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INFLUENCE OF REMOTELY-OPERATED STOP-SLOW CONTROLS ON DRIVER BEHAVIOR IN WORK ZONES

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ABSTRACT

Remotely-operated traffic control devices—portable traffic lights, and automated flagger assistance devices (AFADs)—are used to improve the safety of flaggers in one-lane each-way work zones with lane closure. While previous research has evaluated the effectiveness of these devices in terms of drivers' compliance rates and understanding of the devices, the effects of these devices on driver behavior have not been comprehensively examined yet. This paper aims to fill this important gap in the literature by examining the influence of remotely-operated stop/slow traffic control devices on driver behavior. Using video recording of traffic movements from a rural work zone in the Queensland State of Australia, driver speeds, deceleration profiles, stopping behavior, and compliance rates were obtained for a set of remotely-operated devices new to Australia: Static red-amber-green lights, Static red-amber lights, Static red-amber arrow lights, and Mechanical stop/slow signs. In addition, pneumatic tube traffic counters were used to collect driver speeds before and after the devices and an on-road driver survey was conducted to learn about driver understanding of the devices. The results showed that drivers had difficulty in understanding the new devices, particularly the amber light and amber arrow options which confused drivers about their meaning (to stop or to go). Compared to the flagger method, the new remotely-operated devices produced higher approach speeds, greater variability in approach speeds, and faster deceleration rates. The good levels of compliance rates with the remotely-operated devices imply that they could improve the safety of flaggers by reducing their exposure to traffic, however, their negative effects on driver behavior may indicate that the risks of rear-end crashes could be higher in the advance warning area.

Keywords: Automated flagger assistance device, Stop/go control, Stop/slow control, portable traffic lights, one-lane each-way work zone.

INTRODUCTION

Safety of flaggers is among the major concerns in work zone traffic management. In a flagger control method of traffic management (a.k.a. Stop/Go or Stop/Slow control), flaggers are exposed to traffic with high risk of being injured by errant vehicles (*1*). To reduce the exposure of flaggers to traffic and thereby improve their safety, a ranges of technologies have been developed and tested, including temporary portable traffic light signals and automated flagger assistance devices (*1-5*).

Portable traffic light signals are typically trailer-mounted and placed at both ends of work zones where only one lane is open to alternating two-way traffic. These signals are primarily of two types: unmanned fixed-time based automated operation, and manual operation by flaggers. An early evaluation of unmanned fixed-time portable three-phase traffic signals (*6*) identified a potential trade-off between reduced crashes involving flaggers and increased crashes involving vehicles, but the likely outcomes of this possible compromise could not be estimated. A later evaluation (*7*) of unmanned 3-phase signals with vehicle detection sensors in short-term maintenance operations found generally positive results in terms of feasibility and cost-benefit, driver comprehension and compliance. Despite a small number of violations during the set-up process, 'informal' surveys of queued drivers indicated that the signals and related signage were well understood. However, it has been noted elsewhere that, due largely to the possibility of system malfunction, unmanned signals may only be appropriate for situations where sight distance is sufficient for drivers to see and avoid approaching vehicles (*1, 8*). In the manual method, flaggers control the signals by either observing traffic at both ends of work zones or communicating with other flaggers over radio. Unlike the fixed-time based operation, the manual operation method requires flaggers to remain in close proximity to the traffic stream.

Automated flagger assistance devices (AFADs) are a newer control used to reduce the exposure of flaggers in maintenance work zones. Previous research has examined the use of two main types of AFADs in the US: automated Stop/Go paddles and two-phase red/yellow lights (*3*). The AFADs were accompanied by instructive signage and/or a boom gate to enhance drivers' compliance and understanding of the devices. In an evaluation of AFADs in Texas and review of trials in other States (*3, 9*), the effectiveness of the devices were measured in terms of motorists' compliance with the signals and their understanding of the devices as determined by off-site surveys. The research identified confusion among drivers regarding interpretation of the signals, specifically with the transitional continuous yellow light. Additionally, drivers reported that they may have been inclined to proceed ahead after stopping briefly at the Stop sign (as is standard practice on the general road network in the absence of a perceived conflict) had they not seen a traffic controller nearby. It was also found that while violations were generally infrequent these were able to be reduced with the use of a gate arm.

