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Implications of advanced warning messages on eliminating sun glare disturbances at signalized intersections

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ABSTRACT

Due to sun glare disturbances, drivers encounter fatal threats on roadways, particularly at signalized intersections. Many studies have attempted to develop applicable solutions, such as avoiding sun positions, applying road geometric re-directions, and wearing anti-glare glasses. None of these strategies have fully solved the problem. As one of the “Connected Vehicle” practices proposed by the U.S. Department of Transportation, advanced warning messages (AWMs) are capable of providing wireless information about traffic controls. AWM acts as a supplement to conventional signs and signals, which can be blocked by obstacles or natural disturbances, such as sun glare. The drivers' smart advisory system (DSAS) can provide drivers with AWM. Using a driving simulator this research explores the effects of DSAS messages on driving behaviors under sun glare disturbance. Statistical analyses were applied to assess (1) the negative impacts of sun glare, (2) the compensation of the DSAS AWM to sun glare effects, and (3) the improvement in driving performance due to DSAS AWM. Four performance indexes were measured, including (1) half kinetic energy speed, (2) mean approach speed, (3) brake response time, and (4) braking distance. The effects of the socio-demographic factors, such as gender, age, educational background, and driving experience were also studied. The analytical results illustrate that the DSAS can compensate for reduced visibility due to sun glare and improve driving performance to a normal visual situation, particularly for left turn and through movement.

1. Introduction

At a signalized intersection, traffic control messages are normally delivered to drivers through colored signals (i.e., green, yellow, and red). However, the visibility of a traffic signal can be affected by natural disturbances, such as sun glare. Most people prefer picture-perfect weather to engage in outdoor activities. When sunlight becomes intense, the visibility of objects is impaired, and low-contrast objects may be rendered

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invisible. In these cases, drivers often find it difficult to perceive the dynamic traffic situations, thereby increasing the probability of the crash.

Ranney et al. (2000) found that the immediate presence of glare might lower a driver's ability to detect pedestrians and other targets appearing in mirrors. The glare's immediate effects may lead to a significant change in driving behaviors, including increased lane-position variability, reduced speeds, and, most often, increased steering variability and improper braking.

Glare-related crashes occur around the world. In the Chiba Prefecture of Japan, 10,352 sun glare-related incidents were reported between 2007 and 2011 (Hagita and Mori, 2014). In Great Britain, 36 deaths were attributed to sun glare at dawn during rush hours. In addition, sun glare has been involved in nearly 3000 annual traffic incidents, as they temporarily blind the driver with sunlight on the windscreen (DTGMH, 2013). Since glare-related crashes occur alongside conditions like excessive speed, the glare is not always classified as the official cause of a crash in investigations. As such, the official number of glare-related crashes does not reflect the actual situation, and sun glare is an essential variable in traffic incidents.

Many strategies, such as wearing polarized sunglasses or avoiding driving in a direction that faces the sun, have been applied to mitigate the effects of sun glare (Waldron, 2013). However, as the direction of sunlight varies depending on the time of day and the season, medial countermeasures are difficult to implement. Instead, innovative technologies in advanced warning messages (AWMs), such as remote and wireless messages from the drivers' smart advisory system (DSAS), are needed to supplement traditional traffic signals to obliterate the visual disturbance caused by glare (Qiao et al., 2013a).

To identify driving performance with and without sun glare disturbances at signalized intersections, it is necessary to conduct comprehensive tests and in-depth analyses. These tests and analyses include the impacts of AWM on a driver's signal awareness and reactions to different movement directions (e.g., left, through, and right).

At a traffic conflicting area, such as intersections, the probability of collisions involving other vehicles and/or pedestrians may be obviously higher than in other areas (Li et al., 2013; Qiao et al., 2016a). In light of safety, driving simulator has been often chosen for a safety driving tests, such as in work zones, STOP sign intersection and sidewalk (Qiao et al., 2014a, 2016b). The driving simulator is able to provide an ideal experimental environment of hazardous situations (Crundall and Underwood, 1998; Underwood et al., 2003). Therefore, a driving simulator test may be more feasible and safer for this research before larger scale field tests are conducted.

The visual destruction caused by sun glare can affect driving behaviors at all phases of traffic signals. In particular, during the red phase, drivers may be more likely to run a red light and, consequently, crash into other vehicles at intersections. As such, this paper only focuses on the red phase, when drivers are approaching intersections under sun glare effects.

Specifically, the objective of this paper is to identify the implications of AWMs on drivers' driving performance at intersections under sun glare conditions using driving simulator tests.

1.1. *Advanced warning messages linking drivers with signals*

A "Connected Vehicle" program was initiated with an Intelligent Transportation System (ITS) Research Program in the United States to address complicated transportation problems and maximize the use of cutting-edge technologies (Spear et al., 2010; USDOT, 2010). As a part of the echoes, many new technologies, such as WiFi, Bluetooth, Radio Frequency Identification (RFID), ZigBee, and even a smart phone, have been identified to enhance the communications between vehicles and infrastructure (Li et al., 2016; Qiao et al., 2002, 2013c, 2016c). The predominant idea is to equip drivers with "electronic eyes" and/or "electronic ears" to supplement conventional traffic control devices. In addition, drivers can receive real-time traffic control information effectively in the form of AWM.

Many studies have previously investigated the design of traffic warning systems. More specifically, Wu et al. (2010) developed an advanced driving alert system (ADAS), which contains an in-vehicle ADAS powered by an advanced communication system. Simulator tests were used to evaluate the system performance while traffic signal status (TSS) information was used to reduce energy and emissions.

Schultz and Talbot (2009) developed advance warning signals (AWS) to warn an approaching intersection or impending signal change. Singh et al. (2012) proposed the application of intelligent traffic lights using RFID. Kotchasarn (2009) reported a RFID-based in-vehicle alert system to provide drivers an effective non-line-of-sight (NLOS) distance, with a timely warning message about unexpected traffic jams caused by a crash or other incidents.

Qiao et al. (2014b) developed an RFID-based driver's smart advisory system (DSAS) to supply drivers with early warning messages about traffic control information, such as signals and signs. With such a system, drivers can react earlier to avoid unnecessary waiting time for green lights and/or running red lights at signalized intersections. A pilot test was conducted at an intersection in Houston, Texas (USA), which yielded very promising outcomes (Qiao et al., 2013b).

