



# Driver responses to green and red vehicular signal countdown displays: Safety and efficiency aspects

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## ABSTRACT

This study investigates the effects of green signal countdown display (GSCD) and red signal countdown display (RSCD) on driver behaviours, and thus on intersection safety and efficiency. Three driver responses to GSCD, including late-stopping ratio, dilemma zone and decision to cross, and three driver responses to RSCD, including early start ratio, start-up delay, and discharge headway are observed and analyzed. Results show that although GSCD can reduce late-stopping ratio, the dilemma zone is increased by about 28 m and the decision to cross will be more inconsistent among the approaching vehicles, creating a potential risk of rear-end crashes. Additionally, following the provision of a green countdown the number of vehicles ejecting to cross the intersection reduces. On the other hand, comparisons among four observation periods examining the effects of RSCD—before-RSCD, 1.5 months after-RSCD, 3.0 months after-RSCD and 4.5 months after-RSCD, show that although RSCD significantly reduces the early start ratios of the leading vehicles in various waiting areas, the ratios soon return to their before-RSCD levels, suggesting that RSCD does not significantly improve intersection safety over the longer term. However, RSCD effectively reduces start-up delay, saturated headway, and cumulative start-up delay at 4.5 months after-RSCD installation. Thus, RSCD enhances intersection efficiency. RSCD is clearly less controversial and more beneficial than GSCD.

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## 1. Introduction

To facilitate drivers' decision to cross or to stop during the critical phase-change period and to ease their waiting impatience in red phase, many countries worldwide equipped vehicular signal with green signal countdown display (GSCD) or red signal countdown display (RSCD) to provide drivers with a green or red countdown timing and help them make an informed decision. Taking Taiwan for instance, since the first introduction of GSCD in Hsinjhu City in 2000, a total of 1036 intersections of 22 counties/cities out of 25 have been installed either green, red or both countdown devices at the end of 2007. The pictorial view of two types, externally hanged and built-in, of RSCD and GSCD are depicted in Fig. 1.

Despite the popularity of countdown devices, relatively few studies have examined driver responses to countdown devices. In one of the earliest systematic studies, Lum and Halim (2006), reported a before-and-after study evaluating differences in driver response when approaching a signalized intersection with GSCD. Interestingly, they found a significant 65% reduction in red-running violations at 1.5 months following GSCD installation, but the effec-

tiveness tended to dissipate over time with violations gradually returning to near pre-GSCD installation levels. Additionally, the number of approaching vehicles choosing to stop during the onset of amber significantly increased. Therefore, they concluded that the longer term performance of GSCD would help encourage stopping, but would not curb red-running violations. However, their study only examined red-running and red-stopping behaviours. Other behaviours, such as changes in decision to cross and changes in dilemma zone, are also crucial to intersection safety and efficiency. Additionally, a more comprehensive study should also investigate driver responses to RSCD. In Taiwan, a research report by the Institute of Transportation (Chen et al., 2007), a government-owned transportation research center, examined the effects of RSCD and GSCD on intersection safety. Specifically, this study examined the number of fatal and injury accidents during 2003–2006 at 187 signalized intersections within one year before-and-after RSCD and GSCD installation. The results showed that the number of fatal and injury accidents at intersections with GSCD increased by 100% while the number of accidents decreased by 50% for intersections with RSCD. For the intersections equipped with both devices, the number of such accidents increased by 19%. Based on these comparisons, Chen et al. (2007) postulated that drivers tend to accelerate aggressively when green countdown information is provided, so more crashes are then induced. In contrast, the accident rate can be curtailed because drivers are more likely

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Fig. 1. Pictorial view of two types of RSCD and GSCD.

to obey red signal with the provision of red countdown information. Consequently, Chen et al. (2007) strongly recommended local authorities avoid installing GSCD but consider installing RSCD at intersections with long red time and/or multi-phase signal timing to relieve the impatience and confusion of waiting drivers, although no evidence on these postulated driver behaviours has been proven.

To improve on the gaps in the above researches, this study aims to investigate driver responses to GSCD and RSCD, respectively. Although both GSCD and RSCD are used to display remaining signal timing to drivers, they exert very different effects on driver behaviours. Generally, GSCD may affect driver behaviours that include late-stopping behaviours (red-running), dilemma zone and decision to cross. Meanwhile, RSCD may affect driver behaviours including early start behaviours (red-running), start-up delay of the leading vehicle, and discharge headway of following vehicles.

The rest of this paper is organized as follows. Section 2 classifies possible driver responses to GSCD and RSCD and then introduces the experimental design for observing driver responses. Section 3 then describes the effects of GSCD on three driver responses—late-stopping ratio (red-running ratio), dilemma zone, and decision to cross through a with-or-without approach. Meanwhile, Section 4 compares the effects of RSCD on three driver responses of early start ratio (red-running ratio), start-up delay, and discharge headway through a before-and-after approach. Finally, concluding remarks and suggestions for future studies are presented.

## 2. Experimental design and data collection

### 2.1. Driver responses to countdown devices

Although both GSCD and RSCD provide countdown timing to drivers, they affect driver behaviours differently. GSCD affects drivers during the transition from the motion state to the still state while RSCD affects them during the transition from the still state to the motion state. Consequently, drivers face the two devices from completely different situations, meaning their responses to the

two devices can be observed and analyzed separately. To examine intersection safety and efficiency issues, three phenomena related to driver responses to GSCD are analyzed, including late-stopping ratio (*i.e.* red-running ratio), dilemma zone, and decision to cross. Late-stopping ratio is defined as the percentage of drivers who cross the stop line after the signal turns red (*i.e.* the countdown value shown on the GSCD is zero). The dilemma zone denotes the space of approach where larger than 10% and less than 90% of drivers will decide to stop. The longer dilemma zone implies the concern of intersection safety. Decision to cross is defined as the probability of drivers deciding to cross the intersection under various situations characterized by approach speeds, distances from the stop line, and stages of green countdown.