While existing research has examined the effectiveness of AFADs in terms of driver understanding of the devices and their compliance rates, a key gap in the literature exists in that other effects of the AFADs on driver behavior have not been studied yet. As a result, it remains unknown if these traffic control devices produce consistent or differential effects on drivers' speed, deceleration, and stopping behaviors. Since earlier research (Finely et al., 2015) found that understanding of the devices varies among drivers, it is possible that the devices have differential effects on drivers' speed choice and braking behavior when they approach a traffic control point in work zones (i.e., in the advance warning area). However, the currently limited knowledge of these specific effects of traffic control devices warrants pursuit of a more comprehensive understanding of their effectiveness.

This paper aims to examine the effects of remotely-operated stop/slow traffic control (TC) devices on driver behavior both before and after the devices. In addition to addressing the gap identified earlier, this paper contributes to the global body of knowledge by adding insights in the context of Australian work zones, where the use of such devices is new.

METHODOLOGY

Experimental Setting

This study was conducted in a 1 km work zone on a rural one-lane each-way highway (Moonie Highway) about 5 km west of a rural town (Dalby) in Queensland, Australia. The highway at this point is a sealed one lane each way undivided road with pre-work zone speed limits of 100 km/h at the western end and 80 km/h at the eastern end. This stretch of road is straight and mostly flat with good sight distance. A schematic diagram of the work zone showing the posted signage and the location of speed measurement points is presented in Figure 1. Standard sets of signage following the MUTCD used in Queensland (*10*) were placed at both ends of the work zone. Work involved full closure of one lane within the activity area for the purpose of resurfacing, with the closed lane alternating as required. Traffic movement in the open lane was controlled by certified flaggers using a set of stop/slow TC devices tested in this study.

Traffic control in this work zone was typically conducted by ‘human flagger’ (HF) or ‘Static Red- Static Amber- Static Green traffic lights’ (RAG). In the HF method, a flagger manually operated a ‘Stop/Slow’ sign. The RAG method involved using three-aspect RAG static lights (similar to traffic lights used at road intersections) mounted on a portable trailer. The lights were manually operated by a flagger using a controller wired to the lights, thus allowing the flaggers to stand away from the traffic lanes.

In this study, another three types of TC devices, which were new in Australia, were used. The new devices included ‘Static Red- Static Amber traffic lights’ (RA), ‘Static Red-Static Amber Arrow traffic lights’ (RAA), and ‘Mechanical Stop Slow sign’ (MSS). The RA device is a portable light-weight traffic light system with two-aspects: static red light for ‘stop’ condition and static amber light for ‘slow/go’ condition. A static amber light was preferred over a flashing amber light, as the latter form is commonly understood as a sign of malfunctioned traffic lights in Queensland. The RAA device is similar to the RA device, except that a static amber arrow is used instead of a solid static amber light (an arrow stencil was placed over the solid amber round lens). The idea of using the RA or RAA device as an alternative of the RAG device was to make the traffic light system lightweight (so more portable), reiterate the ‘Stop/Slow’ messages using the two-aspects of the lights, and make the lights distinguishable from normal road intersection lights. The RAG, RA, and RAA devices were operated by flaggers using a controller device wired to the lights systems. The MSS device had a large STOP/SLOW bat mounted on a pole fitted into a battery-operated control base. A single remote controller was used to rotate the STOP/SLOW bats at both ends of the work zone, eliminating the possibility of having the ‘SLOW’ face shown to drivers at both ends. These devices were lightweight, portable, and remote-controlled, thus suitable for quick installation/removal and allowing human flaggers to be positioned away from road when controlling the devices. Photos of the TC devices are presented in Figure 2.

To use a traffic light system in work zones, the Queensland MUTCD (*10*) requires displaying a ‘STOP HERE ON RED SIGNAL’ sign ahead of the lights in order to let drivers know where to stop. This sign is placed close to the pavement surface and acts as an alternative to the traditional Stop pavement marking, which is often impractical to use in work zones due to their transient nature. The same sign was required to be displayed for the RA and RAA devices. In addition, since the RA and RAA devices were new in Australia, it was felt that drivers may not have proper understanding of the Amber light or Amber arrow in the absence of a Green light as found in traditional red-amber-green light systems.