AWM systems will definitely enhance the safety and efficiency of the existing traffic control devices. However, they are currently still in the stages of either lab tests or very small-scale field tests. As such, the implications of these AWM systems on driving performance have not yet been determined. In this paper, driving performance under AWM from DSAS is explored in various intersection scenarios under the condition of sun glare.

1.2. *Measurement of driving performance*

By taking advantage of a driving simulator that provides sufficient information relevant to driver behaviors, many variables have been considered in the evaluation of driving performance. Specifically, the speed, time, and headway distance are often used to evaluate safety performance (Li et al., 2015a; Rahman et al., 2015; Tijerina et al., 2004). Reaction time is then classified into perception response time, brake response time, and time to give an action, in various safety studies (Green, 2000; Lamble et al., 1999; Olson and Farber, 2003; Summala, 2000). In this paper, approach speed, brake response time for traffic signals, and braking distance for red lights, were chosen as the measurement of the DSAS at an intersection with a sun glare disturbance.

Additionally, gender is considered as a crucial factor in determining driving and insurance risk (Al-Balbissi, 2003). Nauert (2011) found that males were more likely to drive aggressively compared with female. Li et al. (2015b) demonstrated that young and highly educated drivers changed lane earlier to preset the vehicle position for further navigation. Besides, highly educated subjects drive apparently slower compared to those with lower level of education (Deaton, 2003). Salthouse (2000) discovered that the elderly required longer response time than young individuals on cognitive performance tasks, which placed additional demands on attentive and visual processing abilities, a phenomenon known as the "slowing effect" (Verhaeghen et al., 2003). Furthermore, elderly drivers had tendency to be more careful and monitor their responses more thoroughly than younger drivers (Botwinick, 1966; Qiao et al., 2016d). Logically, drivers with sufficient driving experience can better grasp driving skills, thereby performing better maneuvers. Therefore, socio-demographic factors, including gender, education, driving experience, and age, are included in the performance measurement.

2. Method

2.1. Participants

Thirty subjects were recruited, and the socio-demographical distribution of which was based on the 2010 Houston census record (Table 1). All subjects possessed a valid C class Texas driver license, had self-reported normal or corrected-to-normal vision, and did not have any hearing problems.

Table 1 – Study subject socio-demographics.

Characteristic	Distribution (%)		Number of test subject
	Houston	Adjusted	
Gender			
Male	49.8	50	15
Female	50.2	50	15
Age (years)			
<5	8	N/A	N/A
5–17	26	N/A	N/A
18–64	57	90	27[a]
≥65	9	10	3[b]
Education			
Associate's degree or lower	73	70	21[c]
Bachelor's degree or higher	27	30	9[d]

[a] Twenty people had completed an associate's degree or lower, and 7 had a bachelor's degree or higher.

[b] One person had completed an associate's degree or lower, and 2 had a bachelor's degree or higher.

[c] Twenty people were between 18 and 64 years old, and 1 was 65 years of age or older.

[d] Seven people were between 19 and 64 years old, and 2 were 65 years of age or older.

Fig. 1 – Driving simulator at an intersection with sun glare.

2.2. Apparatus

This investigation employed a fixed-base driving simulator (Drive Safety DS-600C). A sun glare effect was artificially mimicked by projecting a beam of light onto the screen with the intention to block out the sight of oncoming traffic signals (Fig. 1).

2.3. Scenario design

2.3.1. Description of scenarios

The test scenarios examine three conditions: (a) with sun glare (S) or without ($\overline{S}$); (b) with DSAS AWM (D) or without ($\overline{D}$); (c) movement directions of left turn (L), through movement (T), or right turn (R). Each scenario is coded with three letters based on the response. In total, nine scenarios were designed (Table 2) and embedded in a 10 km long test track with ten signalized intersections (Fig. 2). The DSAS messages are applied only under the sun glare condition. The digits 1–9 represent the scenario number at each intersection (Table 2).

The artificial sun glare was strong enough to block the driver's vision when driving, and only applied to vehicles traveling from east to west, as is illustrated in Fig. 2, to simulate afternoon driving conditions when the sun was in the western sky. No any other ambient vehicle was present

Table 2 – Unique scenario codes for the simulator tests at signalized intersections.

Scenario number	Sun glare	DSAS	Movement direction	Scenario code
1	No	No	Left	$\overline{S}\overline{D}L$
2	Yes	No		$S\overline{D}L$
3	Yes	Yes		SDL
4	No	No	Through	$\overline{S}\overline{D}T$
5	Yes	No		$S\overline{D}T$
6	Yes	Yes		SDT
7	No	No	Right	$\overline{S}\overline{D}R$
8	Yes	No		$S\overline{D}R$
9	Yes	Yes		SDR

