



Improved driver responses at intersections with red signal countdown timers



Mohammad R. Islam^a, David S. Hurwitz^{a,*}, Kristen L. Macuga^b

^a School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, 1501 SW Campus Way, Corvallis, OR 97331, USA

^b School of Psychological Science, Oregon State University, 229 Reed Lodge, 2950 SW Jefferson Way, Corvallis, OR 97331, USA

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ABSTRACT

Traffic Signal Countdown Timers (TSCTs) are innovative, practical and cost effective technologies with the potential to improve efficiency at signalized intersections. The purpose of these devices is to assist motorists in decision-making at signalized intersections with real-time signal duration information. This study focused specifically on driver responses in the presence of a Red Signal Countdown Timer (RSCT). A Linear Mixed Effect (LME) model was developed to predict the effect of RSCT on the headway of the first vehicle waiting on a red signal. The model predicted 0.72 s reduction in the headway of the first queued vehicle resulting from the presence of RSCT, while the observed difference in mean headway was 0.82 s. This result is suggestive of a reduction in start-up lost time at signalized intersections, i.e., an improvement in signalized intersection efficiency when an RSCT is present.

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1. Introduction

1.1. TSCT operations

Traffic Signal Countdown Timers (TSCTs) are clocks that digitally display the time remaining for a particular signal indication, i.e., red, yellow, or green. They provide drivers with real-time information to potentially improve driver decision-making and vehicle control. A red signal countdown timer (RSCT), for example, alerts the driver to an oncoming green signal and reduces the time lost due to driver reaction at the beginning of the green signal. Similar TSCT displays can be shown for a green or yellow signal as well.

A sizeable portion of all signalized intersections in the United States, 272,000 in 2008 (FHWA, 2012), have fixed-time signals. The timing plans for fixed-time signals allocate green time based on prior observation of vehicle volumes (turning movements, vehicle classification, pedestrian volumes, etc.) and are not responsive to real-time traffic demand. Actuated signals utilize vehicle detection and additional timing parameters (minimum green, passage time, maximum green, etc.) so that the green time is allocated in response to real-time traffic demand. Typically, the final determination is made 1–4 s (Tarnoff and Parsonson, 1981) before the indication changes (e.g., green to yellow, or red to green), providing a limited interval for the countdown to be displayed. Therefore, application of TSCT has the greatest potential for green, yellow, and red indications at fixed-time signals and for the predictable yellow change intervals of actuated signals.

* Corresponding author. Tel.: +1 541 737 9242; fax: +1 541 737 3052.

E-mail addresses: islammo@onid.oregonstate.edu (M.R. Islam), david.hurwitz@oregonstate.edu (D.S. Hurwitz), Kristen.Macuga@oregonstate.edu (K.L. Macuga).

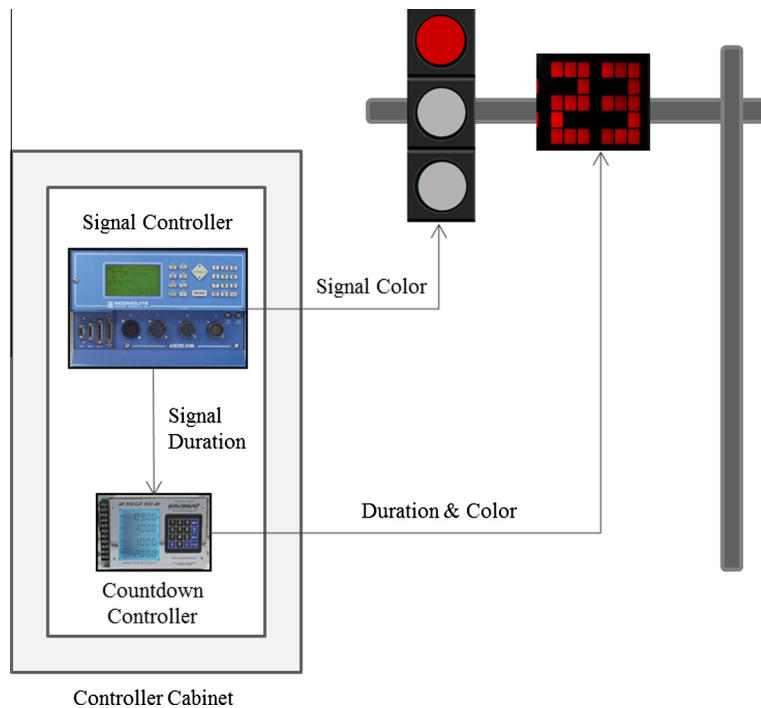


Fig. 1. Diagram of a TSCT that operates via signal and countdown controllers.

Fig. 1 illustrates the concept of operations for a TSCT. “The countdown time display panel is under the control of a countdown controller that runs in step with the signal controller. When a signal is counting down for a specific phase, the countdown control system shows the remaining time for that phase (Chen et al., 2009)”.

As illustrated in Fig. 1, the signal controller feeds the countdown controller with signal duration information, which then displays the information in the form of a countdown timer.

1.2. TSCT efficiency

Most studies have attempted to quantify the operational efficiency benefits of TSCT with the performance measures of delay and throughput. TSCT are generally expected to reduce vehicular delay at signalized intersections (Chiou and Chang, 2010; Limanond et al., 2010, 2009; Sharma et al., 2009), and increase the throughput capacity by more efficiently discharging the queue (Chiou and Chang, 2010; Limanond et al., 2010; Sharma et al., 2009; Ibrahim et al., 2008; Liu et al., 2012). Chen et al. (2009) conducted a comprehensive study of the available literature on both vehicular and pedestrian countdown timers. RSCTs were found to be the only type of countdown devices with a positive influence on traffic safety and delay. However, occasional increases in travel time and decreases in capacity were also reported.

1.3. Reduction in intersection delay due to TSCT

RSCTs inform drivers about when the red signal will turn green, and thus, are expected to reduce the start-up lost time of the standing queue. On the other hand, green and yellow signal countdown timers (CTs) have the potential to reduce “clearance lost time” (i.e., the unused portion of the change or clearance interval) by displaying the amount of time remaining before the signal changes to red, which could reduce the overall delay at the intersection.

Limanond et al. (2009) found that the RSCT in Bangkok, Thailand slightly increased the capacity of the intersection by reducing the start-up lost time. Forty-eight hours of data were collected at an intersection; 24 h while the RSCTs were active, and 24 h while the RSCTs were inactive. The results of the study found that RSCTs reduced the start-up lost time by 1.00–1.92 s per cycle, equivalent to a time savings of 17–32%. This time savings represents an increase in capacity of approximately 8–24 vehicles per hour.

Further investigation by Limanond et al. (2010) in Bangkok, Thailand found a 22% reduction in the start-up lost time at the beginning of the green phase. Chiou and Chang (2010) also reported a similar reduction in the start-up lost time and saturated headway in presence of RSCTs in China. Sharma et al. (2009) investigated the effect of countdown timers on headway distribution in Chennai, India and found that RSCTs effectively reduced the start-up lost time.

1.4. Increase in throughput attributed to TSCT

The discharge or departure headways of a traffic stream are usually highest at the beginning of a green signal for the first few vehicles due to the Perceptual Reaction Time (PRT) of the first few drivers. It is also assumed that the saturation headway will be reached by the fourth (TRB, 2010) or fifth (Roess et al., 2011) vehicle in the queue, and vehicles will continue to process at the saturation flow rate until the last vehicle of the queue is processed.

RSCTs are clearly visible to the first four or five vehicles in a standing queue waiting to respond to the green signal. Thus, headways between the vehicles responding to RSCTs, as the queue starts moving at the end of the red signal, are expected to be lower than those for a traditional signal. This reduction in headways has the potential to increase capacity at signalized intersections. Chiou and Chang (2010) observed a reduction in the saturation headway in the presence of an RSCT when compared to a traditional signal.

