Interlibrary Loans and Journal Article Requests

IMECE2024-141533

VALIDATION OF TARGETS FOR USE IN EVALUATING HAUL TRUCK COLLISION WARNING AND AVOIDANCE SYSTEM DETECTION PERFORMANCE

Matthew Girman[1], Christopher Jobes[1], Yongjun Zhang[1]

[1]CDC NIOSH, Pittsburgh, PA

ABSTRACT

Surface mining haul trucks have been involved in 54 fatal accidents in the United States between 2005 and 2021 [1]. Collision warning and avoidance systems (CXS) could potentially alert drivers of hazards and prevent accidents from occurring. To ensure the efficacy of CXS, the object detection performance must be tested with a reliable detection target to represent an object that could be encountered at a mine, such as a pedestrian, berm, heavy machinery, or light vehicle. For reasons such as safety, cost, or convenience, it may be more desirable to use an alternative detection target in testing. The efficacy of alternative detection targets, when used to characterize the performance of CXS, should be evaluated to ensure that they do not cause any significant performance differences compared to using actual targets typically found in a mine. To address this question, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted a target validation study to compare the detection accuracy of a radar-based CXS with four different detection targets. This research offers potential substitute targets that could be used in CXS testing. CXS manufacturers and mine operators should be mindful of the targets they employ as alternatives when evaluating CXS detection performance.

Keywords: Collision warning and avoidance, radar, object detection, surface mining

NOMENCLATURE

ACARP	Australian Coal Industry's Research Program
CXS	Collision Warning and Avoidance System
CAN	Controller Area Network
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ISO	International Organization for Standardization
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
RCS	Radar Cross Section
RFID	Radio Frequency Identification
SAE	Society of Automotive Engineers
UGV	Unmanned Ground Vehicle

1. INTRODUCTION

Between 2005 and 2021, haul trucks have been involved in 54 fatal accidents at surface mines in the United States [1]. Haul trucks have large blind spots due to the size of the truck, the height of the driver's cab, and the inability to see directly behind the truck. Drivers cannot see the area immediately in front of the truck, leading to an increased risk of an accident when vehicles or pedestrians are in the forward path of the haul truck upon startup. Collision warning and avoidance systems (CXS) can improve visibility by alerting the driver of obstacles such as pedestrians and vehicles near the truck. The increased situational awareness provided by CXS could reduce the number of accidents involving haul trucks. The object detection capabilities of CXS must be tested to determine if the systems can successfully and accurately detect objects that may be encountered at surface mines. Because of safety considerations, cost, and convenience, it may be preferable to use a substitute in place of the actual target.

Of the 54 fatal accidents, 5 involved a collision between a haul truck and a light vehicle (i.e. pickup truck or passenger van) [1]. In 2018, the Mine Safety and Health Administration (MSHA) conducted an analysis of mobile-equipment-related incidents at surface mines from 2003–2017 that were deemed to be preventable by collision warning systems. The study showed that the victims of accidents involving haul trucks were mainly occupants of light vehicles [2]. In the study presented in this paper, researchers from the National Institute for Occupational Safety and Health (NIOSH) have devised a series of tests to measure how the distance reported by a radar-based CXS varied for different targets that represent a light vehicle. The targets included in this study are a pickup truck, an inflatable truck, an unmanned ground vehicle (UGV) with a sheet metal cylinder placed on top to aid in detection, and a wooden structure fixed with sheet metal to match the dimensions of a pickup truck (referred to as "box truck" in this paper). The targets were chosen for certain qualities such as size, shape, and material composition that are similar to that of a pickup truck. Our objective for this study was to determine the adequacy of these targets as potential alternatives to a pickup truck in CXS testing. Rather than evaluating the performance of the radar, the analysis centered on a comparison of the detectability of the targets relative to each other.