Therefore, a new sign 'SLOW ON AMBER' was designed in consultation with industry experts with responsibility for overseeing work zone traffic management. The new sign was approved for field testing by appropriate authorities. While the new sign was originally intended to display beside the 'STOP HERE ON RED SIGNAL' sign close to the pavement surface, during field testing it was found that most drivers failed to notice the new sign as they were paying greater attention to the new set of traffic lights, creating confusion among drivers. Therefore, the new sign was relocated to just below the traffic lights by tying the sign on to the traffic light pole.

Study Method

To collect data concerning driver behavior, such as travel speeds and deceleration rates, traffic movements in the advance warning area of the work zone were recorded using a roadside trailer-mounted high-definition video camera system. In addition, pneumatic tube-based speed measurement devices were placed on pavement to record vehicle speeds at different locations within the work zone. An on-road survey was conducted among drivers stopped at the traffic control points to collect data on driver understanding of and preference for the devices. To understand the effects of the TC devices on driver speeds, the approach of recording their actual speeds using pneumatic tubes was preferred over collecting drivers' self-nominated or perceived speeds from the on-road survey. This is because existing studies (e.g., *11*) showed that self-nominated speeds may not be valid indicators of the actual speeds. The video system and speed measurement tubes were placed at one end of the work zone and the driver survey was conducted at the other end, to eliminate potential effects of the presence of surveyors on driver behavior. The speed tubes, video system, and driver survey methods are described in the following sections.

Speed Measurement Before and After TC Devices

A pair of pneumatic tubes installed 1 meter apart on the pavement was used to record the travel speed, type of vehicle, and time for each vehicle traversing the tubes. Travel speeds were collected at three locations: (1) about 50m after the first speed reduction sign, (2) about 40m ahead of the TC devices, and (3) about 50m inside the work area from the 40 km/h sign. Since the location 2 was ahead of the TC devices, many vehicles were either decelerating to stop or accelerating from a stop position when traversing the speed measurement tubes at this location. The speeds of these vehicles were excluded from the dataset through a manual examination and removal process.

In order to examine the effects of the tested TC devices on the speeds before (location 2) and after (location 3) the TC devices, the speeds obtained from location 1 was used as baseline data. Use of baseline data is important to account for the effects obtained from sources other than the TC devices, such as temporal variations in traffic flow, changes in environmental characteristics etc. Drivers were unable to see the TC devices from location 1, therefore, it was unlikely that the speeds at this location were influenced by the TC devices. The changes in mean speeds and their standard deviations (S.D.) at the locations before and after the TC devices were computed for each of the tested TC devices (RAG, RA, RAA, and MSS) with reference to the baseline TC method (HF).

Change in mean speed at location L = $\left(\bar{v}_{TD,L=2/3} - \bar{v}_{HF,L=2/3}\right) - \left(\bar{v}_{TD,L=1} - \bar{v}_{HF,L=1}\right)$ Eq. 1

Change in speed differential at location L =$\left(\sigma_{TD,L=2/3} - \sigma_{HF,L=2/3}\right) - \left(\sigma_{TD,L=1} - \sigma_{HF,L=1}\right)$ Eq.2

where $\bar{v}$ is mean speed, σ is standard deviation of mean speed, TD is the tested TC devices, L is the speed data collection location (1, 2, or 3).

Video Recording of Traffic Movements

Vehicle movements in the advance warning area were recorded using a high-resolution closed circuit television camera mounted on a roadside parked trailer. The camera had a field of view covering approximately 120m of the road from the location of the TC devices. The recorded video images were processed to obtain three important aspects of driver behavior: approach speed, deceleration rate, and stopped distance.

The ‘approach speed’ variable defines the speed at which a vehicle approached the TC point at the boundary of advance warning area and transition area. By using the pavement markings on the road, the approach speed for each vehicle was measured over a 16 m space about 70 m ahead of the TC devices, which was the furthest point from the TC devices clearly legible in the video field of view.

The ‘deceleration rate’ of a vehicle approaching the TC point was computed by using the timestamps at which a vehicle crossed a point in the 16 m space describe above and the point where the vehicle stopped completely. Depending on where the vehicle stopped, the distance between these two points was between 50 m to 70 m, which was large enough to cover the entire deceleration process and to minimize errors in the timestamp recording process.

The variable ‘stopped distance’ refers to the distance between the location of the ‘STOP HERE ON RED SIGNAL’ sign (where the first vehicle in a queue is supposed to stop) and the location where the first vehicle actually stopped. The stopped distance was zero for cases where the first vehicle stopped at the position of the sign. A positive value of the stopped distance variable indicates that the vehicle stopped before reaching the sign. Similarly, a negative value indicates that the vehicle stopped after passing the sign (i.e., not complying with traffic rules).

