes the yellow and all-red times, plays a crucial role in the safety and operation of signalized intersections. During this interval, drivers not only need to decide to stop or go but also have to interact with drivers both in front and behind, trying to avoid conflicting decisions. Red light running and inconsistent stopping behavior may increase the risk for angular and rear-end crashes. This study aims to investigate the effect of different innovative countermeasures on red light running prevention and safe stopping behavior at signalized intersections. Five different conditions were tested inviting sixty-seven volunteers with a valid driving license. The conditions include a default traffic signal setting (control condition), flashing green signal setting (F-green), red LED ground lights integrated with a traffic signal (R-LED), yellow interval countdown variable message sign (C-VMS), and red light running detection camera warning gantry (RW-gantry). Drivers in each condition were exposed to two different situations based on the distance from the stop line. In the first situation, drivers were located in the indecision zone while in the second situation they were located in the likely stopping zone. A series of logistic regression analyses and linear mixed models were conducted to investigate the overall safety effects of the different countermeasures. The probability of red light running (RLR) was significantly reduced for R-LED in both analyses (i.e. in the total sample, and in the sample of crossed vehicles). Moreover, a clearly inconsistent stopping behavior was observed for the flashing green condition. Furthermore, a unit increase in speed (kph) at the onset of yellow interval significantly increases the probability of RLR by 5.3%.

The study showed that R-LED was the most effective solution for improving red light running prevention and encouraging a consistent stopping behavior at the intersection. In conclusion, the R-LED and the RW-gantry treatments are recommended as effective tools to improve safety at signalized intersections.

KEY WORDS: red light running; signalized intersection; dynamic ground lights; countdown signal; dilemma zone; variable message sign

1. INTRODUCTION

Signalized intersections are one of the most hazardous locations in road networks, accounting for a substantial proportion of fatalities and injuries due to traffic crashes (Huang et al., 2014; PIARC, 2003). According to research conducted by the University of California, 2.5 million crashes occurred at road intersections in 2004 in the United States, and 20% of these intersection crashes were identified as signal-related (Chang et al., 2007). Red light running (RLR), tailgating and inappropriate stopping at intersections could be the main reasons behind signal-related crashes. Devlin et al. (2011) reported that 20% of the serious injuries at signalized intersections in West Australia were related to rear-end crashes during 2004-2009. In 2013, RLR accounted for 697 fatalities and 127,000 injuries in the United States (McCarthy, 2015). Even though, red light running detection camera (RLC) is installed at the majority of signalized intersections in Qatar, a total of 23,152 vehicles in 2016, 26,771 in 2017 and 28,945 in 2018 were caught jumping red lights, with drivers incurring a penalty of QAR 6,000 (Ministry of Development Planning and Statistics, 2017). According to a survey based on a self-report assessment of risky driving behavior in the state of Qatar, 3% of the drivers reported that it is completely acceptable to drive through a traffic signal light that just turned red, while 4% oppose to the implementation of RLR cameras (Timmermans et al., 2019). Since RLR could lead to severe crashes, there is a need to introduce innovative countermeasures to help improving safety at intersections.

Yellow interval plays a crucial role in the safety and operation of signalized intersections. More than half of the total number of crashes at signalized intersections occur due to the yellow interval (Yang et al., 2014). Drivers usually find it difficult to make decisions at the onset of the yellow interval at signalized intersections. Decisions to stop or cross an intersection typically have to be taken quickly at the onset of yellow interval, and are subject to various physical (e.g. distance to the stop line), psychological (e.g., attention allocation, signal comprehension, etc.) and behavioral (e.g. current speed) conditions. Several reasons could explain why drivers decide to cross a red light, such as distraction at the onset of yellow interval (Li et al, 2014; Zhang et al., 2018), biased estimations of distance, time, and speed, aggressive

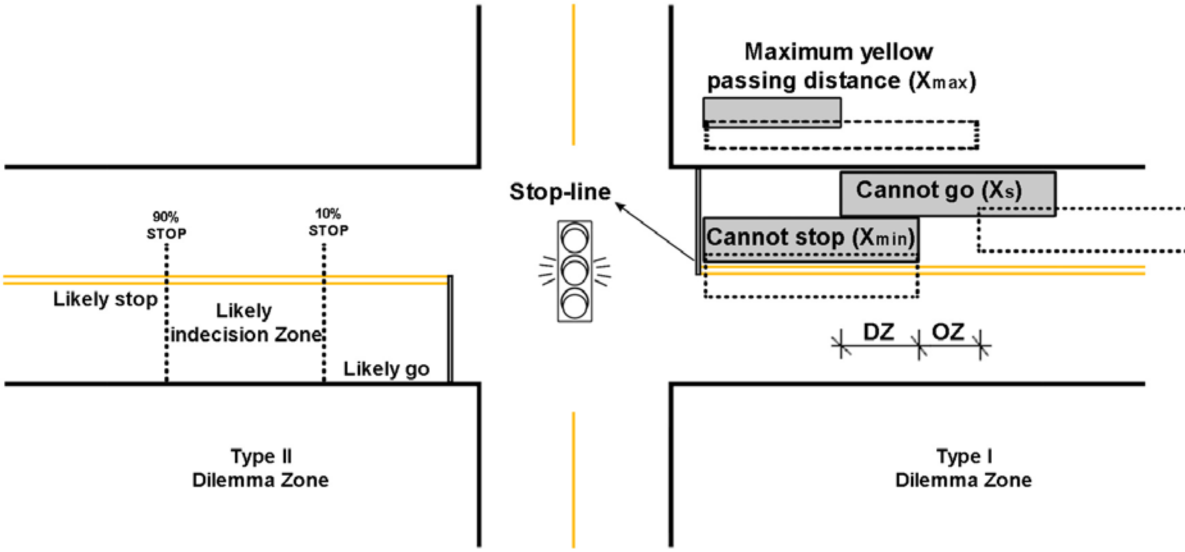


Figure 1. Illustration of the Type I and Type II Dilemma Zones

driving (Zhang et al., 2014) and alcohol impairment (Zhang et al., 2018). Drivers also have to interact with other drivers both in front and behind, trying to avoid conflicting decisions. Inconsistent stopping behavior may increase the risk for rear-end collisions, for instance, in case a front driver unnecessarily stops while still able to proceed and cross the intersection. Furthermore, improper signal design or operation may also promote RLR (Yang et al., 2014). The multitude of potential causative factors explain why RLR and unsafe stopping are considered as difficult to predict and why it remains a complex problem to be solved (FHWA, 2014). Therefore, it is important to study driving behavior such as inconsistent stopping and red light running in sufficient details to improve safety at signalized intersections.

Sackman et al. (1977) identified two types of dilemma situations based on the vehicle position at the onset of yellow interval (see Figure 1). The first dilemma situation (type I) was developed back in the 1960s (Gazis et al., 1960). This situation is based on the maximum distance that can be traveled during the yellow interval (Xmax), and the minimum stopping distance (Xmin). When Xmax is smaller than Xmin, a dilemma zone (DZ) is formed, where drivers positioned in DZ at the onset of the yellow interval can neither stop safely, nor clear the intersection comfortably during the yellow interval. This can be considered as an indication of poor signal design (Gazis et al., 1960; Yang et al., 2014). Alternatively, when Xmax is greater than Xmin, an option zone (OZ) forms, where drivers could either stop or clear the intersection comfortably. Using kinematic equations, Xmin and Xmax are defined in equations 1 & 2, respectively (Gazis et al., 1960).

$$X_{min} = V_o(\delta_1) + \frac{V_o^2}{2a_1} \qquad (1)$$

$$X_{max} = V_o(t_y) + \frac{a_2(t_y - \delta_2)^2}{2} - L \qquad (2)$$

In these equations, V_o is the vehicle's speed (m/s); a1 and a2 are the maximum deceleration and acceleration rates (m/s2) for stopping and crossing, respectively; δ1and δ2 are the driver's perception-reaction time (s) for stopping and crossing, respectively; ty is the duration (s) of yellow interval; L is the length (m) of the vehicle. The equations indicate that the perimeters of a dilemma zone are not only depending on vehicle traveling speeds and yellow interval times, but also depend on acceleration and deceleration (ACC/DEC) rates and drivers' reaction times.

Due to the behavioral differences among drivers, it is not appropriate to use a standardized dilemma zone as indicated by the type I dilemma situation. Therefore, it could better be positioned between flexible boundaries (Chang et al., 2013) as specified in the type II dilemma situation introduced by Parsonson (1974). The type II dilemma situation defines the approach area where 10% to 90% of drivers decide to stop during the yellow interval (i.e. likely indecision zone), as shown in Figure 1 (Zegeer & Deen, 1978). In this study, we used the concept of dilemma type II to identify the positions of drivers with respect to the stop line for two situations. The first situation focuses on the common 80% of drivers who are driving in the indecision zone, referring to drivers who could make wrong decisions of crossing the intersections and consequently get red light tickets. Drivers in the first situation are also likely to face conflicting decisions with fellow drivers, which can increase the risk of rear-end collisions. The second situation focuses on the rare 10% of aggressive drivers, referring to drivers who decide to cross the intersection from likely stop zone while they were supposed to stop, which can increase the likelihood of running a red light.

2. STUDY OBJECTIVES

The aim of this driving simulator study is to investigate the impact of innovative countermeasures on driving behavior at signalized intersections. To this end, five conditions were compared to measure their effectiveness on RLR prevention and promotion of safe stopping at signalized intersections. The five countermeasures include a default signal setting (control condition) and four treated conditions. Two of the four treated conditions are based on advanced warning: a condition with 3 seconds advance warning by flashing green; and a condition with animation-based variable message sign fixed on a gantry about red light running camera detection warning (RW-gantry). The two other treated conditions are based on innovative countdown systems for yellow interval i.e. red LED ground lights integrated with a traffic signal (R-LED) and yellow interval countdown variable message sign (C-VMS). To the best of our knowledge, the approach of using red light units on the ground (R-LED), the countdown clock (C-VMS), and the RLC warning gantry (RW-gantry) have never been tested in the past.

