ANALYSIS OF DRIVING BEHAVIOR DURING DIFFERENT PHASE-SWITCHING MODES BASED ON FIELD DATA

Zhizhou WU, Ph.D.
Associate Professor
Key Laboratory of Road and Traffic Engineering of Ministry of Education
Tongji University
4800 Cao’an Road, Shanghai, China
Tel: 86+13671580518; Email: wuzhizhou@tongji.edu.cn

Guishan TAN
Key Laboratory of Road and Traffic Engineering of Ministry of Education
Tongji University
4800 Cao’an Road, Shanghai, China
Tel: 86+15000128767; Email: 1433985@tongji.edu.cn

Chen WANG* (Corresponding Author), Ph.D.
Assistant Professor
Key Laboratory of Road and Traffic Engineering of Ministry of Education
Tongji University
4800 Cao’an Road, Shanghai, China
Tel: 86+18221148065; Email: wkobec@hotmail.com

Tianzi CHEN
Tongji Architectural Design (Group) Co., Ltd
1230 Siping Road, Shanghai, China
Tel: 86+18921962560; Email: 453107218@qq.com

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ABSTRACT

In this study, drivers’ behavior near intersections was examined under two different signal phase-switching modes, namely green flashing mode and green countdown mode. Two typical at-grade intersections in Shanghai were selected for a case study. Video techniques were employed to obtain traffic data and capture drivers’ behaviors during the period of a signal switching from green to red. Both qualitative and quantitative analysis were conducted to identify drivers’ behaviors and adaptability, considering driver's psychology changes, red-light running maneuvers and speed characteristics. Compared to green countdown mode, green flashing mode results in lower rates of red-light running and rushing, a higher rate of stopping, a lower speed/acceleration dispersion rate, lower average operating speed, and smaller speed fluctuation. These indicate that green flashing mode could induce more conservative maneuvers and hence enhance overall safety, while green countdown mode could cause more aggressive driving behaviors since drivers exactly know the end point of a green light. The downside of green flashing mode could be associated with the increased risk of car-following cases, due to unexpected stops or sudden speed drop-down of leading vehicles at intersections. The efforts were made to enrich the research findings of traffic signal control, providing references for the compilation of relevant norms and specifications and providing the basic for further development of ITS.

Keywords: Phase-Switching Modes; Driving Behavior; Green Flashing Mode; Countdown Mode
1. INTRODUCTION

Intersection phase-switching mode refers to the signal display, sequence and duration of a signal phase switching from green to red light. During a signal phase-switching period, drivers decide whether to cross an intersection based on their own judgments. So during such period, traffic flows near an intersection may dynamically change, leading to traffic conflicts and affecting the safety and efficiency of the whole intersection. According to statistics, intersections are a hotspot of road traffic accidents, especially with high accident frequency during phase-switching periods (1). It has been shown that 85% of intersection-related accidents occurred during phase-switching period in Shanghai (2) (3). Therefore, how to set up an appropriate phase-switching mode to improve traffic safety and efficiency has become an important issue. There are a number of studies focusing on driving behaviors under different traffic treatments, but few were identified for signal phase-switching modes (4). In addition, since driving behaviors, geometrics, and build environment are quite different, research results from other countries cannot be directly transferred in China. Thus, it is necessary to examine the characteristics of Chinese drivers’ behaviors during phase-switching periods, in order to improve intersection safety and traffic efficiency in China.

This paper compares driving behaviors under two most common signal switching modes implemented in urban intersections in China: green light countdown + yellow light phase-switching mode (hereinafter referred to as green countdown mode) and green light flashing + yellow light phase-switching mode (hereinafter referred to as green flashing mode). Based on video data, efforts were made to analyze driving behaviors under the two different phase-switching modes, considering drivers' psychology changes, red-light running maneuvers and speed characteristics.

2. LITERATURE REVIEW

With the quick development of traffic control technology, signal phase-switching modes gradually tend to be diversified. There is still no uniform standard of how to set up phase-switching modes for different intersection types. Some domestic and foreign experts have worked on topics related with phase-switching modes, using different methods including questionnaire survey, mathematical modeling, test run and driving simulator.

