Development and Evaluation of Temporary Traffic Control Devices for Unmanned Aerial System Operations

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Abstract: Unmanned aerial systems (UASs) are an emerging technology being used in many fields, including surveying engineering. When UASs are used for these activities, they may operate in close proximity to active traffic. UASs could be distracting to drivers and increase safety concerns in these situations. Currently, there are no temporary traffic control (TTC) signs approved by the Manual on Uniform Traffic Control Devices (MUTCD) to specifically inform drivers of roadside UASs. For this study, new UAS TTC signs were designed and a questionnaire was developed to explore perspectives on UAS specific TTC. Participants drove in a high-fidelity driving simulator, which measured speed reduction, as participants drove past various configurations of TTC elements in advance of a roadside UAS operation. The results showed that drivers do support the use of UAS specific TTC signs. Speed data from the driving simulator showed that a TTC configuration of two advanced signs caused drivers to decrease their speed by an average of more than 2 km/h than when no TTC was present, while also inducing this deceleration at the most gradual rate. **DOI: 10.1061/(ASCE)SU.1943-5428.0000309.** © *2020 American Society of Civil Engineers.*

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Introduction

Unmanned aerial systems (UASs), commonly known as drones, have recently achieved widespread commercial success from their increased availability and wide range of applications (Austin 2010). Remote sensing for surveying is one field where UASs are being increasingly used for their flexibility and relative low cost compared to traditional methods (Colomina and Molina 2014). These types of activities can occur in roadway work zones, where mapping and monitoring are necessary activities for infrastructure construction and maintenance. For this paper, a work zone is broadly defined as any construction or maintenance activity on or near the roadway where workers are present.

The introduction of UASs in roadside surveying operations constitutes a significant shift in the physical configuration of those operations, where mobile, flying objects are used instead of traditional terrestrial equipment. This change in the physical configuration could be unexpected to increase driver distraction, thereby posing safety risks. Currently, the Manual on Uniform Traffic Control Devices (MUTCD) provides guidance on the configuration of temporary traffic control (TTC) devices for surveying operations (FHWA 2009). However, given the physical and visual change in surveying operations using UASs, there is a potential need to supplement existing traffic control devices (TCD) used to inform drivers of UAS survey operations near the roadway.

This paper evaluates the impact of various TTC configurations on driver behavior as observed through a driving simulator environment. In addition, this work designed new UAS specific TTC signs for UAS specific surveying operations and explored driver attitudes and preferences related to these new designs.

Literature Review

As the utility of UASs for surveying continues to rise, so will the interactions between UAS operations and road users. This is especially likely given the breadth of applications for UASs in roadway infrastructure construction and maintenance, including surveying engineering, traffic monitoring, and structural inspection (Mallela et al. 2017). Safety concerns resulting from these interactions are beginning to be explored. As an example, UAS operations near roadways do have the potential to induce risky glances from drivers away from the roadways toward the operations (Barlow et al. 2019). When UASs are used near the roadside for authorized activities, such as surveying, the presence of workers and equipment for a maintenance or utility activity (i.e., a UAS vehicle) constitutes a roadway work zone (Turner 1999). Traditional roadside surveying activities, without UASs, are also considered work zones. Therefore, this review will explore safety in the context of roadway work zones and highlight the elements of work zones as they relate to roadside surveying operations.

Studies have shown that drivers are at a higher risk of a crash when they are in a work zone (Hall and Lorenz 1989; Meng et al. 2010; Weng and Meng 2011). Research further suggests that the crashes that do occur in work zones are, on average, more severe than others and impact both workers and the drivers (Bédard et al. 2002; Ha et al. 1995; Ullman et al. 2006). An exploration of the literature identified two concepts that impact the safety of work zones and, therefore, could impact the safety of UAS surveying operations: driver expectancy and vehicle speed.

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Driver Expectancy in Work Zones

The concept of driver expectancy in traffic engineering is defined as a "driver's readiness to respond to situations, events, and information in predictable and successful ways" (Alexander and Lunenfeld 1986). There are two types of driver expectancy: (1) a priori, or expectancies drivers develop over time through experience, and (2) ad hoc, or expectancies drivers form in the moment based on the present infrastructure and the current environment (Alexander and Lunenfeld 1986). Expectancy is based heavily on elements, such as the configuration of the infrastructure and traffic operations, meaning traffic engineers can substantially influence the expectancy of the driver's built environment through design and operation (Alexander and Lunenfeld 1986). Several studies have explored the idea of driver expectancy as it relates to work zone safety, concluding that drivers in higher expectancy work zones have quicker and more accurate responses (Heaslip et al. 2011; Pietrucha 1995; Ullman and Schrock 2003).

Vehicle Speed in Work Zones

Vehicle speed is a key topic in transportation safety. Work zones intrinsically have a higher crash risk (Hall and Lorenz 1989; Meng et al. 2010; Weng and Meng 2011), and excessive speed is a contributing factor in many of these crashes (Daniel et al. 2000; Pigman and Agent 1990). For decades, researchers have explored and evaluated countermeasures to lower speeds and improve speed limit compliance in work zones (Maze et al. 2000; Ravani and Wang 2018; Wang et al. 2003).

Temporary Traffic Control in Work Zones

Traffic control devices (TCDs), as defined in the introduction of the MUTCD, are "all signs, signals, markings, and other devices used to regulate, warn, or guide traffic, placed on, over, or adjacent to a street, highway, pedestrian facility, bikeway, or private road open to public travel" (FHWA 2009). Temporary traffic control is a category of TCDs that is used for nonpermanent road conditions and disruptions, and TTC signs are generally identified by black legends and a black border with an orange background (FHWA 2009). The MUTCD, in Section 6B.01, defines the purpose of TTC as "construction, maintenance, utility, and incident zones [that] can all benefit from TTC to compensate for the unexpected or unusual situations faced by road users. When planning for TTC in these zones, it can be assumed that it is appropriate for road users to exercise caution" (FHWA 2009). This definition acknowledges the importance of driver expectancy ("unexpected or unusual situations") and, more indirectly, vehicle speed ("appropriate . . . to exercise caution") in the application of TTC. Therefore, TTC achieves improved safety for road users through, at least in part, these two strategies. A study by Li and Bai (2009) showed that TTC methods can reduced the chance of severe crashes in work zones.