Similarly, three phenomena resulting from driver responses to RSCD are observed and compared, including early start ratio (*i.e.* red-running ratio), start-up delay and discharge headway. Early start ratio is defined as the percentage of leading vehicles crossing the stop line prior to the signal turning green during each cycle. Start-up delay is the time period from the start of the green phase (*i.e.* the countdown value shown on the RSCD is zero) until the leading vehicle crosses the stop line. Because of prevalence of motorcycles on urban streets in Taiwan, a motorcycle waiting area is installed at many intersections in front of queuing cars or buses in the right lanes to reduce potential conflicts among mixed discharge traffic at the beginning of the green phase. Additionally, at many medium to large intersections in Taiwan, another waiting area for left-turning motorcycles coming from the left hand direction on the cross street is located in front of the motorcycle waiting area and pedestrian crossing. The leading vehicles behind these waiting areas definitely suffer from larger start-up delay. Consequently, the driver behaviours for vehicles in the four different waiting areas are compared, including motorcycles in the left-turn waiting area, motorcycles in the through-traffic waiting area, cars in the waiting area immediately behind the stop line (namely in the inner lanes), and cars in the waiting area behind the motorcycle waiting area (namely in the outer lanes). To further analyze the influence of RSCD on sequential vehicles, the distributions of the discharge headway are also compared, where the discharge headway denotes the time that elapses between consecutive vehi-

**Table 1**  
Late-stopping ratios of two consecutive intersections with and without GSCD.

Distance from the stop line as red phase begins (m)		0–5	6–10	11–15	16–20
With GSCD	Number of late-stopping vehicles	9	2	1	5
	Total number of vehicles	26	10	7	16
	Percentage	34.62	20.00	14.29	31.25
Without GSCD	Number of late-stopping vehicles	5	1	1	2
	Total number of vehicles	6	2	4	4
	Percentage	83.33	50.00	25.00	50.00

cles. This headway is a key determinant of intersection capacity and efficiency.

## 2.2. Experimental design

Two analytical approaches can be used to investigate how a device influences human behaviour—before-and-after analysis and with-or-without analysis. For example, Lum and Halim (2006) employed a before-and-after analysis to compare differences in red-running behaviours before GSCD installation and at various periods (1.5, 4.5 and 7.5 months) after installation. However, during the time study, safety issues resulting from GSCD caused a significant debate. An official research report conducted by the Institute of Transportation (Chen et al., 2007) strongly recommended not installing GSCD based on a before-and-after comparison of fatal and injury accident rates. Accordingly, no new GSCD installation plan has since been initiated, leading to difficulties in observing driver behaviours before GSCD installation. Thus, the with-or-without analysis approach is adopted instead by carefully selecting two consecutive intersections—those of Guangming No. 6 Road with Chung-Hua Road (with GSCD) and with Bo-Ai Road (without GSCD), in Jhubei city, which share similar geometric, signal control and traffic conditions. It should be mentioned that a yellow interval is included in the green countdown so as to inform drivers exactly how much green time (green time + yellow time) remained. After the yellow phase, a four-second all-red interval follows. Of course, driver responses to the green countdown with-or-without inclusion of the yellow interval would be significantly different and deserve a further study. Anyway, one can anticipate that if the yellow time is not included in the green countdown, the effective green time and the intersection efficiency will be reduced. Additionally, once drivers become more familiar with GSCD, they will take advantage of yellow time and decide to cross the intersection even after the green countdown has shown zero.

Unlike GSCD, many installation plans for RSCD are still undergoing, of which one at the intersection of Chung-Hsiao East Road and Dun-Hua South Road in Taipei city has been chosen. Since RSCD was installed on September 11, 2007 at this intersection, four observations were conducted, on September 7, 2007 (before-RSCD), October 26, 2007 (1.5 months after-RSCD), December 7, 2007 (3 months after-RSCD), and January 25, 2008 (4.5 months after-RSCD), respectively. All four observations were conducted on Friday morning to reflect daily traffic behaviours and avoid weekend variations. Meanwhile, observations of the two consecutive intersections surveyed in the GSCD experiment were conducted on February 22, 2008 (Friday), approximately one and a half years after GSCD installation.

These observations were conducted by video-taping the traffic on the intersection approaches using synchronized video cameras, followed by manual counting and measurement. Two time periods were observed for gathering data on driver behaviours—peak hours (7:00–9:00 am) and off-peak hours (9:00–11:00 am). Additionally, to facilitate the measurement of distances from specific vehicles to the stop line, white stripes were marked at 5-m intervals on the approaches to the intersections.

## 3. Driver responses to GSCD

To observe the effects of GSCD, driver behaviours during the ten seconds of the green countdown are analyzed. For the intersection with GSCD in this study (the intersection of Guangming No. 6 Road and Chung-Hua Road), by excluding the cycles in which no vehicles are present during the ten second green countdown, a total of 40 and 39 cycles were available for analysis for the peak hour and off-peak hour periods, respectively. As such, a total of 311 and 187 vehicles were gathered during the peak and off-peak hours, respectively. Over-saturation was not observed at both intersections during the experimental periods. For the intersection without GSCD (the intersection of Guangming No. 6 Road and Bo-Ai Road), only 33 and 40 cycles in which at least one vehicle was present are available for peak hour and off-peak hour analyses, respectively. A total of 129 and 145 samples thus were collected for the peak hour and off-peak hour periods, respectively. Changes in driver behaviours are observed and compared below.