Ibrahim et al. (2008) performed a comparative study of the discharge patterns between signals with and without RSCTs. The headway data collected from three intersections equipped with RSCTs suggested that they tend to reduce the discharge headways of the first six vehicles in the standing queue.

The queue discharge characteristics and headway distributions at signalized intersections with TSCT under heterogeneous traffic conditions in India were studied by Sharma et al. (2009). The analysis was carried out with data collected from two intersections, one with and one without TSCT. The headway distributions for locations without TSCT were found to follow a typical distribution. In the presence of TSCT, the gaps remained constant for green durations shorter than 21 s and started to decrease at a rate 0.02 gap-s/s for longer green durations exceeding 21 s.

A similar study was conducted by Liu et al. (2012) to evaluate the effects of TSCT on queue discharge characteristics at signalized intersections in China for protected left-turn and through movements. Data were collected from 13 approaches at seven signalized intersections. It was found that TSCT significantly affected the start-up lost time for both protected left-turn and through movements. The start-up lost times were reduced an average of 0.6 s per cycle for the protected left-turn and 2.25 s per cycle for the through movements. The reduction in start-up lost time for the left-turn movement was smaller than the through movement, because the drivers were already alert about the shorter green duration for left-turn movements at the selected sites. TSCT had little effect on the saturation headways for both movements.

Limanond et al. (2010) also found a similar reduction in headways resulting from TSCT for red signals. A significant reduction in the mean headway of the lead vehicle in the presence of TSCTs was determined. However, the saturation headway was reached at about the eighth vehicle in the queue for both situations, suggesting that the vehicle throughput was not affected by the use of TSCT.

1.5. Research questions

The objective of this research was to investigate whether TSCT had the potential to improve traffic efficiency at signalized intersections in the United States. This is the first study of its kind conducted on a population of US drivers. As suggested by previous literature, RSCTs can help improve signalized intersection efficiency by reducing delays.

Reduction in the start-up lost time at a signalized intersection is of significant importance. It is not only the first vehicle that experiences the benefit, but the entire queue, as the delay incurred by the start-up lost time is a cumulative function. Therefore, it is of great interest to traffic engineers and transportation human factors engineers to apply innovative techniques to reduce start-up delays, i.e., improve efficiency. Using RSCTs has the potential to contribute to this outcome, which formed the basis of our research questions regarding RSCTs.

- Does the presence of RSCTs reduce the start-up lost time by reducing the headway of the first vehicle in a discharging queue and can a model be developed to quantify the relationship between RSCTs and the first vehicle headway?
- Does the duration of wait time during the red signal influence the performance of RSCTs to reduce the headway of the first vehicle in a discharging queue and can a model be developed to quantify the relationship between red signal duration and the first vehicle headway?

It has been documented that drivers waiting at an intersection during longer red signals are more likely to be distracted and respond more slowly at the onset of the green signal, resulting in longer headways (Hurwitz et al., 2013). While the majority of the previous research evaluating RSCTs was conducted with field studies, a driving simulator study was required as a next step for evaluating the behavior of a US driving population, as field implementation is not currently allowed in the US (MUTCD, 2009).

2. Material and methods

2.1. OSU driving simulator

The Oregon State University (OSU) driving simulator consists of a fully functional full-size 2009 Ford Fusion cab mounted on an electric pitch motion system that allows for onset cues for acceleration and braking events. The cab is surrounded by

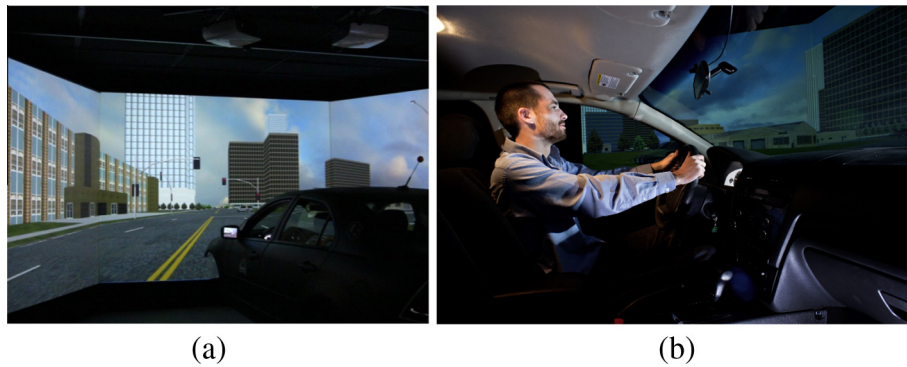


Fig. 2. OSU driving simulator (a) view of forward projection and cab and (b) view from inside the cab.

screens where the simulated environment is projected. As shown in Fig. 2, three projectors project a 180 degree front view. A fourth projector displays the rear image for the driver's center mirror. Two side mirrors have embedded LCD displays that permit the driver to see both rear sides. The cab instrument includes a steering control loading system that accurately represents steering torques based on speed and steering angle. The computer system consists of a quad core host that runs the "SimCreator" Software (Realtime Technologies, Inc.). The data update rate for the graphics is 60 Hz. It is a high-fidelity simulator that can capture and output highly accurate performance data such as speed, position, brake, and acceleration.

A driving simulator may be validated in an absolute (Bella, 2008) or relative (Bella, 2005; Törnros, 1998; Knodler et al., 2001) manner on the basis of the differences in any number of observed performance measures, such as speed or lateral position. For a simulator experiment to be useful, it is not required that absolute validity be obtained; however, it is necessary that relative validity be established (Bella, 2008). Drivers' stopping behavior at traffic signals, perceptual reaction time, deceleration rates, and traffic sign comprehension have previously been validated in the OSU driving simulator (Moore and Hurwitz, 2013; Swake et al., 2013; Neill et al., 2016).

The virtual test tracks were developed using Internet Scene Assembler (ISA) software, which permitted using Java Script-based sensors on the test tracks to change the signal and to display dynamic objects, such as a countdown timer, based on the vehicle's presence. The TSCT triggering sensors were placed at a distance upstream from the intersection. The signal change took place when the vehicle was at a desired distance, measured in terms of Time-to-stop-line (TTSL). The following parameters were recorded at roughly 10 Hz (10 times a second) throughout the entire duration of the experiment:

- Signal Change – To correlate driver responses with respect to the change in signal or RSCT display.
- Instantaneous Speed – To identify changes in speed in response to the RSCT display.
- Instantaneous Position – To estimate the headways and distance upstream from the stop line.

2.2. Test track configurations

This experiment involved two types of TSCT (RSCTs and GSCTs). This manuscript focuses on the implications of the RSCT evaluation. The RSCT experiment included three test scenarios, 20, 40, and 60 s long red signals. Meanwhile, the GSCT experiment was composed of ten different test scenarios; TTSL = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 s. Thus, a total of 13 test scenarios, presented at thirteen different intersections, were included in both types of test tracks, those with and without TSCT. The total length of each test track was close to 6.25 km. Thus, each test subject was required to drive approximately 12.50 km in total combining the total lengths of both test tracks.

The RSCT test scenario intersections were separated by at least two other intersections, to prevent the requirement for stopping at successive intersections. Each scenario was assigned a number, and a random number generator was used to arrive at a final scenario sequence. After placing the intersections for RSCT experiment, GSCT test scenarios were randomly placed at the remaining ten intersections. This process of signal arrangement was used to create four test track configurations – A, B, C, and D. The random assignment of intersections with each level of independent variables, and the counterbalancing of the four track configurations contributed to minimizing the confounding effects of the order of exposures or of an upcoming event. The speed limit was kept the same (35 mph) for the entire roadway to reduce variability due to speed. In all four test tracks, the roadway was divided with one lane going each direction. All four test track configurations are shown in Fig. 3. Each test subject was randomly assigned to a test track configuration and was tested in the same configuration for both scenarios, i.e., with and without RSCT.