Temporary Traffic Control for Surveying Operations

Specific TTC for general surveying operations have been developed. The MUTCD provides guidance for the application of TTC for these activities in Section 6F.38. Currently, roadside surveying operations should use the *Survey Crew* (W21-6, Fig. 1) TTC sign to warn drivers of survey crews working near the roadway (FHWA 2009). The typical application for this sign based on the MUTCD notes that this sign should be placed 152 m (500 ft) in advance of the work site (see TA-1 and TA-16 in Part 6 of the 2009 edition of the MUTCD).

Fig. 1. MUTCD *Survey Crew* sign (W21-6).

However, UASs are an emerging technology that are now being used for survey activities (Mallela et al. 2017). Currently, there are no MUTCD approved TCDs related to UASs specifically. Ordinarily, the *Survey Crew* sign would be the closest appropriate TTC application for UASs operations being used for surveying or similar activities. The use of this traditional sign along the roadside for UAS surveying operations may violate driver expectancy for what constitutes a surveying operation.

Research Purpose and Questions

Safety is a paramount concern as UASs are used for roadside surveying operations. Increasing driver expectancy and decreasing driver speed in these areas can lower risk in these work zones. Given the emerging nature of UAS technology, their use is still a novelty to road users. Therefore, strategies specific to UAS surveying operations should be implemented to impact driver expectancy and vehicle speed to improve safety. The following research questions were developed to explore these two concepts as they relate to roadside UAS surveying operations:

- How do drivers describe their perspective on the helpfulness of UAS specific TTC signs?
- What TTC sign designs better communicate to drivers the presence of an upcoming roadside UAS operation?
- Do various configurations of TTC elements impact vehicle speeds through work zones with UAS operations?

By understanding how drivers perceive the helpfulness of UAS specific TTC signs, and which sign designs are most effective, elements of TTC can be successfully incorporated into UAS-related work zones to potentially improve driver expectancy. In addition, this study explores various configurations of TTC for UAS operations as they impact vehicle speed. These questions guided the methodology of this experiment through TTC related mitigations strategies of safety concerns for UAS surveying operations.

Methods

The purpose of this study was to improve safety for drivers and UAS operators during surveying applications. This study explored TTC sign design and various TTC element applications to evaluate driver expectancy and speed while passing roadside UAS operations. This study was approved by the Oregon State University (OSU) Institutional Review Board (Study #8764).

Effective UAS TTC Sign Design

To evaluate the impact of TTC sign design on driver expectancy, five alternative TTC signs for surveying or other operations using UAS technology were developed. These alternatives were developed to inform drivers about UAS operations more effectively than the MUTCD adopted *Survey Crew* sign.

Road signs can vary in their effectiveness based on a variety of characteristics. Lay (2004) described four "stages" by which a road user must be able to pass through in response to a road sign. The following four stages, therefore, can be used to measure the

Fig. 2. UAS related signs with UAS vehicle symbol from three different countries. (Image of South Korean sign by David S. Hurwitz.)

effectiveness of a sign intended to warn drivers of an upcoming UAS operation (Lay 2004):

- Stage #1—Detectable: Must be visible and conspicuous.
- Stage #2—Readable: Must be legible at an adequate distance with adequate time.
- Stage #3—Comprehensible: Must be precise and unambiguous.
- Stage #4—Actable: Must be credible, correct, appropriate, and timely.

Elements of Road Signs

Road signs rely on two basic elements to communicate information to road users: legends and pictorial elements. Legends consist of words and numbers that convey a text-based message. Pictorial elements include symbols, shapes, and colors (Lay 2004). Text and accompanying images were developed to convey a warning to approaching drivers that a UAS operation may be active ahead. It was determined that the word *drones* should be included. *Drone* is the most ubiquitous term for UASs that the traveling public would have highest likelihood to comprehend (Stage #3). Legends such as *Unmanned Aerial System* and *Unmanned Aerial Vehicle* or abbreviations such as *UAS* or *UAV* were too lengthy or vague to be effective elements on road signs. Regarding the pictures, researchers evaluated examples of UAS related symbols from around the world. Fig. 2 shows examples of various UAS related signs, which communicated UAS no-fly zones in recreational areas.

In a visual inspection of the example signs in Fig. 2, three general themes emerged for the elements of a UAS vehicle symbol. All three of the signs show the following: (1) a quadcopter or multirotor style UAS vehicle, (2) the vehicle in profile view, and (3) the vehicle equipped with a small payload (e.g., camera).

Development of UAS Specific Sign Alternatives

The five sign alternatives evaluated in this study captured the elements of road signs, legends, and pictorial elements. All alternatives incorporated the same shape and color of the traditional *Survey Crew* sign. For the alternatives that include legends, the text uses the same text size and font as the *Survey Crew* sign. These characteristics were kept consistent in the proposed sign alternatives to achieve similar detectability and readability (Stages #1 and #2) to the currently implemented *Survey Crew* sign.

Fig. 3 shows the graphics for the MUTCD adopted *Survey Crew* sign (Sign #1) as well as the five proposed UAS specific alternatives. Two of the alternatives used text-only legends. Sign #2, *Drone Survey Crew*, used a more detailed and specific three-line legend to indicate the activity purpose and the presence of workers, similar to the traditional *Survey Crew* sign. Sign #3, *Drones Ahead*, used a less specific two-line legend but can be read quicker by drivers. Symbols were used on three of the sign alternatives. One of the alternatives incorporated a text legend and a symbol while the other two just used symbols. Sign #4 used a combination of a text legend and a symbol. The symbol was designed based on examples of UAS signs and depicts a quadcopter style UAS in a profile view with a small camera for its payload. Sign #5 did not include any text legend but instead incorporated the profile view symbol of the UAS vehicle, along with a symbol of an operator controlling the vehicle to communicate the presence of human operators near the UAS. Sign #6 only used the profile view UAS symbol and no text legend as a simpler symbolic sign alternative to Sign #5.

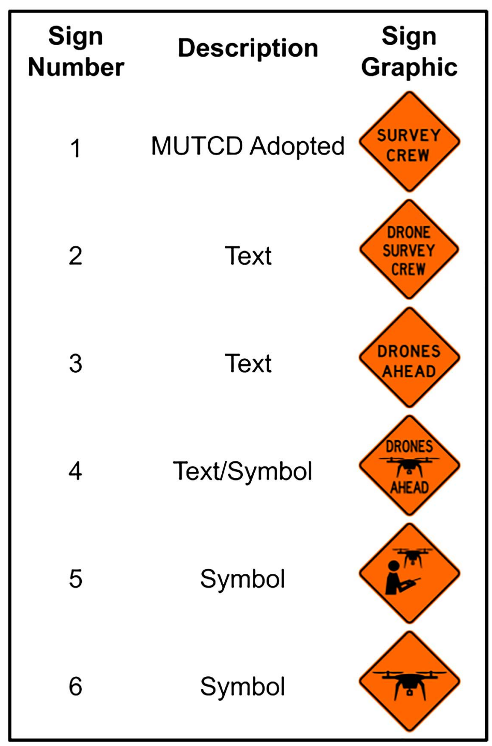

Fig. 3. Descriptions and graphics for alternative UAS signs.

