

CLOSED COURSE PERFORMANCE TESTING OF THE AWARE INTRUSION ALARM SYSTEM

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EXECUTIVE SUMMARY

Oldcastle Materials and ARTIS, LLC have joined forces to develop an innovative work zone intrusion detection and alarm system. This system has been named AWARE, for Advance Warning And Risk Evasion. Unlike previous intrusion alarm systems that rely on the detection of vehicles crossing a predetermined perimeter (typically identified with pneumatic tubes or infrared beams), this new system utilizes a target threat detection and tracking methodology to logically assess approaching vehicle speed, location, and possible trajectory.

This study was conducted to assess performance of the AWARE intrusion alarm system in a closed course environment. This testing was intended to verify that the alarm system does produce the proper alert when conditions warrant (i.e., lights activate and do so when the approaching vehicle is at the appropriate distance based on the threat detection and SSD algorithms). In addition, the testing was also intended to verify that alerts were not activated when conditions did not warrant (i.e., that the system does not produce a false alarm). The performance of the Worktrax devices designed to be worn by field personnel and activated when an intrusion threat is detected was also evaluated. These devices were positioned at the AWARE system vehicle and at locations upstream of the vehicle to assess the ability of the system to correctly determine the location of the devices and their position relative to the intrusion threat.

AWARE systems were tested under two basic operating modes: lane closures and flagging operations. For testing purposes, right lane closures were created for three different scenarios:

- Lane closure in a tangent alignment
- Lane closure in right curve alignment
- Lane closure in a left curve alignment

A flagging operation on a two-lane, two-way highway was also created. A number of approach vehicle trajectories were developed and performed under both operating modes to verify that the system activated when appropriate and did not activate when not appropriate. Several of these trajectories were performed using two different vehicle types, approach speeds, and slightly different alarm orientations relative to the direction of traffic flow.

Based on this methodology, the system achieved a 100 percent success rate in terms of correctly activating or not activating the warning lights and audible alarm across the range of scenarios and vehicle trajectories tested. Similarly, the Worktrax devices achieved a 97 percent success rate measured across the range of device locations, test scenarios, and vehicle trajectories. . However, it was determined that all of the unsuccessful events for the Worktrax device were attributable to the test protocol exceeding the effective communication range of the intrusion detection system with the Worktrax device. Ongoing improvements in the device are expected to significantly increase this communication range. All other device locations, scenarios, and trajectories tested achieved a 100 percent success rate.

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INTRODUCTION

Description of the AWARE System

Oldcastle Materials and ARTIS, LLC have joined forces to develop an innovative work zone intrusion detection and alarm system. This system has been named AWARE, for Advance Warning And Risk Evasion. Unlike previous intrusion alarm systems that rely on the detection of vehicles crossing a predetermined perimeter (typically identified with pneumatic tubes or infrared beams), this new system utilizes a target threat detection and tracking methodology to logically assess approaching vehicle speed, location, and possible trajectory. When the AWARE system is deployed in a roadway environment (i.e., a work zone), threats are detected in two flat, fan-shaped regions, as shown in Figure 1.

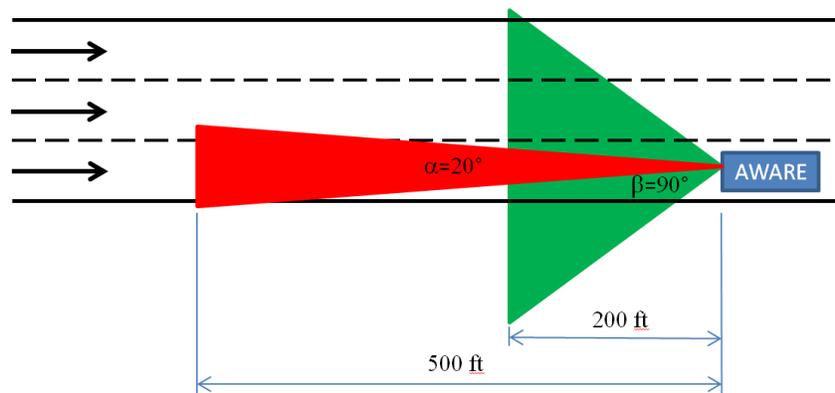


Figure 1. Threat Detection Regions.

The long-range region (shown in red) extends approximately 500 ft upstream of the alarm system. The width of the region expands 10 degrees on either side of the centerline (for a total detection angle $\alpha = 20$ degrees). The short-range region (shown in green) extends approximately 200 ft upstream of the alarm system and expands 45 degrees on either side of the centerline (for a total detection angle $\beta = 90$ degrees).

When a vehicle enters these protected areas, its speed and heading are detected by the AWARE system which uses internal calculations to determine the appropriate response. The calculations are based primarily on the Stopping Sight Distance (SSD) equation from the American Association of State Highway and Transportation Officials' *A Policy on Geometric Design of Highways and Streets*, commonly known as the AASHTO Green Book (1):

$$SSD = 1.47Vt + 1.075 \frac{V^2}{a}$$

Where,

- t is the perception-reaction time of 2.5 seconds;
- a is the deceleration rate of 11.2 ft/s^2 ; and
- V is the approach vehicle closing speed in mph.

Thus, for a vehicle approaching at a speed of 45 mph, the calculated AASHTO SSD would be 360 ft; for a vehicle approaching at 60 mph, the AASHTO SSD would be 566 ft. The equation assumes that sufficient tire-pavement friction exists to create the stated deceleration rate.

The AWARE system also relies on an alternate (more conservative) calculation of SSD assuming that $t=4.5$ seconds to activate some of its alerts and alarms. By substituting this in the equation in lieu of 2.5 seconds, the outcome is longer SSD values. For example, for a vehicle approaching at a speed of 45 mph, the conservative calculated SSD would be 492 ft; for a vehicle approaching at 60 mph, the conservative SSD would be 742 ft. As shown in Figure 2, the conservative SSD is longer than the long-range threat detection capabilities of the AWARE system once approach speeds exceed 45 mph, and the AASHTO SSD is longer than the long-range region once approach speeds exceed 55 mph. This means that the detection range of the system governs activation of its alarms and alerts for system testing purposes.

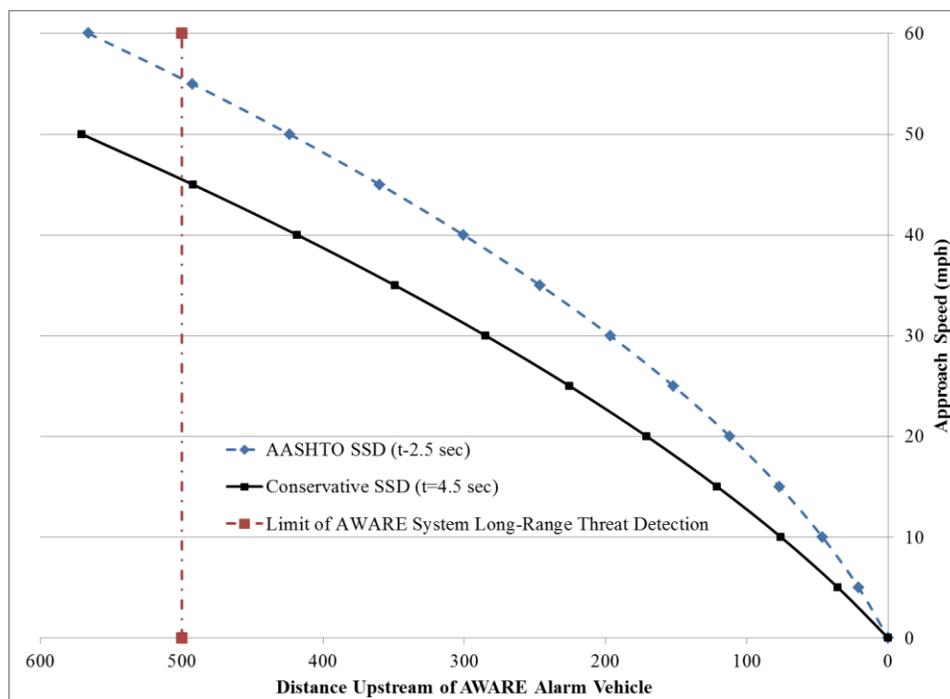


Figure 2. Conservative and AASHTO SSD values used by AWARE.