2. BACKGROUND

In 2020, NIOSH initiated a project to validate collision warning and avoidance systems on surface mining haul trucks [3]. NIOSH researchers conducted tests to evaluate CXS

detection performance for a "static" scenario (i.e. when a CXS-equipped vehicle is stationary) and for a "dynamic" scenario (when a CXS-equipped vehicle is in motion). However, data from these experiments have not yet been published. Additionally, NIOSH tested the accuracy of a Global Navigation Satellite System (GNSS) for its use as a ground truth instrument to measure object positioning for CXS testing [4]. Previously, NIOSH had conducted several tests to evaluate CXS technologies such as radar, GPS, RFID, camera, and mesh radios [5-10]. NIOSH researchers investigated potential alternative targets to stand in for a person in object detection tests by measuring the size of the reliable detection zone. Targets that were tested included trihedral corner reflectors, metallic spheres, and test manikins. The researchers attempted to design targets that closely matched the radar cross section (RCS) of a person. The RCS describes how much of a radar's signal is reflected back towards the radar and is determined by the dimensions of the target. The size, composition, and shape of the object affect the RCS. The researchers found that, if an actual person cannot be used, a metallic sphere is the next best alternative [11]. If a test manikin is used, it should follow the specifications of SAE J1741 [12] and have an RCS similar to that of a human.

CXS testing standards may offer descriptions of target objects that can be used in tests. ISO 16001 describes test procedures for object detection systems (ODS) and visibility aids. It includes test body requirements for testing different ODS technologies, including radar systems, ultrasonic detection systems, ultrasonic transponder systems, electromagnetic signal transceiver systems, and closed-circuit television systems. For radar systems, ISO 16001 states that a real person with the stature of a medium operator as described in ISO 3411 shall be used as the detection target [13, 14]. The Australian Coal Industry's Research Program (ACARP) published the "Proximity Detection System Validation Framework" to provide mine operators with a guide for determining whether a particular CXS is suitable for their application. They outline three target classes that shall be covered in each set of tests: a large vehicle (haul truck), a light vehicle (pickup truck), or human. The framework allows for a fixed plant, such as a demountable structure, to be used in place of a vehicle [15].

3. TEST METHOD

3.1 Test Course Setup and Location
This study was conducted at an outdoor location to test and validate the CXS system detection performance. The tests needed to be done outdoors because the GNSS receivers need to have a clear view of the sky to communicate with satellites. As part of a larger project, a rectangular grid was constructed in the test area for the purposes of completing both "static" and "dynamic" CXS tests. Surveying equipment was used to layout the grid and test paths. All tests were conducted under ideal environmental conditions as follows:

- Open outdoor test area.
- Relatively flat test surface.
- Temperature was between 0°C–38°C (32°F–100°F).
- Maximum wind speed was no greater than 22 mph.
- No precipitation was present during testing.

3.2 Straight Path Dynamic Test
This target validation study involved "dynamic" type tests which comprised a vehicle equipped with the CXS in motion and a stationary target. The CXS-equipped vehicle moved towards the selected target vehicle along a straight path. During these operations, the position and orientation of the CXS-equipped vehicle and alarm events were recorded. Data collection is further explained in Section 3.4. The driver was instructed to maintain a speed of 10 mph before braking short of the target. This speed used for testing was based upon engineering judgment for the CXS-equipped vehicle. The rectangular grid was 30 m (98.42 ft) long by 12 m (39.37 ft) wide with 2 m (6.6 ft) spacing. For the dynamic tests, the CXS-equipped vehicle and the target vehicle were placed 3 m (9.8 ft) from the short edge of the rectangular grid—on opposite sides— and centered across its width. This was done so that the CXS-equipped vehicle was further than 100 ft away from the target vehicle—outside the range of the radar—at the start of the test (see Fig. 1).
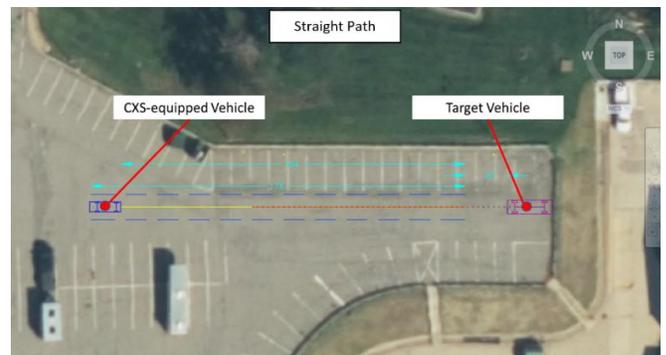
FIGURE 1: STRAIGHT PATH DYNAMIC TEST SETUP. THE CXS-EQUIPPED VEHICLE'S PATH IS SHOWN TO BE 164 FT (50 M) IN THIS FIGURE. FOR EACH TEST, THE VEHICLE STARTED AT LEAST 100 FT (30.5 M) AWAY FROM THE TARGET.