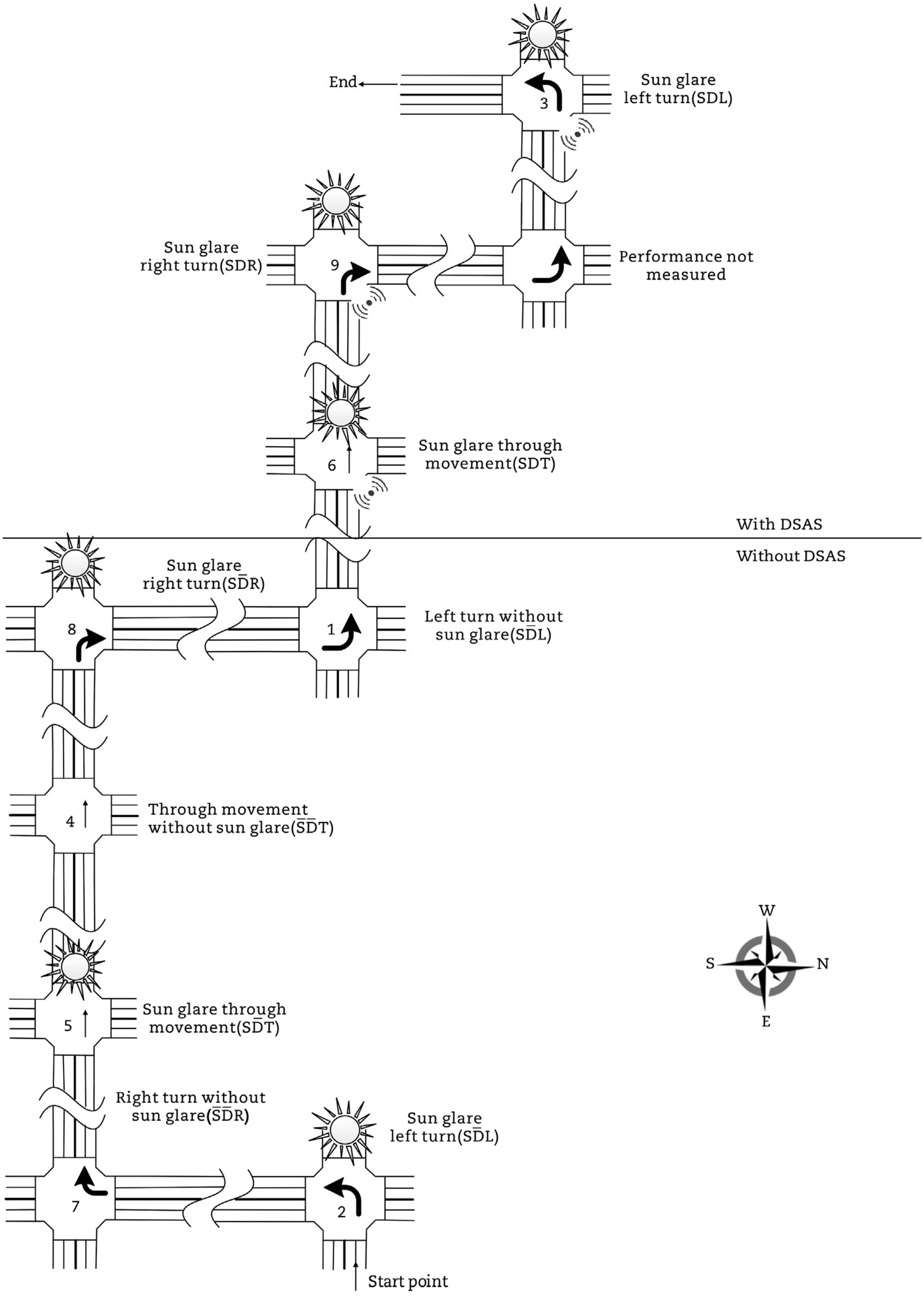

Fig. 2 – Test track with nine scenarios, including three left turns, three right turns, and three through movements, with and without the DSAS AWM.

during the test, and all intersections were standard, with two approaching lanes and no dedicated left turn lane. The sun glare to drivers during the test is shown in Fig. 1, while the illustrations of roadway and intersection layouts, and sun glare directions on all roadway segments are shown in Fig. 2.

Along the track in Fig. 2, subjects were required to depart from the “start point” and follow the predefined audio messages instructing them to make a left turn, right turn, or through movement at each intersection. As Fig. 2 illustrates, each subject first experienced tests without the DSAS AWM (i.e., Scenarios 2, 7, 5, 4, 8 and 1), followed by test scenarios with the DSAS AWM (i.e., Scenarios 6, 9 and 3), which are located above the dashed line from the seventh intersection marked as Scenario 6.

In the three test scenarios with the DSAS AWM (i.e., Scenarios 6, 9 and 3), an artificial sun glare effect was provided. The sequence of the turning movement on the test track is intentionally arranged to complete the three movements (i.e., left, through, and right) in the three situations (i.e., $\overline{\mathrm{SD}}$, S$\overline{\mathrm{D}}$, and SD) with the least number of intersections in the test. Driving behaviors are not measured in one non-code intersection after Scenario 9 simply because its situation is a duplicate of Scenario 1.

To obtain insight into the subjects' inertial driving behaviors in different scenarios, a warming-up training was provided individually right before the formal tests for all of the subjects. During training, each subject drove two to three times through a short route until he/she became familiar with driving in a simulated environment and the messages from the DSAS. They encountered three situations ($\overline{\mathrm{SD}}$, S$\overline{\mathrm{D}}$, and SD) with the random change of traffic signals at intersections.

During the test, each subject was the sole driver through the track. All subjects drove through the same test track; thus, their driving behaviors were comparable. Except for the visual disturbance of sun glare, no other weather conditions were involved in the simulation environment.

2.3.2. *Determining locations to provide audio messages*

Two types of audio messages were used to alert drivers. The first type is the lane preparation message that guides drivers for a suitable lane change, if applicable. For example, if a driver is instructed to turn left, he/she is prompted to change to or stay in the left lane. The distance from where the drivers receive such a lane change message until they complete the entire action is called the "lane preparation distance", denoted as D_{lp} in Fig. 3.

The second type of audio message provided by DSAS is about the status of the signal at the oncoming intersection. The distance between the locations where the second type of the audio message is prompted and the stop line is marked, is called the "signal message distance", denoted as D_{sm} in Fig. 3.

It is assumed that drivers complete their lane change before the second type of audio message (signal light message) is provided. The lane change message "Please turn left/turn right/go straight" lasts for 1.0 s. Within that second, drivers travel for 20 m with the posted speed limit of 72 km/h (20 m/s). A 2.5 s perception/reaction time and a 6 s lane change duration were used to calculate the perception/reaction distance (D_{p} = 50 m) and lane change distance (D_{r} = 20 m) (Chang et al., 1985; Toledo and Zohar, 2007). Therefore, the total lane preparation distance is expressed as $D_{\mathrm{lp}} = D_{\mathrm{a}} + D_{\mathrm{p}} + D_{\mathrm{l}} = 20\ \mathrm{m} + 50\ \mathrm{m} + 120\ \mathrm{m} = 190\ \mathrm{m}$.

For the "signal message distance", D_{sm}, an audio message "red light is on" is played for 1.0 s, resulting in an audio-on distance of D_{a} = 20 m. The perception–reaction distance D_{p} is 50 m for the lane change message. As defined by Federal Highway Administration (FHWA) regarding minimum sight distance for signal visibility in the Manual on Uniform Traffic Control Devices (FHWA, 2009), the minimum sight distance D_{s} for signal visibility is D_{s} = 140 m for a posted speed of 72 km/h. Consequently, the total signal message distance of D_{sm} is expressed as $D_{\mathrm{sm}} = D_{\mathrm{a}} + D_{\mathrm{p}} + D_{\mathrm{s}} = 20\ \mathrm{m} + 50\ \mathrm{m} + 140\ \mathrm{m} = 210\ \mathrm{m}$. The implications of the DSAS messages on driving behaviors performed in this segment are assessed.