2.3. Independent variables

The research hypotheses predict that the mean headway of the first vehicle is a function of two independent variables: presence of RSCTs, and the duration of the red signal. Although, other factors, such as distraction or situational awareness,

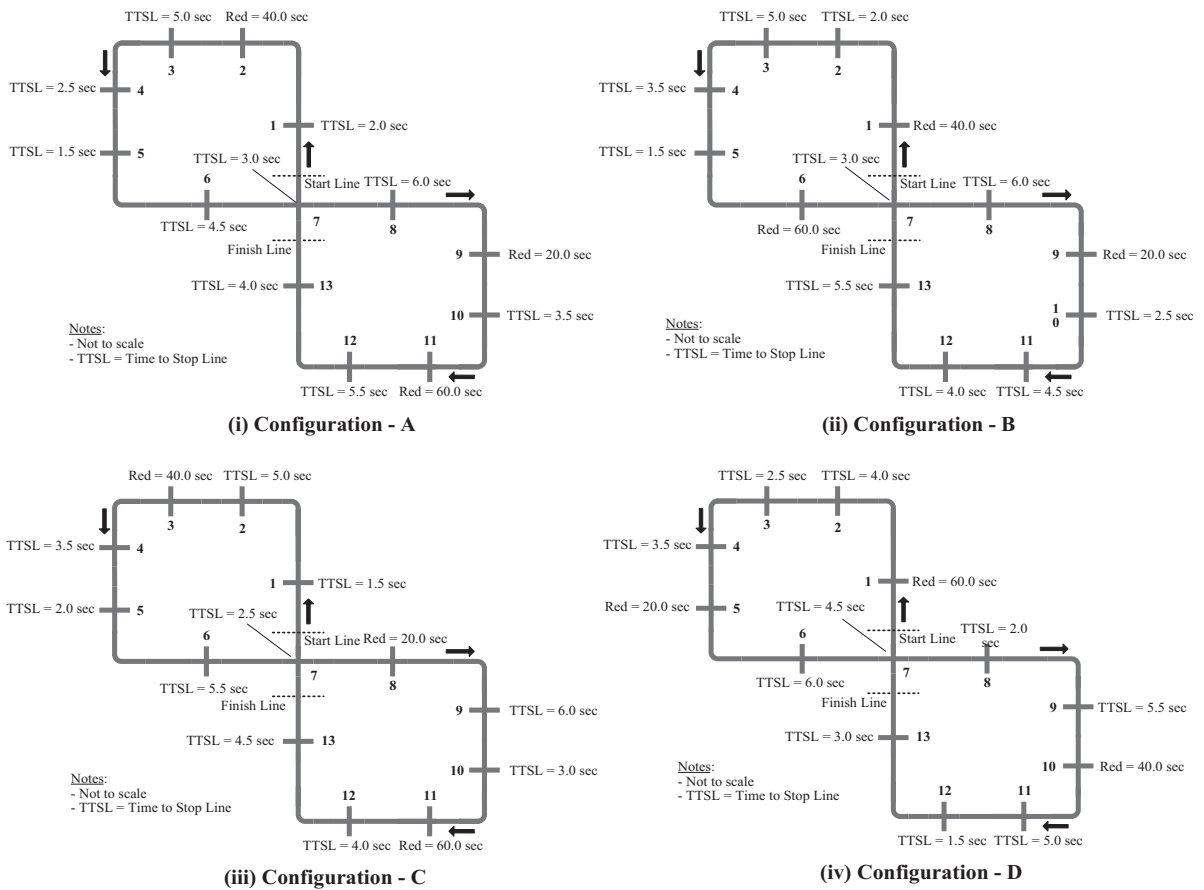


Fig. 3. Test tracks with RSCTs (Red) and GSCTs (TTSL).

may influence driver behavior, the scope of this research was limited to investigating the performance of drivers operating without distraction as the most conservative assumption. To accommodate potential sources of variability from individual subjects, demographics such as age, gender, driving experience, and level of education, were also included in the analysis.

As shown in Table 1, presence of RSCTs, had only two levels (present or not present), which enabled it to be included as a factor in the model. Although the duration of the red signal can have many different levels, three common red durations (20, 40, and 60 s) were tested in this experiment. The red durations were selected from the range of commonly observed wait times at intersections with low to moderate traffic volumes. The interval between red durations was made large enough (e.g., 20 s) to increase the possibility of detecting distinguishable differences in driver behavior due to different wait times.

Subjects' age was included as a continuous variable, while gender, education, and driving experience were included as factors of multiple levels (Table 1). Different levels of education were classified into seven categories: less than high school, high school/GED, some college, 2-year college degree, 4-year college degree, Master's degree, and Doctoral degree. Driving experience was classified into five levels: 1–5, 6–10, 11–15, 16–20, and more than 20 years.

The first two variables, presence of RSCTs and duration of red signal, were purely controlled, while subjects' driving experience and education were purely observed. Subjects' age and gender were not purely observed in the sense that the subject pool was selected to be representative of the Oregon driving population, which was defined on 10 years of previous Oregon DMV records. That is, male/female proportion and the age distribution of the sample were kept close to the Oregon driving population.

Table 1
Levels of independent variables.

Name of the variable	Category	Levels
Presence of the RSCT	Binary	1, and 0 (present or absent)
Duration of red signal	Categorical	20, 40, and 60 s
Age	Continuous	Continuous (18–78 years)
Gender	Binary	M (Male), and F (Female)
Driving experience	Categorical	Five levels (1–5)
Education	Categorical	Seven levels (1–7)

2.4. Dependent variable

When RSCTs can be seen by drivers waiting at the intersection, their reaction time at the onset of green is likely to be reduced. It is not only the first driver in the queue whose reaction time will be impacted by RSCTs, however, the first driver has the greatest potential for improved reaction time (Hurwitz et al., 2013). The first headway is larger than each of the subsequent headways and it controls the delay experienced by the rest of the queued vehicles. Therefore, the first headway was taken as a dependent variable for this experiment. Fig. 4 explains how the first headway was measured in the simulator. The centroid position of the subject vehicle, its speed, and the signal display information were recorded by the simulator every tenth of a second. This data and the position of the stop line were used to compute the first headway. The algorithm (Eq. (1)) of calculating the first headway adopted in this experiment (Roess et al., 2011) was as following:

$$\text{Headway} = T_2 - T_1 \quad (1)$$

where

T_1 = Time recorded when the signal state changed from Red to Green.

T_2 = Time when the front axle cleared the stop line.

The headways were measured at three intersections designed with three red signal durations (20, 40, and 60 s) from each of the test tracks (with RSCTs and without RSCTs). Thus, there were six data points generated for each test subject.

2.5. Experimental procedure

The experimental procedure can be described in six sequential steps. Step 1: Upon arrival in the laboratory, an IRB (Study Number 5990) approved informed consent document was presented and explained to the subject. Step 2: Subject demo-

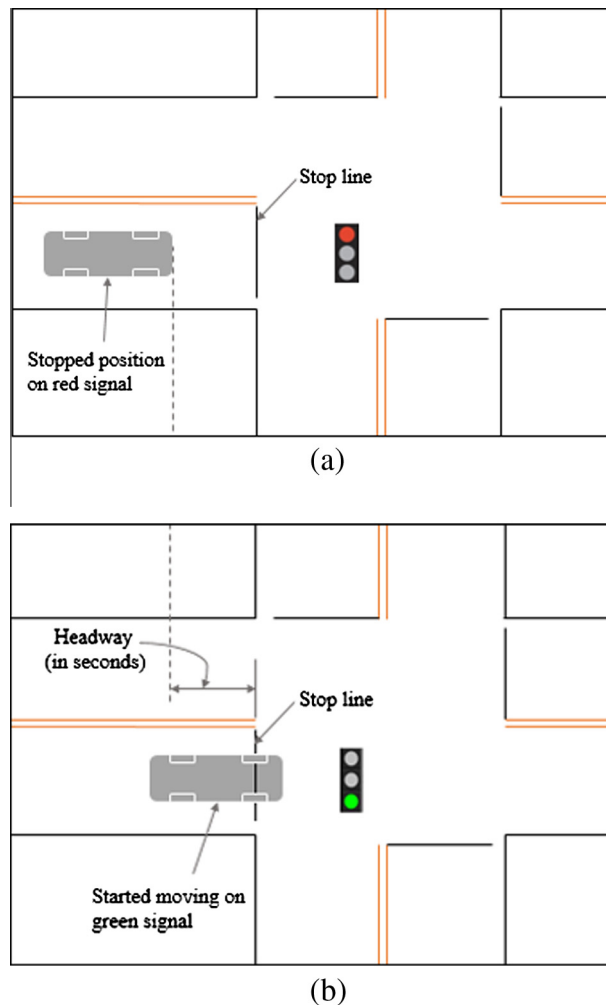


Fig. 4. Headway of the first vehicle in a standing queue.