### 3.1. Changes in late-stopping ratio

Table 1 lists the late-stopping ratios for intersections with and without GSCD. Notably, the late-stopping ratio of the intersection with GSCD can be largely curtailed by the informed decisions, suggesting that aggressive drivers use the countdown information to accelerate and thus cross the intersection successfully while conservative drivers instead use the information to make a timely stop.

### 3.2. Changes in dilemma zone

For vehicles approaching a signalized intersection at a high speed as signal turns yellow, the dilemma zone is the distance from the intersection to the point on the road where it becomes difficult for the drivers to discern whether they should proceed through the yellow light or brake to be safe. Zegeer (1977) suggested that the length of dilemma zone can be measured between two points at which 10 and 90% of approaching drivers will decide to stop, respectively. Based on this measurement, the lengths of dilemma zones of these two intersections are calculated and compared in Fig. 2. Fig. 2 shows that the dilemma zone of the intersection with GSCD, which ranges from 17 m to 75 m (58 m long) from the stop line, is much longer than that of the intersection without GSCD, which ranges from 32 m to 62 m (30 m long), implying that the provision of green countdown causes significant deviations in driver decision to stop. Based on this information, conservative drivers decide to stop further from the stop line, while in contrast aggressive drivers decide to stop closer to the stop line. Such inconsistent decisions among drivers approaching a signalized intersection indicate that GSCD negatively impacts intersection safety.

### 3.3. Changes in decision to cross

To better understand driver decisions to cross when facing a green countdown of less than 10 s, this study employs a binary logistic regression to identify the effect of key factors on driver

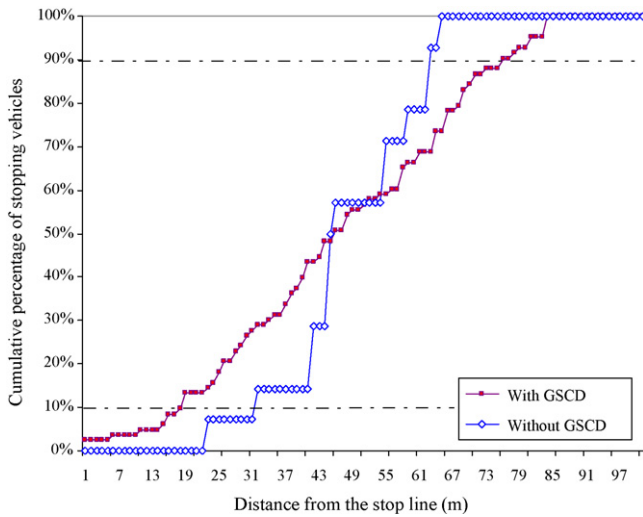


Fig. 2. Dilemma zones of the intersections with and without GSCD.

decision. The model can be expressed as follows:

$$\text{Logit}(p) = a_0 + a_1T + a_2D + a_3V + a_4G + a_5G \times T + a_6G \times D + a_7G \times V \quad (1)$$

where  $p$  denotes the probability of the driver deciding to cross the intersection;  $\text{Logit}(p)$  is the odds ratio of  $p$ ;  $T$  represents remaining green time (namely, green countdown) for the vehicle (second);  $D$  denotes the distance of the vehicle from the stop line (meter);  $V$  represents the vehicle approach speed (km/h);  $G$  is a dummy variable;  $G = 1$  represents the intersection with GSCD and  $G = 0$  represents the intersection without GSCD, and  $a_0$ – $a_7$  are the estimated parameters. The last three items in Eq. (1) represent the interaction effects between  $T$ ,  $D$ ,  $V$  and the presence of GSCD, which allow the estimated coefficients corresponding to  $T$ ,  $D$ , and  $V$  to vary across the intersections with and without GSCD.

The key factors ( $T$ ,  $D$ ,  $V$ ) of all vehicles within the experimental space (100 m from the stop line) are repeatedly measured at every second within 10 s green countdown (7 s green time and 3 s yellow time). In other words, the same vehicle may be observed more than once and the values of its key factors change over time. Nevertheless, the decision to cross (yes or no) of the vehicle will remain unchanged for all repeated observations. As a result, a total of 2739 and 1064 samples associated with 498 and 274 vehicles at the intersections with and without GSCD are obtained. On average, each vehicle was observed five times. Descriptive statistics of these key factors are given in Table 2. Compared to the intersection without GSCD, vehicles approaching to the intersection with GSCD will travel at a lower speed (27.95 km/h < 35.45 km/h) and face shorter remaining green + yellow time (4.82 s < 5.30 s), but they appear at the same distance to the stop line (28.31 m  $\approx$  28.92 m) and have the same crossing percentage (0.262  $\approx$  0.268), approximately.

Table 3 lists the estimation result obtained using Eq. (1). Note that all explanatory variables and interaction terms show significant effects with the anticipated signs to the odds ratio of driver decision to cross the stop line. As shown in Table 3, both green countdown and approach speed positively affect driver decision to cross, indicating that drivers facing a longer green countdown and driving at a higher speed are more likely to cross the intersection. In contrast, distance from the intersection negatively affects driver decision to cross, suggesting that driver far from the intersection are more likely to stop. Additionally, the dummy variable of GSCD significantly negatively affects driver decision to cross, implying that drivers approaching intersections with GSCD are more likely to stop. Furthermore, GSCD not only directly affects the odds ratio

Table 2  
Descriptive statistics of the key factors affecting decision to cross.