If the trajectory of the vehicle is computed to intrude into the work space/protected area (or to be exceeding a reasonable speed approaching the work zone), the AWARE system is activated to alert the motorist and also notify workers of the intrusion threat. If the conservative SSD threshold corresponding to $t=4.5$ seconds is exceeded, the flashing light-emitting diode (LED) warning lights activate. If the SSD threshold corresponding to $t=2.5$ seconds is exceeded, then both the flashing lights and an audible alarm are activated. The expectation is that the AWARE system will reduce potential intrusion events by catching the attention of the targeted approaching motorist with the activation of the flashing LED lights. The audible alarm, while intended for warning of the work crew, will also likely attract the attention of the approaching motorist. Together, it is hoped that these countermeasures will deter vehicle intrusions into the

work space, or if an intrusion does occur, that it will increase worker awareness of the event and increase their chances of escaping unharmed.

The AWARE system also includes personal body alarms called Worktrax. These devices, which can be worn by workers as part of their personal protective equipment (PPE), are linked to the main AWARE alert system and produce both vibratory (tactile) and audible alerts when the main alarm system is triggered if the worker is positioned within the potential trajectory of the intrusion threat vehicle. A hardhat-mounted Worktrax device is shown in Figure 3.



Figure 3. Worktrax Personal Alarm Mounted on Hardhat.

Objective of the Study

APAC-Texas, a subsidiary of Oldcastle Materials, has contracted with the Texas A&M Transportation Institute (TTI) to conduct system performance testing of the AWARE alarm system, including the Worktrax devices. This testing was intended to verify that the alarm system does produce the proper alert when conditions warrant (i.e., lights activate and do so when the approaching vehicle is at the appropriate distance based on the threat detection and SSD algorithms). In addition, the testing was also intended to verify that alerts were not activated when conditions did not warrant (i.e., that the system does not produce a false alarm).

STUDY METHODOLOGY

Overview

An AWARE system performance test was developed for use at a closed course at the Texas A&M Riverside Campus. Testing consisted of TTI researchers driving instrumented approach vehicles toward the AWARE system under various conditions to determine if the system responded as expected. All testing was performed cooperatively with AWARE system developers and technicians on site in August of 2016. ARTIS staff installed, armed, and otherwise operated the system. TTI staff installed and operated separate data collection equipment to observe system responses. Subsequent data analyses were performed to assess actual distances at which alarms were activated to further validate the precision of the algorithms.

Testing Location

The study was performed at the Texas A&M University RELIS Campus in Bryan, Texas. This facility was a former Army airbase that has been converted for use as a testing facility for TTI and for other members of the Texas A&M University System. The facility consists of five different runways and accompanying aprons and taxiways. All of the closed course performance testing of the AWARE alarm system and Worktrax occurred on runway 35L. Runway 35L was constructed with concrete pavement slabs that are approximately 12 ft wide and 20 ft long. For research purposes, the concrete pavement joints are often used to simulate 12 ft wide lanes and the 20 ft longitudinal joints facilitate easy marking of reference points and distances along the lanes. The test runway exceeds 7000 ft in length, which allowed TTI staff sufficient room to accelerate the instrumented vehicle up to 60 mph on the approach when necessary.

Testing Equipment

During testing, the researchers used two different approach vehicles (shown in Figure 4). This allowed the researchers to verify that the AWARE system could detect vehicles of different sizes. The passenger car was a 2012 Ford Fusion and the pickup truck was a 2011 Ford F-150.



(a) Passenger Car



(b) Pickup truck

Figure 4. Approach Vehicles Used in Tangent Alignment Testing.

The approach vehicles were instrumented with a Trimble GPS system using Real Time Kinematic (RTK) satellite navigation to continuously track approach vehicle position via corrected GPS data. The RTK base station was located approximately 3,200 ft (less than 1 km)

from the test site, which reportedly provided positional accuracy of the instrumented vehicle within 0.4 inches. The GPS data were captured by an in-vehicle laptop.

A dash-mounted video camera was also linked to the in-vehicle laptop for continuous capture of the forward scene view from the approach vehicle. As a backup, a separate time-synced video camera also independently recorded the forward scene data. The cameras and laptop are shown in Figure 5.



Figure 5. Approach Vehicle Data Collection Equipment.

During portions of the testing, Worktrax devices were also evaluated for proper response when the main alarm was triggered. The researchers used tripod-mounted video cameras to record the Worktrax responses (i.e., alarm sound and vibration) using time-synchronized videos which could then be matched to the time stamps of the in-vehicle data. A typical test setup is shown in Figure 6.



Figure 6. Worktrax Alarm Monitoring During Testing.

Testing Scenarios

AWARE systems were tested under two basic operating modes: stationary lane closures and flagging operations.

Lane Closures

For testing purposes, right lane closures were created for three different scenarios:

- Lane closure in a tangent alignment
- Lane closure in right curve alignment
- Lane closure in a left curve alignment

The purpose of testing both types of horizontal curves was to verify the ability of the system to correctly detect and assess non-linear vehicle trajectories approaching the work zone.

Lane Closure in Tangent Alignment

For these tests, the AWARE systems were mounted on two different host vehicles, as shown in Figure 7. The black truck was parked facing northbound, while the white truck was parked facing southbound on the opposite side of the test track. This allowed the researchers to obtain two approach runs during a single lap of the test track.



(a) Black truck (northbound)

(b) White truck (southbound)

Figure 7. AWARE Vehicles Used in Tangent Alignment Testing.

With the AWARE vehicles in position, TTI researchers drove the instrumented approach vehicle along a series of designated trajectories, some of which were designed to activate the alarm and others which were intended to verify that the alarm would not activate. Five different trajectories were evaluated in a repeated measures test method:

- Trajectory A – Lane change into adjacent lane within 200 ft of the AWARE vehicle
- Trajectory B – Passing by the system in an adjacent lane
- Trajectory C – Vehicle crossing the intrusion detection region
- Trajectory D – Vehicle approaching at a speed below alarm threshold
- Trajectory E – Vehicle approaching in closed lane and penetrating the SSD threshold

In Trajectory A, TTI staff drove the instrumented vehicle towards the AWARE system beginning two lanes left of the lane in which the AWARE vehicle was located. Once the instrumented vehicle was within 200 ft of the AWARE vehicle (i.e., within the short-range detection region of

the system), the TTI driver made an abrupt lane change into the lane adjacent to the AWARE vehicle, and then continued past the AWARE vehicle in that adjacent lane. This approach path is shown in Figure 8. The expectation was that the alarm system would not produce an alert (i.e., would not activate the lights, audible alarm, or Worktrax).

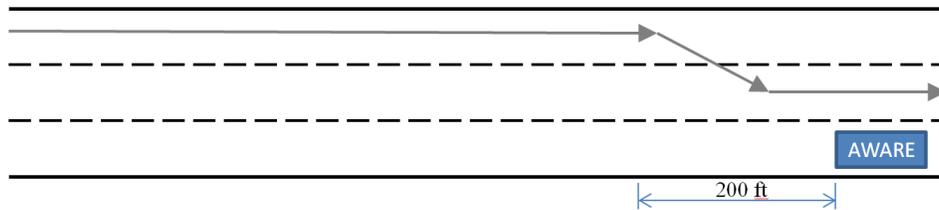


Figure 8. Approach Path for Trajectory A of Tangent Alignment Testing.