graphics were collected through an online survey. Step 3: Subjects performed a calibration drive including roads, signalized intersections, and adjacent land-use similar to that of the experiment lasting approximately 4 min. The purpose of the drive was to acclimate the driver to the operational characteristics of the simulator and to assess the likelihood of simulator sickness. Step 4: The experimental drive without RSCT was administered. The authors did not perform a “crossover” design where the order of exposure to different treatments varies between subjects. In a crossover design, a significant time gap should exist between exposures to different treatments to “washout” the carryover effect and remove statistical bias (Hedayat and Stufken, 2003). Testing each subject at two different times with considerable time gap was not a viable option for this study. However, the instantaneous speeds (measured at a distance upstream of the intersections where no effect of RSCTs should exist) from the control and the treatment scenarios were examined to confirm that subjects’ usual driving behavior did not differ between the two scenarios. Step 5: Subjects were provided instructions regarding the meaning of RSCTs. The instructions included a one-page handout with pictures and text as well as verbal instructions from a researcher. This procedure of instructing drivers on the new traffic signal devices was consistent with previous driving simulator-based research (Knodler et al., 2005). Then the Experimental drive with the RSCTs was conducted. Step 6: A follow-up online survey was conducted to evaluate the subject’s comprehension of and preferences for RSCTs.

2.6. Subjects

Subjects were recruited for the experiment through subject archives, email lists, and flyers posted on the OSU campus and in the surrounding community. All subjects were compensated \$20 for their participation in the study. Demographic information was collected with an online survey administered after the informed consent process was completed. Sixty-seven subjects participated in the simulator study. A test drive followed the prescreening survey. At this stage, drivers were required to perform a 5 min calibration drive to acclimate to the operational characteristics of the driving simulator, and to confirm if simulator sickness was a likely outcome for them. The test drive was conducted on a track similar to the ones developed for the experiments. However, it included only 3 signalized intersections and no CT. In the case that a subject reported simulation sickness during or after the calibration drive, they were excluded from the experimental drives. Approximately 18% (7 female and 5 male) of subjects reported simulation sickness at various stages of the experiment. As soon as simulator sickness was detected in subjects, their test drive was stopped. All responses recorded from the subjects who exhibited simulator sickness were excluded from the data analysis. Thus, the final data set was composed of 55 test subjects; 32 male (58% of total) and 23 female (42% of total). The average age of subjects was approximately 36 with a range of 19 to 73 years and a standard deviation of 17.74 years.

3. Calculation

The objective of this experiment was to determine whether the presence of RSCTs reduced the headway of the first vehicle departing a queue in response to the onset of the green signal. Start-up lost time is the sum of the extra time that drivers waiting in a queue on red signal require over the saturation headway. In the driving simulator, only one subject can be tested in a built environment, which limits the headway measurement for only the first vehicle, i.e., subject’s vehicle. From the previously mentioned studies on start-up lost time, we know that the first headway in a standing queue is a major component of the start-up lost time. Therefore, if the presence of RSCTs helps to reduce the first headway of a standing queue, it can be said that it contributes to reducing the start-up lost time.

Ambient traffic was controlled in such a way that the subject vehicle was always the first vehicle in the standing queue during the experiment. As the subject vehicle was always the first vehicle in the standing queue, the headway was measured as the time lapse between the onset of the green signal and the time when the front axle of the vehicle crossed the stop line (Roess et al., 2011). The headway calculation process is further illustrated in Fig. 4. The centroid position of the vehicle was collected from the simulator every tenth of a second, which was used to calculate the headway.

Driver behavior at signalized intersections is influenced by a variety of environmental factors, including excessive wait times during red signals (Abou-Zeid et al., 2011). It has been documented that drivers waiting at an intersection during longer red signals are more likely to be distracted and respond more slowly at the onset of the green signal, resulting in longer headways (Hurwitz et al., 2013). The experimental design sought to determine if the first headway was influenced by the presence of RSCTs. Additionally, three different red signal durations (20, 40, and 60 s) were used to test first driver headways during different lengths of wait time.

4. Results

4.1. Data exploration

As stated in the previous subsection, for each test subject, the headways were measured with and without an RSCT for three red signal durations, resulting in six different headway measurements for each subject (Table 2).

Each of the six measurements from Table 2 (H_{N20} , H_{N40} , etc.) had 55 observations from 55 test subjects. It is critical to understand that observations for H_{N20} and H_{Y20} came from the same test subject, and thus, were not independent. The same

logic applied to the other measurements listed in the Table 2. A visual representation of the variation in the data based on the two major controlled independent variables (presence of RSCTs, and duration of red signal) was constructed (Fig. 5). Headways appear to have been affected by the presence of RSCTs, although variations due to different red signal durations and other sources, such as subjects' demographics, have not been taken into account in this figure. The first headway appeared to be decreased in the presence of RSCTs, as anticipated.

A logical step before developing a mathematical model was to statistically test whether the presence of RSCTs truly affected the headways. As the data were collected from the same sample, paired *t*-tests were conducted to report the variations in the sample means for different scenarios. Although, the two values that made up each paired difference were not independent from each other, the paired differences were independent. Thus, the assumption of the independence of the paired differences, required for the tests, was not violated.

Three independent tests were conducted to compare the means of observations H_{N20} with H_{Y20} , H_{N40} with H_{Y40} , and H_{N60} with H_{Y60} . It can be seen from the test results (Table 3) that regardless of the red signal duration, the mean differences in first vehicle headways were statistically significant ($p < 0.001$). In addition, the mean headways for the scenarios where RSCTs were present were smaller in all three cases of red durations. This indicated that the presence of RSCTs effectively reduced drivers' reaction time at the onset of green (0.44, 1.41, and 0.60 s for red duration equals to 20, 40, and 60 s, respectively).

4.2. Development of mathematical model

The experiment was designed with a plan to develop a mathematical model for the first headway with reasonable predictive power. This section includes a justification for the type of statistical model used, and an explanation of the model finalizing process.

4.2.1. Model selection: Linear Mixed Effect (LME) model

The variables included in the model were explained in Subsection 2.3 described as well as potential sources of variations which were assumed to have a "fixed effect". It was also imperative to consider the variation in response due to the inherent differences among subjects; a "random effect".

In addition, a simple linear regression model requires independent observations, i.e., a single measurement per experimental unit. However, in this experimental design, multiple measurements were taken per subject. Each subject gave six headway responses, which violated the independence assumption of a linear model. Multiple responses (in statistical terminology, "repeated measures") from the same subject cannot be regarded as independent (Winter, 2014). Every subject was different from one another, even when two subjects had identical demographics. Thus, a "mixed effect" model (Fox, 2002) was considered as the most appropriate mathematical model for the data.

In order to further explain the subjective variations, headways for five randomly selected males and females were plotted (Fig. 6). As can be seen in the figure, the responses were visually different for different test subjects. Also noticeable, the between-subjects variation was higher for females than for males. Because all test subjects were exposed to the same experimental treatments, this graphical presentation supports the argument that every test subject was indeed different from one another, which also supports the inclusion of subject in the model as a random effect.