The approach speed, deceleration rate, and stopped distance variables were computed only for the first vehicle to stop in a stop/slow cycle, as the values of these variables for the follower vehicles were dependent on the actions taken by the first vehicle.

On-Road Driver Survey

The speed data collection and video recording was at one end of the work zone. At the other end, two researchers conducted questionnaire surveys with the first two drivers stopped at the traffic control. To collect information about drivers’ understanding of the TC devices present on site during the surveys, drivers were asked how they would know when to proceed from the stop position. In the case of RA and RAA devices, if the respondents did not mention these TC devices, researchers asked what they would do if they saw an amber light or an amber arrow. Driver understanding of and preference for the TC devices were recorded for both the ‘stop’ and ‘slow’ conditions. Drivers were shown laminated photos of the TC devices on an A3 sheet and were asked if they clearly understood ‘when to stop’ and ‘when to proceed’ for each of the devices. In addition, they were asked which of the TC devices they think is the best in terms of understanding ‘when to stop’ and ‘when to proceed’. If drivers named more than one TC device as their preferred option, then all of the preferred TC devices were noted. Upon concluding the survey, the researchers recorded some additional information: type of vehicle, company vehicle or not, gender of respondent, apparent age of respondent (younger, middle, and older), presence of passenger, and if passenger participated in the survey.

A total of 137 drivers were surveyed, about three quarters of whom were male. Among the respondents, 62% were driving a passenger car and 36% were driving a utility vehicle. About 40% had at least one passenger on board, among whom the passenger responded to the survey questions in 87% cases as the researchers approached the vehicle from the passenger side.

RESULTS AND DISCUSSION

Driver Understanding of the TC Devices

Results obtained from the driver survey are presented in Table 1 for the remotely-operated TC devices studied: Static Red- Static Amber- Static Green traffic lights (RAG), Static Red- Static Amber traffic lights (RA), Static Red- Static Amber Arrow traffic lights (RAA), and Mechanical Stop Slow sign (MSS). After seeing pictures of each TC device, almost all drivers understood ‘when to stop’ for the RAG (96.3%) and MSS devices (99.3%). Those values were slightly lower for the RA (92.6%) and RAA devices (94.0%). Although all devices had a static red light or a ‘STOP’ bat face to indicate the ‘STOP’ condition, it was surprising that some failed to clearly understand the meaning of these devices. Perhaps the absence of flaggers on road was a key reason for not comprehending these devices. ‘When to go’ was understood by all for the RAG device and almost all (97.8%) for the MSS device. However, many drivers did not understand ‘when to go’ for the RA (33.3%) and RAA devices (23.7%). Some drivers mentioned that they would go when they are directed by the flagger, who was standing away from the road.

Overall the amber light and amber arrow in the RA and RAA devices respectively caused confusion among some drivers. Asked what they would do upon seeing an amber (RA) light, 10 of 69 drivers were unsure of its meaning (‘caution’/‘go’), while another 9 said they would call the traffic lights fault line to report a fault (note that Queensland drivers are generally aware that a flashing amber light indicates a malfunctioned light system). Similarly, 16 of 69 drivers were unsure what to do upon seeing an amber arrow (RAA).

Drivers’ preferred option for knowing ‘when to stop’ was the RAG device (49.2%) which looks similar to the traffic lights at road intersections, followed by MSS (20.3%), RA (13.6%) and RAA (11.9%), while 5.1% drivers had no preference. The RAG device was also the best option for knowing ‘when to go’ (72.8%), followed by MSS (20.4%), RAA (4.1%) and RA (2.7%). These values, particularly the small shares for the RA and RAA devices, suggest that drivers like to see on road what they are familiar with.

Driver Behavior

Influence of the TC devices on driver behavior was examined in terms of a set of driver behavior related variables:

1. Compliance with stop condition of the TC devices (for all vehicles)
2. Changes in driver speeds before the TC devices (for all vehicles)
3. Changes in driver speeds after the TC devices (for all vehicles)
4. Approach speed and Deceleration rate (for first vehicle in each Stop/Slow phase)
5. Stopped distance (for first vehicle in each Stop/Slow phase)

Compliance with Stop Condition

Compliance rate with the direction to stop was 100% for all TC devices except for the MSS device. In a 6 hours 40 minutes observation period for the MSS device, 4 vehicles failed to stop and proceeded into the transition area (who were later safely stopped by flaggers). It was not possible to interview the non-compliant drivers as to why they failed to stop. While the MSS has a very large sized STOP sign, the device was needed to be placed on site ahead of a set of trailer-mounted RAG lights (not in operation, but kept on site for use during the non-working hours). The presence of the non-operational RAG lights in the background might have confused the non-compliant drivers.