Some researchers conducted questionnaire survey to obtain driver's subjective attitudes to phase-switching modes (5, 6, 7). It was found that the majority of drivers were in favor of green light countdown mode, because it could make them drive smoothly with well mental preparation, avoiding sudden brake or continuous acceleration when traffic lights were changing. And most drivers were willing to decelerate at the end of countdown in order to avoid running red lights. The questionnaire survey method is easy to be carried out and can reflect driving attitudes to some extent, however, it may not fully and truly reflect driving behaviors.

Driving behavior models at intersections were also developed, through traffic simulation experiments data (8, 9). The models could reflect driving behaviors, such as acceleration, deceleration at intersection area. However, these models didn’t account for the effect of different signal phase-switching modes on driving behaviors, and all these experiments were based on simulations that may not be entirely consistent with real traffic flow.

Some examined the adaptability and effectiveness of different phase-switching modes through test run (10, 11, 12). They compared traffic conditions before and after setting up a green countdown mode. Their results showed that it could reduce the frequency of running red lights under low traffic volume, whereas it had no significant
effect on reducing red-light running under high traffic volume. Test run could be a choice to examine phase-switching modes, but the cost is considerably large.

In addition, driving simulators have been widely used in recent years to evaluate driving behaviors under unconventional traffic design, such as flashing yellow arrow indication (13), diverging diamond interchange (14), and guide signing at complex interchanges (15). Driving simulators can build a virtual driving environment to capture detailed information of drivers. However, since it cannot completely replicate real-world driving environment, the transferability of results based on driving simulations could be questioned.

In conclusion, field data collection with advanced techniques could be a viable option for researchers to examine drivers’ behaviors under signal phase-switching modes, which fulfills the requirement of high data accuracy and low labor cost. Therefore, in this study, we decided to analyze the differences of driver’s behavior under different phase-switching modes, based on field data collection.

3. METHODOLOGY

3.1 Selection of Road Intersection

According to statistics, at-grade intersections in urban road network in Shanghai, China occupy a high proportion of the whole intersections (16), so this paper will focus on the analysis of at-grade intersections. Two typical at-grade intersections with similar features in Shanghai were selected for the study. Details will be discussed in the following sections.

3.2 Selection of Phase-switching Mode

For signal switching modes from green to red, there are about 27 combinations as shown in Table 1. They are classified in accordance with the signal display status at the end of a green light, during the switching period and at the early stage of a red light, respectively. Among them, most are less likely to be used in practice, such as normal green light + yellow light countdown, green light countdown + yellow light countdown, etc. So these phase-switching modes were not considered. For large cities in China (e.g. Shanghai), the most two typical phase-switching modes are green countdown mode and green flashing mode, for at-grade intersections where arterial roads intersect with each other. These almost account for over eighty five percent of all in Shanghai (16). In light of these, the two phase switching modes were compared in this study: 1) green light countdown + normal yellow light + normal red light phase-switching mode (referred to as green countdown mode); 2) green light flashing + normal yellow light + normal red light phase-switching mode (referred to as green flashing mode).

<table>
<thead>
<tr>
<th>Analysis Area</th>
<th>At the End of Green Light</th>
<th>During Phase-switching Period</th>
<th>At the Early Stage of Red Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status of Signal Display</td>
<td>Normal green light</td>
<td>Normal yellow light</td>
<td>Normal red light</td>
</tr>
<tr>
<td></td>
<td>Green light flashing</td>
<td>Yellow light countdown</td>
<td>Red light countdown</td>
</tr>
<tr>
<td></td>
<td>Green light countdown</td>
<td>No yellow light</td>
<td>Red and yellow light</td>
</tr>
</tbody>
</table>

**TABLE 1** The Classification of Display Status during Signal Phase-switching Period
3.3 Scenarios
Two at-grade intersections in Shanghai were selected for the study, Tibet Road – East Yanan Road (signalized with green countdown mode) and Pudong Road - Pujian Road (signalized with green flashing mode) as shown in Fig.1 (a) and Fig.1 (b). These two intersections are comparable because of very similar geometric layout (five lanes on each direction), traffic condition (i.e. annual average daily traffic and peak hour volumes), and traffic control strategy (i.e. signalized with surveillance system). Video camera is the most common tool of traffic data collection at present, and the image information can be converted into quantitative data by software or manual calculation. Video recorders can not only collect various traffic data directly or indirectly, such as traffic flow, speed, traffic incidents, but also be more conducive to observe driving behaviors repeatedly, promoting data analysis and scientific research. In this paper, video recorders were used to investigate driving behaviors and data were collected from 8 to 11 am and 15 to 19 pm on April 21 (for Tibet Road – East Yanan Road) and 22 (for Pudong Road - Pujian Road), 2015. Note that the data collection periods include both non-peak and peak hours. Pedestrian overpasses near the intersections were chosen as observation spots as they provide a clear view without any obstructions.