4.2.2. Finalizing the model

The entire data set was randomly split in half, for the purpose of developing the model with one half, and cross-validating the model with the second half. This method of "data-splitting" for cross-validating predictive models is very common in statistics (Picard and Cook, 1984; Picard and Berk, 1990). To divide the data, the responses from males and females of different age groups were placed into separate bins, and then the first half was picked randomly from each bin (Table 4). The age groups were defined based on the crash statistics of Oregon drivers involved in injury or fatal crashes (ODOT, 2013). However, the first age group was modified to include drivers 18 years of age or above, which ensured that the younger test subjects had the legal authority to sign informed consent documentation. In addition, test subjects over age 65 were combined into one group due to comparatively lower participation rates.

The influence of education and of driving experience on drivers' responses to RSCTs was included in the statistical model as categorical variables. Small differences (e.g., 1 or 2 years) in driving experience are not likely to significantly alter driving behavior.

Table 2

Six measurements from each individual test subject.

		RSCT present? (N/Y)	
		No	Yes
Duration of Red signal (s)	20	H_{N20}	H_{Y20}
	40	H_{N40}	H_{Y40}
	60	H_{N60}	H_{Y60}

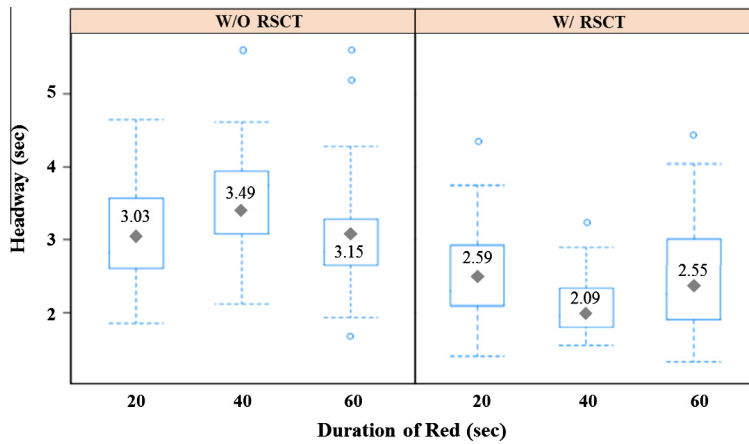


Fig. 5. Box-plot of first vehicle headway data with mean values.

Table 3
Results of paired *t*-test (without RSCT and with RSCT).

Hypothesis tested	Sample size	<i>t</i> -value	<i>p</i> -value	Comment	Mean differences and 95% confidence intervals (s)
No difference in first headways caused by the presence of RSCT for red-signal duration = 20 s	55	4.78	<0.001	Significant difference	0.44 0.25–0.62
No difference in first headways caused by the presence of RSCT for red-signal duration = 40 s	55	19.24	<0.001	Significant difference	1.41 1.26–1.56
No difference in first headways caused by the presence of RSCT for red-signal duration = 60 s	55	5.83	<0.001	Significant difference	0.60 0.39–0.80

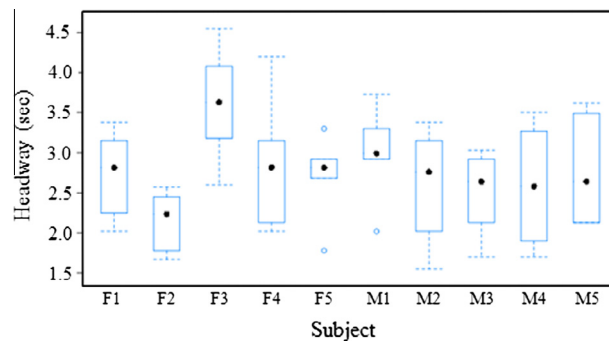


Fig. 6. Box plot of headway responses from 10 subjects.

Table 4
Splitting data for model development and cross-validation.

	Column 1 Age group 1	Column 2 Age group 2	Column 3 Age group 3	Sample
# of Males (total data set)	M1	M2	M3	so on
# of Females (total data set)	F1	F2	F3	
Data for model (randomly picked)	(M1/2) + (F1/2)	(M2/2) + (F2/2)	(M3/2) + (F3/2)	$\sum(\text{Column } N) (N = 1, 2, \dots \text{ Number of age groups})$
Total				55/2 \approx 28 subjects

As the first step of developing the LME, only a random intercept model was considered rather than selecting a model with both a random intercept and a random slope. In this “null model”, a baseline difference in headway was accounted for, but the effect that the presence of RSCTs might have on subjects, was assumed to be the same. This assumption might have compromised the precision of the model to some degree, but provided a simpler model, less complex than a random slope model.

In order to verify whether a random intercept only model unacceptably compromised the model accuracy, two random slope models (i.e., interaction between subject and the treatment) were developed. These models considered the possibility that the effect of the treatment (presence of CT or the red-signal duration) had varying effects on the subjects. A comparative analysis of these two models with the null model is given in Table 5. As can be seen, the likelihoods that the null model generates a different outcome than the full models were not statistically significant, and the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values suggest that the intercept only model is slightly better than the random slope models. Additionally, a validation attempt was conducted, and the prediction accuracy was estimated, which is presented later in this paper. The mathematical model with a random slope for the presence of RSCT, as coded in R statistical package, is shown in Eq. (2).

$$\begin{aligned} \text{rsct.model} &= \text{lme}(\text{Headway} \sim \text{RSCT} + \text{Red} + \text{Age} + \text{Gender} + \text{Edu} + \text{DExp}, \text{random} = \sim 1 + \text{CT} | \text{Subject}, \text{data} \\ &= \text{rsct.lmm}) \end{aligned} \quad (2)$$

The full model with random intercept (Eq. (3)), previously called the “null model”, included all explanatory variables was as following:

$$\text{Headway}_1 \sim (1 | \text{Subject}) + \text{RSCT} + \text{Red} + \text{Age} + \text{Gender} + \text{Edu} + \text{DExp} \quad (3)$$

where

*Headway*₁ = First headway, or the headway measured in different test scenarios.

(1|*Subject*) = Random effect of subjects.

RSCT = Presence of RSCTs; 1 if present, and 0 otherwise.

Red = Duration of red signals; 20, 40, and 60 s.

Age = Subject's age in years.

Gender = Subject's gender; factor with two levels.

Edu = Subject's education; factor with seven levels.

DExp = Subject's driving experience; factor with five levels.

The full model was taken as the starting point for selecting the final model. As shown in Table 6, the next iteration of the LME model was taken based on the AIC and significant fixed effect predictors. At each iteration, one non-significant fixed effect predictor was removed and the resulting model was compared with the previous model(s). For example, in iteration 2, driving experience was excluded from the model as it was found non-significant.

In the fourth iteration, the coefficients of red-duration 60 s (0.24) and 40 s (0.023) were found to be statistically significant (p -value = 0.015) and non-significant (p -value = 0.76), respectively. Both of these coefficients represent the difference in coefficients with red-duration equal to 20 s. In other words, the first headway for red-duration 60 s is expected to be 0.24 s longer than the red duration 20 s, if all other predictors remain unchanged. Similarly, the difference between 20 s and 40 s is expected to be only 0.023 s. Due to these inconsistent results, it was of interest whether the red-duration variable improved the model fit. To check that, red-duration was excluded in iteration 5 and a likelihood ratio test was conducted between the two linear models; one with, and one without the red-duration as a predictor. The likelihood ratio test was non-significant (p -value = 0.12), suggesting that excluding the red-duration from the model should not result in a significant reduction of its predictive power. As such, the final model (Eq. (4)) included subject as random effect, and presence of RSCTs, and age as fixed effects. The presence of age in the final model was evidence of the influence of age on driver response to signal change from red to green. The negative coefficient of age in the final model (−0.013) suggests that the headway will be slightly shorter for an older driver. Age has been shown to influence perceptual reaction times to an event and driver distraction. Both younger

Table 5
Intercept-only vs. random slope models comparison.