Key factors	Statistics	With GSCD	Without GSCD
Distance from stop line (m)	Max	90	70
	Min	0	0
	Average	28.31	28.92
Approach speed (km/h)	Max	72.12	72.00
	Min	3.62	7.20
	Average	27.95	35.45
Green countdown (seconds) (remaining green + yellow)	Max	10.00	10.00
	Min	0.00	0.00
	Average	4.82	5.30
Decision to cross (Yes/No)	Yes	568	267
	No	2171	997
	Total	2739	1064

but also neutralizes the effects of green countdown, approach speed and distance from intersection, suggesting that the red-stopping ratio for intersections with GSCD will be higher than for those without GSCD. This finding concurs with Lum and Halim (2006).

Basically, according to the estimated model in Table 3, driver decisions to cross intersections with and without GSCD can be represented using the following two functions:

$$\text{Without GSCD : } \text{Logit}(p) = 1.1939 + 1.1995T - 0.1688D + 0.1686V \quad (2)$$

$$\text{With GSCD : } \text{Logit}(p) = 0.5908 + 0.5436T - 0.0906D + 0.0718V \quad (3)$$

Notably, all the parameters in Eq. (3) show the same sign as in Eq. (2), but all shrink to approximately half of their values at the intersection without GSCD (in Eq. (2)). Taking a scenario in which a driver faces a three seconds green countdown at 50 m from the stop line and an approach speed of 50 km/h, the probabilities of deciding to cross the intersections with and without GSCD are 78.28% and 99.17%, respectively, indicating that GSCD remarkably decreases the probability of the driver deciding to cross the intersection and reduces intersection efficiency.

To further investigate driver decision to cross under various scenarios characterized by three key factors: green countdown, distance from the stop line, approach speed, the distributions of the crossing probabilities during the last six seconds of the green countdown (including the last three seconds of green time and the three seconds of yellow time, respectively denoted as  $G_3$ ,  $G_2$ ,  $G_1$ ,  $Y_1$ ,  $Y_2$ ,  $Y_3$ ) within the dilemma zone are compared for different approach speeds. Since the dilemma zone of the intersection with

Table 3  
Estimated logistic regression model.

Explanatory variables	Estimated parameters	Chi-square	Pr > Chi-square
Intercept	1.1939	52.4145	<0.0001
$T$	1.1995	62.7497	<0.0001
$D$	-0.1688	53.7163	<0.0001
$V$	0.1686	42.8469	<0.0001
$G$	-0.6031	10.0307	0.0015
$G \times T$	-0.6559	18.2064	<0.0001
$G \times D$	0.0782	11.1711	0.0008
$G \times V$	-0.0968	13.7883	0.0002
Sample size		3803	
Likelihood ratio		1844.7031	<0.0001