3.3 Curved Path Dynamic Test
Dynamic tests with the CXS-equipped vehicle traveling in a curved path were completed with two of the four targets: the pickup truck and the box truck. To match the path that the CXS-equipped vehicle travelled to that of a turning full-sized haul truck, the curved path was designed with a radius of 33 ft (10.1 m). At the start, the CXS-equipped vehicle was positioned at a 90° offset from the target vehicle. The target vehicle was positioned in the path of the CXS-equipped vehicle so that a collision would occur if the CXS-equipped vehicle does not stop short of the target. The same data as the straight path tests (position and orientation of the CXS-equipped vehicle and alarm events) was recorded. Due to the difficulty of maintaining a constant speed through the curve, there were some slight differences in speed for each trial. However, the speed remained below 10 mph for each of the curved path tests. The layout for the curved path test is displayed below in Fig. 2.
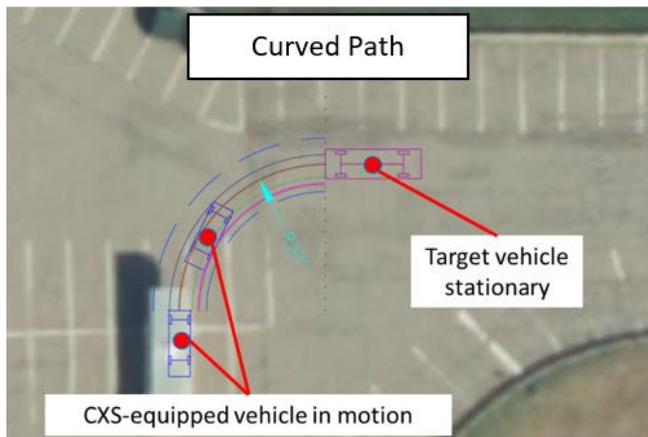
FIGURE 2: CURVED PATH DYNAMIC TEST SETUP.

3.4 CXS Technology Tested

During the performance of this test, researchers conducted four sets of tests of up to 10 trials each–one for each target to be validated. Researchers collected data from three GNSS receivers, the Controller Area Network (CAN) system, and detection report logs from the CXS. Figure 3 shows the two GNSS receivers that were mounted on top of the CXS-equipped vehicle and the radar mounted on the front. The sensor settings and the mounting parameters were selected to comply with the CXS manufacturers' recommendations for the equipment being employed. Key features of the radar in this test are presented in Table 1. The detection zone was set to a range of 100 ft (30.5 m) and a width of 14 ft (4.3 m). The remaining GNSS receiver (stationary base station) was used to provide real-time kinematic correction (RTK) and for Wi-Fi communication. For the two receivers on top of the CXS-equipped vehicle, one receiver collected position data (reference) and the other collected orientation data (attitude). The "reference" GNSS device was positioned in front and vertically aligned with the center of the CXS, and the other device was the "attitude" receiver. In these tests, researchers did not attempt to accurately control the path of the CXS-equipped vehicle. However, they collected accurate measurements from the GNSS devices, which allowed them to analyze system performance with respect to the executed path. In addition, the effect of path accuracy could be further explored in future studies through modeling and laboratory experiments.
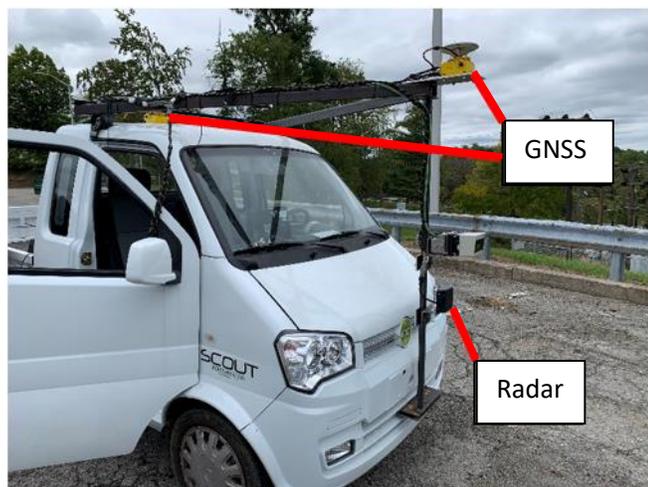
FIGURE 3: CXS-EQUIPPED VEHICLE (SOME INSTRUMENTATION PICTURED NOT RELEVANT TO THIS STUDY).