Comparison	Comparison results				
	AIC	BIC	Likelihood Ratio	p -value	Comment
“Null” (random intercept only) vs. Random intercept and random slope for CT	343.9 vs. 345.9	392.5 vs. 400.6	1.98	0.37	No evidence of statistically significant difference
“Null” vs. random intercept and random slope for red-signal duration	343.9 vs. 348.2	392.5 vs. 411.9	5.73	0.33	No evidence of statistically significant difference

Table 6
Model selection of RSCT experiment.

Iteration	Model	AIC	Significant fixed effects	Comments
1	$Headway_1 \sim (1 Subject) + RSCT + Red + Age + Gender + Edu + DExp$	343.9	RSCT, and Red	–
2	$Headway_1 \sim (1 Subject) + RSCT + Red + Age + Gender + Edu$	342.9	RSCT, and Red	Similar to model 1
3	$Headway_1 \sim (1 Subject) + RSCT + Red + Age + Gender$	333.8	RSCT, Red, and Age	Improved model over 1 and 2
4	$Headway_1 \sim (1 Subject) + RSCT + Red + Age$	331.4	RSCT, Red, and Age	Improved model over 1, 2, and 3
5	$Headway_1 \sim (1 Subject) + RSCT + Age$	328.5	RSCT and Age	Final model

and older drivers lack ability to “share attention between two concurrent tasks” (Young and Regan, 2007). Older drivers suffer from decreased visual and cognitive ability to maintain attention on the driving task. Younger drivers usually outperform older drivers in terms of perceptual reaction times (i.e., quicker to respond), but they are more susceptible to distraction due to a lack of driving experience.

Final Linear Mixed Model:

$$Headway_1 \sim (1|Subject) + RSCT + Age \tag{4}$$

The numerical representation of the equation is a bit more complex than multiple linear regression due to the presence of a random effect in the equation. The random effect is presented in matrix form including one intercept for each test subject. Eq. (5) represents a general form of the equation (Fox, 2002):

$$Y_i = X_i\beta + Z_i b_i + \varepsilon_i \tag{5}$$

where

- $Y_i = n_i \times 1$ response vector for observations in i -th group.
- $X_i = n_i \times p$ model matrix for the fixed effects for observations in group i .
- $\beta = p \times 1$ vector of fixed-effect coefficients.
- $Z_i = n_i \times q$ model matrix for the random effects for observations in group i .
- $b_i = q \times 1$ vector of random-effect coefficients for group i .
- $\varepsilon_i = n_i \times 1$ vector of errors for observations in group i .

Numerically, the final model is as following (Eq. (6)):

$$\begin{pmatrix} Headway_{11} \\ Headway_{12} \\ \vdots \\ Headway_{128} \end{pmatrix} = \underbrace{\begin{pmatrix} 3.54 \\ 3.53 \\ \vdots \\ 3.79 \end{pmatrix}}_{\text{Random Effect}} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{28} \end{pmatrix} + \underbrace{\begin{pmatrix} -0.72 \\ -0.72 \\ \vdots \\ -0.72 \end{pmatrix}}_{\text{Fixed Effects}} RSCT + \underbrace{\begin{pmatrix} -0.013 \\ -0.013 \\ \vdots \\ -0.013 \end{pmatrix}}_{\text{Fixed Effects}} Age \tag{6}$$

where

- $Headway_{1i}$ = The first headway for i -th subject
- $X_i = 1$ for i -th subject, and 0 otherwise.

The coefficients of intercept in Eq. (6) are different, representing the random effect of subject. The coefficients for the fixed effect variables are the same because the random slopes for the by-subject effect were not considered. The summary output and the coefficients of the final model (Eq. (6)) are given in detail in Table 7. Certain aspects of the result are worth noted. First, the standard deviation for the intercept of random effect suggests that the subject causes a significant variability (0.44 s) in the first headway. Second, unlike the coefficients RSCT and Age, the coefficients for the random intercept are different. It suggests that the subject was considered a random effect in the model, while the other two variables were considered to have fixed effect on the first headway.

In general, the model assumptions, such as linearity, normality, and homoscedasticity held. The fitted values of headways were computed from the model and a paired t -test was performed to test the difference between the headways with and without RSCTs. The t -test result indicated the difference in headways (0.73 s) was statistically significant (p -value < 0.001).

The residuals were plotted in the form of a histogram (Fig. 7a) and as expected, they were approximately normally distributed around a mean zero. The residual vs. fitted values plot (Fig. 7b), and the normal quantile–quantile plot (Fig. 7c) support the assumptions of homoscedasticity and normality, respectively.

4.2.3. Validation of the model

In an attempt to validate the model, the second half of the data (27 subjects) was used, and the headways were considered as the “observed” responses, while the headways computed from the model were taken as the “predicted” responses. The results of the comparison between the predicted and the observed responses are presented in Table 8.

Table 7
Summary/results of the final model.

Model summary:					
AIC		BIC		logLik	
328.58		344.11		-159.29	
<i>Random effects:</i>					
Formula: ~1 Subject					
		(Intercept)		Residual	
Std. Dev:		0.44		0.53	
Fixed effects: Headway ~ CT + Age					
	Value	Std. Error	DF	t-value	p-value
(Intercept)	3.770	0.236	139	15.957	<0.001
CT1	-0.726	0.081	139	-8.955	<0.001
Age	-0.013	0.005	26	-2.717	0.0116
Number of Observations: 168					
Number of Groups: 28					

The comparison of the predicted vs. observed mean headways showed no significant difference for both scenarios - presence and absence of RSCTs. Thus, it can be concluded that the mathematical model developed using the first half of the data was capable of predicting the variation in headways explained by the second half of the data.

5. Discussion

5.1. Study limitations

TSCTs have predominantly been used internationally for pre-timed signals. The reason why TSCT are typically used for actuated signals is that the current vehicle detection mechanisms and signal control algorithms for actuated systems permit the precise estimation of time remaining for a signal only a few seconds before phase termination. Typically, the final determination is made 1–4 s (Tarnoff and Parsonson, 1981) before the signal changes (e.g., green to yellow, or red to green), providing a limited interval for the countdown to be displayed. This characteristic has widely been described as the most significant limitation to applying TSCT in actuated traffic signal systems (Chen et al., 2009). Therefore, this research studied driver behavior in presence of TSCT exclusively at pre-timed traffic signals.

The research also focused on the investigation of TSCT effectiveness by considering the RSCT. The YSCT was not considered as previous research (Long et al., 2011) has shown minimal positive impact.

To simplify the experimental design and reduce the potential occurrence of simulator sickness, left-turns were excluded from the study design. Although, TSCT have been used for left-turn movements as well, limiting the scope to through movements enabled the researchers to focus on the effectiveness of RSCTs while minimizing the risk of simulator sickness for participating drivers.

Another potential limitation was the use of a repeated measures experimental design. In this type of design each subject is repeatedly exposed to experimental scenarios, resulting in the potential for the results to be confounded by time (e.g. learning effects, familiarization to the simulator, drivers becoming less attentive with time, etc.). However, instantaneous speeds were examined upstream of the signals where no effect of RSCTs should exist. Analysis confirmed that subjects' usual driving behavior did not differ between the two scenarios.

5.2. Interpretation of results

The effectiveness of a RSCT was quantified in terms of the time a driver took to cross the stop line (after the onset of the green signal) from the stopped condition (on red signal), also referred to as the first vehicle headway. The *t*-test result confirmed that the presence of RSCTs influences drivers' reaction times to the change in signal (from red to green), resulting in the reduction of the first vehicle headway by 0.73 s (*p*-value < 0.001). On the other hand, the influence of red-duration on the headways was not as clear. No significant difference in the headways was reported between red durations of 20 and 40 s. However, a significant difference in the first vehicle headways of 0.24 s was found between red durations of 20 s and 60 s. Drivers frequently encounter red durations of 20–40 s at low volume intersections. Thus, they may have been more alert when the wait time at intersection was below 40 s. Driver distraction increases with delay at signalized intersections, which can encourage drivers to engage in secondary tasks. As a result, driver perceptual reaction time and response time to a change in the traffic signal increases, leading to an increase in the first headway. This result provides some evidence that drivers become more distracted as intersection delay increases.