The total message distance is expressed as $D_{\mathrm{t}} = D_{\mathrm{lp}} + D_{\mathrm{sm}} = 190\ \mathrm{m} + 210\ \mathrm{m} = 400\ \mathrm{m}$. This means that the first audio message on lane preparation should be played 400 m away from the stop line at an intersection. The audio message of a signal light should be prompted at 210 m from the stop line.

At the minimum sight distance (D_{s} = 140 m), drivers are supposed to sense the traffic signal through their visual observations without disturbance. The artificial sun glare was applied at the minimum sight distance in the situation of SD.

Once a vehicle reaches the stop line, the traffic signal is triggered from red to green. If the DSAS AWM is in use, an audio message "Green Light Is On" will be played, to prompt the vehicle to continue to the next scenario(s) along the test track.

2.4. *Data collection for driving performance measures*

During the simulator test, sixty records were stored for each second, including vehicle's geo-location, speed, and braking

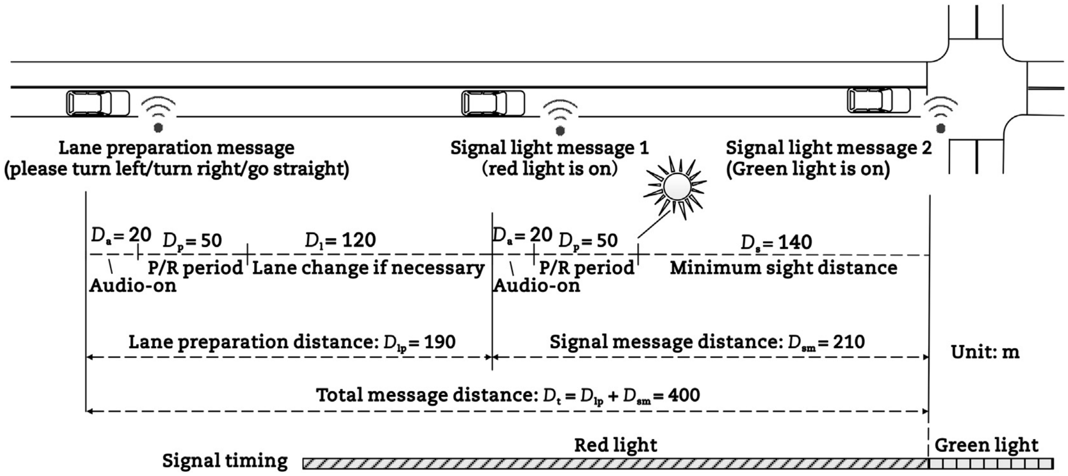

Fig. 3 – Layout of the lane preparation distance and the signal message distance.

levels, ranging from 0.0 to 1.0 (0.0 is the minimum level with no brake and 1.0 is the maximum with full brake). A self-developed MATLAB program was used in the data processing for test drivers' driving performance.

Four performance measure indexes were used to investigate the sun glare effects and the application of the DSAS AWM, including (1) speed decreasing process with the attenuation of kinetic energy, (2) mean approach speed, (3) brake response time, and (4) braking distance to the stop line (Fig. 4).

As Fig. 4 shows, the speed reduction process and mean approach speed are analyzed during the signal message distance D_{sm}. When drivers receive an audio message “red light is on”, they are supposed to decelerate; thus, the vehicle's kinetic energy would start to attenuate. The −3 dB point indicates the speed at which the vehicle's kinetic energy attenuated to its half, which corresponds to 70.7% of the initial speed. This is known as half energy speed in this study. For more details about the −3 dB point, please refer to studies by Van Valkenburg (2008) and IEEE (2000). To some extent, the corresponding distance for the −3 dB point could be a clear indication of how quickly a vehicle decelerates or how hard the brake paddle the driver's foot is applied to. The half kinetic energy speed would represent how steep it is for the vehicle's initial speed to be decreased to zero due to the driver's awareness of the red light signal and/or message(s).

The brake response time is the duration between the moment when the signal audio message is provided and the moment the driver starts to apply the brake pedal. In the situation without an audio message, subjects are assumed to be able to recognize the traffic signal at 210 m away from the intersection. The braking distance is measured from the first brake action, after the delivery of the audio/visual message for the traffic signal, to the intersection's stop line at the.

To comprehensively study the implications of the DSAS AWM on driving behavior, comparisons among three visual situations ($\bar{S}\bar{D}$, $S\bar{D}$, and SD) were carried out using *t*-tests (Fig. 5) to examine the impacts of sun glare, compensation of DSAS, and impacts of DSAS.

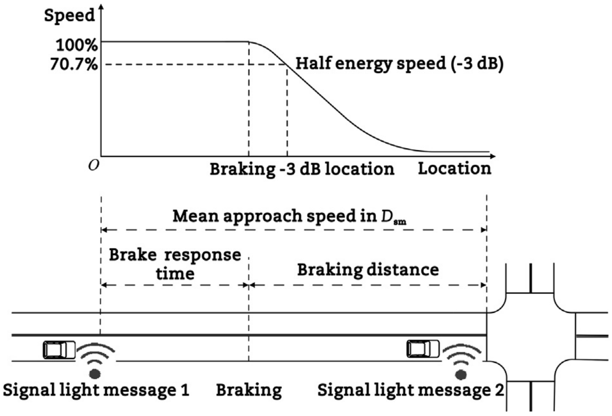

Fig. 4 – Illustration of four performance measure indexes.