The first objective of this study is to analyze which of the tested conditions have a positive impact on RLR prevention. The second objective is to investigate if the tested conditions reduce variations among drivers' speed and ACC/DEC maneuvers.

3. LITERATURE REVIEW

3.1 Driving simulator studies

Previous research have proven that driving simulators are effective in the evaluation of human factors on road safety (Fisher et al., 2011; Hussain et al., 2019a; Llopis-Castelló et al., 2016). For instance, driving behavior in response to the road safety hazards can be studied in a safe environment using driving simulator to eliminate the risks of testing in real-world scenarios (Ariën et al., 2013; Daniels et al., 2010; Nilsson, 1993).

More specifically related to the topic under study here, Newton et al. (1997) studied the efficacy of a proposed signal indication with a sequence of green, followed by flashing yellow in conjunction with green, followed by steady yellow, and then red. The proposed signal indication sequence was compared with the most commonly used signal indication sequence i.e. green-yellow-red. Forty-one subjects (23 female) participated in their driving simulator study ranging in age from 15-58 years. Although the authors observed a substantial reduction in red light violations (RLVs), the new signal indication sequence prolonged the indecision zone and increased potential conflicting decisions between vehicles approaching an intersection at the same time. Therefore, the authors concluded that the proposed signal indication sequence would not improve the safety at intersections. Similar conclusions were drawn in another simulator study investigating the impact of advance warning flasher (AWFs) strategies on driving behavior at signalized intersections (Smith & Harney, 2001). The authors concluded that AWFs often motivate stopping at the intersections, but at the same time prolonged the indecision zone and resulted in a higher probability of risky decisions such as unnecessary or early stooping.

Another study examined an in-vehicle stopping decision advisory system in a driving simulator in a sample of 20 participants (Bar-Gera et al., 2013). The system provided an auditory and visual indication on odometer with blinking red light indicator to warn drivers for the upcoming red light phase. The system was designed taking into account the distance to the traffic light and remaining time of the green phase. The in-vehicle advisory system reduced RLVs by 96% and the range of the indecision zone was shortened by 70%.

Abbas et al. (2014) devolved an Adaptive Randomized Incomplete Block Split-plot (ARIBS) design to investigate drivers' behavior and factors influencing drivers' decision at the start of yellow interval in a driving simulator research. Results from their study showed that the adaptive process of the design allows the examination of drivers' stop or go decisions prediction mechanism with an accuracy of about 97.3%.

3.2 Field observation studies

The design of traffic signal timing can play an important role in improving safety at signalized intersections. Several studies have analyzed the effect of lengthening the yellow interval on RLR. A cross-sectional study on signalized intersections in three cities found that RLR occurrences were lower at the intersections where yellow interval was longer (Bonneson & Son, 2003). Another study on four urban intersections and two rural intersections found changes in RLVs one year after the yellow signal interval was increased by 1 second, demonstrating a reduction of almost 50% in RLVs (Bonneson & Zimmerman, 2004). Retting et al. (2008) assessed RLV based on data collected before and after the yellow signal interval was increased by approximately one second at several intersections. Based on logit models, they found that RLVs reduced by 36% when the duration of the yellow interval was increased.

Polanis (2002) evaluated the impact of size of the signal heads in a before-after study, where the signal heads of 8" were replaced with 12" signal heads. The results showed an aggregate reduction of 49% in right angle crashes at the intersections where the signal heads were upgraded.

Mahalel & Zaidel (1985) examined the indecision zone for warning of a three-second flashing green just prior to the yellow interval. The authors concluded that although flashing green increases the probability of stopping at intersections, it increases the length of the indecision zone and thereby the probability of rear-end collisions as well.

Another study investigated the efficacy of a green signal countdown device (GSCD) in an observational field study in Shanghai at two intersections (Ma et al., 2010). The authors reported a significant decrease in RLVs with higher average traffic flow speeds at the intersection with GSCD installed, as compared to the intersection without GSCD. The effectiveness of countdown timers on red light running has also been evaluated in several other studies where potential decrease in RLVs was reported (Chiou & Chang, 2010; Kidwai et al., 2005; Limanond et al., 2010; Lum & Halim, 2006; Rijavec et al., 2013).

Tydlacka et al. (2011) investigated the effectiveness of lighted stop bar system (LSBS) installed parallel to the intersection stop line for three intersections in Houston, Texas. The LSBS containing red LED light units was operated in a steady burn mode during the red interval while it was deactivated during the yellow and green intervals. Results from the study showed a statistically significant reduction in RLR for two of the three intersections. However, results from before-and-after study with a comparison site (non-treated) did not show any notable change in the number of RLR violations. According to the authors, the LED light units and connection wiring performed well under adverse weather conditions and in case of any failure of an individual LED light unit, it could easily and quickly be replaced.

Numerous studies have investigated the impact of red light running detection cameras (RLCs) on road crashes and frequency of RLVs at signalized intersections. A positive impact of RLCs on overall crashes, and injury crashes has been reported (Aeron-Thomas & Hess, 2005; Retting & Kyrychenko, 2002). Hu et al. (2011) estimated the effect of RLC enforcement on fatal crash rates. The study results showed that fatal crashes significantly reduced by 35% after the installation of RLCs at the intersections. Additionally, several studies evaluated the effectiveness of RLCs in reducing RLVs.

Polders et al. (2015) investigated the effect of integrated speed and red light cameras (SRLC) on the occurrence of RLR and the risk of rear-end collisions, observing driving behavior in the real-world in combination with a driving simulator study. Based on the observational field study, the authors reported a reduction in crossing instances during red and yellow intervals after the installation of SRLC, with a decrease in time headway. Furthermore, observations in the driving simulator study revealed that odds of rear-end collisions increased by 6.42 times for the condition with SRLC, compared to the intersections without SRLC. However, the odds of rear-end collisions increased only 4.01 times when an SRLC with an additional static roadside posted sign was installed providing drivers with a warning about the RLC at the intersection. Literature shows the importance of advance warning information, indicating it could motivate drivers to reduce their speeds in advance, resulting in substantial reductions of RLR (Ahmed & Abdel-Aty, 2015; McCartt & Hu, 2014; Retting et al., 2008).

Gates et al. (2014) compared drivers' reaction and stopping behavior with and without the presence of RLC. They found that drivers tended to react 5% (0.05 s) quicker to a yellow light change in the presence of RLC. Moreover, at RLC intersections, the likelihood of a driver stopping increased by 2.4% in their study.

Besides the observational studies, researcher also presented V2I (Xie & Wang, 2018) and I2V (Grembek et al., 2019) models based on the smart in-vehicle support systems to help drivers in making appropriate decisions in the indecision zones at signalized intersections. However, the effectiveness of these systems is not evaluated in the observational studies.

As indicated in the literature review, numerical countdown systems were tested for yellow and green intervals in the past, however, this study provides new insights on yellow interval countdown by introducing innovative treatments (C-VMS and R-LED). C-VMS counts down the yellow interval by graphic circular clock while R-LED counts down the yellow interval by means of intelligent LED light units on the road surface. Furthermore, the animation-based VMS displaying warning about RLC has never been tested in previous research. The paper also address the effectiveness of flashing green in the State of Qatar, where the driver population is very heterogeneous with many different cultural backgrounds (Soliman et al., 2018; Timmermans et al., 2019). The implementation of 3 seconds flashing green interval before the onset of yellow interval, as commonly applied at signalized intersections in the state of Qatar, is expected to increase the probability of inconsistent decisions by drivers such as early and unnecessary stopping which may lead to rear end collisions and reduction in the efficiency of signal control. In short, this study initiates the assessment of the three new innovative countermeasures and tests their impact on RLR prevention and promotion of safe stopping.

4. METHODS

4.1 Driving simulator

The driving simulator at Qatar University from the Qatar Transportation and Traffic Safety Center was utilized to perform the experiment. The driving simulator has been validated for the external (i.e. actual speed & speed perception) and subjective validity (Hussain et al., 2019a). The driving unit and three large screens with geometric field of view of 135 degrees (5760 x 1080 pixels; 60 hertz refresh rate) are the primary elements of the driving simulator (see Figure 2). The fixed-base cockpit was equipped with force-feedback steering wheel with indicators, automatic gearbox, speedometer, and pedals resembling an authentic Range Rover Evoque. The components are interfaced with STISIM Drive® 3 software and the CalPot32 program. The integrated system offers high-speed graphics and sound processing. The simulator

Figure 2. Driving simulator: Qatar Transportation and Traffic Safety Centre, Qatar University.

is capable of collecting a wide range of data including speed, lateral/longitudinal acceleration, lateral/longitudinal position, number of accidents, number of red light tickets, number of speeding tickets, pedal inputs, reaction time, etc.