TTC Evaluation Questionnaire Development

After the sign alternatives were designed, they were incorporated into a questionnaire. The primary purpose for the questionnaire was to measure comprehension (Stage #3) of the sign design alternatives in comparison to the *Survey Crew* sign. The sign alternatives use the same shape, color, and size as the *Survey Crew* to maintain a similar detectability (Stage #1) and readability (Stage #2). In addition, the actability (Stage #4) of the signs is simply cognitive awareness generated through comprehension—thereby increasing the importance of Stage #3. Therefore, the questionnaire questions were developed and coded into Qualtrics, an online questionnaire platform, to target participant comprehension as a valid method to evaluate the effectiveness of the UAS specific sign design alternatives (Neill et al. 2016).

To measure participant comprehension for the six sign designs (the *Survey Crew* and five alternatives), participants were asked to individually rate each of the following road signs based on how well they think they would work at communicating the presence of an upcoming drone operation. Graphics for all six signs were presented next to a 5-point Likert scale sliding bar for each of the signs, which allowed participants to rate the signs as follows: 1—would not work at all; 2—would likely not work; 3—might work; 4—would likely work; or 5—would work very well.

Participants were also asked the following question: do you feel that having specific warning signs for drone operations is helpful to you as a driver? They were given the response options of *Yes*, *No*, and *Unsure*. All respondents were then prompted to briefly describe their reasoning for their choice. This question was developed to ascertain participant attitudes on UAS specific signs beyond just the comprehension of the design itself.

These questions were posed to the participants in a post-drive questionnaire after they had completed a course in the driving simulator in which they were exposed to various TTC configurations surrounding roadside UAS operations. In addition to the questions related to UAS specific road signs, a standard set of demographic questions was used and comprised the predrive questionnaire. Participants were asked to respond to the predrive questionnaire before completing the driving simulator portion of the experiment.

Driving Simulator

To explore participant speed as they drove past UAS operations with various TTC configurations, the high-fidelity driving simulator at OSU was used. Driving simulation provides a safer, more cost effective, and more controllable environment for researchers to measure driver behavior than traditional field studies (Allen et al. 2011). Validated results have shown that data produced from driving simulation has, at least, relative validity. Numerical results of driver behavior, which are of the same magnitude and direction as real-world results while not necessarily producing identical numerical values, demonstrate relative validity as opposed to absolute validity (Mullen et al. 2011). In some cases, such as a study exploring driver decision making and deceleration rates (Moore and Hurwitz 2013), driving simulation has been shown to produce results with absolute validity.

The OSU driving simulator (Fig. 4) is a high-fidelity simulator implementing a 2009 Ford Fusion cab sitting atop a pitch motion system. The visual display consists of a projected three-panel forward display encompassing 180°. In addition, a rear projected screen provides the participant a view through the rearview mirror and LCD screens are mounted in the side mirrors. The simulated environment is generated with Realtime Technologies SimCreator software (version 3.2); vehicle dynamics data and video captures of participant behavior were recorded with the Realtime Technologies SimObserver software (version 2.02.4).

Virtual Scenarios

This study evaluated how various elements of TTC impacted vehicle speed when passing by roadside UAS operations. A within-groups, counterbalanced, and partially randomized experimental design was used to explore the change in vehicle speed from a baseline condition to the speed as the vehicle passed the UAS operation based on various TTC configurations in advance of the operation. In this type of experimental design, all participants encountered all six TTC configuration scenarios in three tracks presented to the participants in a random order.

First, a standard UAS operation was developed within the simulated environment. Federal UAS regulations in the United States require UAS vehicles to be piloted within the line-of-sight of

(a)

(b)

Fig. 4. (a) Projected environment in the simulator; and (b) the exterior of the OSU driving simulator.

Table 1. Descriptions of the six simulator scenarios

Scenario number	Scenario name	Description
1	Control	• No TTC or PPE for UAS operation.
2	Operator vests	• Operators wearing orange and yellow construction vests (PPE).
3	Single TTC sign	• A UAS specific TTC sign 152 m (500 ft) in advance of operation. • UAS operators wearing vests.
4	Two TTC signs	• A UAS specific TTC sign 152 m (500 ft) in advance of operation. • *Survey Crew* sign 304 m (1,000 ft) in advance of operation. • UAS operators wearing vests.
5	Work vehicle	• A UAS specific TTC sign 152 m (500 ft) in advance of operation. • A white work truck parked off the road in front of UAS operators with a roof mounted flashing light bar. • UAS operators wearing vests.
6	Channelizers	• A UAS specific TTC sign 152 m (500 ft) in advance of operation. • A white work truck parked off the road in front of UAS operators with a roof mounted flashing light bar. • Channelizing devices along road edge line closing the shoulder around the work truck and UAS operation. • UAS operators wearing vests.

the pilot at all times. The guidelines also recommend that a spotter accompany the pilot (14 C.F.R. 107) (CFR 2016). Therefore, a single UAS operation arrangement was used throughout the experiment. This operation consisted of two operators (a pilot and a spotter) and a 1 m × 1 m quadcopter UAS vehicle. In the experiment, the UAS vehicle operated in a slow back-and-forth scanning pattern to simulate a typical surveying activity.