Speeds Before and After the TC Devices

Table 2 presents the mean speeds of all vehicles at the three speed measurement locations, along with comparisons of speeds for each TC device with the base case (HF). Analysis of the speeds was done aggregately for all types of vehicles as the numbers of heavy vehicles observed were low during some observation periods.

The speeds at location 1 (after the first speed reduction sign) were quite similar for all TC devices. This was expected as the TC devices were not likely to influence speeds at this location because of drivers' inability to see the TC devices from this location. Speeds at the other locations varied under different TC devices. Speeds for all TC devices at location 2 (before the TC devices) were higher than that for HF which implies that drivers slow down to a greater extent when they see a human flagger on road. However, this was not true for location 3 (after the TC devices). The speeds under HF option were higher than those for RA, RAA, and MSS devices.

Using the speeds at location 1 as control, the changes in speeds at location 2 and 3 were computed for each of the tested TC devices, with respect to the HF option. Compared with HF, the mean speeds before the TC devices were higher for all other TC options (4.8 Km/h for RAG, 7.3 Km/h for RA, 5.0 Km/h for RAA and 6.0 Km/h for MSS). A possible explanation for observing the highest upstream speeds with the RA device is that drivers may have increased their speed anticipating an imminent change from solid Amber to Red under this condition. This phenomenon does not seem to have occurred under the RAA condition where mean speed was almost similar to the RAG.

After the TC devices (location 3), changes in mean speeds were similar for HF, RAG and RAA (less than 1 km/h difference). Speeds for RA and MSS were lower than for HF (4.4 and 2.6 Km/h, respectively). The relatively low speed for RA likely reflects a greater speed reduction after approaching (and passing) the TC location at relatively high speed, as observed at location 2.

In addition to the mean speeds, the speed differentials (S.D. of mean speed) were also analyzed to examine if driver speeds varied under different TC devices. Overall, the speed differentials at location 3 were much smaller than those at other locations, possibly due to the pattern of driving at these locations and the posted speed limits. Location 3 was inside the work area with a lower speed limit (40 km/h) than the other locations (60 km/h). Compared with the HF option, the speed differentials at the location before the TC devices were higher for all devices (3.9 for RAG, 1.5 for RAA, and 0.6 for RA), except for the MSS device (-2.0). The MSS device again produced smaller speed differentials (-2.0) than the HF option at the location after the TC devices. The changes in speed differentials for the other devices were less than 1.0 at this location.

Approach Speed and Deceleration Rate

Table 3 presents the average approach speeds and deceleration rates of the first vehicle to stop in stop/slow cycles. The changes in the mean values in comparison with the base case (HF) and their statistical significance (tested using unpaired t-tests by accounting for the equality of variances) are also presented in Table 3.

When RAG and RA devices were in place, drivers approached the TC point at significantly higher speeds (about 7 km/h faster) than when HF was in place. Similar results were found for MSS (6.5 km/h faster). While drivers on average approached the TC point at 3.7 km/h higher speed under the RAA condition than the HF condition, the difference was not statistically significant.

Compared to the HF, drivers decelerated at significantly higher rates when intending to stop at the TC point in response to all other TC devices. The highest difference in mean deceleration rates was found for RA (0.51 m/s^2), followed by MSS (0.46 m/s^2), RAA (0.34 m/s^2), and RAG (0.31 m/s^2). A faster rate of deceleration by the lead vehicle (the vehicle which was the first to stop in a stop/slow cycle) implies that following vehicles would have less time to react to the changes in the speeds of the lead vehicle, consequently leading to higher risk of rear-end crashes. Therefore, the higher deceleration rates observed for the trialed TC devices than the HF is not encouraging.