4.2 Participants

Sixty-seven volunteers were invited to participate in the driving experiment on the basis of a valid Qatari driving license type B (allows to drive all types of passenger cars). Sixty-two participants were driving cars with automatic transmission while five were driving manual transmission cars. The subjects included Qatar University community (students, faculty and staff) and drivers from outside the university (including some taxi drivers). With respect to the minimum requirements of the standard simulation sickness questionnaire (Kennedy et al., 1993), the drivers were told on forehand not to eat or drink (except water) two hours before the experiment. Despite the provided instructions, three participants were affected by simulation sickness and excluded from the results. Moreover, two participants were considered as outliers, resulting in a total study sample of 62 drivers. Descriptive statistics represent 47 male and 15 female drivers from 20 different countries of whom 30 Arabic and 32 non-Arabic drivers. The mean age was 28.93 years (SD: 7.3 years) ranging from 19 to 58 years, and the mean driving experience was 8.61 years, ranging from 1 to 30 years driving experience with a SD of 6.3 years. Furthermore, the proportion of participants' groups who drove less than 10,000 km, 10,000 – 20,000 km, and more than 20,000 km per annum were 24.2%, 30.6%, and 45.2%, respectively.

4.3 Implementation of the indecision zone

In this study, each driver was confronted with two situations for all conditions on a road with a speed limit of 80 kph. At the onset of the yellow interval, the distance between the vehicle and stop line was 80 m and 95 m in the first (S1) and second (S2) situation, respectively. According to Webster & Ellson (1965) the boundaries of the indecision zone in type II dilemma zone are set at 56 m and 91 m prior to the stopping line on a road with a speed limit of 80 kph where the assumption is that 10% and 90% of the drivers are likely to stop, respectively. Therefore, in our study these situations were proposed aiming that S1 would be an indecision zone for a substantial number of drivers (inside the boundaries) while S2 will be only for a limited number of (more aggressive) drivers as it is situated prior to the outer boundary.

4.4 Virtual road environment

The experiment was designed as a 5x2 within-subject factorial design with as independent variables five conditions: control condition, flashing green (F-green), red LED ground lights (R-LED), countdown variable message sign (C-VMS) and red light camera warning gantry (RW-gantry), offered to participants in two situations (s1: indecision zone; and s2: likely stopping zone). This means that every participant was exposed to 10 study intersections, i.e. 5 conditions x 2 situations. The ten study intersections were randomly alternated with filler pieces to create variations in the simulated scenarios. The filler pieces included 12 dummy intersections, pedestrians crossing the road, and lane changing and harsh braking maneuvers by front vehicles. As all the study intersections were designed with changing signal phases, most of the dummy intersections had a green signal phase to reduce the probability of learning effects.

Two driving scenarios were designed replicating the road layout and surrounding environment of the north bound of the Corniche road in the city of Doha. In total, 11 intersections were incorporated in each driving scenario. The 22 intersections (12 dummy and 10 study intersections) appeared in randomized order in both driving scenarios. To maximize realism of the driving experience in the simulator (Bella, 2005, 2008), the road environment was replicated as naturalistic and detailed as possible with inclusion of exact geometrical alignment, cross-section furniture and roadside elements. To that end, we relied upon the real road environment based on Google Earth images and video footages. SketchUp Pro (version 18.0.16975) was used to design the roadside objects such as buildings, RLC, and streetlights. Furthermore, based on the real-world observations, vehicle composition replicated in the simulation environment was constituted of 47.8% sedan cars, 45.7% SUV, and 6.5% commercial vehicles (trucks, vans and buses).

4.5 Design of scenarios

The control condition was an untreated typical signalized intersection with the signal order of green-yellow-red. The yellow interval was set at 4 seconds in accordance with the Qatar Traffic Control Manual QTCM (Qatar Ministry of Transport and Communications MOTC, 2015). Important is that signal order in the control condition was also used in the treatment conditions, except in the F-green where signal order was changed into green-flashing green-yellow-red. The flashing green interval had a duration of 3 seconds with three instances of green light blinking (i.e., at a frequency of 2HZ) (Mahalel & Zaidel, 1985). As described in section 4.3, each condition was programmed for two situations with the distance to the stop line fixed in each situation. However, this distance to the stop line was increased by 66 m (3 seconds x 80 kph ≃ 66 m) in both situations in the F-green condition since it included the 3 seconds warning advance to the yellow interval. More precise details on the other three (treated) conditions follow below.

4.5.1 Red LED ground lights (R-LED)

In this condition, red LED ground lights were installed on the road surface, more specifically within pavement marking strips indicating lane division and edge lines (see Figure 3). Activation of these lights was aligned with functioning of the respective traffic light. Light units were operational during the yellow interval and turned to red one by one in a sequential order towards the intersection. The main objective of these moving light units is to provide direct and exact information to the drivers to stop if light units are activated in front of them. Figure 3 shows the simulation views for two hypothetical vehicles V_{S1} & V_{S2}, positioned at S1 and S2 at the onset of yellow interval, respectively. V_{S1} is pictured in an indecision zone (i.e. Situation 1) where there still is opportunity to lead and stay in front of the LED lights and where safely crossing the intersection remains possible without a harsh acceleration being necessary. On the other hand,

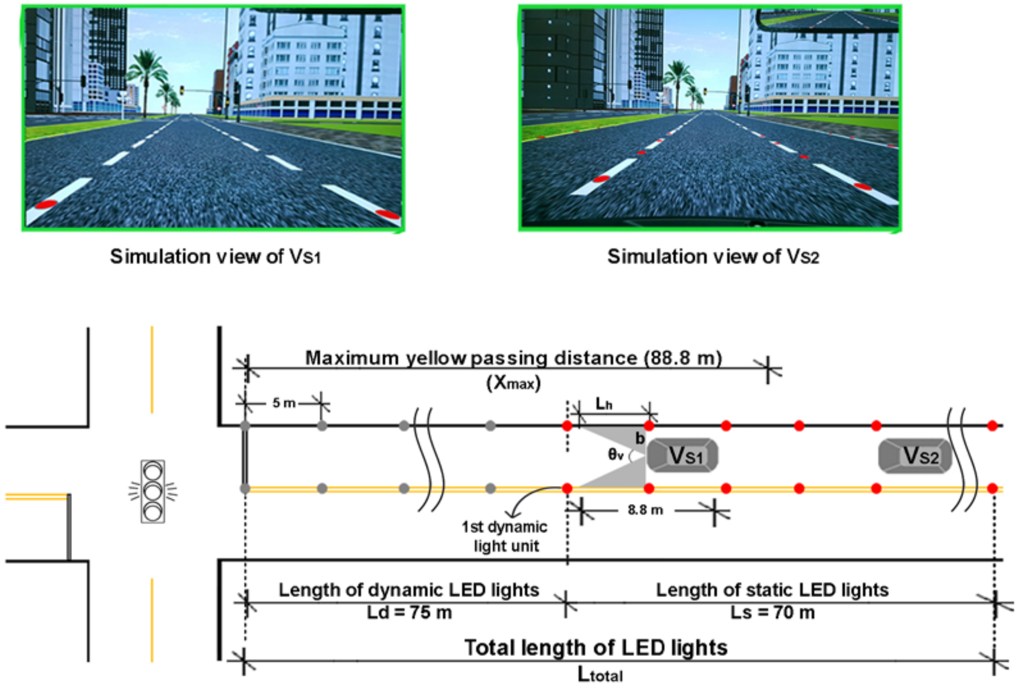


Figure 3. Red LED dynamic ground lights

V_{S2} is positioned in the stopping zone (i.e. Situation 2), where it is not possible anymore to cross the stop line safely without harsh acceleration. The gray dots in Figure 3 represent the lights yet to flash.

The whole stretch of the LED lights was divided into two parts, i.e. static and dynamic. A series of static LED lights were located in the stopping zone, turned red instantly and simultaneously at the onset of yellow interval, and remained red until the signal phase changed to green. These static lights indicate the area in which drivers cannot proceed smoothly to cross the intersection and thus they should prepare to stop. Meanwhile, the dynamic lights were activated one by one approaching to the intersection from a certain distance starting at the start of the yellow interval and remained red until the signal phase changed to green. The stretch of static lights (L_s) can be of any appropriate length (i.e. stopping zone), where around 10% of drivers still decide to cross (Zegeer & Deen, 1978). In our study, we implemented a 70 m long stretch for static red LED lights aiming to prevent those 10% of aggressive drivers from making unsafe crossing decisions. In addition, the length of the stretch with dynamic lights should be calculated based on the maximum yellow passing distance (X_{max}) considering the length of the vehicle (L_v) and the invisible distance (L_h) due to the front body of the subject vehicle as shown in Figure 3. The last dynamic red LED shall reach to the stop line before the end of yellow interval allowing the subject vehicle to cross the distance $(\mathrm{L}_h + \mathrm{L}_v)$ safely. Therefore, length of the stretch with dynamic lights can be calculated based on the following equation:

$$\mathrm{L}_d = \mathrm{X}_{max} - (\mathrm{L}_h + \mathrm{L}_v) \qquad (3)$$

In this study, we assumed $(\mathrm{L}_h + \mathrm{L}_v) \approx 8.3$ m based on the average vehicle length (4 to 4.5 m) and 4 to 4.5 m of length hidden due to the front of the simulator car.

As the speed limit on the road was 80 kph, we calculated the speed of the dynamic LED lights as 75 kph. This was done with a reason that if any driver located closer to the moving light units decide to cross the intersection, he/she will have the opportunity to accelerate up to the speed limit and still cross the red LED lights safely. Accordingly, with a speed of 75 kph and 4 seconds of yellow interval, length of the stretch with dynamic lights can be estimated around 75 m [Ld=20.83 m/s x 4 s - (8.3 m)]. This means that with speed of 75 kph the red lights will reach the intersection in 3.6 seconds (75 m ÷ 20.83 m/s) allowing 0.4 second to the last driver to cover the 8.3 m distance before the yellow interval ends. The intensity of color, dimensions, and longitudinal spacing of the LED lights (i.e., 5 m) were adjusted based on suggestions given by traffic experts involved in the pilot study.