In Trajectory B, the instrumented vehicle began in the lane adjacent to the lane in which the AWARE vehicle was located. The instrumented vehicle passed by the AWARE vehicle in the adjacent lane. This approach path is shown in Figure 9. Similar to Trajectory A, the alarm system was not expected to produce an alert for this trajectory.

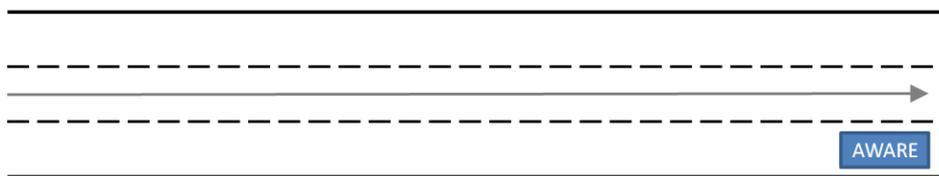


Figure 9. Approach Path for Trajectory B of Tangent Alignment Testing.

In Trajectory C, the instrumented vehicle began in the left lane adjacent to the lane in which the AWARE vehicle was located. At a location between 360 ft and 200 ft upstream of the AWARE vehicle, the instrumented vehicle crossed over into the lane adjacent to the AWARE vehicle on the right side. This approach path is shown in Figure 10. The red stars indicate the Worktrax locations for this series of tests. The expectation was that this trajectory would produce an alert which would trigger the lights and audible alarm. The Worktrax devices would activate only if the threat was detected upstream of the Worktrax locations (i.e., the devices located at 0 ft and potentially 300 ft upstream).

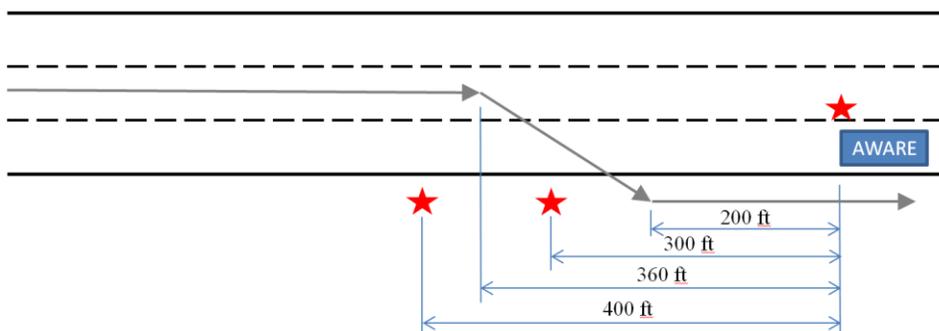


Figure 10. Approach Path for Trajectory C of Tangent Alignment Testing.

In Trajectory D, the instrumented vehicle began in the same lane in which the AWARE vehicle was located and traveled towards the system at a speed of 15 mph. Within 100 ft of the AWARE vehicle, the instrumented vehicle came to a full stop, and then passed the AWARE vehicle on the left at a speed no greater than 15 mph, similar to how a construction vehicle might enter and pass by a work crew. This approach path is shown in Figure 11. For this trajectory, the expectation was that the alarm system would not produce an alert. Once proper system response was verified using the instrumented passenger car, the sponsor agreed that the pickup truck need not be also tested under this trajectory.

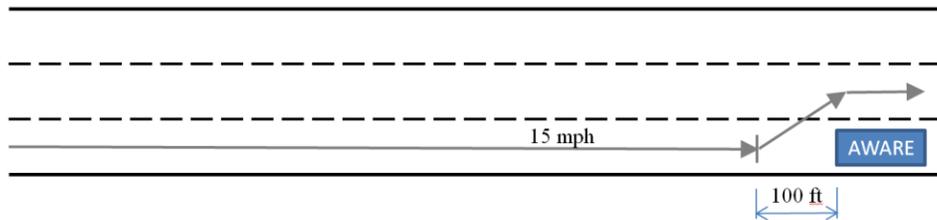


Figure 11. Approach Path for Trajectory D of Tangent Alignment Testing.

In Trajectory E, the instrumented vehicle penetrated the SSD threshold for a prescribed approach speed. In the northbound direction, the approach speed was 45 mph, yielding an AASHTO SSD limit of 360 ft and a conservative SSD of 492 ft. In the southbound direction, the approach speed was 60 mph, yielding an AASHTO SSD limit of 566 ft and a conservative SSD of 742 ft. This approach path is shown in Figure 12. Again, the red stars indicate the Worktrax locations for this series of tests. The expectation was that this trajectory would produce an alert which would trigger the lights, audible alarm, and Worktrax components of the system. For both approach speeds, the lights and Worktrax devices should be activated upon penetration of the long-range threat detection region since the conservative SSD in both cases was equal to or greater than the 500 ft long-range threat detection region.

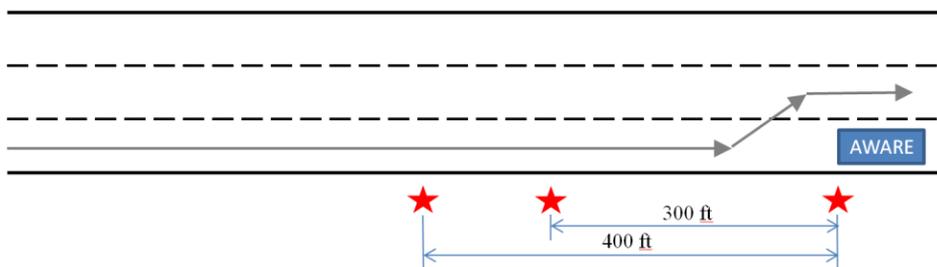


Figure 12. Approach Path for Trajectory E of Tangent Alignment Testing.

Each of the trajectories was replicated at least three times at each speed in each instrumented approach vehicle with the AWARE vehicle parked parallel to the lane lines.

Next, TTI staff evaluated the ability of the AWARE system to operate in slightly skewed deployments. This was intended to simulate a condition where the AWARE vehicle may not be perfectly aligned during deployment in a real work zone. These data were collected with the AWARE vehicle alignment skewed approximately 10 degrees left and 10 degrees right from

parallel to the travel lane. In addition, data were collected with the AWARE vehicle aligned parallel with the lanes, but with the left tires lifted approximately four inches to simulate the AWARE vehicle parked on a paved shoulder (at approximately six degrees of tilt). The normal and skewed AWARE vehicle alignments are shown in Figure 13.

Overall, there were 16 different test conditions for trajectories A, B, C, and E and 4 different test conditions for trajectory D. Accounting for the multiple passes using each instrumented vehicle (except for Trajectory D), a total of 204 test runs were completed during the tangent alignment testing.