Stopped Distance

The results (Table 3) showed that compared to the HF condition, drivers stopped significantly closer to the work zone under the RA and RAG devices (3.8 m and 3.5 m respectively). Drivers stopped 1.8 m closer to the work zone under the RAA device and 1.9 m away from the work zone under the MSS condition, however, these differences were not statistically significant. The higher gaps between the first vehicle stopped at traffic controls and the location of traffic controls for the HF condition imply that visible presence of flaggers on road encourages drivers to keep a larger gap.

Implications of Results

The results from the driver survey showed that drivers had a reasonably good understanding of the tested TC devices in terms of 'when to stop'. However, many drivers did not understand the RA and RAA devices in terms of 'when to go'. The amber light and amber arrow caused confusion among drivers, despite having a 'SLOW ON AMBER' sign just below the traffic lights. It appears that drivers expect to see traffic lights in a format that they are familiar with, such as the RAG lights found at non-work zone intersections. While the use of traditional RAG light formats largely ensures driver understanding of the lights, public education campaigns may be helpful to make drivers familiar with the other formats of TC devices. Use of TC devices in a format different from the traditional traffic lights could also help drivers to distinguish a work zone traffic control point from a normal road intersection.

Compared to the HF option, drivers approached the TC point at higher speeds and consequently decelerated at a faster rate when the other TC devices were in place. On the other hand, drivers stopped at a further distance when approaching a HF or a MSS than when approaching the traffic lights. These results suggest that visible presence of a human flagger encourages drivers to drive less aggressively by reducing their speeds early (as found in *12*), decelerating at a gentler rate, and keeping a larger gap from the position of the flagger when stopped. While these results are encouraging for the traditional flagger method, to reduce the exposure of flaggers to traffic, attention needs to be given to improving driver behavior under the TC devices that allow flaggers to stay away from the traffic lanes.

The higher approach speeds, greater variability in speed, and faster deceleration rates for the remotely-controlled TC devices may have implications regarding increased risk of rear-end crashes in the advance warning area. Multiple studies have shown (e.g., *13, 14, 15*) that the advance warning area has the highest risk of rear-end crashes in work zones. Use of these TC devices may further increase the risk of rear-end crashes, despite the likely benefit of reducing the exposure of flaggers to traffic. Future research is required 1) to investigate the risk of rear-end crashes for different TC devices and 2) if found to increase crash risk, to develop guidelines on how to balance the two key objectives of the remote controlled TC devices: to improve safety of flaggers, and to minimize the risk of rear-end crashes introduced by the TC devices.

This study adds important knowledge to the literature about the influences of remotely-operated traffic control devices on driver behavior. However, interpretation of the results needs to be done by keeping two issues in mind: 1) the results were based on a rural highway work zone in the Queensland State of Australia, without further investigation on the repetitiveness of the results from other work zones, and 2) the tested TC devices were new to Queensland drivers, therefore, their effects on driver behavior are likely to have some novelty effects which could be examined by conducting a longer duration study. Future research should extend this research by incorporating these issues. In addition, understanding the residual effects of the TC devices on driver speeds at downstream locations (e.g., towards the middle and the end of the activity area, in the termination area, or even after the end of the work zone) could be an important topic of future research.

CONCLUSIONS

This paper examined the influences of remotely-operated stop/slow controls on driver behavior. Four devices new to Australia—static red-amber-greed lights, static red-amber lights, static red-amber arrow lights, and mechanical stop/slow signs—were trialed in a rural work zone. On-road survey among drivers revealed that the amber light and amber arrow created confusions regarding their meaning (stop/go) and drivers expected to see a static green light similar to the one found in intersection traffic lights. Analysis of driver behavior data showed that compared to the traditional flagger method, drivers approached the work zone at a higher speed, decelerated at a faster rate, and had greater variability in speeds when the remotely-operated devices were in place. These influences on driver behavior are of concern as they may indicate higher risks of rear-end crashes in the advance warning area. While the remotely-operated devices have potential to improve the safety of flaggers by allowing them to stand away from the road, the potential consequences of these devices in terms of causing rear-end crashes in the advance warning area should be examined in future research.