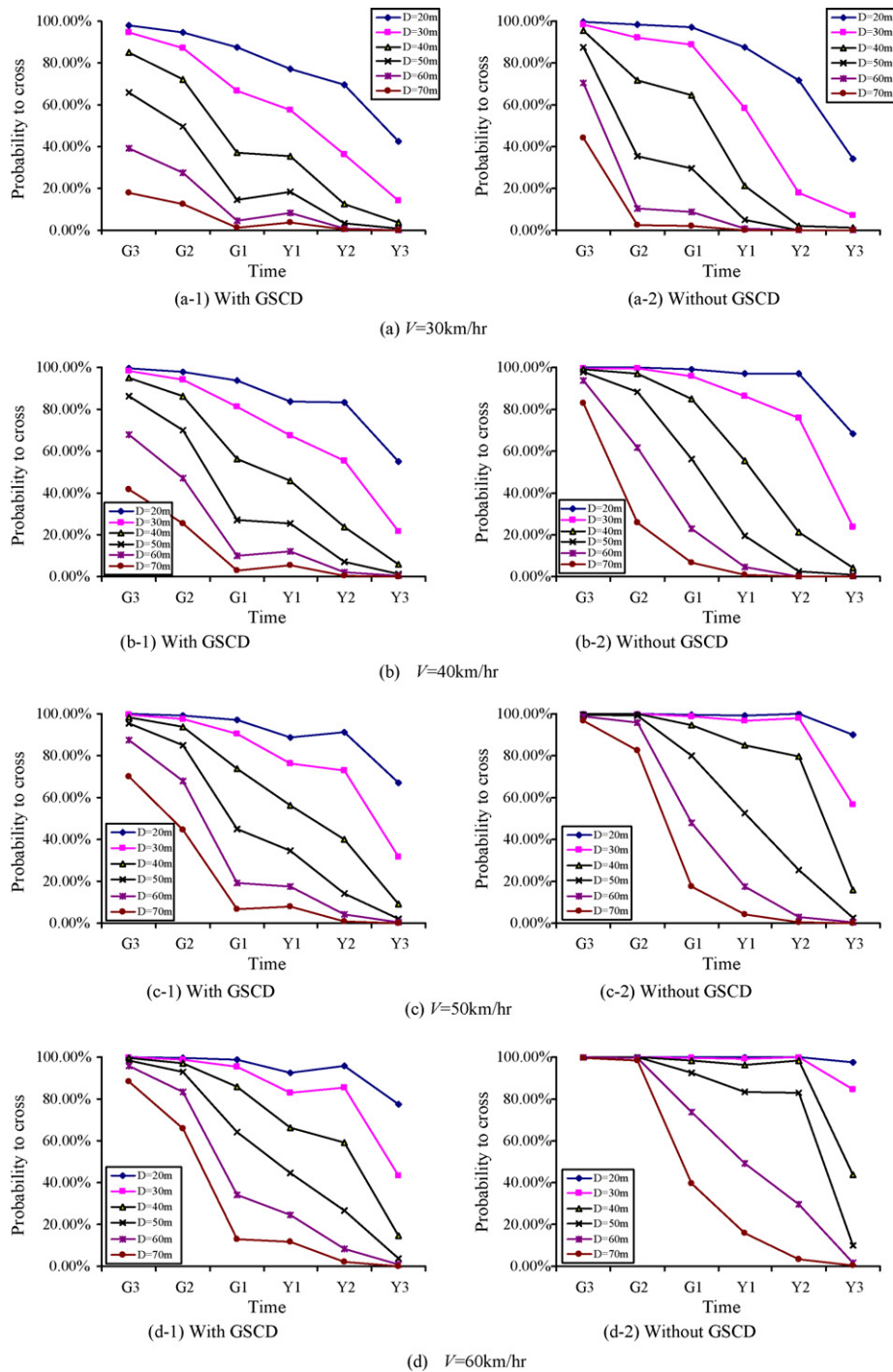


Fig. 3. Crossing probability at various distances and approach speeds.

GSCD ranges from 17 m to 75 m, the decisions are analyzed for 10 m intervals between 20 m and 70 m, a range that also covers the dilemma zone of the intersections without GSCD. In addition, the effect of approach speed is analyzed at 10 km/h intervals from 30 km/h to 60 km/h.

Fig. 3 shows the crossing probabilities at various distances from the stop line under a range of approach speeds. Note that the distributions of crossing probability for the intersection with GSCD resemble those for the intersection without GSCD at the approach speed of 30 km/h. However, differences in the distributions of crossing probability between intersections with and without GSCD become more apparent as the approach speed increases. Also

noticed from Fig. 3(a-1) to (d-1), the distributions of crossing probabilities for the intersection with GSCD are similar to each other regardless of approach speed. In contrast, the crossing probabilities for the intersection without GSCD exhibit rather different distributions of various approach speeds as depicted in Fig. 3(a-2)–(d-2).

Observing the time point at which the crossing probability sharply drops from Fig. 3(a-1) to (d-1) for the intersection with GSCD, the point remains at the time of G1 regardless of approach speed and distance from the stop line, with the decrease in crossing probability becoming sharper at longer distances and higher approach speeds. For the intersection without GSCD, Fig. 3(a-2)–(d-2) show that the point moves towards the green phase (shifting left)



Fig. 4. A top-view of the experimental intersection with four waiting areas marked (taken from Google Map).

with increasing distance from the stop line, and moves towards the yellow phase (shifting right) with increasing approach speed. Taking  $V = 30$  km/h, 40 km/h, 50 km/h, 60 km/h, for example, the point continuously moves from G2 to G1, Y3, and finally Y2, respectively. This phenomenon indicates that drivers approaching intersections without GSCD gradually adjust their decision-making from crossing to stopping based on their approach speeds and distances from the stop line. However, drivers approaching intersections with GSCD simultaneously decrease their crossing probability regardless of their distance from the intersection and approach speed, creating potential for rear-end collisions and negative impacts on intersection efficiency.

Taking a platoon approaching an intersection without GSCD at 40 km/h for instance (as depicted in Fig. 3(b-2)), one of the vehicles in the platoon at  $D = 50$  m has a low crossing probability of 19.44% at the time point of Y1, while another vehicle 10 m behind the vehicle (at  $D = 60$  m) at the time point of G1 would have approximate same probability of 23.07% to cross the intersection. A one second shift in the distribution of the crossing probability is explained by the 10 m distance between these two vehicles, and provides a buffer for collision prevention. However, under the same scenario at the intersection with GSCD (as shown in Fig. 3(b-1)), the former vehicle (at  $D = 50$  m) will have a probability of 27.16% to cross at the time point of G1 while the following vehicle (at  $D = 60$  m) still has a high crossing probability of 47.16% at one second earlier to G1 (*i.e.* G2), resulting in inconsistent decisions among the vehicles in the platoon that may contribute to a rear-end crash.

#### 4. Driver responses to RSCD

To investigate the effect of RSCD on driver behaviours, four observations are conducted, including before-RSCD, 1.5 months after-RSCD, 3.0 months after-RSCD, and 4.5 months after-RSCD. Changes in three phenomena—early start ratio, start-up delay, and discharge headway are observed and compared at the intersection of Chung-Hsiao East Road and Dun-Hua South Road in Taipei City as follows.

##### 4.1. Changes in early start ratio

Early start ratios of the leading vehicles in various waiting areas are respectively compared. Fig. 4 illustrates a top-view of the experimental intersection taken from Google Map with the various waiting areas marked. The geometric layout is typical of moderate- to large-scale intersections in Taipei City. From the fig-