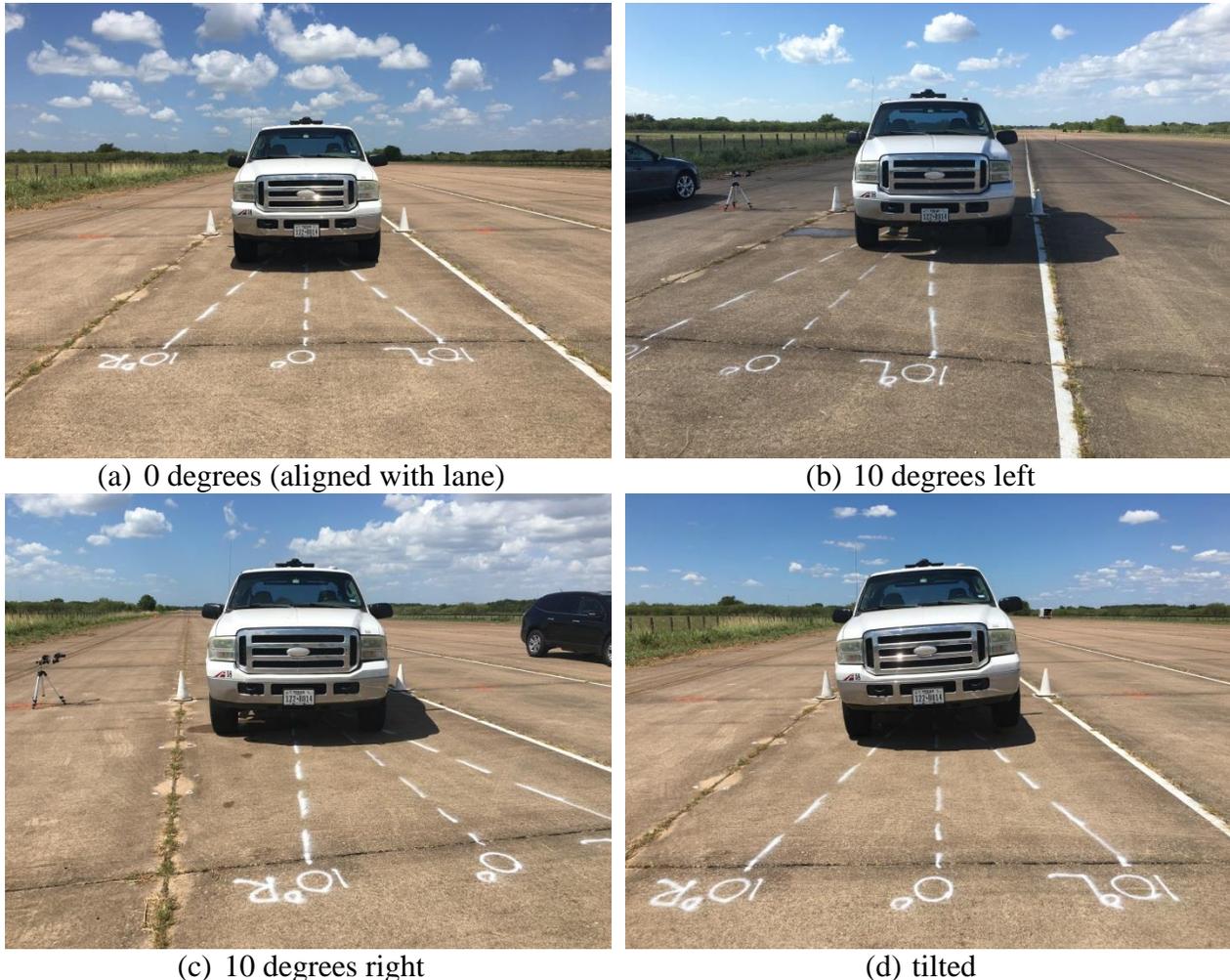


Figure 13. AWARE Vehicle Alignments Used in Tangent Alignment Testing.

Lane Closure in Curved Alignments

Curved alignment tests were conducted to determine if the AWARE alarm system would respond properly in roadway conditions where a horizontal curve is present. A horizontal curve equivalent to a 40 mph design speed was marked on the test area pavement. This curve was believed to be sufficient to test the ability of the AWARE system to properly assess whether the trajectory of the approaching vehicle would or would not pose a threat for the work zone.

Only one approach vehicle (the passenger car) was used for the curved alignment. Based on observations of the tangent alignment lane closure testing, the researchers concluded that (1) the alarm system had no apparent difference in activation between the two different approach vehicles and (2) the smaller approach vehicle would present a worse case challenge of detection and trajectory tracking by the system. Thus, the pickup truck was not used in the curved alignment testing. In addition, only the 0 degree and tilted AWARE vehicle alignments were evaluated (10 degrees left and right were omitted).

With the AWARE vehicle in position, TTI researchers drove the instrumented vehicle along a designated path at 40 mph according to four trajectories (A, B, C, and E). Figure 14 through Figure 17 show the trajectories used for the right and left curve alignment testing. A total of 48 runs were made during the curved alignment testing. Although the distances shown in the Figures indicate straight line chord distances, they were in fact measured along the curve during these tests.

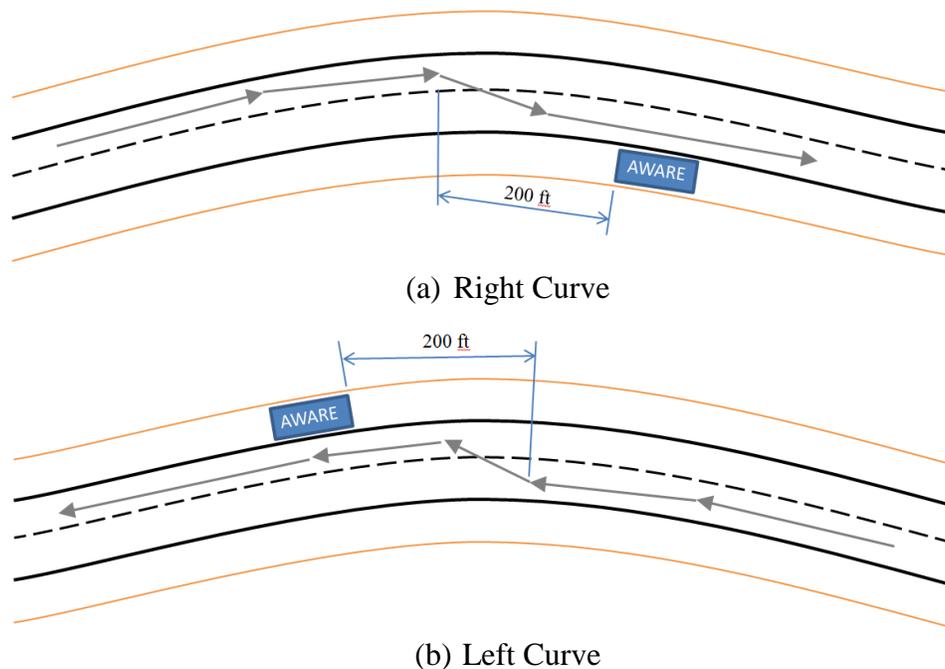
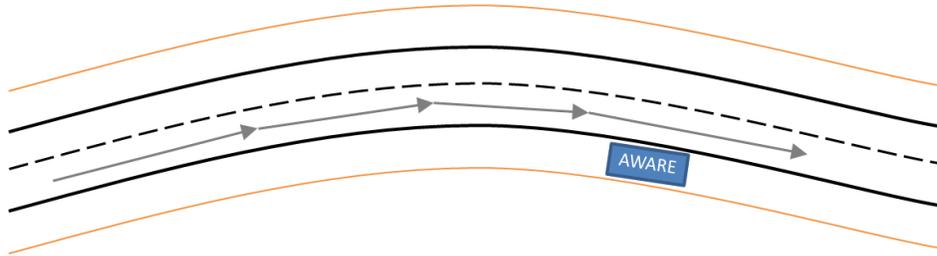
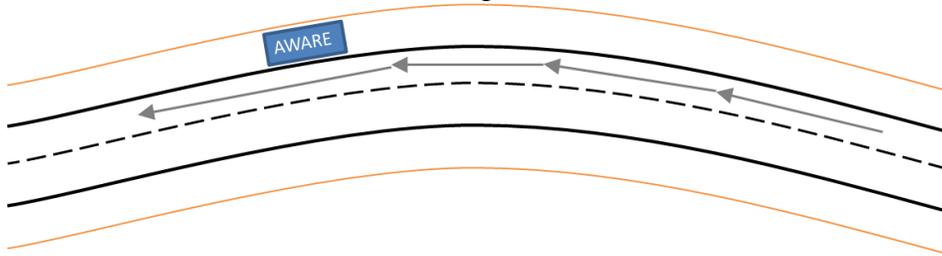


Figure 14. Approach Path for Trajectory A of Curve Alignment Testing.