![Diagram](image.png)

(a) Tibet Road – East Yanan Road (countdown mode)  (b) Pudong Road - Pujian Road (green flashing mode)

FIGURE 1 The survey spots

3.4 Video Data Processing
The Traffic Capacity Data Survey and Processing System (CDSP) was utilized to process video data (16). It is an assistant support system to help record the traffic data. For example, set the button "Q" of keyboard to record traffic volume, then the traffic volume would increase one by one as button "Q" was pressed everytime. Meanwhile, the corresponding recording times and the location of the recorded vehicles would be saved. These data could be used to derive traffic information, such as speed, acceleration, etc., and the formula will be discussed in section 4.2.2. The data processing mainly includes the following steps:
- Import the video files into the CDSP.
- Set basic information including intersection name, investigating time, etc.
- Define variables to be counted, such as traffic volume, red-light running behavior.
- Record and save the data needed, and you can get the output tables of excel format, including intersection name, time, signal cycle, the beginning of signal cycle, the ending time of signal cycle, custom statistic variables, etc.

4. COMPARATIVE ANALYSIS
Based on the video data, both qualitatively and quantitatively analysis were conducted to identify the advantages and disadvantages of the two phase-switching modes. The
comparison analysis focus on driver's psychology changes, red lights running maneuvers, and the characteristics of speed, acceleration and deceleration.

4.1 Qualitatively Analysis of the Comparison of Driver's Psychology Changes

Green countdown and green flashing are both early warning signals in advance of a green light changing into red. The usage of early warning signals are based on the following logic: if drivers get the information that a green light will end (or yellow light there will be), their decisions will be easier and more predictable. For example, when they are away from the stop line, warning signals will make them more prone to stop; and if they are close to the stop line, the warning signals will induce them to cross the intersection without running red light. However, different phase-switching modes could affect judgements of drivers, resulting in different driving behaviors. Therefore, it is necessary to analyze phase-switching modes from the perspective of drivers' psychology changes.

A green countdown signal is activated at the late stage of a green light so that drivers can also make early decisions in advance of reaching the stop line. From the perspective of individual drivers, green signal countdown could make them feel more comfortable and prepared when crossing intersections. From the perspective of the whole intersection, on one hand, the mode could induce some conservative drivers to drive safely. However, on the other hand, it could also induce aggressive drivers to rush through intersections, increasing risk of running red lights and accidents. Aggressive drivers could be more tense and anxious than normal drivers, when they see the seconds of countdown declining (17, 18).

Unlike green countdown mode, green flashing mode just flashes for few seconds without additional information. Thus, it could induce more drivers to be conservative, reducing red-light running behaviors. From the individual perspective, drivers could feel less comfortable under green flashing mode, for they are not sure about the remaining green time. For traffic safety, green flashing mode may increase the chance of rear-end accidents (leading vehicles could suddenly stop at intersections), since signals switch to red unexpectedly (19, 20).

In general, drivers could feel more comfortable under green countdown mode than flashing mode. However, green flashing mode could intuitively induce more conservative driving decisions, decreasing overall traffic accidents risk, though possibly increasing rear-end accident risk.

4.2 Quantitatively Analysis

4.2.1 Running Red Light

Driving behaviors could be very different under various phase-switching modes, especially for red-light running. “Regulation on the Implementation of the Law of the People’s Republic of China on Road Traffic Safety” stipulates explicitly that red-light running refers to the vehicles violate the traffic signal lights and cross the stop line to keep driving when the red light is on. Red light running rate, namely the number of vehicles running red light per 100 vehicles, can directly reflect the effects of phase-switching mode on driving behavior. We calculated the red light running rates by analyzing video data of the whole observed time, which are shown in table 2. The lane number are shown in Fig.1.
Table 2 Traffic Flow and Red Light Running Rate in Each Lane