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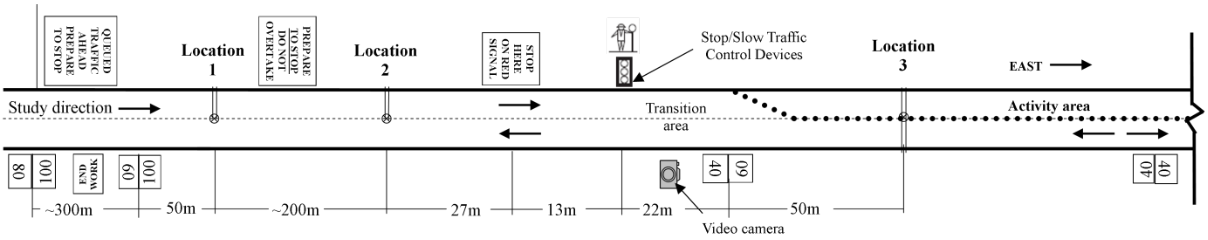

FIGURE 1 Study site

FIGURE 2 Photos of traffic control (TC) devices studied

TABLE 1 Driver Survey Results

TC device	% Respondents (N = 137)		% Votes*	
	Correctly understood 'when to stop'	Correctly understood 'when to go'	Preferred option for 'when to stop' (N = 177)**	Preferred option for 'when to go' (N = 147)
RAG	96.3	100.0	49.15	72.8
RA	92.6	33.3	13.56	2.72
RAA	94.0	23.7	11.86	4.08
MSS	99.3	97.8	20.34	20.41

RAG: Static Red- Static Amber- Static Green traffic lights, RA: Static Red- Static Amber traffic lights, RAA: Static Red- Static Amber Arrow traffic lights, MSS: Mechanical Stop Slow sign, * Some respondents nominated multiple TC devices as preferred option, therefore, the % preferences were calculated using the total number of votes; ** 5.08% of the votes were considered as 'no preference'

TABLE 2 Speeds Before and After the TC Devices (For All Vehicles)

TC device	Location 1			Location 2			Location 3			Increase in speed at Location 2*	Increase in S.D. at Location 2*	Increase in speed at Location 3*	Increase in S.D. at Location 3*
	No. of Obs.	Mean speed (km/h)	S.D.	No. of Obs.	Mean speed (km/h)	S.D.	No. of Obs.	Mean speed (km/h)	S.D.				
HF	486	52.15	10.81	167	30.46	10.96	499	36.43	6.07	Base	Base	Base	Base
RAG	542	53.93	11.97	184	37.06	16.04	559	38.12	7.56	4.83	3.92	-0.08	0.33
RA	251	53.02	10.19	32	38.66	10.96	254	32.94	6.43	7.33	0.62	-4.36	0.98
RAA	173	50.45	11.92	31	33.75	13.57	181	34.46	6.80	5.00	1.50	-0.27	-0.38
MSS	399	53.61	12.60	74	37.93	10.75	407	35.25	5.83	6.02	-2.00	-2.64	-2.03

HF: Human Flagger, RAG: Static Red- Static Amber- Static Green traffic lights, RA: Static Red- Static Amber traffic lights, RAA: Static Red- Static Amber Arrow traffic lights, MSS: Mechanical Stop Slow sign, * Increase in Mean speed and S.D. were computed by considering HF as base case using Eq.1 and Eq.2, respectively

TABLE 3 Driver Behavior at Work Zone Approach (For First Vehicle to Stop in a Stop/Slow Cycle)

		Approach speed (km/h)			Deceleration rate (m/s²)			Stopped Distance (m)		
TC device	**No. of obs.**	**Mean**	**S.D.**	**Increase in speed compared to HF****	**Mean***	**S.D.**	**Increase in deceleration rate compared to HF****	**Mean**	**S.D.**	**Increase in stopped distance compared to HF****
HF	30	30.23	7.70	Base	-0.88	0.46	Base	14.27	7.02	Base
RAG	34	37.81	12.51	**7.58**	-1.19	0.62	**-0.31**	10.79	8.66	**-3.47**
RA	46	37.34	11.81	**7.11**	-1.38	0.75	**-0.51**	10.41	7.60	**-3.85**
RAA	25	33.90	13.25	3.67	-1.22	0.87	**-0.34**	12.52	8.92	-1.75
MSS	31	36.68	7.08	**6.45**	-1.34	0.94	**-0.46**	16.15	9.37	1.88

HF: Human Flagger, RAG: Static Red- Static Amber- Static Green traffic lights, RA: Static Red- Static Amber traffic lights, RAA: Static Red- Static Amber Arrow traffic lights, MSS: Mechanical Stop Slow sign, * A smaller value means faster deceleration; ** **Bold** values indicate statistically significant difference at 95% confidence level