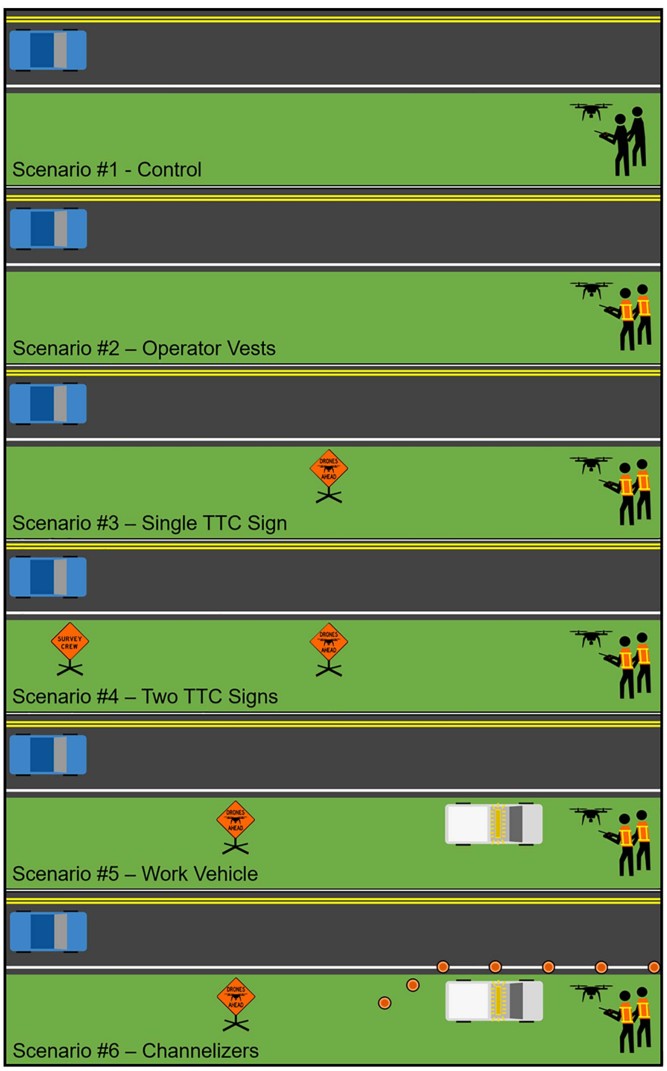

Fig. 5. Schematics for the six simulator scenarios.

Six scenarios were developed that represented various levels of TTC configurations. All scenarios included a UAS operation (two operators and a UAS vehicle) with varying configurations of TTC and associated complexity. Some scenarios included the implementation of personal protective equipment (PPE), which, in this case, was an orange and yellow construction vest. Table 1 and Fig. 5 provide a description and schematic for each scenario.

The scenarios that had a sign present used Sign #4, the text legend and symbol combination alternative. Scenario #4 also implemented Sign #1, the *Survey Crew* sign. Due to the potential for learning effects in a repeated measure driving simulator environment, it was not possible to incorporate all five UAS specific sign alternatives. Therefore, in consultation with state traffic engineers in Oregon, Sign #4 was selected to be used throughout the simulator experiment. Participants in the experiment were exposed to all six of the TTC configurations in a partially randomized order in the simulated environment, and their speed profiles were recorded to evaluate any change in speed between the approach to the UAS operation and the point when the vehicle was passing the operation.

Across all six scenarios, participants drove on a two-lane rural road. A rural environment was developed for this experiment because previous research has shown that roadside UAS operations in rural areas cause drivers to make more unsafe glances away from the roadway (Barlow et al. 2019). The road throughout the experiment had a posted 35 MPH speed limit and light ambient traffic. Participants drove in dry daylight conditions with a cloudless sky.

Fig. 6 displays various elements of the virtual environment as seen from the perspective of the participants as they drove past the UAS operations. At each of the roadside UAS operations, participants approached a tangent segment of roadway [Fig. 6(a)]. The UAS operation itself was identical across all scenarios with the operators located on the right side of the edge of the roadway with the UAS vehicle operating 10 m (32.8 ft) above the ground in a zig-zag scanning pattern adjacent to the roadway. The only variation in the UAS operation was that for Scenario #1; the operators were in plain clothes, while in the other five scenarios, the operators had orange and yellow construction vests [Figs. 6(b and c)]. Figs. 6(d–f) depict the other elements of TTC as rendered in the virtual environment.