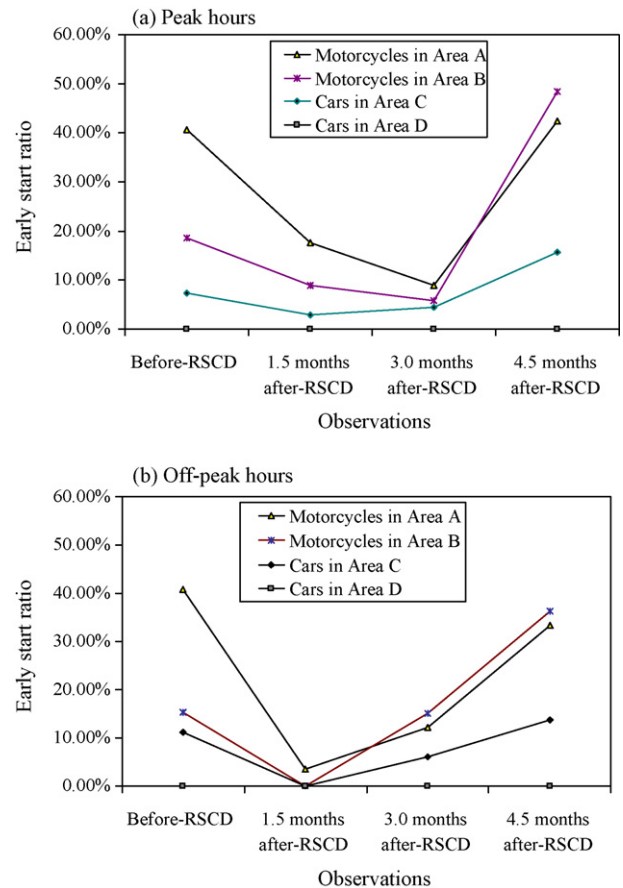


Fig. 5. Early start ratios of the leading vehicles in various waiting areas.

ure, the leading vehicles can be divided into four groups, denoted as A–D, based on waiting areas. Waiting Area A is designed for left-turning motorcycles coming from the left hand direction on the cross street. In many scaled intersections in Taiwan, motorcycles are not allowed to turn left during the green phase. Instead, they are required to stop in the motorcycle left-turn waiting area and wait for the green phase of this approach to reduce potential conflicts between through-traffic and left-turning motorcycles. Area A is located in front of the stop line, so early start behaviours for left-turning motorcycles are counted if they cross the front border of Area A prior to the green phase. Area B is designed for motorcycles waiting for the green light, and helps separate mixed traffic when the green phase begins, by giving priority to motorcycles which have a shorter start-up delay than cars. Areas C and D are the waiting areas for cars or buses in the inner and outer lanes, respectively. The difference between these two areas is that the start-up delay for the leading vehicle in Area D is queued behind the motorcycles in Areas A and B while vehicles in Area C are free to start on their own timing.

Fig. 5 depicts the early start ratios of the leading vehicles in four waiting areas during peak and off-peak hours, respectively. Notably, the early start ratios of cars in Area D equal 0 for both peak and off-peak hours, since they are usually blocked by the motorcycles in Areas A and B and remain further from the stop line. The motorcycles in Area A have the highest early start ratios, followed by those in Area B. Examining the effect of RSCD reveals that early start ratios surprisingly are curtailed immediately after RSCD installation and reach their lowest at 3.0 months after-RSCD (for peak hours) and 1.5 months after-RSCD (for off-peak hours). However, the early start ratios for leading vehicles in Areas A–C all bounce back to their original levels 4.5 months after-RSCD

**Table 4**

Start-up delays of the leading vehicles in various areas (in seconds).

Traffic condition	Areas	Before-RSCD	1.5 months after-RSCD	3.0 months after-RSCD	4.5 months after-RSCD
Peak	Motorcycles in Area A	1.40	2.00 ( $p=0.0128$ )	1.91 ( $p=0.0049$ )	1.10 ( $p=0.0977$ )
	Motorcycles in Area B	1.82	2.41 ( $p=0.0057$ )	2.51 ( $p=0.0009$ )	1.09 ( $p<0.0001$ )
	Cars in Area C	3.74	4.62 ( $p=0.0025$ )	4.45 ( $p=0.0276$ )	3.24 ( $p=0.1011$ )
	Cars in Area D	6.58	6.52 ( $p=0.8992$ )	6.14 ( $p=0.3427$ )	5.03 ( $p=0.0029$ )
Off-peak	Motorcycles in Area A	1.76	2.51 ( $p=0.0002$ )	2.17 ( $p=0.0498$ )	1.60 ( $p=0.4680$ )
	Motorcycles in Area B	2.14	3.05 ( $p<0.0001$ )	2.32 ( $p=0.4183$ )	1.50 ( $p=0.0035$ )
	Cars in Area C	3.88	4.79 ( $p=0.0013$ )	4.06 ( $p=0.5574$ )	3.61 ( $p=0.3359$ )
	Cars in Area D	5.49	6.43 ( $p=0.0260$ )	5.94 ( $p=0.3175$ )	5.20 ( $p=0.5068$ )

Note. (1)  $p$ -Values for testing the difference from before-RSCD are given in parentheses. (2) The sample size for each cell equals to 36.

**Table 5**

Estimated regression models for discharge headway of cars in Area C.

Traffic condition	Observations	Estimated regression models	F-value	$R^2_{adj}$	Sample size
Peak	Before-RSCD	$T=2.31N+1.57$ ( $p<0.0001$ )	1411.40 ( $p<0.0001$ )	0.88	324
	1.5 months after-RSCD	$T=2.23N+2.71$ ( $p<0.0001$ )	1454.24 ( $p<0.0001$ )	0.87	327
	3.0 months after-RSCD	$T=2.16N+2.77$ ( $p<0.0001$ )	1629.72 ( $p<0.0001$ )	0.88	313
	4.5 months after-RSCD	$T=2.09N+1.55$ ( $p<0.0001$ )	1485.54 ( $p<0.0001$ )	0.88	307
Off-peak	Before-RSCD	$T=2.33N+2.25$ ( $p<0.0001$ )	1126.95 ( $p<0.0001$ )	0.77	280
	1.5 months after-RSCD	$T=2.21N+3.33$ ( $p<0.0001$ )	1198.07 ( $p<0.0001$ )	0.80	249
	3.0 months after-RSCD	$T=2.37N+2.35$ ( $p<0.0001$ )	1314.98 ( $p<0.0001$ )	0.78	293
	4.5 months after-RSCD	$T=2.33N+1.83$ ( $p<0.0001$ )	1740.42 ( $p<0.0001$ )	0.80	291

Note.  $p$ -Values are given in parentheses.

installation, indicating that RSCD effectively reduces the early start ratio in the short term but its effectiveness dissipates over time.