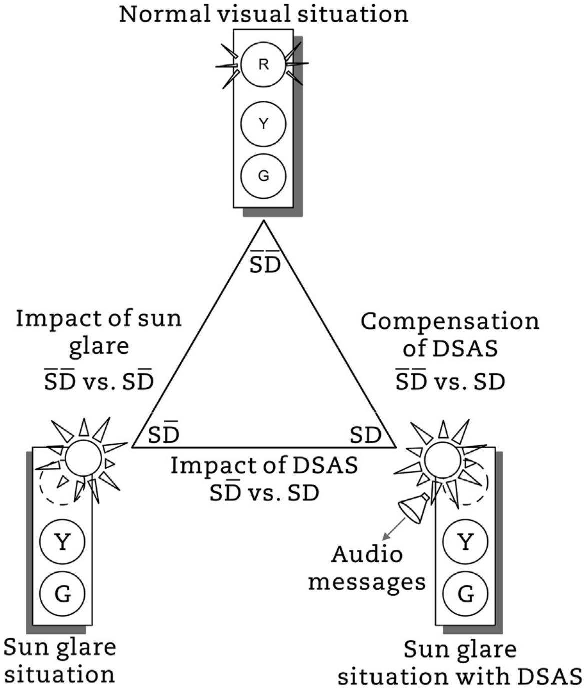

Fig. 5 – Comparisons among three visual situations.

3. Results and discussion

3.1. *Mean speed decreasing process*

Fig. 6 illustrates the 30 subjects' mean speed reducing process to approach an intersection under three visual situations of $\overline{SD}$, SD, and $S\bar{D}$.

3.1.1. *Impacts of sun glare*

In Fig. 6, in a normal visual situation ($\bar{S}\bar{D}$), a vehicle's kinetic energy attenuates to its half (at the speeds curve of −3 dB) earlier on through movement of 89 m, followed by left turn and right turn of 79 and 69 m, respectively. Under the visual disturbance of sun glare condition ($S\bar{D}$), half energy distance was shortened to 46 m for left turn, 54 m for through movement, and 50 m for right turn. The half energy distances differ among the three movements by only a few meters. This implies that the sun glare disturbance is an important factor in the shortening of half energy distance across the three movements. The drivers may have trouble recognizing the traffic signal, which decreases the half-attenuation distance.

The curve for $S\bar{D}L$ shown in Fig. 6 represents a relatively lower speed compared to with other curves for left turn at the distance of 210 m. The lower speed could be due to a small limitation in the design of the scenarios. As all subjects started with Scenario 2 (Fig. 1), the buffer distance may not have been sufficient to increase to a relatively higher speed (72 km/h) before they approached the upcoming intersection.

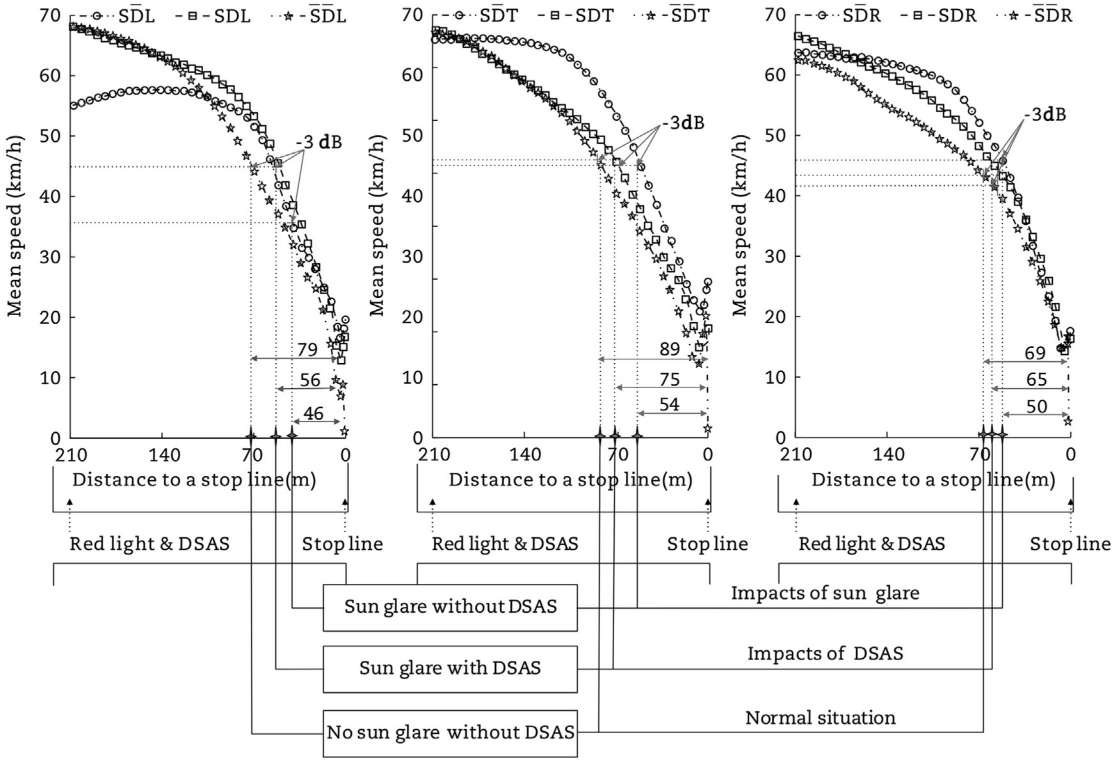

Fig. 6 – Mean approach speed profile and distance from the 70.7% (3 dB) of the original speed to a stop line at a signalized intersection on left turn, through movement, and right turn.

3.1.2. *Compensation of the DSAS AWM*

When the DSAS messages were provided for the SD situation, the distance at the speed of the −3 dB points was apparently extended to 75 and 65 m for through movement and right turn, respectively. For left turn, the extended distance, 56 m, was comparatively shorter. Left turn was usually considered as one of the most challenging and dangerous driving maneuvers (Hyatt, 2014), which might explain the unapparent improvement of the half energy distance. Though the extended half energy distance was still slightly shorter compared with the one in a normal situation ($\overline{S}\overline{D}$), subjects' speed profile for the SD situation shown in Fig. 6 was gradually decreasing. Unlike the $S\overline{D}$ situation, no hard braking was observed, suggesting that the DSAS AWM can help drivers to perform a smoother deceleration and increase the half energy distance to the stop line at intersections with sun glare disturbances.

3.1.3. *Implications of the DSAS AWM*

Compared with the $S\overline{D}$ situation, the half energy distance in the SD situation was obviously longer for through movement and right turn. The extension of the half energy distance on left turn is comparative smaller, but a ten meter longer distance was still observed (56 m for SDL vs. 46 m for $S\overline{D}$L). Under sun glare, the half energy distance disturbances improved for all movements when DSAS messages were provided. In this way, it is believed that the DSAS messages did draw drivers' attention to the traffic situation, rather than distracting them.