<table>
<thead>
<tr>
<th>Grade crossing</th>
<th>Tibet Road – East Yanan Road (countdown mode)</th>
<th>Pudong Road - Pujian Road (green flashing mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane number</td>
<td>1a</td>
<td>1b</td>
</tr>
<tr>
<td>Traffic flow</td>
<td>1653</td>
<td>1830</td>
</tr>
<tr>
<td>Number of Running red light</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Running red light rate</td>
<td>0.544</td>
<td>0.273</td>
</tr>
<tr>
<td>Mean*</td>
<td>0.564</td>
<td>0.253</td>
</tr>
</tbody>
</table>

* The mean expresses the red light running rate of the whole intersection, such as the mean of a countdown intersection \(\frac{590+57+15}{1653+1830+1543+1356} \times 100\), the mean of a green flashing intersection can be obtained in the same way.

From table 2, it can be seen that the frequency and rate of red-light running of each lane are higher under green countdown mode than green flashing mode. Additionally, the maximum red-light running rate is much higher under countdown mode than green flashing mode (1.106 versus 0.367). Meanwhile, the average red-light running rate under green countdown mode is 0.564, more than twice as many as that under green flashing mode. The results shown in table 2 are in good agreement with the previously speculation in section 4.1 that drivers may tend to rush through intersections at the end period of green time under green countdown mode. In general, compared to green countdown mode, green flashing mode appears to better improve intersection safety, being associated with a lower rate of red light running violation.

4.2.2 Operating Speed and Acceleration

To collect speed data, a series of data collection points were set up at the two intersections every 10 meters, from 80 m away to stop lines. Then, CDSP was applied to record the whole process of vehicles passing by these points and stop lines. Based on the data, the average operating speed and acceleration can be calculated as follows:

\[
V_i = \frac{10}{(t_i-t_{i+1})} \quad (1)
\]

\[
V_0 = \frac{10}{(t_0-t_1)} \quad (2)
\]

\[
a = \frac{V_0-V_i}{(t_0-t_1)} \quad (3)
\]

Where \(V_i\) refers to the operating speed of a vehicle when a yellow light is on.

\(V_0\) refers to the speed of a vehicle passing by a stop line, and if the vehicle stopped in front of the stop line, then \(V_0\) is 0.

\(a\) refers to the average acceleration of a vehicle passing by or stopping at the a stop line when a yellow light turns on.

\(i\) refers to the distance range of a vehicle when a yellow light is on, and the distance ranges of 0~10m, 10m~20m, etc. from stop line can be expressed 0, 1, etc., respectively.
t_i refers to the moment when a yellow light is on.

\[ t_{i+1} \] refers to the moment when a vehicle passes by a point which is \( s_i + 10 \) m far from a stop line, note that the \( s_i \) refers to the distance away from the stop line when a light turns yellow.

\[ t_0 \] refers to the moment when a vehicle passes a stop line or stops in front of the stop line.

Note that since average speed in a very short distance can be treated as instantaneous speed, the speed of a vehicle when crossing the stop line or when a signal turns yellow can be approximately measured by \( V_i \) and \( V_o \), respectively. With such method, we obtained the speed data of 262 and 210 vehicles under two modes, respectively. The following discussions are based on these data.

(1) Vehicle speed when yellow light is on

For the two modes, vehicle speeds at different locations when a yellow light is on are shown in Fig. 2. According to the box plots, the average speeds at the same area (i.e. the same distance away from stop lines) within 40m far from stop lines are slightly higher under green flashing switching mode than green countdown mode, when a yellow light is on. However, when the distance to stop lines are more than 40m, the average speeds are almost lower under green flashing mode.

![FIGURE 2. Speed at different phase-switching modes when a yellow light on](image)

(a) Green countdown mode  
(b) Green flashing mode

(2) Vehicle speed when crossing stop lines

At the end of a phase transition from green to yellow, drivers have to decide whether to rush through intersections or pull up at stop lines. Before comparing vehicle speed passing by stop lines under two phase-switching modes, driver’s decision on stopping/passing should be analyzed separately, and the sample results are shown in table 3.
### TABLE 3 The Statistical Results under Different Switching Modes