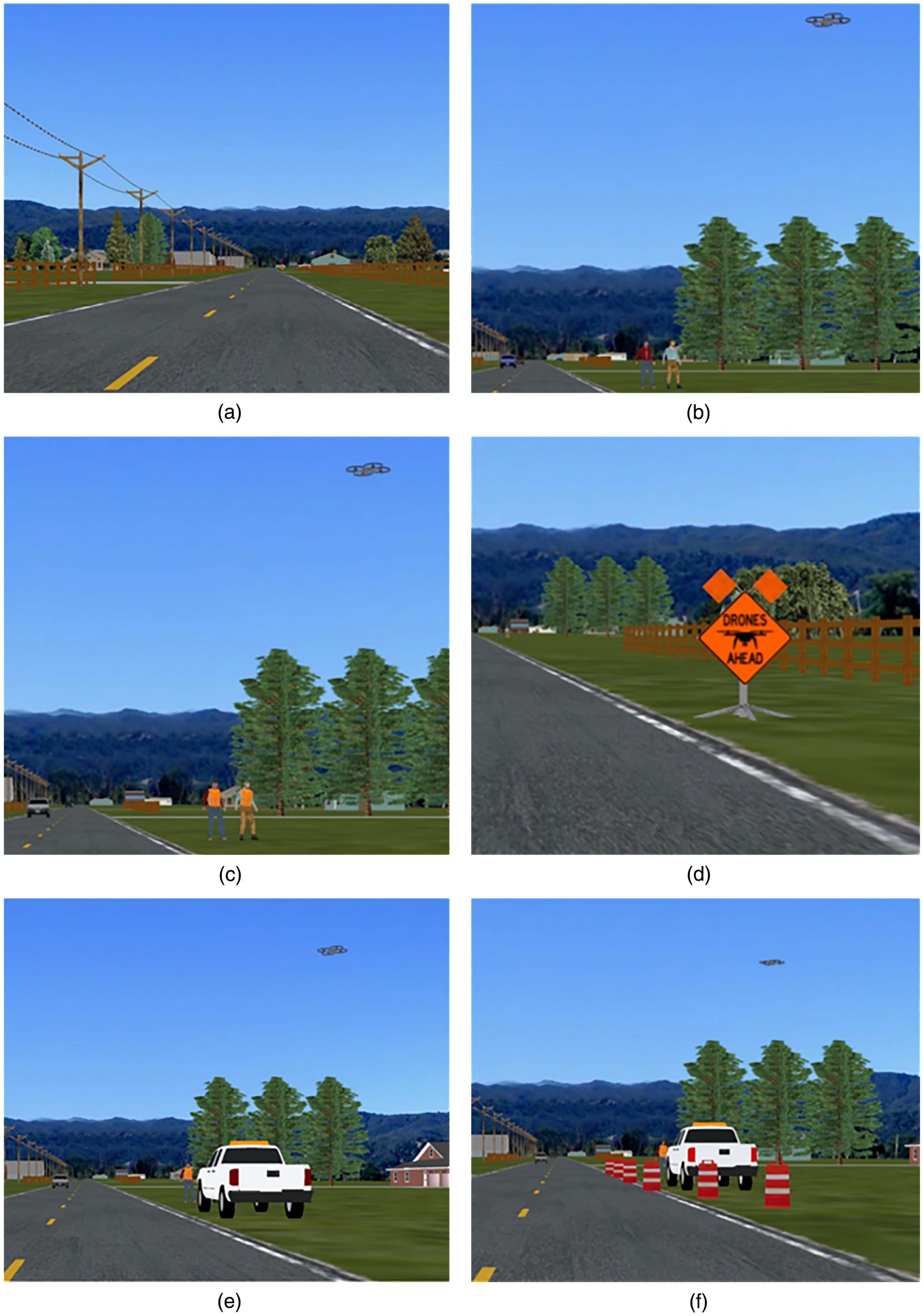

Fig. 6. Elements of TTC in simulated environment: (a) standard approach to UAS operations; (b) control UAS operation (no TTC or PPE, Scenario #1 only); (c) UAS operation with operator vests (Scenarios #2–#6); (d) UAS specific TTC sign (Scenarios #3–#6); (e) configuration of work vehicle for Scenario #5; and (f) configuration of channelization devices for Scenario #6.

Participant Demographics

Individuals aged 18–89 were recruited through email listserves, social media, and paper flyers in Corvallis, Oregon, to participate in the driving simulator and the TTC evaluation survey at the OSU driving simulator lab. Participants were required to have at least 1 year of driving experience and have a valid driver's license. Sixty-one total participants came to the OSU driving simulator lab. Of the total, four participants (6.6%) experienced simulator sickness and did not finish the experiment. Issues with the data recording equipment resulted in data loss from two additional participants (3.3%).

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Complete data sets, including the driving simulator portion and a response to the TTC evaluation survey, were collected from 55 participants. For the 55-participant sample, 31 (56.4%) identified themselves as male, 23 (41.8%) identified themselves as female, and one (1.8%) preferred not to say. The age of participants ranged from 19 to 71 years ($M_{\mathrm{age}} = 28.9$ years, $SD_{\mathrm{age}} = 11.6$ years).

Data Analysis

Data for this experiment was collected in two parts: participant responses to the postdrive survey and the speed data from the driving simulator. Through exploring both participant perspectives and participant behavior in the simulator, this analysis provided a more robust understanding of driver interaction with UAS specific TTC.

All participants in the simulator experiment also provided responses to questions in a postdrive questionnaire regarding their perspective on UAS specific signage and their preference on sign design alternatives. First, participants provided qualitative responses to explain their reasoning for choosing *Yes*, *No*, or *Unsure* regarding whether they believed UAS specific signs were helpful to them. These responses were collected and analyzed in Dedoose v.8.2.14. Thematic analysis was conducted on responses in alignment with Creswell's *Research Design* (Creswell 2014). Themes were inductively generated, meaning codes emerged from the data after an in-depth, repeated review of participant responses. The coding process was iterative; codes were generated and then applied to all previous and subsequent datasets. Themes were used to generate patterns surrounding participants' rational regarding UAS specific signage.

The other portion of the questionnaire collected responses on how effective participants thought that the six sign designs (the *Survey Crew* sign and the five alternatives) were at communicating the presence of an upcoming drone operation. The responses were collected on a 5-point Likert scale, so a Friedman's test in SPSS version 26 was used to determine if there were any differences in the rated effectiveness of the six sign designs. The Friedman's test was chosen as it distinguishes differences in responses across multiple groups of ordinal data, as was the case (Mccrum-Gardner 2008). A posthoc Wilcoxon rank-signed test in SPSS was used to compare pairs of individual signs because this method can compare paired ordinal data (Ramsey and Schafer 2002). For this study, the preference ratings for each of the five alternative designs was compared to the preference ratings for the adopted *Survey Crew* sign using this method. To account for the five comparisons, a Bonferroni adjustment was used with the Wilcoxon rank-signed test to establish the p-value needed to achieve significance for this portion of the analysis (Ramsey and Schafer 2002).

For the second part of data analysis, participant speed was recorded in the simulator as they approached each of the UAS operations. An approach speed was recorded 533 m (1,750 ft) in advance of the UAS operation before the operation or any TTC was visible. A second speed point, at the UAS operation itself, was also recorded. For each participant, the change in speed between these two measurement points was calculated to explore the change in speed induced by the TTC and UAS operation. Because each participant encountered each treatment level, the experiment is considered a crossover repeated measures experimental design (Ramsey and Schafer 2002). Therefore, a repeated measures analysis of variance (ANOVA) was appropriate for evaluating the effect of the TTC configuration on the mean change in speed of participants.

Table 2. Summary of participant responses on TTC sign usefulness

Response	Number of responses	Percent of responses
Yes	41	74.5
No	6	10.9
Unsure	8	14.5

Results

The experimental design and analysis methods yielded results in three parts. The first two parts were generated with data from the questionnaire: perspectives on the use of UAS specific TTC and assessment of the sign design alternatives developed in this experiment. The third part used data from the driving simulator and evaluated changes in participant speed caused by the UAS operations.

Participant Perspectives on TTC Sign Usefulness

In the postdrive survey, participants were asked if they believed that specific signs for UAS operations were helpful to them as a driver. Table 2 summarizes the responses across the 55 participants.

Participants (74.5%) believed that specific TTC signs for roadside UAS operations were helpful to them. Participants were also asked to briefly describe their reasoning for their selection, allowing for a qualitative exploration of participant perspectives on the use of specific TTC for UAS operations.

A thematic analysis was conducted on the qualitative participant responses. Table 3 is a summary of the themes inductively generated through the coding of the participant responses. A brief description of the themes as well as an example response from a participant related to each theme is included.

By far the most common theme observed in the responses was the idea of driver expectancy. This theme was found across participant responses to the question of whether they believed UAS specific signs were helpful to them. One respondent who answered *No* stated "I felt normal driving by the drone that had no warning. When there was a warning before it I felt like I should slow down to prepare myself since I wasn't sure what was coming." An *Unsure* respondent noted that "it was nice to know what they were doing but it was not completely necessary." In contrast, one respondent,

Table 3. Summary of themes from participant responses

Themes	Description	Example response
Caution	Signs increased participant caution	"When the sign appears . . . I am likely to . . . be a more cautious driver."
Distraction—decreasing	Signs reduced chance of distraction	". . . knowing what was coming made [the UAS] less distracting once it appeared."
Distraction—increasing	Signs increased chance of distraction	"[The sign] makes me look for the drone and potentially become distracted by it."
Expectancy	Signs improved participant expectancy	"It's nice to have some warning so [the UAS is] not unexpected."
Operators	Signs made participants aware of human operators	"I do appreciate that [the sign] draws attention to the workers at the roadside."
Speed	Signs impacted participant speed	"Warning signs were helpful to limit my speed."