This study produced a statistical model to calculate the first vehicle headway at a signalized intersection in the presence of RSCTs. A linear mixed effect model was used to examine between-subject variations, and there was convincing evidence

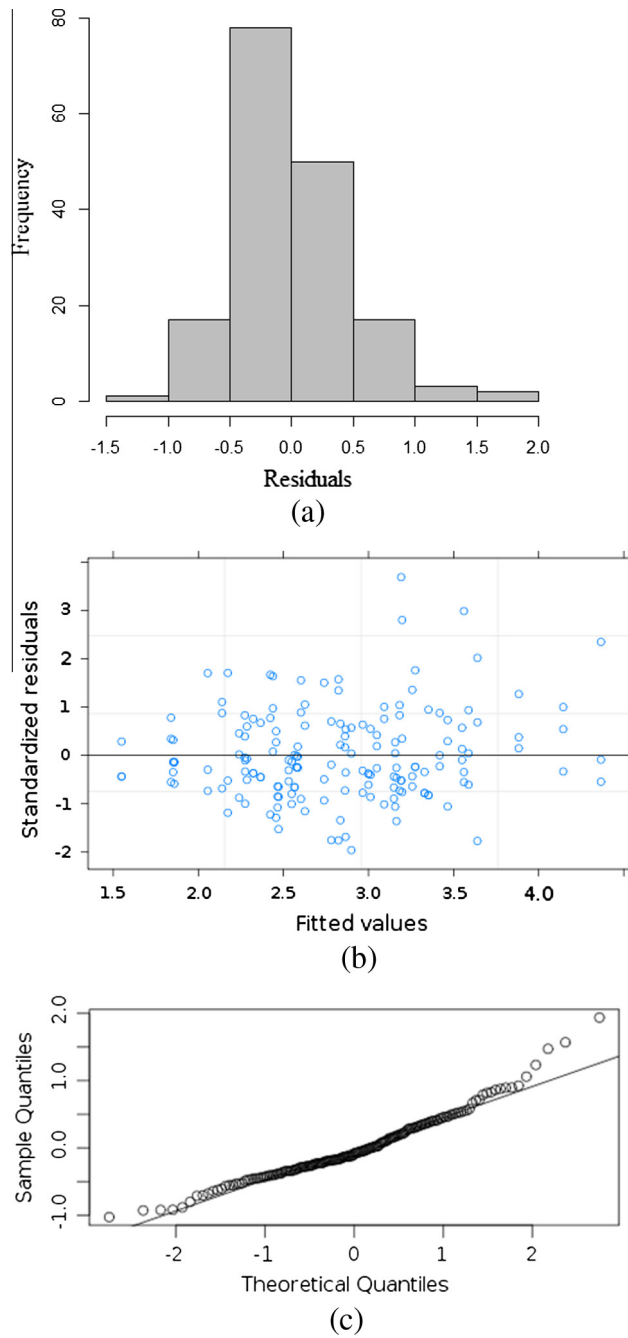


Fig. 7. (a) Histogram of the residuals, (b) residual vs fitted plot, and (c) normal Q–Q plot.

Table 8
Validation of the model.

	Mean first headway	
	Without RSCT	With RSCT
Predicted (model)	3.19	2.47
Observed	3.26	2.35
Two sample <i>t</i> -test result	No evidence of difference (<i>p</i> -value = 0.46)	
Prediction accuracy	97.8%	95.5%

that the random effect of subjects explains a large percentage of the variation (52.6%) in the headway. This result suggests that the response time at the onset of green, and distraction while waiting on red, vary widely between subjects. The negative coefficient of age in the final model indicates that the older subjects were more responsive (or more attentive) to the information displayed by RSCTs. This result supports the previously presented hypothesis that the younger drivers are more susceptible to distraction while waiting at a signal. Distraction among the younger test subjects was also evident in researchers' observation during the simulated driving test in the lab. Although, in general younger drivers were found to be more comfortable with the simulator than other drivers of older age groups, many of them were found to be less attentive in the simulated driving task and engaged in other non-driving related tasks. The model suggests a 0.72 s reduction for the first vehicle headway in the presence of RSCTs. The first headway of a discharging queue ranges from 2.65 s to 4.5 s (Bonnensen, 1992), and both predicted and observed headways from the study fell in this range. The study concludes that the presence of RSCTs will reduce the first headway by approximately 22.5%. As such, in the best possible scenario (the driver is not distracted), the model estimates that the reduction in delay per cycle per intersection approach will occur in the magnitude of $0.72N$ vehicle-seconds/hour, where N is the number of phases per hour. This is the most conservative estimate of the reduction in delay as it only considers the time saved from the first vehicle. If similar reductions in delay occur for subsequent vehicles (which was outside the scope of this research), that will result in additional increases to the total time saved.

The likelihood ratio test between the two models (with and without red-duration as a predictor) suggested that the exclusion of the red-duration from the final model did not result in a significant reduction in the prediction power. A comparison of the predicted and observed headways performed with half the data (not used in model development) showed convincing prediction accuracy (>95%). A comparison of the mean predicted vs. observed headways showed no significant difference, meaning that the model which was calibrated with half of the data, accurately predicted the observed headways of the remaining half of the data.

This study reports a mean reduction of 0.72 s in the first headway resulting from the presence of RSCTs. Limanond et al. found that RSCTs reduced the start-up lost by 1.00–1.92 s (2009), and 1.24 s (2010) at the beginning of the green phase. Chiou and Chang (2010) reported 0.6 s and 2.25 s reduction in the start-up lost time for left-turns and through movements respectively in the presence of RSCTs. As previously described, the first headway is the major contributor to the start-up lost time. The reduction in start-up lost time determined by this research is consistent with the findings of previous field work conducted internationally, providing important evidence that driving simulation is a valid experimental tool for evaluating traffic psychology and behavior issues at signalized intersections. However, the current work represents the first predictive model describing the responses of US drivers to RSCTs.

6. Conclusion

Given our results, we conclude that the implementation of RSCTs at signalized intersections in Oregon will likely result in a significant reduction in the first vehicle headway, which in turn will reduce the start-up lost time and improve intersection efficiency. There are several reasons that we chose the classification scheme from the Oregon crash statistics for driver age-grouping.

This study developed an LME model that predicted the presence of RSCTs reduces the first vehicle headway by 0.72 s (at a minimum) in a discharging queue at the onset of the green signal. The observed reduction in first vehicle headways was 0.82 s. It was also determined that the effect of the duration of red, i.e., the duration of wait time, on the first vehicle headway, was minimal for red signal times ranging from 20 to 60 s.

This research established preliminary evidence supporting the benefit of applying TSCT at signalized intersections. It developed and validated several predictive models, with high levels of accuracy. However, the scopes of inference for the developed models were limited due to the scope of the experiments, and subject recruitment. These limitations form the basis of recommendations for future work including:

- A larger and more diverse sample. Older age groups were slightly under-represented in the sample. A larger sample size has the potential of eliminating unexpected bias on the response variable.
- Expanding the driving simulation studies to include GSCT, YSCT, other TSCT display configurations, and other intersection types. Additional evidence will strengthen the case for the use of these signals.
- Field-testing and multi-driver simulation (a connection of several driving simulators) of TSCT. The correspondence between the real-world and the simulated environment needs to be good enough to insure that driver behavior is reasonably similar in both situations. Although reasonable validation efforts were made in this work, studying driver responses to TSCT in the field is critical if they are to be considered for adoption at any scale in the United States.
- Multi-driver simulation (a connection of several driving simulators) would allow for a robust evaluation of the 2nd, 3rd, 4th, etc. vehicle headways simultaneously.