<table>
<thead>
<tr>
<th>Phase-Switching Modes</th>
<th>Countdown mode</th>
<th>Green flashing mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver’s stopping/passing decision-making behavior</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stopping before red light on</td>
<td>Stopping frequency</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>Stopping ratio</td>
<td>0.47</td>
</tr>
<tr>
<td>Passing before red light on</td>
<td>Passing frequency</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>Passing ratio</td>
<td>0.53</td>
</tr>
<tr>
<td><strong>The statistical results of speed when a yellow light is on</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average speed (m/s)</td>
<td>10.46536</td>
<td>12.56168</td>
</tr>
<tr>
<td>Variance (m²/s²)</td>
<td>17.88967</td>
<td>14.62226</td>
</tr>
<tr>
<td>V85-V15 (m/s)</td>
<td>8.86477</td>
<td>8.04598</td>
</tr>
<tr>
<td>t-test</td>
<td>t=5.583</td>
<td></td>
</tr>
<tr>
<td><strong>The statistical results of acceleration when a yellow light is on</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average acceleration (m/s²)</td>
<td>-0.63764</td>
<td>-0.95246</td>
</tr>
<tr>
<td>Variance of acceleration</td>
<td>2.36444</td>
<td>1.91735</td>
</tr>
<tr>
<td>t-test</td>
<td>st=2.310</td>
<td></td>
</tr>
<tr>
<td>Accelerating and crossing</td>
<td>Number</td>
<td>30</td>
</tr>
<tr>
<td>Crossing with constant velocity</td>
<td>Number</td>
<td>82</td>
</tr>
<tr>
<td>Decelerating and crossing</td>
<td>Number</td>
<td>27</td>
</tr>
<tr>
<td>Decelerating to stop</td>
<td>Number</td>
<td>123</td>
</tr>
</tbody>
</table>

From Table 3, it can be seen that the ratios of stopping and passing are very close under countdown switching mode. However under green flashing mode, a large percentage of drivers (61%) are more inclined to stop. And passing rate is higher under green countdown mode than green flashing mode, indicating that countdown mode could provide higher capacity for intersections. However, countdown mode could also increase the probability of running red lights and traffic accidents, while the high stopping ratio under green flashing mode could be helpful to ensure traffic safety.

For the vehicles crossing intersections during phase-switching periods, their speed were collected at stop lines, shown in Fig. 3. It can be seen that for vehicles being the same distance away from stop lines at the initial moment of yellow lights, the average operating speed is higher under green flashing mode than countdown mode. Note that vehicles that fully stopped at the two intersections were excluded in Figure 3, since their speeds are zero. Fig.3 also indicates that vehicles being 40 meters or more away from stop lines are mostly likely to stop at intersections, when a yellow light turns on.
FIGURE 3. Speed scatter diagram at the moment when crossing stop lines

(3) Speed dispersion

Speed dispersion reflects, to some extent, driving behavior and road safety. A relatively small speed dispersion indicates stable driving behavior and traffic condition. Speed dispersion can be measured by calculating speed variance:

\[ S^2 = \frac{\sum_{i=1}^{n}(v_i - M)^2}{n} \]  

(4)

Where \( v_i \) refers to the speed of vehicle i, \( M \) refers to the average speed of the observed vehicles, \( n \) refers to the total number of observation samples.

Here the average speed, velocity variance, and the difference between 85% and 15% speed (represented as V85-V15) were calculated, as shown in table 3. The cumulative frequency diagrams of speed and speed variance are shown in Fig. 4.
The most common type of t-test, namely the student t-test, is often used to assess whether the means of two classes are statistically different from each other. From Table 3, we calculated the value of t-test for speed is 5.583, greater than the critical value of 2.008, so we reject the null hypothesis and conclude that the speeds at these two phase-switching modes are different at the 0.05 significance level. And from Figure 4, vehicle speed is more dispersed under green countdown mode than green flashing mode. Since drivers can be informed by the remaining seconds of a green light in advance, their behaviors could be more diverse under countdown mode, depending on their personal characteristics, traffic conditions, and mental state. On the other hand, most drivers tend to be conservative under green flashing mode, because they may have concerns of red-light running violations without knowing the exact end point of a green light.