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who answered *Yes* to the question, wrote "With the warning signs, I was better able to anticipate that something out of the ordinary was happening in the area. It did not surprise [me] when there was something just flying over head."

Distraction was an interesting theme with some participants noting they felt signs decreased the potential for distraction and others feeling the presence of the signs increased the chance of distraction. Participants who believed that the signs were helpful sometimes cited decreased distraction as a reason. Those that did not think the signs were helpful, or were unsure, wrote of the potential for the signs to increase distraction.

Two of the themes related to the driver taking action in response to seeing the sign, whether mentally (caution) or physically (speed). While the UAS signs do not explicitly call for a driver to respond in a certain way (unlike, for example, a *Right Lane Closed Ahead* sign), these themes of driver action emerged. An analysis of these two themes uncovered an interesting contrast; respondents who mentioned speed were more likely to be male. Sixty-nine percent of responses mentioning the *speed* theme were from men while only 31% were from women. In contrast, 80% of the responses with incorporating the *caution* theme were from women (20% from men).

The final theme demonstrated that participants showed concern and awareness that there were human operators in the work zone. None of the respondents who answered *No* to whether they believed the signs were helpful to them mentioned the operators. Those who answered *Yes* or *Unsure* mentioned the operators as a reason to implement the signs.

TTC Sign Design Preference

Participants were asked to rate the six TTC sign alternatives on a 5-point Likert scale based on how well they felt that the sign communicated to them the presence of an upcoming UAS operation (1—would not work at all, and 5—would work well). Fig. 7 shows the descriptive statistics of participant responses for each of the TTC sign alternatives.

A Friedman's test was conducted on the effectiveness ratings recorded in the postdrive survey. There was a statistically significant difference in the rated effectiveness of road signs depending on the design of the sign, $\chi^2(5) = 78.8$ and $p < 0.001$.

A post hoc analysis of the road sign effectiveness ratings was conducted with a Wilcoxon signed-rank test. Each of the five UAS specific TTC signs was compared to the MUTCD accepted *Survey Crew* sign, resulting in five comparisons. These specific comparisons were conducted to evaluate if any of the UAS specific TTC sign designs were preferred to the *Survey Crew* sign. A summary of the five Wilcoxon comparisons is presented in Fig. 8. As multiple comparisons were made in the Wilcoxon signed-rank test, a Bonferroni correction was applied, resulting in a significance level of $p < 0.010$.

According to the Wilcoxon signed-rank test, three of the sign alternatives were rated significantly higher than the *Survey Crew* sign. Both of the text only alternatives and the text and symbol alternative were seen as more effective at communicating the presence of an upcoming roadside UAS operation. Neither of the symbol only alternatives were seen as more effective than the *Survey Crew* sign.

Vehicle Speed near UAS Operations

The speed of the participants as they approached and passed the UAS operation in the simulated environment may provide greater understanding of the effect of various TTC scenarios on drivers for roadside UAS operations. Fig. 9 is a synthesis of the average speed of all participants at four measurement locations for each of the six TTC scenarios (see Fig. 5 for schematics of the TTC scenarios). The speed values in Fig. 9 are relative to the average speed before the UAS operation or associated TTC elements were visible to the participant (approach speed) to explore the change in participant speed.

The first (approach speed) was recorded before the UAS operation or associated TTC elements were visible to the participant (533 m or 1,750 ft before the UAS operation). The second measurement (advance sign) was recorded 304 m (1,000 ft) before the

Sign Number	Sign Graphic	Description	Descriptive Statistics: Minimum	25th Percentile	Median	75th Percentile	Maximum
1		MUTCD Adopted	1	1	2	4	5
2		Text	1	3	4	5	5
3		Text	2	3	4	5	5
4		Text/Symbol	2	4	5	5	5
5		Symbol	1	2	4	4	5
6		Symbol	1	2	3	4	5

Fig. 7. Descriptive statistics of participant ratings for TTC sign alternatives and the MUTCD accepted *Survey Crew* sign (W21-6).

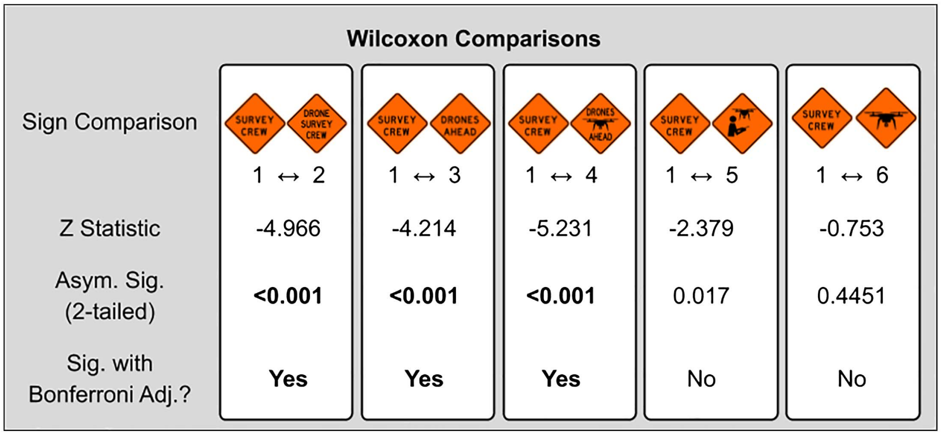

Fig. 8. Wilcoxon comparisons of the *Survey Crew* sign (W21-6) to UAS alternatives.