#### 4.2. Changes in start-up delay

Table 4 lists the average start-up delays of the leading vehicles in the four areas, and also tests the differences in delays between before-and-after RSCD installation. Since the signal cycle length of the intersection equals 200 s, a total of 36 samples were collected for peak and off-peak analyses, respectively.

Regarding the start-up delays of various leading vehicles before-RSCD installation, motorcycles in Area A have the smallest delays, of 1.40 s (peak) and 1.76 s (off-peak), followed by motorcycles in Area B, with 1.82 s (peak) and 2.14 s (off-peak). The average start-up delay for cars in Area C is almost twice that of motorcycles, at 3.74 s (peak) and 3.88 s (off-peak). Finally, as anticipated, cars in Area D had the largest average start-up delay, at 6.58 s (peak) and 5.49 s (off-peak), three times that for motorcycles. Additionally, the peak hour start-up delays of cars or motorcycles in Areas A–C are all smaller than those during off-peak hours. This phenomenon might result from the urges from the vehicles behind and driver eagerness to get to school and work during rush hours. In contrast, the start-

up delays for the cars in Area D have smaller values during off-peak than peak hours. This phenomenon may result from there being fewer blocked motorcycles in Areas A and B during off-peak hours, reducing the potential for blocking of cars in Area D.

Comparing start-up delay before-and-after RSCD installation reveals that delays increase significantly during the initial period following installation of RSCD (first 1.5 months) and then slightly decrease. The delays of leading vehicles in various areas all decrease to below their original values, with the decrease achieving significance in some cases, 4.5 months after-RSCD installation. This phenomenon indicates that drivers facing the device in the initial period tend to obey the countdown timings by holding their intention to accelerate, once drivers are used to the device they will then take advantage of the countdown timing to further reduce their start-up delays, enhancing the operation efficiency of the intersection.

#### 4.3. Changes in discharge headway

The above analyses of early start ratio and start-up delay focus on the effect of RSCD on the leading vehicles in various waiting areas. To examine the effect of RSCD on following vehicles, the headway distributions of discharge vehicles before-and-after

**Table 6**

Estimated regression models for discharge headway of cars in Area D.

Traffic condition	Observations	Estimated regression models	F-value	$R^2_{adj}$	Sample size
Peak	Before-RSCD	$T=2.98N+4.88$ ( $p<0.0001$ )	324.55 ( $p<0.0001$ )	0.71	185
	1.5 months after-RSCD	$T=2.57N+5.75$ ( $p<0.0001$ )	265.56 ( $p<0.0001$ )	0.65	192
	3.0 months after-RSCD	$T=2.44N+5.37$ ( $p<0.0001$ )	312.86 ( $p<0.0001$ )	0.70	177
	4.5 months after-RSCD	$T=2.51N+3.86$ ( $p<0.0001$ )	250.09 ( $p<0.0001$ )	0.68	156
Off-peak	Before-RSCD	$T=2.82N+3.88$ ( $p<0.0001$ )	409.19 ( $p<0.0001$ )	0.77	163
	1.5 months after-RSCD	$T=2.47N+5.08$ ( $p<0.0001$ )	540.44 ( $p<0.0001$ )	0.80	179
	3.0 months after-RSCD	$T=2.81N+3.99$ ( $p<0.0001$ )	540.79 ( $p<0.0001$ )	0.78	151
	4.5 months after-RSCD	$T=2.69N+3.35$ ( $p<0.0001$ )	615.01 ( $p<0.0001$ )	0.80	155

Note.  $p$ -Values are given in parentheses.

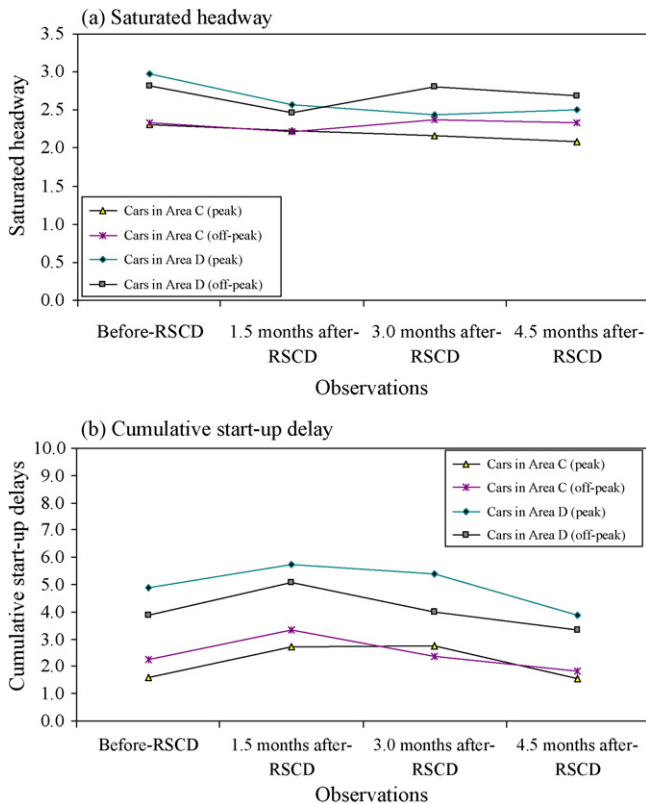


Fig. 6. Changes in saturated headway and cumulative start-up delay of discharge vehicles.