3.2. *Mean approach speed*

Table 3 lists the *t*-test results, which identify the statistically significant differences in the mean approach speed caused by either sun glare or DSAS audio messages.

3.2.1. *Impacts of sun glare*

The *t*-test results in Table 3 (*t*-test 1) illustrate that the impacts of sun glare on the mean approach speed are significant for through movement and right turn, but insignificant for left turn. This is probably because of the longer left turn radius. Furthermore, the challenging and dangerous driving maneuvers associated with left turn require increased attention, even under normal visual situation. Consequently, drivers may decrease speed. Meanwhile, less visibility caused by sun glare also decreases driving speed. In this case, the difference in left turns between the two visual situations ($\overline{S}\overline{D}$ vs. $S\overline{D}$) is not expected to be significant.

3.2.2. *Compensation of the DSAS AWM*

For *t*-test 2 (Table 3), insignificant differences in mean speed between $\overline{S}\overline{D}$ and SD are expected if the DSAS can fully compensate for the impacts of sun glare. However, this only emerged for through movement (through: $t(426) = 0.87$ and $p = 0.39$). Significant differences were found for turning movements (i.e., left and right turn). For left turn, the *p*-value of 0.03 ($t(426) = 2.16$) is close to the critical value of 0.05, which indicates that the DSAS messages can help drivers to manage their approach speed effectively, but not

Table 3 – *t*-test results of the mean approach speed in the comparisons of the visual situations.

Test	Left	Through	Right
t-test 1: on the impacts of sun glare			
$\overline{SD}$ (no sun glare, no DSAS) vs. $S\overline{D}$ (sun glare without DSAS)			
$t(426)$	0.92	4.73	4.00
$p_{\text{two tail}}$	0.36	3.08E−06	7.34E−05
Significant*	No	Yes	Yes
t-test 2: on the compensation of DSAS AWM			
$\overline{SD}$ (no sun glare, no DSAS) vs. SD (sun glare with DSAS)			
$t(426)$	2.16	0.87	1.65
$p_{\text{two tail}}$	0.03	0.39	1.6E−03
Significant*	Yes, but close	No	Yes
t-test 3: on the implications of DSAS AWM			
$S\overline{D}$ (sun glare without DSAS) vs. SD (sun glare with DSAS)			
$t(426)$	3.59	3.66	0.87
$p_{\text{two tail}}$	3.72E−04	2.79E−04	0.38
Significant*	Yes	Yes	No

"*" means significance at level of 0.05.

return to a normal visual situation. For right turn, with the aid of DSAS messages, subjects drive significantly faster ($t(426) = 1.65$ and $p = 1.6\text{E}{-}03$), but performed smoothly deceleration profile (Fig. 6). Therefore, the significant difference may due to drivers' confidence in driving with the DSAS messages.

In other words, the application of the DSAS AWM is able to compensate for the negative impacts of sun glare and correct the visibility, while making through movements and partially left turns, and increase drivers' confidence in driving.

3.2.3. *Implications of the DSAS AWM*

When $S\overline{D}$ and SD is compared, with the help of the DSAS message, the mean approach speed for left turn and through movement are significantly different from that without the DSAS message. The significant distinction is not present for right turn. In fact, Fig. 6 shows a sharp drop in the speed profile for the $S\overline{D}$ situation when right turns are made, whereas the profile of the SD situation is apparently smoother. In this case, the DSAS messages do not significantly affect the mean values, but do reduce the fluctuations of the approach speed.

3.3. *Mean brake response time*

Tables 4 and 5 list the brake response time and significant test results for different visual situations.

3.3.1. *Impacts of sun glare*

When both sun glare and DSAS are absent in the $\overline{SD}$ situation, the brake response time for all movement directions falls between approximately 5–6 s (Table 4). In the visual $S\overline{D}$ situation, the brake response time is extended to approximately 7–10 s. Table 5 shows that the distinction in the brake response time between the two situations ($\overline{SD}$ vs. $S\overline{D}$) is statistically significant different across the three movements (left turn: $t(58) = 3.77$ and $p = 3.82\text{E}{-}04$; through: $t(58) = 3.37$ and $p = 1.35\text{E}{-}03$; right turn: $t(58) = 2.19$ and $p = 3.26\text{E}{-}02$). These results are reasonable, as sun glare can impair subjects' visibility of the upcoming red light, and thereby, significantly delay their response time.

Table 4 – Brake response time to the given signal, red light, at the intersection (unit: s).

Movement direction	Mean brake response time		
	$\overline{SD}$	$S\overline{D}$	SD
Left turn	5.94	9.47	6.37
Through	5.03	7.37	4.44
Right turn	5.85	7.90	6.82

3.3.2. *Compensation of the DSAS AWM*

When DSAS message is provided in the sun glare situation (SD), the brake response time returns to 6 + s for left and right turns. For through movement, the brake response time is further shortened to 4.44 s (Table 4). The *t*-test results of the brake response time show no significant difference between the $\overline{SD}$ and SD situations (left turn: $t(58) = 0.41$ and $p = 0.68$; through: $t(58) = 0.87$ and $p = 0.39$; right turn: $t(58) = 0.72$ and $p = 0.48$), as shown in Table 5. This means that in terms of the brake response time, the DSAS AWM can compensate for the sun glare disturbance fully to a normal situation.

3.3.3. *Implications of the DSAS AWM*

Significant differences emerged between the visual $S\overline{D}$ and SD situation for left turn and through movement (Table 5) (left turn: $t(58) = 3.05$ and $p = 3.4\text{E}{-}03$; through: $t(58) = 4.15$ and $p = 1.10\text{E}{-}04$) but not right turn ($t(58) = 0.96$ and $p = 0.34$; 6.82 s for SD and 7.90 s for $S\overline{D}$). Due to the smoother speed profile in the SD situation, the longer response time can be explained by driver's intentional reaction to the red light. As long as they are confident in managing their speeds, they may react to the signal later intentionally.