(4) Speed fluctuation

In this section, the speed fluctuation of each vehicle during a phase-switching period was analyzed. Here, speed fluctuation refers to how a vehicle speed changes with time and location. It indicates the adaptability of drivers to different phase-switching modes, and can indirectly reflect the approximate range of drivers’ decision in the late phase-switching period (21). When drivers perceive phase-switching information, their decisions could be very different, resulting in varied speed fluctuation. Especially, speed fluctuation could be associated with vehicles’ initial locations (i.e. the distance away from a stop line). Based on the video data, SPSS (Statistical Product and Service Solutions) was employed to get the statistics of speed fluctuation of different vehicle groups (classified by their initial locations at the beginning of a phase-switching signal, i.e.) at each data collection location (e.g. 0m, 10m, 20m ...... 60m from a stop line). Figure 5 shows the speed statistics (e.g. the max, min and mean speed) of each vehicle group at each location, under green countdown and flashing mode.
Green countdown mode
(a) Perceiving yellow light information within 16-24m away from a stop line

Green flashing mode
(b) Perceiving yellow light information within 25-34m away from a stop line

Green countdown mode
(c) Perceiving yellow light information within 35-44m away from a stop line

Green flashing mode
(d) Perceiving yellow light information within 45-54m away from a stop line
Green countdown mode

(e) Perceiving yellow light information at 55m or more away from a stop line

FIGURE 5 Comparison of speed fluctuation

- It can be seen that vehicle speeds are relatively stable under green countdown mode, when vehicles are relatively close to a stop line (<34m). However, when vehicles are far away from a stop line (>35m), their speeds become fluctuant. In this case, drivers could suddenly accelerate or decelerate, indicating that they were facing with the dilemma of whether or not to cross the intersections. This is similar with green flashing mode. In general, vehicle speeds start to be fluctuant, when vehicles are more than 35m away from a stop line at the initial moment of a phase-switching signal. The degree of fluctuation is overall lower under green flashing mode than countdown mode, according to Figure 5.

(5) Acceleration Fluctuation

During a phase-switching period (i.e. from green to red), drivers’ behaviors near intersections can be divided into four types: accelerating and crossing, crossing with a constant velocity, decelerating and crossing, and decelerating to stop. The statistical results are shown in Table 3. The value of t-test for acceleration is 2.310, greater than the critical value of 2.008, so we reject the null hypothesis and conclude that the acceleration at these two phase-switching modes are different at the 0.05 significance level. The largest proportion of driving behavior is decelerating to stop under green flashing mode, implying that such mode could induce drivers to decelerate when a yellow light turns on. Similar to the analysis of speed dispersion, the greater fluctuation of acceleration (deceleration) rate, the higher probabilities of traffic accidents may occur, especially for rear-end accidents. Seen from Fig 6, the fluctuation of acceleration is lower under green flashing mode than green countdown mode.

FIGURE 6 Comparison of acceleration
5. CONCLUSIONS

In this study, drivers’ behavior near intersections were examined and compared under two different phase-switching modes, namely green flashing and green countdown. Two typical at-grade intersections in Shanghai were selected for a case study. Video techniques and CDSP were employed to obtain traffic data and capture driving behaviors. Both qualitative and quantitative analysis were conducted to identify drivers’ behaviors and adaptability under these two modes, considering driver's psychology changes, red-light running maneuvers, and speed characteristics. The main conclusions of this study are summarized as follows:

- Red-light running rate is significantly lower (about half) under green flashing mode than green countdown mode;
- At the late stage of a phase switching, the rate of rushing through intersections is higher under countdown mode than flashing mode; the rate of stopping is relatively higher under green flashing mode than countdown mode;
- The average operating speed at stop lines is slightly higher under green flashing mode, and vehicles more than 35m away from stop lines tend to stop, when a phase-switching signal turns on under both modes;
- The dispersion rates of speed and acceleration are relatively lower under green flashing mode than green countdown mode;
- When a phase-switching signal turns on (either green countdown or flashing), the speeds of vehicles being 35 m or more away from the stop line tend to fluctuate. In addition, the degree of fluctuation is overall lower under green flashing mode than green countdown mode.

In general, green countdown mode makes drivers feel more comfortable than green flashing mode by resulting in lower speed/acceleration fluctuation; but from the safety perspective, green flashing mode could be safer than countdown mode, by decreasing the rate of red-light running and rushing. Thus, this study provides references for the compilation of some relevant norms and specifications as well as providing the basic implication for the traffic management department to ensure the traffic safety and execute traffic control. And these conclusions also provide the basic for the further development of ITS (Intelligent Transportation Systems).

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