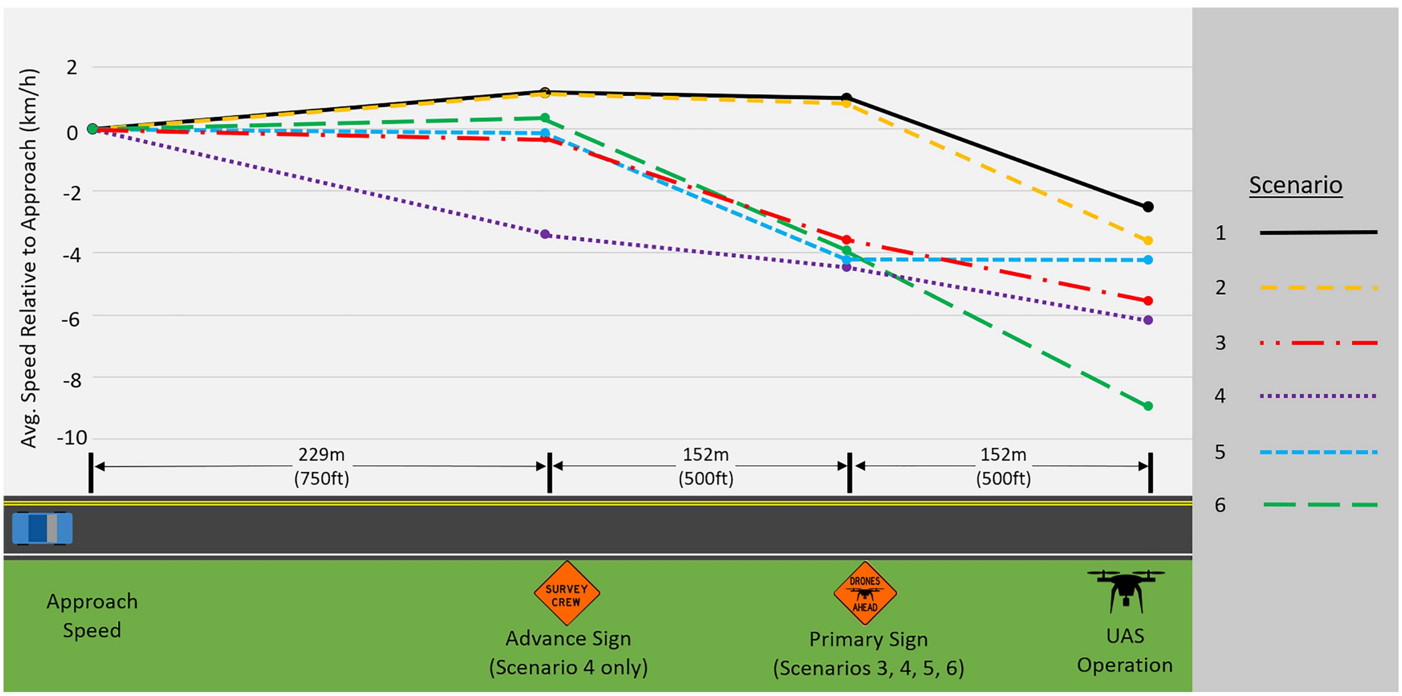

Fig. 9. Average speed profiles of participants for each of the six scenarios. Refer to Fig. 5 for schematics of each of the six scenarios.

UAS operation. In Scenario 4, which used two TTC signs, the first sign was located at this second measurement. Nothing was present for the other five scenarios at this measurement. The third measurement (primary sign) was captured 152 m (500 ft) in advance of the UAS operation. For Scenarios 3, 4, 5, and 6, the UAS specific TTC sign was located at this measurement location. The final measurement was taken as the participants passed the UAS operation.

Fig. 9 highlights patterns in the speed of the participants as they approached the UAS operation. In all scenarios, there was some decrease in the speed from the approach mark to the point where participants passed the UAS operation. The signs do appear to have some impact on participant speed. In addition, this figure highlights that the TTC signs, in addition to the UAS operation itself, may have an impact on participant speed. For example, Scenario 4, which implemented an advanced sign, resulted in an earlier decrease in speed and a more gradual decrease over the course of the approach. Scenarios 1 and 2, which did not have any advanced TTC, did not record any average speed decrease until participants were passing the UAS operation. Table 4 provides a descriptive summary of the mean speed changes of the 55 participants between the approach and the UAS operations in the different TTC scenarios.

Table 4. Descriptive statistics for change in speed during participants' approach to the UAS

Senario number	Description	Average Δ speed (km/h)	Standard deviation Δ speed (km/h)
1	Control	−1.54	3.71
2	Operator vests	−2.22	4.00
3	Single TTC sign	−3.44	4.44
4	Two TTC signs	−3.79	5.13
5	Work vehicle	−2.67	3.97
6	Channelizers	−5.50	4.90

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Table 5. Bonferroni corrected post hoc comparisons between TTC configurations and the control

Pairwise comparison	Mean difference in Δ speed (km/h)	Standard error	Bonferroni corrected significance
Scenarios 1 and 2	1.08	0.78	1.000
Scenarios 1 and 3	3.02	0.98	**0.049**
Scenarios 1 and 4	3.52	1.11	**0.037**
Scenarios 1 and 5	1.77	0.84	0.590
Scenarios 1 and 6	6.44	1.12	**<0.001**

Note: Bold values are significant at the 95% confidence level (<0.05).

The mean change in driver speed between the approach mark and the mark at the UAS operation across the six TTC configurations was evaluated using a repeated measures ANOVA. A Greenhouse-Geisser corrected repeated measures ANOVA found that there was a statistically significant effect of TTC configuration on the change in driver speed as they approached the UAS operation, $F(4.149, 224.029) = 11.037$ and $p < 0.001$. Bonferroni corrected post hoc tests were generated to compare the mean speed changes in a pairwise fashion. A subset of the post hoc tests that compare the control UAS operation (Scenario 1, no TTC or PPE) to each of the five alternative TTC configurations are shown in Table 5.

From Table 5, it can be concluded that several of the TTC configurations resulted in greater speed reduction than the control scenario. Scenario 3—Single TTC Sign, Scenario 4—Two TTC Signs, and Scenario 6—Channelizers all saw statistically greater speed reduction than the control scenario. Scenario 2—Operator Vests and Scenario 5—Work Vehicle did not result in a statistically larger change in speed than the control scenario.

Discussion

The following sections discuss recommendations for sign designs as well as the configuration of TTC elements aimed at improving driver expectancy and safety in these work zones.

UAS TTC Usefulness

The majority of participants in this study believed that UAS specific signs were helpful to them as drivers. The first research question (How do drivers describe their perspective on the helpfulness of UAS specific TTC signs?) guided a qualitative analysis of participant responses for their reasoning as to whether UAS specific signs were helpful. Two of the themes uncovered in the analysis were also found in the literature related to work zone safety: driver expectancy and vehicle speed (Daniel et al. 2000; Morgan et al. 2010; Pigman and Agent 1990). Effective work zones should seek to achieve maximum driver expectancy and limit speed to improve safety. Participants' references to these concepts validate their understanding of the purpose of TTC and rationalize the use of participant perspectives to recommend UAS specific TTC signs in this type of work zone.

The results of this analysis provide a two-fold justification for the use of UAS specific warning signs. First, the wide majority of participants believed that the signs were helpful to them. Second, consistency between the themes in participant responses and the purpose of the TTC signs as discussed in the literature validates the appropriateness of implementing this new sign type.