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References

- Abou-Zeid, M., Kaysi, I., Al-Naghi, H., 2011. Measuring aggressive driving behavior using a driving simulator: an exploratory study. In: Third International Conference on Road Safety and Simulation, Indianapolis, USA, September 14–16, 2011.
- Bella, F., 2008. Driving simulator for speed research on two-lane rural roads. *Accid. Anal. Prevent.* 40 (3), 1078–1087.
- Bella, F., 2005. Validation of a driving simulator for work zone design. *Transport. Res. Rec.: J. Transport. Res. Board* 1937, 136–144.
- Bonnensen, J.A., 1992. Study of headway and lost time at single-point urban interchanges. *Transport. Res. Rec.* 1365, 30–39.
- Chen, H., Zhao, H., Hsu, P., 2009. What do we know about signal countdown timer? ITE Journal on the Web.
- Chiou, Y.C., Chang, C.H., 2010. Driver responses to green and red vehicular signal countdown displays: safety and efficiency aspects. *Accid. Anal. Prevent.*, 1057–1065.
- Federal Highway Administration (FHWA), 2009. Manual on Uniform Traffic Control Devices. U.S. Department of Transportation.
- Federal Highway Administration (FHWA), 2012. The evolution of MUTCD. Manual on Uniform Traffic Control Devices (MUTCD). Available at: <<http://mutcd.fhwa.dot.gov/kno-history.htm>> (last modified: May 11, 2012. Accessed: May 27, 2013).
- Fox, J., 2002. Linear mixed models. Appendix to an R and S-PLUS Companion to Applied Regression. Available at: <<http://cran.r-project.org/doc/contrib/Fox-Companion/appendix-mixed-models.pdf>>.
- Hedayat, A.S., Stufken, J., 2003. Optimal and efficient crossover designs under different assumptions for the carryover effects. *J. Biopharm. Stat.* 13, 519–528.
- Hurwitz, D., Heaslip, K., Shrock, S., Swake, J., Marnell, P., Tuss, H., Fitzsimmons, E., 2013. Implications of distracted driving on driver behavior in the standing queue of dual left-turn lanes. *J. Transport., ASCE*, 923.
- Ibrahim, M., Karim, M., Kidwai, F., 2008. The effect of digital count-down display on signalized junction performance. *Am. J. Appl. Sci.* 5 (5), 479–482.
- Knodler Jr., M.A., Noyce, D.A., Kacir, K.C., Brehmer, C.L., 2001. Driver understanding of the green ball and flashing yellow arrow permitted indications: a driving simulator experiment. In: Presented at ITE Conference, Chicago, Ill, 2001.
- Knodler, M., Noyce, D., Kacir, K., Gardner, S., 2005. An Evaluation of the Flashing Yellow Arrow Permissive Indication for Use in Simultaneous Indications. Transportation Research Record: Journal of the Transportation Research Board, No. 1918, Transportation Research Board of the National Academies, Washington, D.C., pp. 46–55.
- Limanond, T., Chookerd, S., Roubtonglang, N., 2009. Effects of countdown timers on queue discharge characteristics of through movement at a signalized intersection. *Transport. Res. Part C* 17, 662–671.
- Limanond, T., Prabjapok, 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.
- Liu, P., Yu, H., Wang, W., Ma, J., Wang, S., 2012. Evaluating the effects of signal countdown timers on queue discharge characteristics at signalized intersections in China. *Transport. Res. Rec.: J. Transport. Res. Board* 2286, 39–48.
- Long, K., Han, L.D., Yang, Q., 2011. Effects of countdown timers on driver behavior after the yellow onset at Chinese intersections. *Traffic Injury Prevent.* 12, 538–544.
- Moore, D., Hurwitz, D.S., 2013. Fuzzy logic for improved dilemma zone identification: driving simulator study. *Transport. Res. Rec.: J. Transport. Res. Board* 2384, 25–34.
- Neill, J., Hurwitz, D., Olsen, M., 2016. Alternative information signs: an evaluation of driver comprehension and visual attention. *ASCE: J. Transport. Eng.* 142 (1), <<http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29TE.1943-5436.0000807>>.
- Oregon Department of Transportation (ODOT), 2013. Oregon traffic crash summary 2012. Transportation Data Section, Crash Analysis and Reporting Unit, September 2013.
- Picard, R.R., Berk, K.N., 1990. Data splitting. *Am. Stat.* 44 (2), 140–147.
- Picard, R.R., Cook, R.D., 1984. Cross-validation of regression models. *J. Am. Stat. Assoc.* 79 (387), 575–583.
- Roess, R., Prassas, E., McShane, W., 2011. *Traffic Engineering*, fourth ed. Pearson Higher Education Inc., Upper Saddle River, NJ.
- Sharma, A., Vanajakshi, L., Rao, N., 2009. Effect of phase countdown timers on queue discharge characteristics under heterogeneous traffic conditions. *Transport. Res. Rec.* 2130, 93–100.
- Swake, J., Jannat, M., Islam, M., Hurwitz, D., 2013. Driver response to phase termination at signalized intersections: are driving simulator results valid? In: Presented at Seventh International Driving Symposium on Human Factors in Driving Assessment, Training, and Vehicle Design, Bolton Landing, N.Y., 2013.
- Tarnoff, P., Parsonson, P., 1981. NCHRP Report 233: Selecting Traffic Signal Control at Individual Intersections. Transportation Research Board, National Research Council, Washington, D.C.
- Törnros, J., 1998. Driving behaviour in a real and a simulated road tunnel—a validation study. *Accid. Anal. Prevent.* 30 (4), 497–503.
- Transportation Research Board, 2012. HCM 2010. Volume 3, Interrupted Flow.
- Winter, B., 2014. A Very Basic Tutorial for Performing Linear Mixed Effects Analyses (Tutorial 2). University of California, Merced, Cognitive and Information Sciences. <http://www.bodowinter.com/tutorial/bw_LME_tutorial.pdf>.
- Young, K., Regan, M., 2007. Driver distraction: a review of the literature. In: Faulks, I.J., Regan, M., Stevenson, M., Brown, J., Porter, A., Irwin, J.D. (Eds.), *Distracted Driving*. Australasian College of Road Safety, Sydney, NSW, pp. 379–405.

Glossary

- Akaike Information Criterion (AIC):** for a given data set, the AIC statistic provides a relative measure of the quality of one statistical model over another. Thus, AIC was used as a means of selecting the best fit model
- Perceptual Reaction Time (PRT):** total time taken by a driver to perceive a change of event in the driving environment (e.g., change of signal) and commence an appropriate response to the change
- Traffic Signal Countdown Timer (TSCT):** a device that displays the remaining number of seconds of the active signal for vehicular traffic
- Headway:** the time gap, in seconds, between successive vehicles at a given point on the road
- First headway:** the time, in seconds, taken by the first car in a standing queue to reach the stop-line (i.e., front axle over the stop-line) from a stopped position after the signal changes from red to green
- Start-up lost time:** start-up lost time is the sum of the extra time that the first four or five drivers waiting in a queue during a red signal require beyond the saturation headway
- Signalized intersection Efficiency:** characterized by a set of predefined performance measures (e.g., delay, queue length, number of stops etc.). In this study, the control delay at signalized intersection was applied to quantify efficiency
- Actuated signal:** vehicle's presence is detected by the signal controller, and hence, the signal is responsive of actual vehicle demand at the intersection
- Discharging queue:** the queue of vehicles at the intersection that is currently being served by the traffic signal at the onset of the green
- Driving Simulator:** a research tool that facilitates the measurement of driver responses/reactions in a simulated driving environment
- Fixed-time signal:** signal timing parameters do not respond to the vehicle's presence, rather they are based on a pre-assumed traffic demand
- Timer controller:** a device of mechanism (add-on or integrated with the Signal controller) that controls the display on the traffic signal countdown device
- Clearance lost time:** the time, in seconds, between signal phases during which cannot be used by the traffic
- Time-to-stop-line (TTSL):** the time, in seconds, required for a vehicle traveling at a particular speed to reach the stop line of the intersection approach from its current position