3.4. *Braking distance*

Once the subjects step on the brake pedal during the simulator tests, the levels of braking (ranging from 0.0 to 1.0) are immediately recorded. The corresponding geo-locations when braking are utilized to calculate the braking distance to the target intersection. Tables 6 and 7 list the braking distance and significance test results for the different visual situations.

3.4.1. *Impacts of sun glare*

In a normal situation ($\overline{SD}$), the braking distance for all movements is similar. More specifically, they are all approximately 120 m before the stop line (Table 6). However, this distance is reduced to about 80 m for through movement and right turn under sun glare effects ($S\overline{D}$). For left turn, the distance becomes even shorter (66.55 m). The difference in braking distance between the two situations ($\overline{SD}$ vs. $S\overline{D}$) is significant for all movements (left turn: $t(58) = 4.12$ and $p = 1.21\text{E}{-}04$; through: $t(58) = 4.56$ and $p = 2.72\text{E}{-}05$; right turn: $t(58) = 3.48$ and $p = 9.72\text{E}{-}04$) (Table 7). This result is expected, as longer brake response time caused by less visibility mentioned above may lead to shorter braking distance.

Table 5 – *t*-test results for the brake response time (unit: s).

Movement direction	$\overline{S}\overline{D}$ vs. $S\overline{D}$		$\overline{S}\overline{D}$ vs. SD		$S\overline{D}$ vs. SD	
	t(58)	p-two tail	*t*(58)	p-two tail	*t*(58)	p-two tail
Left turn	3.77	3.82E–04*	0.41	0.68	3.05	0.34E–02*
Through	3.37	1.35E–03*	0.87	0.39	4.15	1.10E–04*
Right turn	2.19	3.26E–02*	0.72	0.48	0.96	0.34

"*" means significance at level of 0.05.

Table 6 – Braking distance to a stop line at a signalized intersection (unit: m).

Movement direction	Mean braking distance		
	$\overline{S}\overline{D}$	$S\overline{D}$	SD
Left turn	114.69	66.55	107.28
Through	126.62	85.43	136.81
Right turn	122.38	80.52	106.19

3.4.2. *Compensation of the DSAS AWM*

When the DSAS AWM is present under a sun glare situation (SD), the braking distance increases back to 107.28 and 106.19 m for left and right turns, respectively. For through movement, the braking distance (approximately 140 m) becomes 136.81 m (even longer than 126.62 m for $\overline{S}\overline{D}$). Even more, the braking distances are not significantly different from normal visual situation ($\overline{S}\overline{D}$) distances (left turn: $t(58) = 0.61$ and $p = 0.54$; through: $t(58) = 0.87$ and $p = 0.39$; right turn: $t(58) = 1.19$ and $p = 0.24$) (Table 7). These results demonstrate that the DSAS AWM can fully compensate for the impairment due to sun glare, in terms of braking distance.

3.4.3. *Implications of the DSAS AWM*

The comparison of $S\overline{D}$ and SD situations shows that with the DSAS messages, the braking distance increases from 66.55 m to 107.28 m for left turn, from 85.43 m to 136.81 m for through movement, and from 80.52 m to 106.19 m for right turn. The differences are significant for left turn ($t(58) = 3.02$ and $p = 3.7\text{E}{-}03$) and through movement ($t(58) = 5.29$ and $p = 1.96\text{E}{-}06$), but insufficient for right turn ($t(58) = 1.82$ and $p = 0.07$). The p-value of 0.07 is quite close to the confidence level of 0.05. Similar to the approach speed and brake response time, the insignificant difference in braking distance may be due to subject's intentional actions.

It seems that the intentional action only emerges on right turn. For right turn, subjects do not need to wait for a red light to turn right. The difference in tasks could be the possible reason for such approach maneuvers on right turn, when DSAS messages were provided under a sun glare disturbance.

3.5. *Socio-demographic impacts on travel maneuvers*

Additional analyses test the differences between subjects' socio-demographic factors (i.e., gender, education, driving experience, and age) in driving performance under the application of DSAS AWM. The test results are presented in Table 8, where significant differences are marked in bold. They indicate that the specific socio-demographic factor may interfere with the compensation performance of the DSAS AWM to a normal visual situation.

At first glance, Table 8 seems to indicate that socio-demographic factors rarely affect the mean braking distance, whereas driver's age is an essential variable in determining significant differences in approach speed and brake response time. More specifically, regarding gender, education, and driving experience, significant differences in speed emerged only for the gender of the driver when approaching through movement ($t(28) = 2.35$ and $p = 0.03$) and for education levels when approaching right turn ($t(28) = 3.03$ and $p = 0.01$). Nevertheless, p-values of 0.03 and 0.01 are very close to the confidence level of 0.05, which implies that the application of DSAS AWM may compensate the negative impacts of the sun glare disturbance partially in these two cases.

Compared to young subjects, drivers aged 65 years or older drive significantly slower in all movements (left turn: $t(28) = 5.83$ and $p = 2.88\text{E}{-}06$; through: $t(28) = 3.42$ and $p = 1.96\text{E}{-}03$; right turn: $t(28) = 3.53$ and $p = 1.44\text{E}{-}03$). Elder drivers' also require significantly longer time to respond to DSAS messages, particularly when making left and right turns (left turn: $t(28) = 6.08$ and $p = 1.48\text{E}{-}06$; right turn: $t(28) = 2.72$ and $p = 0.01$). It is reasonable that elderly subjects may drive more carefully at lower speed, and when completing left and right turns, their brake response time is even longer with the aid of the DSAS AWM. This may be due to paying special

Table 7 – *t*-test results for the mean braking distance to a stop line at a signalized intersection (unit: m).

Movement direction	$\overline{S}\overline{D}$ vs. $S\overline{D}$		$\overline{S}\overline{D}$ vs. SD		$S\overline{D}$ vs. SD	
	t(58)	p-two tail	*t*(58)	p-two tail	*t*(58)	p-two tail
Left turn	4.12	1.21E–04*	0.61	0.54	3.02	3.70E–03*
Through	4.56	2.72E–05*	0.87	0.39	5.29	1.96E–06*
Right turn	3.48	9.72E–04*	1.19	0.24	1.82	0.07

"*" means significance at level of 0.05.

Table 8 – *t*-test results of the socio-demographic factors in the application of DSAS AWM.