Recommendations

Results from this study, in conjunction with the literature, led to recommendations for new TTC signs specific to UAS operations

Fig. 10. Recommended sign alternatives for UAS operations.

as well as a recommendation for a TTC configuration where the new signs could be most effectively implemented to improve safety.

The *Survey Crew* sign is the only MUTCD adopted TTC sign for roadside survey operations. Current guidance would approve the use of the *Survey Crew* sign for any type of surveying operation, including surveying using UASs. However, sign theory notes that signs need to be precise and unambiguous to achieve necessary effectiveness (Lay 2004). Effective signs improve driver expectancy and, subsequently, driver safety (Alexander and Lunenfeld 1986; Weng et al. 2016). Therefore, to explore alternative signs to the *Survey Crew* option, this study asked the second research question (What TTC sign designs better communicate to drivers the presence of an upcoming roadside UAS operation?). After the development of five alternative sign designs, participants rated these five signs and the *Survey Crew* sign based on their perception of the effectiveness of each sign at indicating the presence of an upcoming UAS operation. Three signs, shown in Fig. 10, achieved a statistically higher participant effectiveness rating than the adopted *Survey Crew* sign.

Any of the three signs shown in Fig. 10 are recommended to inform drivers of a survey operation using UASs. The variations across the three preferred sign alternatives could allow for individual users and agencies to select the option that best works for them and their constraints. Either of the text only options would work well for cases where getting a new symbol approved for a sign is more challenging. The text and symbol combination sign, which performed the best in participant ratings, conveys the information in two modes: providing more specificity to the driver and not requiring the driver to necessarily comprehend the English word *Drones*.

The third research question (Do various configurations of TTC elements impact vehicle speeds through work zones with UAS operations?) explored vehicle speed while approaching and passing roadside UAS operations. Driver speed is an important factor in the safety of work zones, with excessive speed contributing to crashes in work zones (Daniel et al. 2000; Pigman and Agent 1990).

The experiment and subsequent analysis compared the speed decrease of participants in a scenario with no PPE or TTC (the control) to five experimental conditions with various levels of TTC configurations. Three of the configurations resulted in a statistically higher reduction in speed than the control scenario. Through a review of literature and practice, the researchers recommend the two-sign configuration for work zones implementing UASs as a survey tool, as depicted in Fig. 11.

This recommendation is made based on the concepts of driver expectancy and the effects of speed on safety in work zones. Pairing an accepted sign with a new, more specific sign will introduce drivers to a new sign design and provide additional detail regarding the UAS survey operation, thus improving driver expectancy. Increased driver expectancy, as can be provided through TTC devices, improves driver compliance and reaction time (Alexander and Lunenfeld 1986). In addition, the speed profile for this configuration was more gradual with participants decelerating at a slower rate over a greater distance, yet still achieving a statistically higher speed decrease than the control scenario. Sharp decelerations are

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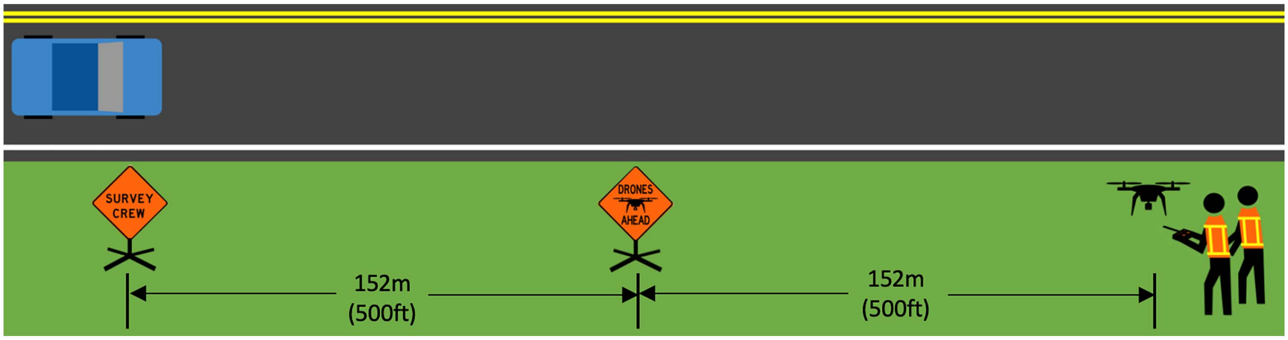

Fig. 11. Recommended TTC configuration and distances for UAS surveying operations.

known to be more unsafe and increase the risk of rear-end crashes (Tak et al. 2015).

The two-sign configuration is preferred to the single sign configuration, despite both alternatives achieving more speed reduction than the control, due to the more gradual deceleration induced by the two-sign configuration. The channelizer configuration did result in greater speed reduction than the two-sign configuration, but, again, the two-sign configuration resulted in a more gradual deceleration and does not require as much equipment or set-up time as the channelizer alternative.

Local and National Implementation

For the recommendations of this research to be applied and improve safety at roadside UAS operations, implementation is a necessary next step. At the national level, this implementation should be in coordination with updates to the MUTCD. At the local and state level, state transportation departments, particularly those that implement UASs for transportation related projects, should incorporate research and field testing of these TTC configurations in conjunction with their UAS operations.

Future Research

Implementation of these recommendations should be a key focus of future research efforts on this topic. As noted, it is important that this research explore implementation at both the local and the national levels to achieve greater understanding of the potential safety issues related to UAS operations near roadways. In addition, expanding the breadth of this study and exploring other sign combinations, including rectangular distance plaques in conjunction with the UAS signs, would provide more data regarding how TTC configurations impact driver speed.

Conclusion

As UAS technology continues to improve, the applications for surveying will continue to increase. Some of these applications will be useful in roadway construction and maintenance, resulting in UAS operations near active roadways. Current TTC cannot effectively communicate to drivers the nature of the disruption to their expectancy. The recommendations for the sign design alternatives and the two-sign configuration for UAS surveying operations were made in this study, on the basis of the findings of reduced driver speed at a gradual rate, to guide surveyors and engineers as they seek to improve the safety of drivers and UAS operators. Further research could be done in collaboration with transportation departments to explore the methods and feasibility of implementing a UAS specific sign design. Field testing of these sign designs and TTC configurations would be useful to further validate the simulator results and explore other potential configuration alternatives.

Data Availability Statement

Some or all data, models, and code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data). Specifically, drivers' visual attention data (the number of fixations and durations) for each scenario aggregated by area of interest is available.

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