4.5.2 Countdown variable message sign (C-VMS)

As discussed in the literature, the effectiveness of different countdown systems has been tested in simulated environments as well as on the road. Most of those studies used numerical countdown to warn drivers of the upcoming phase change. However, a visual representation of the countdown can be advantageous over the numerical countdown approach, because hypothetically the remaining time interval can be perceived and processed easier with the visual representation. For that reason, we designed a variable message sign (VMS), visually displaying a circular clock that counts down (i.e. ‘ticks away’) the 4 seconds yellow interval (as shown in Figure 4a). The complete circle is green during the green interval, and turns first from green to yellow exactly at the onset of the yellow interval. Then, the bars in the countdown circle gradually change

a) Countdown VMS b) Red light camera warning gantry

Figure 4. Simulation view of two conditions

from yellow to red one by one during the yellow interval. The C-VMS contains a flashing camera pictogram in the middle to inform drivers of the presence of RLC at the intersection. The C-VMS is installed alongside the traffic lights.

4.5.3 Red light camera warning gantry (RW-gantry)

An animated RLC warning VMS was designed and displayed on a gantry in this scenario. This VMS was aimed at informing drivers about the presence of a RLC at the next intersection and was installed 150 m prior to the intersection (as shown in Figure 4b). The animated picture shows a moving radar that flashes in the presence of a moving car leaving the intersection. On the right side of the panel, a text message mentioning ‘camera ahead’ is displayed in both Arabic and English.

4.6 Procedure

After obtaining the Qatar University’s Institutional Review Board (QU-IRB) ethical approval, participants were recruited by putting up announcements on social web-portals with a link to the registration website (www.qatardrivingsimulator.com). Additional recruitment was done by sending official emails to the staff and students of Qatar University. The experimental session lasted for about one hour and was organized as follows:

1. Upon arrival to the simulation lab, each participant was asked to sign an informed consent form and to answer a pre-test questionnaire focusing on sociodemographic variables and driving experience.

2. To reduce bias due to a lack of knowledge, pictures of the countermeasures were presented to the participants prior to the driving experiment. Subsequently, participants were asked if they understood the functioning of the countermeasures. Additional information (about the functioning of the countermeasures only) was provided when they did not understand, especially in case of the innovative countermeasures. No information was shared about the study objectives or the purpose of applying the countermeasures.
3. After that, participants were given a practice drive to get familiar with the driving simulator. The drive consisted of an approximately 7 km long stretch of Doha Expressway. Drivers were instructed to stop abruptly a few times to develop a more accurate estimation of the minimum stopping distance.
4. Before starting the experimental drives, participants received the following instruction: "Drive as you would normally do, follow the traffic rules and continue driving until you are instructed to stop. You have right of choice to quit the experiment anytime and for any reason". Each participant undertook two test drives with a short break in between.
5. After completing the test drives, each participant was asked to answer a post-test questionnaire. The questionnaire included feedback/thoughts on the driving experience and on the driving simulator itself.

4.7 Data collection and analysis

Data was collected for several driving parameters using STISIM Drive® Software. The collected data included elapsed time (time passes from the beginning of the driving runs), longitudinal distance, longitudinal speed, total longitudinal ACC/DEC, deceleration due to brake, and occurrence of red light/speed violations. Data were collected for about one month of period with maximum six participants were tested per weekday.

Two types of models were used to evaluate the performance of each scenario. For analyzing RLR prevention logistic regression models were fitted, while for analyzing drivers' stopping behavior linear mixed models were used. In the logistic regression models, the extracted data were fitted to predict the probabilities of

RLR for each of the tested conditions. Logistic regression was opted since the dependent variable (RLR event) was dichotomous. To estimate the probability of RLR, red light runners were labelled as "0" while other vehicles were labelled as "1". The dependent variables considered for the regression analyses were of different types, i.e. categorical variables: situations (0=situation 1, 1=situation 2), conditions (0=Control, 1=F-green, 2=R-LED, 3=C-VMS, 4=RW-gantry), and ethnicity (0=Non-Arab, 1=Arab); and continuous variables: speed at the onset of yellow interval in kph, age in years, and experience in years.

For analyzing drivers' stopping behavior, repeated measures analysis of variance ANOVA is often applied to analyze speed and acceleration differences between tested conditions (Ariën et al., 2013; Calvi, 2018; Charlton et al., 2018; Hussain et al., 2018; Reinolsmann et al., 2019). However, in this study it was not appropriate to conduct repeated measures ANOVA tests, as for different conditions some of the drivers stopped at the intersection while other passed. According to Pinheiro and Bates (2000), linear mixed models can be used on unbalanced data where fixed effect factors and random effect factors are considered. Therefore, a series of linear mixed models for speed and acceleration/deceleration were conducted to analyze drivers' stopping behavior at intersections. For these models, data were extracted for a 500 m analysis section (300 m before and 200 m after the stop line). For the speed models, the analysis section was divided into 11 points with a constant 50 m spacing. Different from that, the analysis section was divided into 10 equal zones of 50 m, where SD of ACC/DEC in each 50 m zone were extracted. Standard deviations were estimated for ACC/DEC in each zone to evaluate the homogeneity of acceleration/deceleration pattern among drivers. The independent variables considered for these models include Situation (2), Condition (5), and Point (11) / Zone (10).

Outlier analysis was performed separately for each of the 110 possible combinations (i.e. 11 points x 5 treatments x 2 situations). Any participant that was identified by SPSS as an extreme outlier (i.e. drove the analysis section faster than 3 interquartile range from the group's mean) in more than 15% of the total combinations was eliminated from the analysis.

Table 1. Summary statistics of stop/go and RLR observations for each scenario(s)

	S1: indecision zone			S2: likely stopping zone		
Scenario	*Stop*	*Go safely*	*RLR*	*Stop*	*Go safely*	*RLR*
Control (n=62)	44(71.0%)	9(14.5%)	9(14.5%)	57(91.9%)	0	5(8.1%)
F-green (n=62)	56(90.3%)	4(6.5%)	2(3.2%)	59(95.2%)	0	3(4.8%)
R-LED (n=62)	42(67.8%)	17(27.4%)	3(4.8%)	61(98.4%)	0	1(1.6%)
C-VMS (n=62)	37(59.7%)	18(29.0%)	7(11.3%)	53(85.5%)	2(3.2%)	7(11.3%)
RW-gantry (n=62)	56(90.3%)	2(3.2%)	4(6.5%)	62(100%)	0	0

5. RESULTS

Table 1 presents the summary of statistics for stop/go and RLR for 62 subjects. Each subject was exposed to the 10 analysis intersections (5 conditions x 2 situations) where their decisions were recorded. As for Situation 1 (i.e. drivers are in the indecision zone), it can be read from the table that the frequency of RLR is lower for all the treatment conditions as compared to the control condition. The lowest number of RLR was observed for F-green (3.2%) followed by R-LED (4.8%) and RW-gantry (6.5%). The, highest number of stopping decisions (90.3%) was made in the F-green and the RW-gantry condition.

For situation 2 (i.e. drivers are in the likely stopping zone), all the drivers decided to stop when RW-gantry was installed before the intersection, while in the R-LED lights condition one driver decided to go and as a result, got a red light violation ticket. In the other conditions, the RLR occurrence was higher, as visible in Table 1. The highest number of crossing decisions (14.5%) was observed for C-VMS condition of which 11.3% were RLR.

5.1 Analysis of red light running prevention

Two logistic regression models (Model 1&2) were developed to identify significant predictors for the probability of RLR (Table 2). Total sample (i.e. stopped and crossed vehicles) was considered for estimating Model 1. Compared to the control condition, probability of RLR reduced significantly for the R-LED (β=-1.453, V2=5.986, p=0.014) and F-green (β=-1.272, V2=5.344, p=0.021) treatments. The highest reduction was obtained for R-LED i.e. a 4.2 times (1/expβ) lower probability of RLR as compared to the control condition. Furthermore, compared to the male drivers, the probability of red light running increased significantly for female drivers (β=.829, V2=5.316, p=0.021).

Table 2. Probability of red light running (significant p-values at 95% confidence level are indicated in bold)

	Model 1: Sample of stopped and crossed vehicles					**Model 2: Sample of crossed vehicles only**				
Variables	***β***	**Standard error**	**Wald**	**df**	**Sig.**	***β***	**Standard error**	**Wald**	**df**	**Sig.**
Constant	-4.735	1.994	5.638	1	**.018**	4.161	3.315	1.576	1	.209
Condition										
F-green	-1.272	.550	5.344	1	**.021**	.455	1.067	.182	1	.669
R-LED	-1.453	.594	5.986	1	**.014**	-1.753	.892	3.866	1	**.049**
C-VMS	-.030	.410	.005	1	.942	-1.006	.709	2.015	1	.156
RW-gantry	-.979	.601	2.654	1	.103	.292	1.059	.076	1	.783
Situation 2	-.582	.343	2.881	1	.090	4.152	1.122	13.706	1	**.000**
Gender (Female)	.829	.359	5.316	1	**.021**	.993	.629	2.495	1	.114
Ethnicity (Arab)	.106	.391	.074	1	.786	.449	.677	.441	1	.507
[a] Age	-.021	.049	.187	1	.666	.126	.085	2.183	1	.140
[b] Speed	.052	.019	7.477	1	**.006**	-.077	.033	5.301	1	**.021**
[a] Experience	.009	.050	.031	1	.860	-.159	.089	3.153	1	.076

a: a unit increase in year, b: a unit increase in speed in kph at the onset of yellow interval

Model 2 was developed to predict the probability of RLR for crossed vehicles only, without considering vehicles that had stopped. Ninety-three such cases could be identified and were subjected to analysis. Results from the logistic regression models are presented in Table 2, Model 2. Of all the treatments, only the R-LED condition showed a significant difference in comparison to the control condition: the probability of RLR reduced about 6 times (β=-1.753, V2=3.866, p=0.049). Interestingly, although not significant, for the F-green condition Model 2 yielded to opposite results compared to Model 1, indicating the probability of RLR to increase. This was perhaps because most drivers decided to stop in this condition.