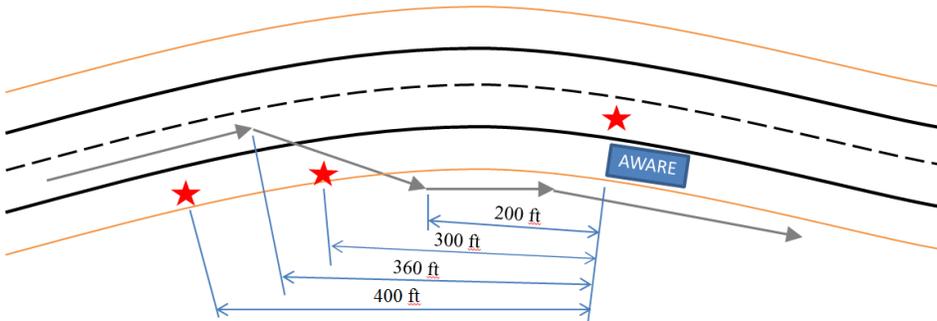


(a) Right Curve

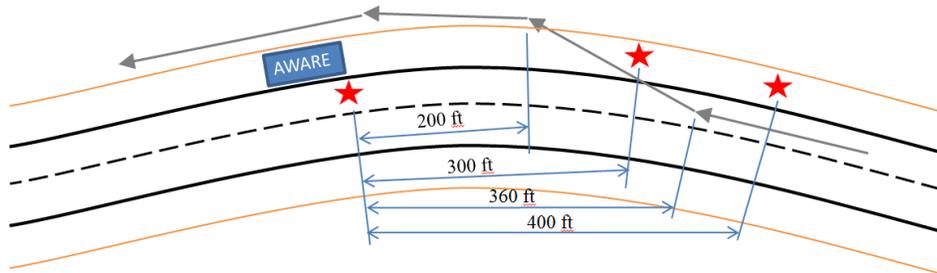


(b) Left Curve

Figure 15. Approach Path for Trajectory B of Curve Alignment Testing.



(a) Right Curve



(b) Left Curve

Figure 16. Approach Path for Trajectory C of Curve Alignment Testing.

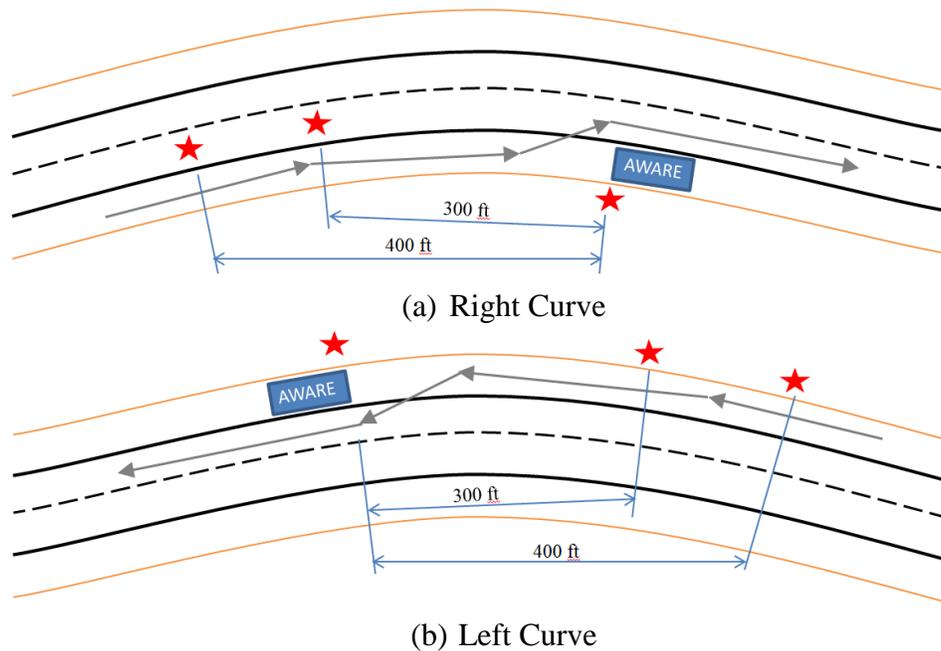


Figure 17. Approach Path for Trajectory E of Curve Alignment Testing.

Flagging Operations

For the flagging operation, a single AWARE system was mounted on a hand truck to replicate a freestanding alarm system, or “flagger cart” that is under development. This system is shown in Figure 18. The cart was positioned approximately two feet from the travel lane used for the instrumented vehicle approaches (to simulate where a flagger would stand). The researchers used a sledge hammer to apply dead weight to the flagger cart foot pedal. When the pedal was pressed, the cart was operating in SLOW PADDLE mode. This simulated a flagger holding the pedal down and allowing vehicles to pass by. When the sledge hammer was removed, the cart was operating in STOP PADDLE mode. This simulated a flagger holding traffic and not allowing vehicles to pass by.



Figure 18. AWARE System Used in Flagging Operation.

Three approach runs were made in the instrumented vehicle for each trajectory. The trajectories for the flagging operation differed from those used for the lane closures. Each flagging operation trajectory is described below:

- Trajectory F – Lane change during SLOW PADDLE operation
- Trajectory G – Lane change during STOP PADDLE operation
- Trajectory H – Decelerate below SSD during STOP PADDLE operation
- Trajectory I – Passing queued traffic on the left during STOP PADDLE operation
- Trajectory J – Passing queued traffic on the right during STOP PADDLE operation
- Trajectory K – Lane change passing queued traffic on the left during STOP PADDLE operation

In testing of Trajectories F and G, TTI staff drove the instrumented vehicle towards the flagger cart in the approach lane at 45 mph. Once the instrumented vehicle was within 360 ft of the flagger cart, the TTI driver made a lane change into the adjacent (left) lane and completed that maneuver before reaching a point 150 ft upstream of the flagger cart. The driver then continued past the flagger cart in that adjacent lane at 45 mph. This approach path is shown in Figure 19.

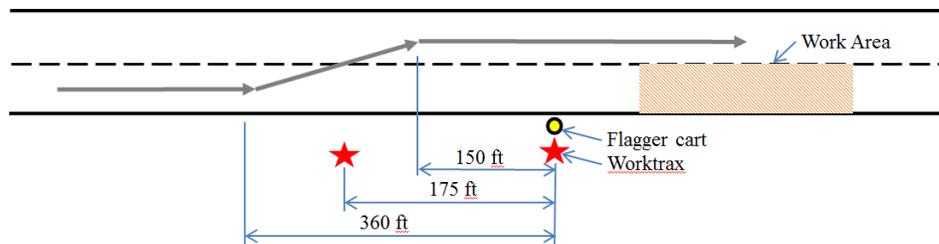


Figure 19. Approach Path for Trajectories F and G of Flagging Operation Testing.

The flagger cart was operating in SLOW PADDLE mode during Trajectory F. This simulated a flagger waving a car around into the open lane, so the alarm system was not expected to produce an alert. During Trajectory G, the flagger cart was operating in STOP PADDLE mode. This was to simulate a vehicle disregarding the flagger instruction and the alarm system was expected to produce an alert and trigger the Worktrax as well.