RSCD installation are modeled and compared by regressing the time when a vehicle crosses the stop line on the sequential order of the vehicle in the platoon. Note that only the headways of discharge vehicles, which are originally queued in the platoon prior to green phase, are used to estimate the model. It explains the sample size differs across observations. Additionally, due to the complexity of measuring motorcycle headway, this study only analyzes car headways. The regression model can be expressed as follows:

$$T = aN + b \quad (4)$$

where  $T$  denotes the time when a specific car crosses the stop line.  $N$  represents the sequential position of a specific car in the queuing platoon. Two estimated parameters  $a$  and  $b$  in Eq. (4), respectively, represent the saturated headway and cumulative start-up delay. Tables 5 and 6 list the regression results of cars in Area C and D, respectively. The tables reveal that all parameters and regression models are tested to have good model fit.

Fig. 6 compares the differences between the situations before-and-after RSCD installation on the estimated parameters,  $a$  and  $b$ , for cars in Areas C and D. Notably, during peak hours the saturated headways of the cars in Areas C and D gradually decrease from 2.31 s to 2.09 s and 4.88 s to 3.86 s, respectively, after-RSCD installation, and this effect appears to persist over time. However, for off-peak traffic, the effects of RSCD in curtailing saturated headway do not last, with a slight reduction during the first 1.5 months followed by a return to original levels after 3.0–4.5 months. Based on the above, RSCD appears to effectively increase intersection efficiency during peak hours, but not off-peak hours.

With regard to the cumulative start-up delay, a similar pattern can be recognized for the cars in Areas C and D during peak and off-peak hours, with an initial increase gradually giving way to a level lower than that before-RSCD installation, suggesting that RSCD can

slightly curtail cumulative start-up delay and increase intersection efficiency, but this effect takes time to become observable.

## 5. Concluding remarks

To investigate how signal countdown displays affect driver behaviours, and thus on intersection safety and efficiency, this study examines two such displays, GSCD and RSCD. This study observes and analyzes three driver responses to GSCD, including late-stopping ratio, dilemma zone and decision to cross, and three driver responses to RSCD, including early start ratio, start-up delay, and discharge headway. Results show that although GSCD can reduce late-stopping ratio, the dilemma zone is increased by about 28 m and the decision to cross will be more inconsistent among the approaching vehicles, creating a potential risk of rear-end crashes. Additionally, following the provision of a green countdown the number of vehicles ejecting to cross the intersection reduces.

On the other hand, comparisons among four observation periods examining the effects of RSCD, before-RSCD, 1.5 months after-RSCD, 3.0 months after-RSCD and 4.5 months after-RSCD, show that although RSCD significantly reduces the early start ratios of the leading vehicles in various waiting areas, the ratios soon return to their before-RSCD levels, suggesting that RSCD does not significantly improve intersection safety over the longer term. However, RSCD effectively reduces start-up delay, saturated headway, and cumulative start-up delay at 4.5 months after-RSCD installation. Thus, RSCD enhances intersection efficiency. RSCD is clearly less controversial and more beneficial than GSCD.

Possible directions for future studies include the following. First, this study used a combination of video-taping and then manually tracing and recording vehicle behaviours, but there is potential for applying advanced traffic information collection systems to reduce the intensity of labor demands. For example a specific-purpose traffic data logger, such as that used in Lum and Halim (2006), or an image processor capable of simultaneously tracing and recording the dynamics of individual moving vehicles could be used in future investigations. Second, due to the intensive work involved, only one case of GSCD (at two consecutive intersections) and one case of RSCD (at one intersection), each involving four hours of data, were observed and compared in this study. Driver responses to GSCD and RSCD at different types of intersections characterized by various geometric layout, signal timing plan, and traffic conditions deserve to be more comprehensively and systematically compared. Third, since there was no new GSCD installation plan in Taiwan at the time of this research, a before-and-after analysis approach cannot be performed, making it impossible to observe dynamic changes in driver responses to such a device during various periods. If possible, for research purposes it would be worth installing a new GSCD at a designated intersection and then observing driver behaviours at various intervals after installation. Fourth, it would be interesting to examine the different effects of GSCD and RSCD on drivers with various demographics and degrees of aggressiveness. Such a study might resemble that of Papaioannou (2007), who examined yellow signal obedience or violation for various groups of drivers, differentiated by gender, age and various aggressive degrees of drivers, including conservative, normal and aggressive. Last but not the least, this study only focused on the effects of GSCD and RSCD on intersection safety and efficiency. However, such devices also ease the impatience of waiting drivers, and this effect also deserves exploration via a carefully designated experimental observation.

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## References

- Chen, I.C., Chang, K.K., Chang, C.C., Lai, C.H., 2007. The impact evaluation of vehicular signal countdown displays. Research Report. Institute of Transportation, Ministry of Transportation and Communications, Taiwan.
- Lum, K.M., Halim, H., 2006. A before-and-after study on green signal countdown device installation. *Transportation Research F* 9, 29–41.
- Papadimitriou, P., 2007. Driver behaviour, dilemma zone and safety effects at urban signalised intersections in Greece. *Accident Analysis and Prevention* 39, 147–158.
- Zegeer, C., 1977. Effectiveness of green-extension systems at high-speed intersections. Research Report. Bureau of Highways, Division of Research, Kentucky Department of Transportation, Lexington.