Splits	Gender		Education		Driving experience		Age (<65 and 65+)	
	t	*p*-two tail	*t*	*p*-two tail	*t*	*p*-two tail	*t*	*p*-two tail
Mean approach speed								
SDL	1.31	0.20	0.70	0.49	0.12	0.9	5.83	**2.88E−06***
SDT	2.35	**0.03**^{*1}	1.50	0.15	0.73	0.47	3.42	**1.96E−03***
SDR	1.92	0.07	3.03	**0.01**^{*2}	0.10	0.92	3.53	**1.44E−03***
Mean brake response time								
SDL	0.17	0.87	1.54	0.13	0.51	0.61	6.08	**1.48E−06**^{*3}
SDT	0.44	0.66	1.45	0.16	0.54	0.59	0.73	0.47
SDR	0.71	0.48	1.40	0.17	0.49	0.63	2.72	**0.01**^{*3}
Mean braking distance								
SDL	0.56	0.58	0.91	0.37	0.51	0.61	1.09	0.28
SDT	1.43	0.16	1.01	0.32	0.54	0.59	1.66	0.11
SDR	0.17	0.87	1.10	0.28	0.49	0.64	0.12	0.90

“*” means significance at level of 0.05; “^{*1}” means significant difference between males (52.85 ± 9.30) and females (45.96 ± 6.50); “^{*2}” means significant difference between people with higher (44.93 ± 7.10) and lower (54.01 ± 7.72) education; “^{*3}”means significant difference between older (left turn: 11.55 ± 8.33; right turn: 9.23 ± 9.59) and younger (left turn: 5.58 ± 2.99; right turn: 6.45 ± 4.03) individuals.

attention to the DSAS messages, particularly for turning movements (left and right turns).

Elders prefer to be aware of the signal status by receiving the DSAS messages before they respond. Meanwhile, when the speed is slow enough, they do not need to start braking early. In this case, the significantly longer brake response time for turning movements could fall into their intentional action. Furthermore, such a slow brake response time does not result in significant differences in braking distance, which satisfies the assumption of intentional actions. Even so, the significant slower speed and intentionally delayed braking response time are positive outcomes of the application of DSAS AWM. Slow driving is always associated with safe driving, especially when the traffic situation is unclear.

4. Conclusions

In this paper, the negative impacts of sun glare disturbance, compensation of the DSAS AWM for sun glare disturbance, and the implications of the DSAS are investigated. Four performance measures were employed, including the mean speed reduction process with attenuation of kinetic energy, mean approach speed, brake response time for red light signals, and braking distance to the stop line. The effects of socio-demographic factors (i.e., gender, education, driving experience, and age) on travel maneuvers are also assessed in the performance measures. Statistical tests were conducted to identify the significant differences in driving performance affected by the sun glare effect and the application of the DSAS AWM.

The analytical results demonstrate statistically significant differences in all performance indexes caused by sun glare and DSAS message. A sun glare effect can obviously impair drivers' visibility of the upcoming traffic signal, though the significant impairment does not appear at the mean approach speed for left turn. DSAS messages can compensate for disturbances in normal visual situations caused by sun glare in terms of brake response time, braking distance, and approach speed when moving through an intersection. The DSAS message can significantly improve subjects' driving performance for left turns, through movements, while slightly for right turns. More specifically, the implementations of the DSAS are defined as below.

(1) The distance from 70.7% original speed to a stop line could be longer than the scenarios without DSAS messages (56 m vs. 46 m for left turn, 75 m vs. 54 m for through movement, and 65 m vs. 50 m for right turn);
(2) The mean approach speeds are significantly decreased for left turn ($t = 3.59$, $p = 3.72\text{E}{-}04$) and through movement ($t = 3.66$, $p = 2.79\text{E}{-}04$), but not for right turn ($t = 0.87$, $p = 0.38$);
(3) The mean brake response time is significantly shortened for left turns (6.37 s vs. 9.47 s) and for through movements (4.44 s vs. 7.37 s), but not significantly shortened for right turns (6.82 s vs. 7.90 s);
(4) The mean braking distance increases from 66.55 m to 107.28 m for left turns, from 85.43 m to 136.81 m for through movements, and from 80.52 m to 106.19 m for right turns. The differences are significant for left turns ($t(58) = 3.02$ and $p = 3.7\text{E}{-}03$) and through movements ($t(58) = 5.29$ and $p = 1.96\text{E}{-}06$), but not for right turns ($t(58) = 1.82$ and $p = 0.07$).

The socio-demographic impacts of DSAS messages are discussed below.

(1) A significant difference is found for gender, but only in the mean approach speed for through movements ($t = 2.35$, and $p = 0.03$). There no significant differences of gender for other directions and other demographical factors.
(2) Significant differences in speed emerged only for gender when approaching through movement ($t(28) = 2.35$ and $p = 0.03$) and for education for right turn ($t(28) = 3.03$ and $p = 0.01$). The DSAS message partially compensates for the negative impacts of sun glare.
(3) Compared with younger subjects, elderly subjects (65 years or older) drive significantly slower in all

movements (left turn: $t(28) = 5.83$ and $p = 2.88E{-}06$; through: $t(28) = 3.42$ and $p = 1.96E{-}03$; and right turn: $t(28) = 3.53$ and $p = 1.44E{-}03$).

(4) Elders require a significantly longer time to respond to DSAS messages, particularly when making left and right turns (left turn: $t(28) = 6.08$ and $p = 1.48E{-}06$; right turn: $t(28) = 2.72$ and $p = 0.01$).

Continued testing on the implications of the DSAS AWM with even more scenarios, such as different types of DSAS AWM and different signal phase settings (i.e., green, yellow, "green to yellow" and "red to green"), is recommended as future research. In addition, more variables can be monitored during the tests, such as tracking driver's eye and steering movements. The implications of DSAS AWM on the safety indexes should also be tested in driving simulators.

While the tests and analyses of DSAS impacts are conducted in the scenarios when driving under sun glare, the designed procedure and analytical method can also be easily applied to other scenes such as instant incident awareness on roadways, work zone dynamic traffic operations, and unsignalized intersection control. These are extremely important elements to the advancement of an Intelligent Transportation System and collected vehicle technologies for the design and operation of smart vehicles, intelligent infrastructure, and even smart cities.

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