In testing of Trajectory H, TTI staff drove the instrumented vehicle (starting at 45 mph and decelerating to a stop) according to the approach path shown in Figure 20.

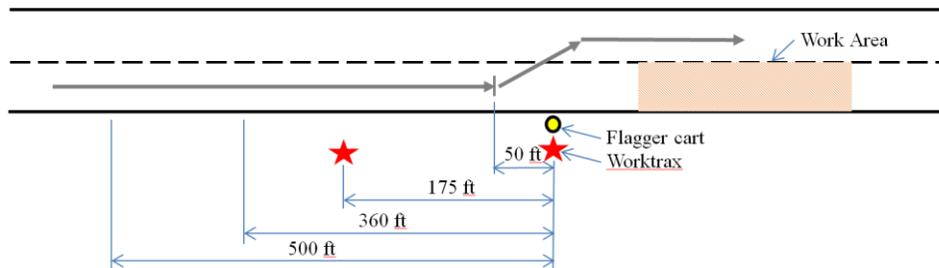


Figure 20. Approach Path for Trajectory H of Flagging Operation Testing.

Testing of Trajectory H was intended to demonstrate that the AWARE system would not respond to vehicles traveling just under the conservative SSD threshold while the flagger cart is in STOP PADDLE mode. This trajectory test would require that the driver of the instrumented vehicle continuously maintain a vehicle speed below the conservative SSD (i.e., less than 45 mph at the 500 ft mark, less than 30 mph at the 300 ft mark, etc.). This proved to be challenging in the field, so the researchers performed six runs using this trajectory, some of which exceeded the threshold and some which did not (these are described in greater detail in the Results section). The target approach speeds for the instrumented vehicle during testing of Trajectory H are shown in Figure 21.

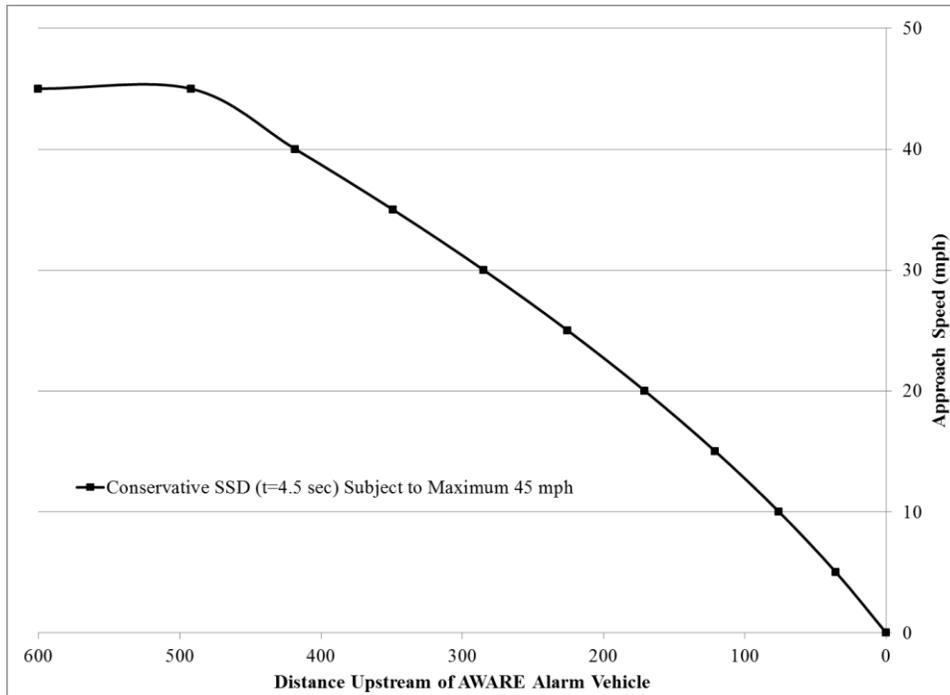


Figure 21. Target Approach Speeds for Trajectory H of Flagging Operation Testing.

In testing of Trajectories I and J, the flagger cart was operating in STOP PADDLE mode. A TTI fleet vehicle was parked in the approach lane approximately 20 ft upstream of the flagger cart. This was intended to simulate a condition where a queue of waiting traffic would potentially block detection of a vehicle jumping the queue and proceeding into the work zone (i.e., ignoring the STOP PADDLE instructions). This setup is shown in Figure 22.



Figure 22. Simulation of Queued Traffic in Trajectory I and J Testing.

TTI staff began the tests with the instrumented vehicle stopped in the approach lane just behind the queued vehicle. For Trajectory I, the driver accelerated and passed the queued vehicle on the left. For Trajectory J, the driver accelerated and passed the queued vehicle on the right. These trajectories are shown in Figure 23. In both cases, the alarm system was expected to produce an alert which would trigger the lights, audible alarm, and Worktrax components of the system.

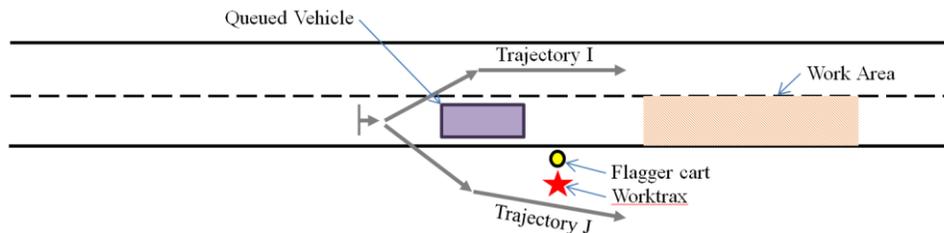


Figure 23. Approach Path for Trajectories I and J of Flagging Operation Testing.

In testing of Trajectory K, the researchers repeated the approach path used in Trajectories F and G (with the flagger cart in STOP PADDLE mode) and added the queued vehicle (similar to Trajectories I and J). The approach speed was 45 mph. This would test whether the AWARE system could still detect a high-speed lane change (and disregard of flagger instruction to stop) around the queued vehicle. In this case, the alarm system was expected to produce an alert which would trigger the lights, audible alarm, and Worktrax components of the system.

A total of 21 runs were made during the Flagging Operations testing: three runs for each of the five different trajectories (F, G, I, J, and K) and six runs for Trajectory H.

RESULTS

Stationary Lane Closure on Tangent Alignment

For the tangent alignment trajectories, the alarm system did not activate during Trajectories A, B, and D for any of the test conditions, all of which were the appropriate responses. Table 1 summarizes test results for all of the trajectory tests. For Trajectories C and E, the alarm system was expected to activate the lights.

Where appropriate, the researchers calculated the distance between the GPS coordinates of the alarm system and those of the approach vehicle at the time of the flashing light activation. The corresponding vehicle speed at the time of the flashing light activation was noted and verified to be within 1.3 mph of the intended speed (45 mph or 60 mph).

In Trajectory C testing, the Worktrax device located adjacent to the AWARE vehicle was expected to activate, but the Worktrax device located at 300 ft and 400 ft upstream of the vehicle were not expected to activate. As stated previously, the trajectory vehicle entered the protected lane between 360 ft and 200 ft from the AWARE system vehicle (typically around or closer than 300 ft) and therefore did not activate the upstream devices. Of 144 potential Worktrax device responses, 15 could not be accurately ascertained due to TTI equipment failure. However, all of the remaining responses were correct.

In Trajectory E testing, the approach vehicle made a direct penetration of the SSD in the lane where the AWARE vehicle was parked. Due to road noise inside the instrumented vehicle at higher speeds coupled with being at a further distance from the alarm than in Trajectory C, the time at which the audible alarm was activated could not be determined for all test runs. Therefore, the researchers focused solely on the activation of the flashing lights and the Worktrax devices for analysis of Trajectory E data.