TABLE 1: KEY FEATURES OF CXS TECHNOLOGY TESTED.

Technology	Radar
Working Range	0-30 m (98.4 ft)
Azimuth Field of View	±75°
Operating Frequency	24–24.25 GHz
Range Accuracy	0.3 m (0.98 ft)
Angle Accuracy	±2° @ ±10° FOV, ±5° @ ±30° FOV, ±10° @ ±75° FOV
Velocity Accuracy	0.2 m/sec (0.5 mph)
Target Resolution	1.4 m (4.6 ft) for static targets, approaching 0.3 (0.98 ft) m for dynamic targets

3.5 Stationary Target

As described, various targets, including the UGV, were used to represent the stationary target vehicle (see Fig. 4). Table 2 lists the cross-sectional dimensions of the targets. While the target remained in place, the CXS-equipped electric truck was driven along a rectangular grid at 10 mph to evaluate system positional accuracy and alert onset. Ten (10) test runs were made for each stationary target to collect sufficient data for analysis. A GNSS receiver was used to survey the location of the four corners of each target. For the purpose of determining the distance between the CXS-equipped vehicle and the target, an average of the two points closest to the CXS-equipped vehicle was used as the location of the target. This point represents the part of the target that is closest to the radar.

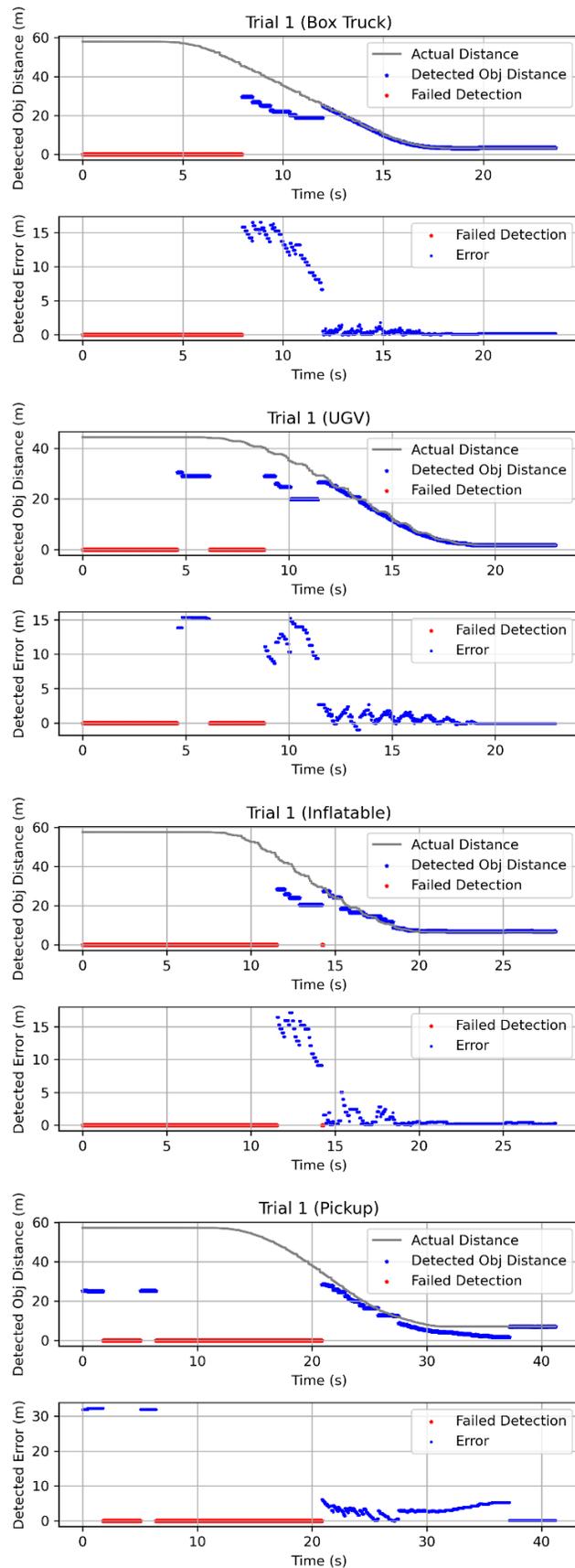**TABLE 2:** CROSS-SECTIONAL DIMENSIONS OF TARGETS USED IN THIS STUDY.