Moreover, speed at the onset of yellow interval had a direct relation with the likelihood of RLR in both models. A unit increase in speed (kph) at the onset of yellow interval significantly increased the probability of RLR by 5.3%.

5.2 Analysis of stopping behavior at intersections

5.2.1 Analysis of speed

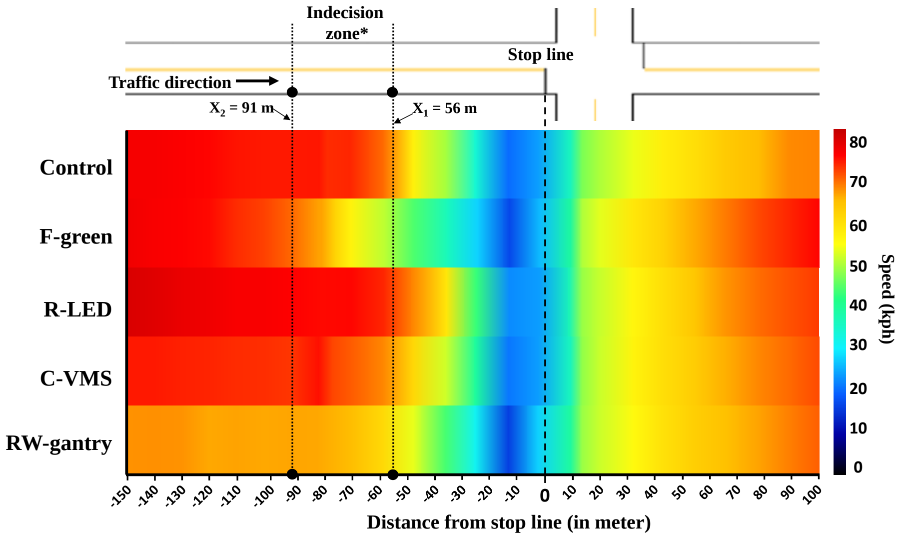
Table 3 presents the results for the linear mixed models regarding speed, for stopped and crossed vehicles taken separately (Model 3 and 4, respectively). Results for both models show significant main effects for the factors Point, and Condition. This implies that independent of any other factor, drivers' traveling speed was significantly different across the 11 points, and for the five conditions. All the interaction effects were

Table 3. Linear mixed models – analyses of speed (significant p-values at 95% confidence level are indicated in bold)

	Model 3: Stopped vehicles			**Model 4: Crossed vehicles**		
	F	***dfs***	***Sig.***	***F***	***dfs***	***Sig.***
Point	1866.9	10, 5614	**<.001**	2.8	10, 882	**.002**
Condition	61.0	04, 5629	**<.001**	10.3	4, 921	**<.001**
Situation	<1	01, 5634	.455	2.6	1, 907	.106
Point x Condition	11.2	40, 5614	**<.001**	1.1	40, 882	.422
Point x Situation	7.7	10, 5614	**<.001**	<1	10, 882	.751
Condition x Situation	27.5	04, 5625	**<.001**	2.5	3, 917	.055
Point x Condition x Situation	3.2	40, 5614	**<.001**	1.2	30, 882	.184

insignificant for Model 4 (crossed vehicles) meaning that speed was not significantly influenced by a combined effect. For instance, the insignificant interaction effect of 'Condition x Situation' shows that speed was not varying significantly between conditions, for both situations (i.e. indecision zone (S1) and likely stopping zone (S2)) taken separately. On the contrary, all the interaction effects were significant in Model 3 (vehicles that stopped). Two of these significant interactions are explained in more detail below:

- Condition x Situation: Independent of the factor 'Point', drivers' traveling speed was significantly different between the conditions under both situations, separately.
- Condition x Situation x Point: The results from the post hoc of this interaction effect along 6 points (150 before and 100 m after the stop line) for S1 (indecision zone) are presented in Figure 5. The figure illustrates the mean speed profiles for all the conditions (using hue and saturation bars of different colors) at different points (-150 to 100 m to the stop line with 10 m interval). The dashed line represents location of the stop line while two dotted lines represent the boundaries of indecision zone (X_1 and X_2) on a road with speed limit of 80 kph (Webster & Ellson, 1965). It can be seen from the figure that there is a steep reduction in speed between X_1 (-56 m) and X_2 (-91 m) in the F-green scenario. Mean differences in speed ($d\mu = V@ X_1 - V@ X_2$), SD of differences in speed, and range of speed differences (see the table attached to Figure 5) were highest for the F-green condition, indicating high variations among drivers' speed in the indecision zone. On the other hand, lowest values for dµ, SD, and ranges were observed in the R-LED condition, indicating a more consistent speed reduction (stopping



Differences in speed (kph) ($X_1 – X_2$)	Condition				
	Control	***F-green***	***R-LED***	***C-VMS***	***RW-gantry***
Mean of speed differences	-8.11	-16.09	-1.76	-3.11	-2.13
SD of speed differences	3.8	8.1	2.4	3.7	3.2
Range of speed differences	4.8 to -13.4	-0.1 to -41.4	1.6 to -10.5	2.6 to -12.9	3.7 to -14.5

* Boundaries of indecision zone for 80 kph (Webster & Ellson, 1965)

Figure 5. Mean speed profiles of stopped vehicles for S1 (indecision zone)

Table 4. Linear mixed models – analyses of SD of acc/dec (significant p-values at 95% confidence level are indicated in bold)

	Model 5: Stopped vehicles			Model 6: Crossed vehicles		
	F	***dfs***	***Sig.***	***F***	***dfs***	***Sig.***
Point	2053.5	9, 5098	**<.001**	4.8	9, 792	**<.001**
Condition	3.4	4, 5148	**.008**	3.3	4, 666	**.011**
Situation	1.6	1, 5157	.199	<1	1, 823	.417
Zone x Condition	8.7	36, 5098	**<.001**	1.2	36, 792	.179
Zone x Situation	32.8	9, 5098	**<.001**	<1	9, 792	.552
Condition x Situation	1.4	4, 5140	.246	1.2	3, 756	.315
Zone x Condition x Situation	3.5	36, 5098	**<.001**	<1	27, 792	.587

behavior) among drivers. Furthermore, we found an early gradual speed reduction in the RW-gantry condition where a warning gantry was installed at 150 m prior to the intersection.

5.2.2 Analysis of ACC/DEC

Table 4 presents the results for the linear mixed models regarding SD of ACC/DEC, for vehicles that stopped and vehicles that crossed taken separately (Model 5 and 6, respectively). The results show significant main effects for the factor Zone and factor Condition in both models. Again, there was no significant interaction effect observed for vehicles that crossed (Model 6). The interaction effect of Condition x Situation was not significant in Model 5 which indicates that variations in ACC/DEC were not significantly different for vehicles that stopped in the different conditions for both situations taken separately. However, the three-way interaction effect (Condition x Situation x Point) was significant, which means if we analyze the results on separate zones, the variations in ACC/DEC become significant between the conditions for the two