At 45 mph, the range of flashing light activation distance was 382 ft to 522 ft. Statistically, there was no difference in activation distances between the car and the truck. Overall, the average activation distance was 478.8 ft. Considering that the data collection methods may have introduced some lag time due to laptop recording speed, etc., the researchers concluded that the AWARE system met the performance requirements of a 500 ft detection range for Trajectory E at 45 mph.

At 60 mph, the range of flashing light activation distance was 388 ft to 554 ft. Statistically, there was no difference in activation distances between the car and the truck. Overall, the average activation distance was 477.9 ft, essentially equal to that observed for the 45 mph tests. Once again, this demonstrates the verification of the 500 ft detection range of the system.

With regards to the Worktrax devices for Trajectory E, the researchers expected all devices to activate as the trajectory vehicle entered the protected lane at the upstream end of the long-range threat detection region. At the 0 ft and 300 ft locations, the Worktrax devices activated each time as expected. There were three additional instances where TTI data collection equipment malfunctioned and the researchers could not verify that the device activated during these runs. Meanwhile, the Worktrax device positioned at the 400 ft location experienced mixed responses,

most likely because the test protocol was exceeding the communication range limits of the system at the time of the test. At 45 mph, the Worktrax device activated during 17 of 24 runs; at 60 mph, the Worktrax activated during 14 of 18 runs (with data collection equipment malfunctions not allowing verification of 6 runs). Work continues on the system to improve the communication range of the device, which will undoubtedly improve its performance at this farther distance.

Stationary Lane Closure on Curved Alignment

For the curved alignment tests, the alarm system did not activate during any of the A and B trajectories, which was the appropriate response. Trajectory D was not tested in the curved alignments. For Trajectories C and E, the alarm system was expected to activate. Again, the researchers calculated the distance between the GPS coordinates of the alarm system and those of the approach vehicle at the time of the alarm activation. The corresponding vehicle speed at the time of the alarm activation was noted and verified to be within 1 mph of the intended speed (40 mph).

In Trajectory C testing, the approach vehicle made a crossover maneuver and the AWARE system responded with both flashing light and sound activation as expected. The Worktrax device located adjacent to the AWARE vehicle was expected to activate, and did so in all 12 runs for this trajectory. The Worktrax devices located at 300 ft and 400 ft should not have activated since the crossover maneuver did not occur until the trajectory vehicle was within 300 ft of the AWARE vehicle. At these locations, the proper response (no alert) was documented during all 12 runs. Thus, all responses were correct.

In Trajectory E testing, the approach vehicle made a direct penetration of the conservative SSD in the lane where the AWARE vehicle was parked. As before, the researchers focused solely on the activation of the flashing lights for analysis of Trajectory E data. At 40 mph, the range of flashing light activation distance was 265 ft to 424 ft, measured along the curve trajectory. Figure 24 shows the results of the curved alignment testing.

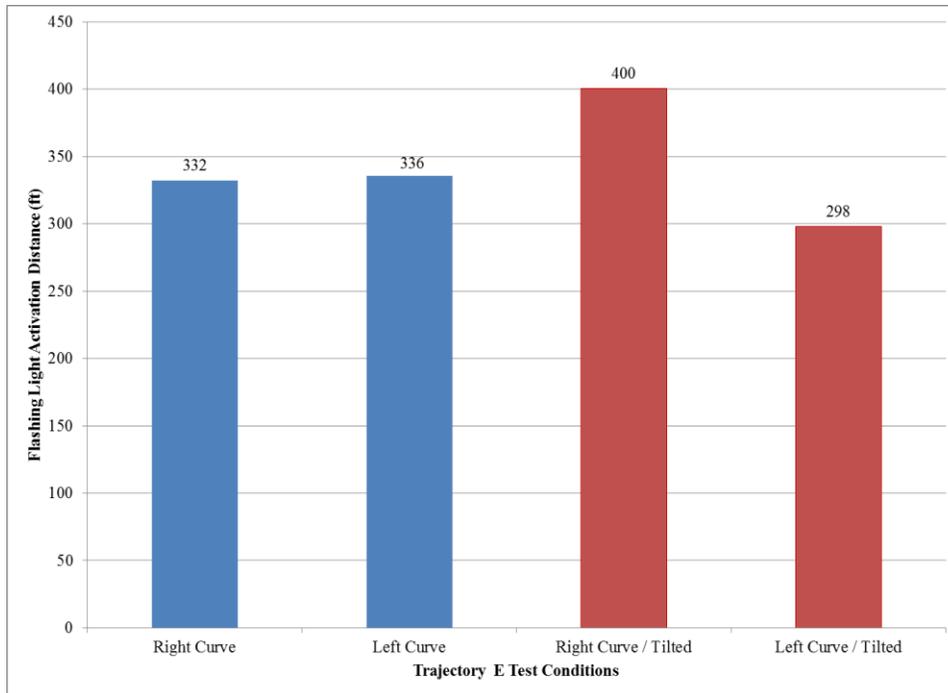


Figure 24. Curved Alignment Trajectory E Testing Results.

It appears that the direction of the curve had no impact on the AWARE system’s ability to detect the passenger car (as shown by the blue bars). Note that the conservative SSD for 40 mph is 418 ft and the AASHTO SSD is 301 ft. Thus, the system did activate prior to the AASHTO SSD value but after the conservative SSD value, on average, when the AWARE system vehicles were level. Interestingly, when the AWARE system vehicle was tilted, there was a noticeable difference in the activation distances. With the AWARE system vehicle tilted, the activation distance in the right curve is substantially longer than in the left curve. This is likely due to the small passenger car approaching the AWARE system underneath the fan-shaped threat detection region in the left curve and proceeding much closer to the AWARE system before it is detected. Conversely, on the right curve, the tilted AWARE system detection area appeared to activate at a distance closer to the conservative SSD than the AASHTO SSD value. Nonetheless, the AWARE system did detect the instrumented vehicle and produce an alert prior to the instrumented vehicle reaching the AASHTO SSD in all cases.

Meanwhile, the Worktrax located adjacent to the AWARE vehicle was expected to activate, and did so in all 12 runs for Trajectory E. Because of the issues already identified during tangent tests regarding the Worktrax devices when located upstream of the AWARE system, they were not also tested again at the 300 ft and 400 ft distances during the horizontal curve tests.

Flagging Operation

The AWARE system was expected to activate during testing of Trajectories G, H, I, J, and K. The results showed that alarm activation during testing of Trajectory G occurred at an average distance of 452 ft upstream of the flagger cart. Once again, this corresponds to immediate

detection upon entering the long-range (500 ft) region of the AWARE system's threat detection capabilities.

The analysis of Trajectory H test results was more complex. During three of the six test runs, the AWARE system lights activated, but the audible alarm did not. Further analysis of the data revealed that the instrumented vehicle speed equaled or exceeded the conservative SSD threshold at some distance upstream of the cart for some of the runs, but not others. Figure 25 illustrates those trajectories. The conservative SSD values were matched or exceeded by the instrumented vehicle at some point during test runs 2, 4, and 6. Conversely, the trajectories for runs 1, 3, and 5 remained below the conservative SSD line until speeds were below 25 mph and so correctly did not activate. Therefore, the AWARE system responded appropriately in all six test runs of Trajectory H.