Target	Dimensions (Height x Width)
UGV	65.6″ x 42″
Pickup truck	78″ x 80″
Box truck	76″ x 76″
Inflatable truck	70.8″ x 74.4″

FIGURE 4: TARGETS USED IN THIS STUDY (FROM TOP TO BOTTOM: UGV, PICKUP TRUCK, BOX TRUCK, INFLATABLE TRUCK).

4. RESULTS AND DISCUSSION

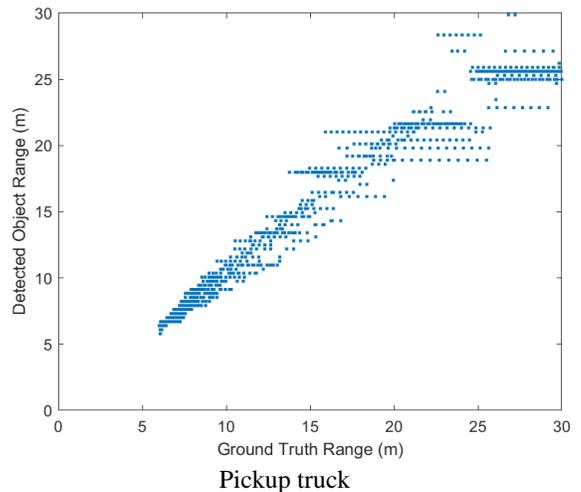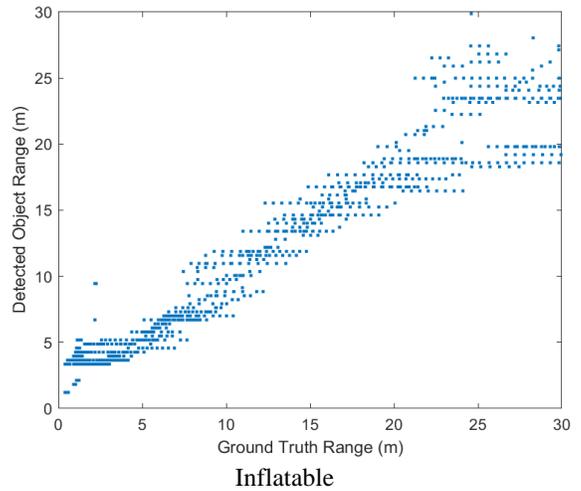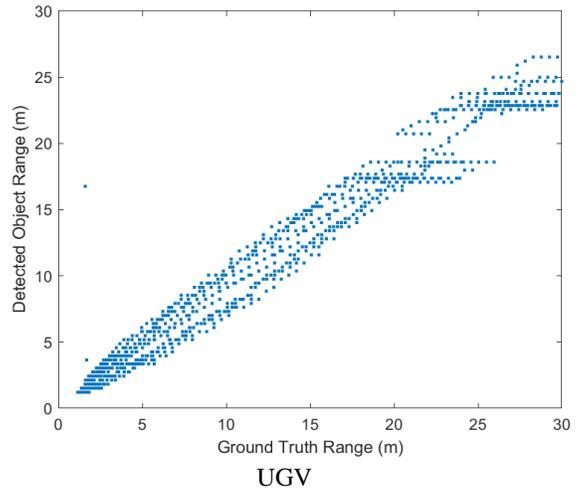**FIGURE 5:** SINGLE TEST RESULT FOR BOX TRUCK, UGV, INFLATABLE, AND PICKUP TRUCK.

4.1 Straight Path

Figure 5 shows the radar range detection results from a single test on four objects: a box truck, a UGV, an inflatable truck, and a pickup truck. It is observed that the detection capability of the radar seems to reach its threshold at about 25 m (82 ft). This is indicated by the abundance in failed detections before the CXS-equipped vehicle reaches 25 m (82 ft), suggesting the radar's tracking and detection efficacy diminish beyond this range.

The box truck shows superior detection consistency. Its detected range maintains a strong correlation with the ground truth range, exhibiting low error within the effective radar range of 25 m (82 ft). The UGV demonstrates reliable detection up to about 25 m (82 ft). Beyond this, the detection deviates from the actual distance, and errors become more evident, signaling occasional losses in tracking accuracy.