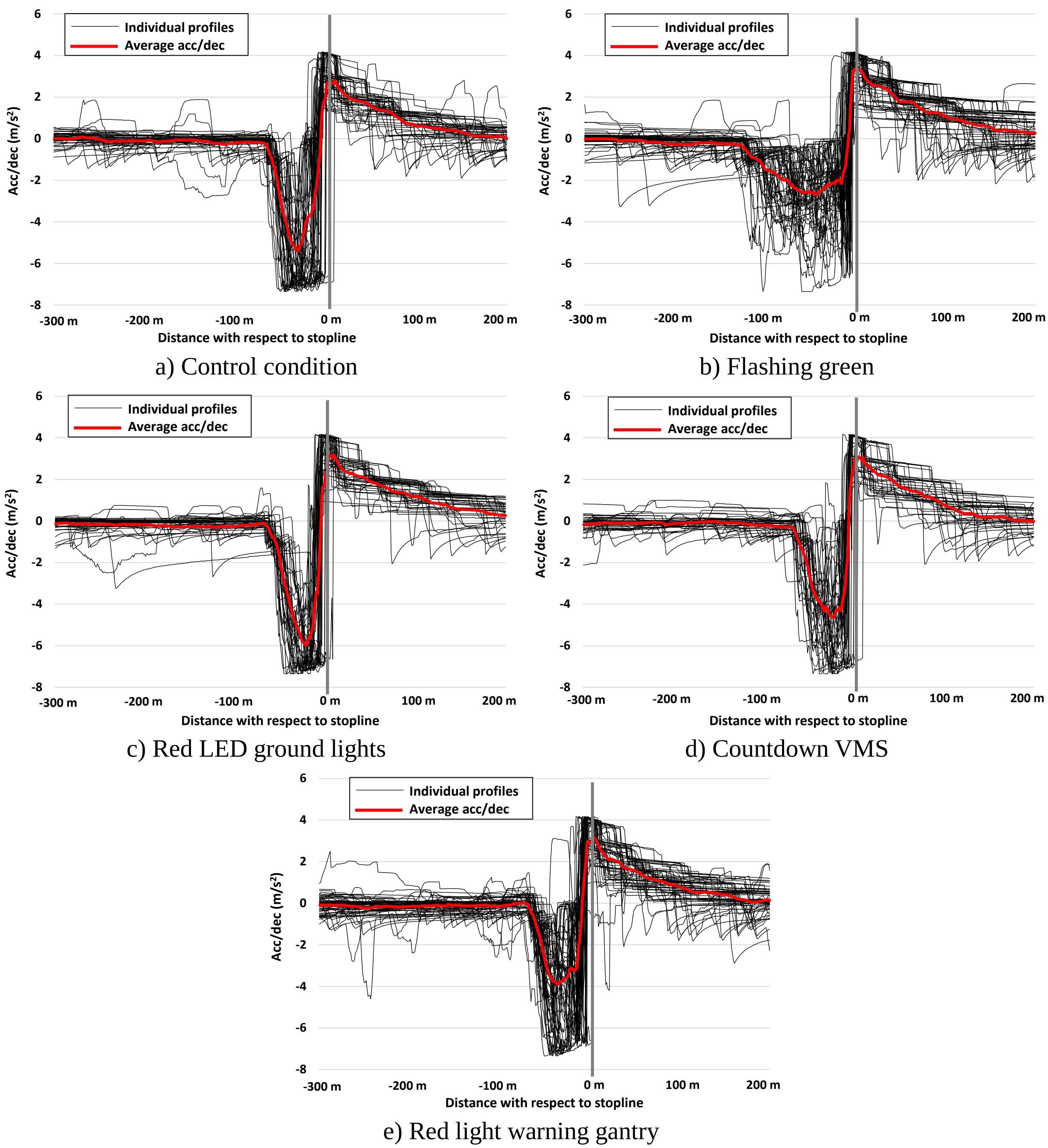


Figure 6. ACC/DEC profiles of stopped vehicles for S1 (indecision zone)

situations taken separately. Consequently, Figure 6 (a-e) presents the ACC/DEC profiles of drivers who stopped at intersections in the first situation (indecision zone) for all conditions separately. Except for the F-green condition, most drivers started to decelerate from between 100 - 70 m, with a comparable consistent trend in all the other conditions. However, in the F-green condition the consistency in drivers' stopping behavior was lower. Some drivers started to decelerate in advance probably due to the advance flashing green warning, while others continued for a while and started to decelerate in their approach to the intersection.

5.3 Subjective evaluation of the driving simulator

The results for subjective evaluation of the experience in driving simulator and the performance of the different components of the driving simulator are presented in Table 5. A 5-point Likert scale was used to measure all the items. The results indicate that drivers were comfortable with the driving simulator (Mean: 3.51) and gave highest rating for the overall general experience of using the driving simulator (Mean: 4.21). Regarding the performance comparison of the components of the driving simulator, all examined measures were higher than the middle value (i.e. 3). The highest rating was given to the steering wheel (Mean: 4.03) followed by the overall performance (Mean: 3.61). The lowest rating was given for the engine sound produced by the sound system of the simulator.

6. DISCUSSION

This study aims at investigating the effectiveness of different countermeasures to prevent RLR violations and help drivers to stop safely and consistently at signalized intersections. RLR prevention was investigated by means of two analyses, i.e. one for the overall sample (i.e. both the stopped and crossed vehicles), and another for only vehicles that had crossed the intersection. The second analysis was done to reveal if the tested conditions could assist drivers in making correct decision of crossing the intersections or not. Stopping at the signalized intersections indeed completely eliminates the hazard related to running a red signal light. However, inconsistency or differences among drivers' stopping behavior who are approaching the

Table 5. Post-test Questionnaire for the evaluation of the driving simulator (1 = not effective, 5 = highly effective)

		No. of responses for each level of rating					Mean Ratings	SD Ratings	Sample Size
		1	2	3	4	5			
General experience of using the simulator	*Overall*	1	3	2	31	24	4.21	0.8	61
	Comfort	7	7	11	20	16	3.51	1.3	61
Performance comparison	*Overall*	3	7	12	28	11	3.61	1.1	61
	Steering wheel	1	7	4	26	23	4.03	1.0	61
	Accelerator	3	9	15	25	9	3.46	1.1	61
	Brake	6	17	7	22	9	3.18	1.3	61
	Sound of engine	9	8	12	23	9	3.25	1.3	61

intersections at the same time could increase conflicting decisions and the risk of rear-end collisions. In this study, inconsistency among drivers' stopping behavior is assessed by variations in drivers' speed and ACC/DEC maneuvers.

In this regard, the R-LED condition was the best treatment for lowering the probability of RLR at intersections for both samples. Furthermore, the lowest variations in drivers' speed and ACC/DEC were observed for the R-LED, which indicate that the R-LED could assist drivers in making consistent stopping behavior while approaching the intersections. According to Wu et al., (2013), the lower variations in speed and ACC/DEC could shorten the indecision zone. The advantage of R-LED indicted by both results could be explained giving that the dynamic series of red light units installed on the ground provide direct information about the upcoming red phase to assist drivers in making safer stop/go decisions, based on their location at the intersections. The red ground lights provided by R-LED could reduce cognitive load for judgment about the stop/go decision, as they create a visual experience that allows drivers to more accurately estimate space and time, which is also in accordance with the subjects' feedback derived from the post-test questionnaire. On the other hand, when drivers are confronted with the default yellow signal light, they have to take into account the distance, speed and the remaining time in the yellow interval before deciding to stop or go (Gazis et al., 1960). It is important to mention that the functioning of these lights can be modified in different ways to increase the safety or efficiency at signalized intersections considering local driver behavior. For instance, a shorter stretch of R-LED with more slowly moving lights could increase the efficiency, as those drivers approaching the intersections will have the chance to accelerate and be in front of the light units.

Although F-green was effective in reducing RLR for both crossed and stopped vehicles, opposite results were obtained when only analyzing vehicles that had crossed. Besides, results showed that the F-green treatment stimulated drivers to stop when they were in the indecision zone. This could be explained by the advance warning in the F-green condition motivating most drivers to stop (Mahalel & Zaidel, 1985; Smith & Harney, 2001) and drivers interpret the flashing signal as a call for immediate action to stop rather than as an advance warning for the yellow interval (Factor et al., 2012). Furthermore, observation of the highest speed differences, the highest range of differences in speed across participants and the large variations in the acceleration profiles indicate more inconsistent and unsafe stopping behavior in the F-green condition. This incorrect understanding of the function of the flashing green prolongs the length of the indecision zone, and consequently increases suboptimal decisions among traffic approaching the intersections at the same time (Mahalel & Zaidel, 1985). Moreover, research shows that there is increased potential for conflicting decisions if two consecutive drivers are approaching the intersection with a flashing green signal (Factor et al., 2012; Newton et al., 1997).

The countdown system (C-VMS) motivated drivers situated in the stopping zone to cross the intersection which yielded to a large number of red light tickets (11.3%). The results are in line with the previous studies showing that countdown systems could lead more vehicles to cross the intersections (Long et al., 2013; Ma et al., 2010) and more RLR (Chiou et al., 2010; Long et al., 2013). This might be because the remaining time in the countdown systems makes drivers impulsive and aggressive to accelerate and cross the intersection, which results in higher number of RLR. Moreover, an early and smooth mean speed reduction was observed for the RW-gantry treatment indicating the importance of warning messages in reducing risk of rear-end collisions (Høye, 2013; Polders et al., 2015).

The results from several previous studies show that female drivers are more likely to be less aggressive than male drivers (Anderson et al., 1999; Lewis et al., 2012, 2013). In contrast, our the results from logistic regression model (Model 1) shows that compared to a male driver, the probability of red light running is higher in case of a female driver approaching the intersection with yellow interval. The results are in line with a study conducted in the state of Qatar showing that female drivers are more aggressive and drove faster than male drivers (Hussain et al., 2019b). Finally, traveling speed is an important parameter contributing to drivers' decision on stop/go at signalized intersection (Gazis et al., 1960). In accordance, this study showed that the higher the speed at the onset of yellow interval is, the higher the probability of RLR will be.

7. LIMITATIONS AND FUTURE RESEARCH

There are several limitations in this study that need to be addressed. The experiment was conducted using a fixed-base driving simulator, which might have reduced the level of realism. However, results from the subjective evaluation of the quality and performance of the driving simulator are in line with a validation study (Hussain et al., 2019a) indicating that the settings of the simulator are comparable with the settings offered by a real car. The sample used in this study was skewed more towards the younger age group with no participants of more than 60 years old age. Forty subjects participated in the study were of age 30 or less including 18 university students. The percentage of Qatar population with more than 60 years old is less than 2.4% in 2018 as reported by the Planning and Statistics Authority Qatar (2019). Most of these elderly (>60 years old) do not drive but rather have chauffeurs for their daily activities. Moreover, it is important to note that the recruited sample of drivers might not be representative of the driving population Qatar. In spite of that, the results of this study may vary for a sample with higher proportion of the old-aged drivers or different representative sample. Traffic driving in the same direction was triggered in a way to isolate the participants' car by not driving in front or parallel while the car was approaching the intersection. This was done to overcome the effect of conformity on stop/go behavior (Nordfjærn & Şimşekoğlu, 2014). Finally yet importantly, due to the length of the driving scenarios, all the participants were tested twice for each condition (once for each situation) during one session of driving. The results may vary for testing the drivers in multiple sessions for the same driving scenarios.

In this study, C-VMS and R-gantry were installed at a single location i.e. alongside the traffic lights and 150 m before the intersection, respectively. The effectiveness of these treatments can be tested for installing them at different locations, such as installing C-VMS system at the start of dilemma zone. Further research and real-world implementation will allow practitioners to find clearer and long term effect of the proposed treatments such as the R-LED on driving behavior. Another feasible option for real-world implementation of R-LED is to alternate the ground lights with the roadside light poles. However, in this case it is needed to calculate the hidden length concealed due to the peripheral visual field instead of the hidden length concealed by the front of the vehicle (see Figure 3), which can estimated as follows;

$$L_h = (b)\tan\frac{180-\theta_v}{2} \qquad (4)$$

where θ_v is the peripheral visual field angle, which is dependent on the driving speed; and b is the half width of one direction road.