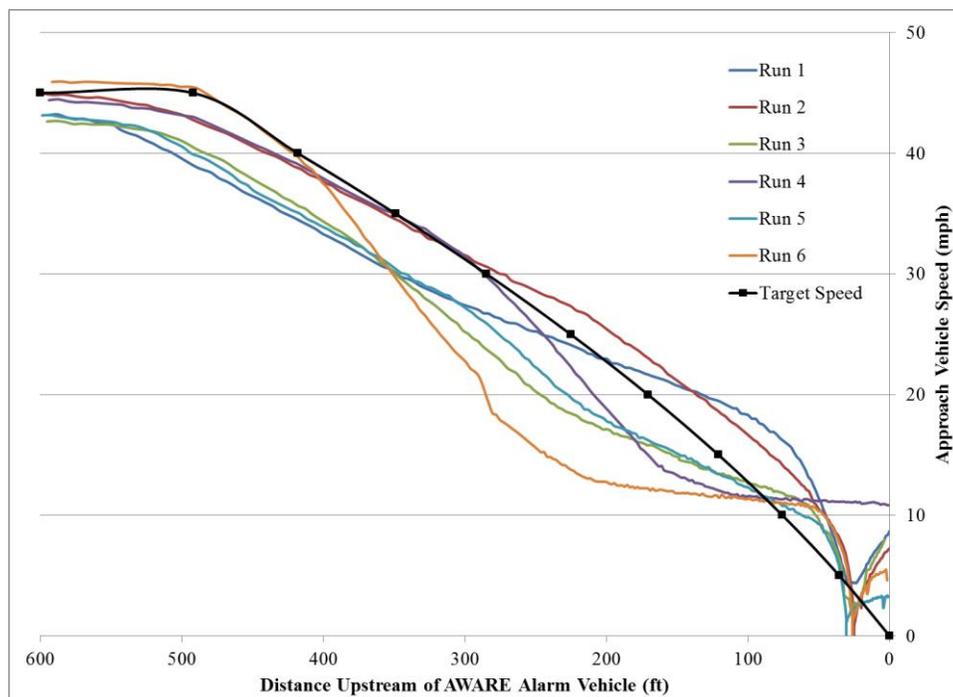


Figure 25. Test Runs versus Conservative SSD Threshold for Trajectory H.

After Trajectories F, G, and H were completed, heavy rain forced the researchers to suspend Worktrax testing to prevent water damage to the testing equipment. Thus, Worktrax data were collected for these 12 runs only. The Worktrax data recorded at the flagger station (0 ft) responded correctly in 12 of 12 runs. However, video data at the upstream Worktrax device location at 175 ft was found to be unusable due to the weather conditions that day and was not included in this analysis.

Testing of the AWARE alarm continued with testing of Trajectories I and J, the AWARE system was able to detect the instrumented vehicle passing a queued vehicle on either side from a stopped position behind the queued vehicle. In addition, the queued vehicle did not prevent the AWARE system from detecting a high-speed lane change further upstream.

Summary

Table 1 provides a summary of the AWARE system performance testing results with regards to the activation of lights/audible alarm (when the audible alarm was evaluated). Based on the methodology utilized, the system achieved a 100 percent success rate across the range of scenarios and vehicle trajectories tested.

Meanwhile, Table 2 summarizes the results of the evaluation of the Worktrax device activations during the tests. Evaluated across the range of device locations, test scenarios, and vehicle trajectories, the Worktrax devices achieved a 97 percent success rate. However, it was determined that all of the unsuccessful events for the Worktrax device were attributable to limitations in the effective communication range of the intrusion detection system with the Worktrax device. Ongoing improvements in the device are expected to significantly increase this communication range. All other device locations, scenarios, and trajectories tested achieved a 100 percent success rate.

Table 1. Summary of AWARE System Lights and Audible Alarm Performance Testing Results.

| Trajectory | Number of Runs Performed | # of Runs with Correct AWARE Response | Percent Correct |
|------------------------------|---|--|------------------------|
| <i>Tangent Lane Closures</i> | | | |
| A | 2 vehicles x 2 speeds x 4 AWARE vehicle orientations x 3 runs = 48 | 48 | 100 |
| B | " | 48 | 100 |
| C | " | 48 | 100 |
| D | 1 vehicle x 1 speed x 4 AWARE vehicle orientations x 3 runs = 12 | 12 | 100 |
| E | 2 vehicles x 2 speeds x 4 AWARE vehicle orientations x 3 runs = 48 | 48 | 100 |
| <i>Curved Lane Closures</i> | | | |
| A | 1 vehicle x 1 speed x 2 curves x 2 AWARE vehicle orientations x 3 runs = 12 | 12 | 100 |
| B | " | 12 | 100 |
| C | " | 12 | 100 |
| E | " | 12 | 100 |
| <i>Flagging Operations</i> | | | |
| F | 1 vehicle x 1 speed x 1 paddle condition x 3 runs = 3 | 3 | 100 |
| G | " | 3 | 100 |
| H | 1 vehicle x 1 speed x 1 paddle condition x 6 runs = 6 | 6 | 100 |
| I | 1 vehicle x 1 speed x 1 paddle condition x 3 runs = 3 | 3 | 100 |
| J | " | 3 | 100 |
| K | " | 3 | 100 |
| Totals | 273 | 273 | 100 |

Table 2. Summary of AWARE System Worktrax Device Performance Testing Results

| Trajectory | Number of Potential Worktrax Responses | # of Runs with Correct Worktrax Responses | Percent Correct |
|------------------------------|--|--|------------------------|
| <i>Tangent Lane Closures</i> | | | |
| C | 3 device locations x 48 runs – 15 data collection equipment malfunctions = 129 | 129 | 100 |
| E | 0 ft location x 48 runs = 48 | 48 | 100 |
| | 300 ft location x 48 runs – 3 data collection equipment malfunctions = 45 | 45 | 100 |
| | 400 ft location x 48 runs – 6 data collection equipment malfunctions = 42 | 31 | 74 |
| <i>Curved Lane Closures</i> | | | |
| C | 3 device locations x 12 runs = 36 | 36 | 100 |
| E | 0 ft location x 12 runs = 12 | 12 | 100 |
| <i>Flagging Operations</i> | | | |
| F | 1 location x 3 runs = 3 | 3 | 100 |
| G | " | 3 | 100 |
| H | 1 location x 6 runs = 6 | 6 | 100 |
| Totals | 324 | 313 | 97 |

CONCLUSIONS AND RECOMMENDATIONS

A system test plan was developed to evaluate the accuracy and precision of the AWARE system. The system successfully detected all actual intrusion threats as designed and performed in this test, and did not generate any false alarms under test conditions that were close to, but not actual, intrusion threats. Although the operation of the system in a mobile work operation was not evaluated, the system is designed to function the same way in a mobile environment as in a stationary lane closure condition. Given that the system functioned correctly under all lane closure tests, the researchers expect the system to function as designed under mobile operations as well.

With regards to the operation of the Worktrax devices, researchers found that the system properly activated as well as long as the devices were in the effective range of the intrusion detection unit. Efforts continue to improve the effective range so as to further increase worker warning distances. It is recommended that field personnel also be reminded to monitor themselves and avoid straying farther away from the system than its effective communications range with the intrusion detection unit.

It should be noted that the research team was unable to create a significant vertical curvature condition at its test facility. Consequently, it is not known how this factor would impact AWARE system performance. Typically, it is recommended that work zones not be established just beyond the crest of vertical curves or beyond significant horizontal curves, and so the need for the system to protect under this condition is likely to be limited. The AWARE system does offer significant opportunity to reduce work space intrusion risks to workers and motorists. However, field personnel should be regularly reminded that the system is designed to provide supplemental safety to work crews, and does not alleviate them of their responsibility to remain vigilant and ensure their own safety at all times. It is possible that field conditions not tested here may arise that exceed the parameters for which the system was designed to handle. Field personnel should also be reminded to regularly check and maintain the system once it is fully deployed and in regular use.

REFERENCES

1. *A Policy on Geometric Design of Highways and Streets, 4th Edition*. American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, 2001.