8. CONCLUSION

In this study, different types of countermeasures have been proposed and compared to evaluate the safety at signalized intersections. Two logistic regression models were used as an indicator for RLR prevention while variations in speed differences were measured as an indicator for (in)consistent stopping behavior at the intersections. The results showed that none of the tested conditions was effective in reducing the probability of RLR in both models except R-LED treatment for which the probability of RLR reduced significantly in both models (i.e. Model 1: β= -1.453, V2=5.986, p=0.014; Model 2: β=-1.753, V2=3.866, p=0.049). Furthermore, the lowest variations in speed differences (mean of -1.76 kph; SD of 2.4 kph; range varies from 1.6 to -10.5 kph) were also observed for R-LED, showing the most consistent stopping behavior at signalized intersections among all the tested conditions. Based on these outcomes we conclude that R-LED can be an effective treatment to improve safety at signalized intersections. According to FHWA (2009), such kind of in-roadway LED light units have already been used by several agencies with different purposes, and an LED unit costs approximately $50 including labor and material costs.

Although, flashing green is the default traffic signal setting in Qatar, highest variations in acc/dec profiles and speed differences (mean of -16.09 kph; SD of 8.1 kph; range varies from -0.1 to -41.4 kph) were observed in this condition. The results clearly indicate that F-green could prolong the length of indecision zone and hence a potential for conflicting decisions among traffic approaching the intersection (such as unnecessary or early stopping). Therefore, it is important for policy makers to consider the results from this study while making decisions about traffic signal settings at signalized intersections.

Furthermore, results showed that the higher the speed at the onset of yellow interval, the higher would be the probability of RLR. A unit increase in speed (kph) at the onset of yellow interval would significantly increase the probability of RLR by 5.3%. Therefore, the stopping zone and start of the indecision zone can be supported by appropriate speed calming countermeasures such as perceptual countermeasures, road markings, and rumble strips to motivate drivers lowering their traveling speeds at the onset of yellow interval.

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REFERENCES

Abbas, M., Machiani, S. G., Garvey, P. M., Farkas, A., & Lord-Attivor, R. (2014). Modeling the Dynamics of Driver's Dilemma Zone Perception Using Machine Learning Methods for Safer Intersection Control. US DOT, RITA, Washinton, DC (2014)

Aeron-Thomas, A. S., & Hess, S. (2005). Red-light cameras for the prevention of road traffic crashes. (1469-493X (Electronic)). doi:https://doi.org/10.1002/14651858.CD003862.pub2

Ahmed, M. M., & Abdel-Aty, M. (2015). Evaluation and spatial analysis of automated red-light running enforcement cameras. *Transportation Research Part C: Emerging Technologies, 50*, 130-140. doi:https://doi.org/10.1016/j.trc.2014.07.012

Anderson, C. L., Winn Dg Fau - Agran, P. F., & Agran, P. F. (1999). Differences between pickup truck and automobile driver-owners. (0001-4575 (Print)).

Ariën, C., Jongen, E. M. M., Brijs, K., Brijs, T., Daniels, S., & Wets, G. (2013). A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. *Accident Analysis & Prevention, 61*, 43-53. doi:https://doi.org/10.1016/j.aap.2012.12.044

Bar-Gera, H., Oron-Gilad, T., & Musicant, O. (2013). In-Vehicle Stopping Decision Advisory System for Drivers Approaching a Traffic Signal. *Transportation Research Record, 2365*(1), 22-30. doi:https://doi.org/10.3141/2365-04

Bella, F. (2005). Validation of a Driving Simulator for Work Zone Design. *Transportation Research Record: Journal of the Transportation Research Board, 1937*, 136-144. doi:10.3141/1937-19

Bella, F. (2008). Driving simulator for speed research on two-lane rural roads. *Accident Analysis & Prevention, 40*(3), 1078-1087. doi:https://doi.org/10.1016/j.aap.2007.10.015

Bonneson, J. A., & Son, H. J. (2003). Prediction of Expected Red-Light-Running Frequency at Urban Intersections. *Transportation Research Record, 1830*(1), 38-47. doi:https://doi.org/10.3141/1830-06

Bonneson, J. A., & Zimmerman, K. H. (2004). Effect of Yellow-Interval Timing on the Frequency of Red-Light Violations at Urban Intersections. *Transportation Research Record, 1865*(1), 20-27. doi: https://doi.org/10.3141/1865-04

Calvi, A. (2018). Investigating the effectiveness of perceptual treatments on a crest vertical curve: A driving simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 1074-1086. doi:https://doi.org/10.1016/j.trf.2018.06.002

Chang, G.-L., Franz, M. L., Liu, Y., Lu, Y., & Tao, R. (2013). Design and Evaluation of an Intelligent Dilemma-Zone Protection System for a High-Speed Rural Intersection. *Transportation Research*

Record, *2366*(1), 1-8. doi: https://doi.org/10.3141/2356-01

Chang, J., Cohen, D., Blincoe, L., Subramanian, R., & Lombardo, L. (2007). *CICAS-V Research on Comprehensive Costs of Intersection Crashes*. Paper presented at the 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Location: Lyon , France. http://www-nrd.nhtsa.dot.gov/departments/esv/20th/

Charlton, S. G., Starkey, N. J., & Malhotra, N. (2018). Using road markings as a continuous cue for speed choice. Accident Analysis & Prevention, 117, 288-297. doi:https://doi.org/10.1016/j.aap.2018.04.029

Chiou, Y.-C., & Chang, C.-H. (2010). Driver responses to green and red vehicular signal countdown displays: Safety and efficiency aspects. *Accident Analysis & Prevention, 42*(4), 1057-1065. doi:https://doi.org/10.1016/j.aap.2009.12.013

Daniels, S., Vanrie, J., Dreesen, A., & Brijs, T. (2010). Additional road markings as an indication of speed limits: Results of a field experiment and a driving simulator study. *Accident Analysis & Prevention*, *42*(3), 953-960. doi:https://doi.org/10.1016/j.aap.2009.06.020

Devlin, A., Candappa, N., Corben, B., & Logan, D. (2011). *Designing safer roads to accommodate driver error*. Retrieved from http://cmuarc.curtin.edu.au/local/docs/DevlinCandappaCorbenLogan_DSRCDE.pdf

Factor, R., Prashker, J. N., & Mahalel, D. (2012). The flashing green light paradox. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(3), 279-288. doi:https://doi.org/10.1016/j.trf.2012.01.003

FHWA, Federal Highway Administration. (2009). LED Raised Pavement Markers. (No. FHWA-SA-09-007). Retrieved from https://safety.fhwa.dot.gov/intersection/conventional/unsignalized/tech_sum/fhwasa09007/

FHWA, Federal Highway Administration. (2014). *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running*. Retrieved from https://safety.fhwa.dot.gov/intersection/conventional/signalized/rlr/rlr_toolbox/

Fisher, D. L., Rizzo, M., Caird, J. K., & Lee, J. D. (2011). Handbook of Driving Simulation for Engineering, Medicine, and Psychology. *CRC Press - Taylor & Francis Group*.

Gazis, D., Herman, R., & Maradudin, A. (1960). The Problem of the Amber Signal Light in Traffic Flow. *Operations Research, 8*(1), 112-132. doi: https://doi.org/10.1287/opre.8.1.112

Grembek, O., Kurzhanskiy, A., Medury, A., Varaiya, P., & Yu, M. (2019). Making intersections safer with I2V communication. Transportation Research Part C: Emerging Technologies, 102, 396-410. doi:https://doi.org/10.1016/j.trc.2019.02.017

Høye, A. (2013). Still red light for red light cameras? An update. *Accident Analysis & Prevention, 55*, 77-89. doi:https://doi.org/10.1016/j.aap.2013.02.017

Hu, W., McCartt, A. T., & Teoh, E. R. (2011). Effects of red light camera enforcement on fatal crashes in large US cities. *Journal of Safety Research, 42*(4), 277-282. doi:10.1016/j.jsr.2011.06.002

Huang, H., Wang, D., Zheng, L., & Li, X. (2014). Evaluating time-reminder strategies before amber: Common signal, green flashing and green countdown. *Accident Analysis and Prevention, 71*, 248-260. doi:10.1016/j.aap.2014.05.018

Hussain, Q., Pirdavani, A., Arien, C., Brijs, T., & Alhajyaseen, W. K. M. (2018). The impact of perceptual countermeasures on driving behavior in rural-urban transition road segments: a driving simulator study. *Advances in Transportation Studies, 46*(XLVI - November 2018), 83-96.

Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Reinolsmann, N., Brijs, K., & Brijs, T. (2019a). Speed perception and actual speed in a driving simulator and real-world: A validation study. Transportation Research Part F: Traffic Psychology and Behaviour, 62, 637-650. doi:https://doi.org/10.1016/j.trf.2019.02.019

Hussain, Q., Alhajyaseen, W. K. M., Brijs, K., Pirdavani, A., Reinolsmann, N., & Brijs, T. (2019b). Drivers' estimation of their travelling speed: a study on an expressway and a local road. International Journal of Injury Control and Safety Promotion, 1-9. doi:10.1080/17457300.2019.1618342

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness

Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. The International Journal of Aviation Psychology, 3(3), 203-220. doi:10.1207/s15327108ijap0303_3

Kidwai, F. A., Ibrahim, M. R., & Karim, M. R. (2005). *Traffic flow analysis of digital count down signalized urban intersection.* Paper presented at the Eastern Asia Society for Transportation Studies.

Lewis, I., et al. (2012). How males and females define speeding and how they'd feel getting caught for it: Some implications for antispeeding message development. Australasian Road Safety Research Policing & Education Conference. Wellington, New Zealand.

Lewis, I. M., et al. (2013). Examining gender differences in drivers' thoughts and feelings about different outcomes of speeding: Implications for future anti-speeding messages. Australasian College of Road Safety National Conference, National Wine Centre of Australia, Adelaide, SA.,

Li, P., Li, Y., & Guo, X. (2014). A Red-light running prevention system based on artificial neural network and vehicle trajectory data. *Computational Intelligence and Neuroscience, 2014*. doi:10.1155/2014/892132

Limanond, T., Prabjabok, P., & Tippayawong, K. (2010). Exploring impacts of countdown timers on traffic operations and driver behavior at a signalized intersection in Bangkok. *Transport Policy, 17*(6), 420-427. doi:https://doi.org/10.1016/j.tranpol.2010.04.009

Llopis-Castelló, D., Camacho-Torregrosa, F. J., Marín-Morales, J., Pérez-Zuriaga, A. M., García, A., & Dols, J. F. (2016) Validation of a low-cost driving simulator based on continuous speed profiles. *Vol. 2602. Transportation Research Record* (pp. 104-114): National Research Council.

Long, K., Liu, Y., & Han, L. D. (2013). Impact of countdown timer on driving maneuvers after the yellow onset at signalized intersections: An empirical study in Changsha, China. Safety Science, 54, 8-16. doi:https://doi.org/10.1016/j.ssci.2012.10.007

Lum, K. M., & Halim, H. (2006). A before-and-after study on green signal countdown device installation. *Transportation Research Part F: Traffic Psychology and Behaviour, 9*(1), 29-41. doi:10.1016/j.trf.2005.08.007

Ma, W., Liu, Y., & Yang, X. (2010). Investigating the Impacts of Green Signal Countdown Devices: Empirical Approach and Case Study in China. *Journal of Transportation Engineering, 136*(11).

Mahalel, D., & Zaidel, D. M. (1985). Safety evaluation of a flashing green light in a traffic signal. *Traffic Engineering & Control, 26*(2), 79-81.

McCarthy, N. (2015). The Most Dangerous US Cities for Red-light Running. Available at: https://www.statista.com/chart/3717/ red-light-running/. (Retrived 08 October 2018).

McCartt, A. T., & Hu, W. (2014). Effects of red light camera enforcement on red light violations in Arlington County, Virginia. *Journal of Safety Research, 48*, 57-62. doi:https://doi.org/10.1016/j.jsr.2013.12.001

Ministry of Development Planning and Statistics (2017). *Qatar Ministry of Development Planning and Statistics* Retrieved from https://www.mdps.gov.qa/en/statistics/Statistical%20Releases/General/QMS/QMS_MDPS_60_Jan_2019.pdf

MOTC. (2015). Qatar Traffic Control Manual. *Qatar Ministry of Transport and Communications, QTCM_Vol1_Part05_TrafficSignals*.

Newton, C., Mussa, R. N., Sadalla, E. K., Burns, E. K., & Matthias, J. (1997). Evaluation of an alternative traffic light change anticipation system. *Accident Analysis & Prevention, 29*(2), 201-209. doi:https://doi.org/10.1016/S0001-4575(96)00073-5

Nilsson, L. (1993). Behavioural Research in an Advanced Driving Simulator - Experiences of the VTI System. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 37*(9), 612-616. doi:10.1177/154193129303700921

Nordfjærn, T., & Şimşekoğlu, Ö. (2014). Empathy, conformity, and cultural factors related to aberrant driving behaviour in a sample of Urban Turkish drivers. *Safety Science, 68*, 55-64. doi:https://doi.org/10.1016/j.ssci.2014.02.020

Parsonson, P. (1974). Small area detection at intersection approaches: A section technical report. Washington, DC: Institute of Transportation Engineers.

PIARC. (2003). Road safety manual. *Cedex: World Road Association*.

Pinheiro, J.C., Bates, D.M., 2000. Mixed-Effects Models in S and S-PLUS. Springer-Verlag, New York, Berlin, Heidelberg.

Planning and Statistics Authority Qatar. (2018). First Section Population And Social Statistics. Retrieved from https://www.psa.gov.qa/en/statistics/Statistical%20Releases/General/StatisticalAbstract/2018/Population_social_1_2018_AE.pdfPline, J. L. (1999). *Traffic engineering handbook*. Englewood Cliffs, N.Y. : Prentice-Hall: Institute of Transportation Engineers.

Polanis, S. F. (2002). *Improving intersection safety through design and operations*. Paper presented at the ITE Spring Conference, Washington, DC: Institute of Transportation Engineers (ITE).

Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., . . . Wets, G. (2015). Drivers' behavioral responses to combined speed and red light cameras. *Accident Analysis & Prevention, 81*, 153-166. doi:https://doi.org/10.1016/j.aap.2015.05.006

Reinolsmann, N., Alhajyaseen, W., Brijs, T., Pirdavani, A., Hussain, Q., & Brijs, K. (2019). Investigating the impact of dynamic merge control strategies on driving behavior on rural and urban expressways – A driving simulator study. Transportation Research Part F: Traffic Psychology and Behaviour, 65, 469-484. doi:https://doi.org/10.1016/j.trf.2019.08.010

Retting, R. A., Ferguson, S. A., & Farmer, C. M. (2008). Reducing red light running through longer yellow signal timing and red light camera enforcement: Results of a field investigation. *Accident Analysis & Prevention, 40*(1), 327-333. doi:https://doi.org/10.1016/j.aap.2007.06.011

Retting, R. A., & Kyrychenko, S. Y. (2002). Reductions in Injury Crashes Associated With Red Light Camera Enforcement in Oxnard, California. *American Journal of Public Health, 92*(11), 1822-1825. doi:10.2105/AJPH.92.11.1822

Rijavec, R., Zakovšek, J., & Maher, T. (2013). Acceptability of countdown signals at an urban signalized intersection and their influence on drivers behaviour. *Promet - Traffic - Traffico, 25*(1), 63-71. doi:10.7307/ptt.v25i1.1248

Sackman, H., Monahan, B., Parsonson, P. S., & Trevino, A. F. (1977). Vehicle detector placement for high-speed, isolated traffic-actuated intersection control. Volume 2. Manual of theory and practice. Federal Highway Administration, FHWA-RD-77- 32 Final Rpt.

Soliman, A., Alhajyaseen, W., Alfar, R., & Alkaabi, I. (2018). Changes in driving behavior across age cohorts in an Arab culture: The case of state of Qatar. Procedia Computer Science, 130, 652-659. https://doi.org/10.1016/j.procs.2018.04.116

Smith, T. J., & Harney, R. (2001). Effects of Advanced Warning Flashers on Driver Interaction with Signalized Intersections. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 45*(23), 1680-1684. doi:10.1177/154193120104502325

Timmermans, C., Alhajyaseen, W., Reinolsmann, N., Nakamura, H., & Suzuki, K. (2019). Traffic safety culture of professional drivers in the State of Qatar. IATSS Research. doi:https://doi.org/10.1016/j.iatssr.2019.03.004

Tydlacka, J., Voigt, A. P., & Langford, W. C. (2011). Evaluation of Lighted Pavement Marker Stop Bars at Intersections with Light Rail Lines. Transportation Research Record, 2250(1), 49-56. doi:10.3141/2250-07

Webster, F. V. r., & Ellson, P. B. (1965). Traffic signals for high speed roads. *Roads Research Laboratory, Technical Paper No. 74*.

Wu, M., Ma, W., & Li, L. (2013). Characterize Dilemma Zone and Minimize its Effect at Coordinated Signalized Intersections. *Procedia - Social and Behavioral Sciences*, *96*, 766-778. doi:https://doi.org/10.1016/j.sbspro.2013.08.087

Xie, X.-F., & Wang, Z.-J. (2018). SIV-DSS: Smart In-Vehicle Decision Support System for driving at signalized intersections with V2I communication. Transportation Research Part C: Emerging Technologies, 90, 181-197. doi:https://doi.org/10.1016/j.trc.2018.03.008

Yan, X., Radwan, E., Guo, D., & Richards, S. (2009). Impact of “Signal Ahead” pavement marking on driver behavior at signalized intersections. Transportation Research Part F: Traffic Psychology and Behaviour, 12(1), 50-67. doi:https://doi.org/10.1016/j.trf.2008.07.002

Yang, Z., Tian, X., Wang, W., Zhou, X., & Liang, H. (2014). Research on Driver Behavior in Yellow Interval at Signalized Intersections. *Mathematical Problems in Engineering, 2014*, 8. doi:10.1155/2014/518782

Zegeer, C. V., & Deen, R. C. (1978). Green-extension systems at high-speed intersections. *ITE Journal, 48*(11), 19-24.

Zhang, Y., Fu, C., & Hu, L. (2014). Yellow light dilemma zone researches: a review. *Journal of Traffic and Transportation Engineering (English Edition), 1*(5), 338-352. doi:https://doi.org/10.1016/S2095-7564(15)30280-4

Zhang, Y., Yan, X., Li, X., Wu, J., & Dixit, V. V. (2018). Red-Light-Running Crashes' Classification, Comparison, and Risk Analysis Based on General Estimates System (GES) Crash Database. International Journal of Environmental Research and Public Health, 15(6).doi:10.3390/ijerph15061290