The detection pattern for the pickup truck, which may have a variable RCS due to its shape and size, has a higher error at short distances, suggesting sporadic detection and tracking issues. This inconsistency, as well as the weaker correlation with the ground truth range, indicates that the radar's ability to track the truck is unstable. The inflatable object shows the most erratic detection pattern. The multiple gaps seen in the data and lack of detections beyond 25 m (82 ft) imply significant challenges in consistent detection and tracking, which could be due to its low reflectivity affecting its radar visibility.

Below, Fig. 6 compiles the outcomes of ten tests to illustrate the collective range detection performance for each type of object. As depicted, the box truck and UGV demonstrate more uniform detection across the ten tests, whereas the pickup truck and the inflatable object exhibit a wider variance in their results.

UGV

Inflatable

Box truck

Pickup truck

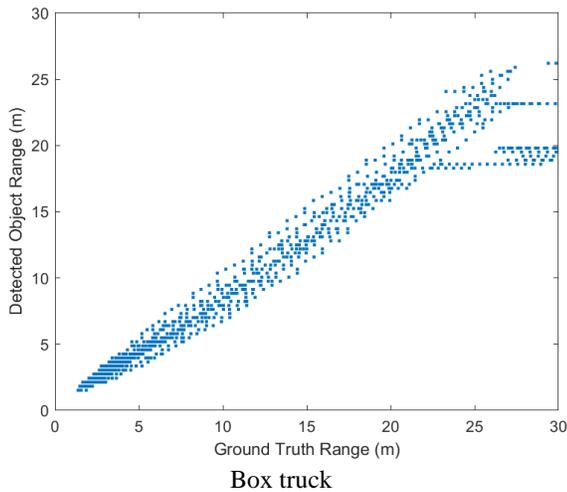**FIGURE 6:** AGGREGATED 10 TEST RESULTS FOR BOX TRUCK, UGV, INFLATABLE, AND PICKUP TRUCK.

This trend is evident in the mean and standard deviation of the data. Table 3 shows those statistics for each target, broken down by distance between the CXS-equipped vehicle and the target. Some tests exhibited multiple erroneous data points, so the data is also presented with outliers removed from the data in Table 4. On occasion, the radar would detect the ground, a guard rail, or some other object and report a wrong distance.

When multiple targets are detected, the radar system is configured to only report the distance of the closest target. If the false objects were closer than the target object, the radar system would record the distance of the nearest false object. There were also moments when the radar would fail to detect the target and report the distance of an object that was much farther away. The outliers were considered to be any data point with a greater than two standard deviation difference from the mean.

TABLE 3: AVERAGE ERROR AND STANDARD DEVIATION (IN METERS) FOR EACH OF THE FOUR TARGETS.

Target		<30 m	<25 m	<20 m	<15 m	<10 m
Inflatable	Mean	1.688	1.401	1.328	1.351	1.407
	Std Dev	1.898	1.410	1.361	1.403	1.457
Pickup	Mean	1.077	0.893	0.791	0.737	0.741
	Std Dev	1.379	1.267	1.173	1.192	1.290
UGV	Mean	1.138	0.837	0.732	0.677	0.660
	Std Dev	2.210	2.032	2.061	2.180	2.332
Box Truck	Mean	0.922	0.423	0.326	0.282	0.220
	Std Dev	1.994	0.664	0.370	0.316	0.228

TABLE 4: AVERAGE ERROR AND STANDARD DEVIATION (IN METERS) WITH OUTLIERS REMOVED FOR EACH OF THE FOUR TARGETS.

| Outliers Removed		<30 m	<25 m	<20 m	<15 m	<10 m
Inflatable	Mean	1.345	1.269	1.119	1.120	1.283
	Std Dev	1.236	1.166	1.011	1.030	1.211
Pickup	Mean	0.819	0.647	0.551	0.487	0.428
	Std Dev	1.000	0.819	0.715	0.688	0.680
UGV	Mean	0.828	0.589	0.462	0.368	0.300
	Std Dev	1.160	0.797	0.567	0.481	0.424
Box Truck	Mean	0.442	0.338	0.249	0.215	0.176
	Std Dev	0.664	0.360	0.230	0.185	0.129
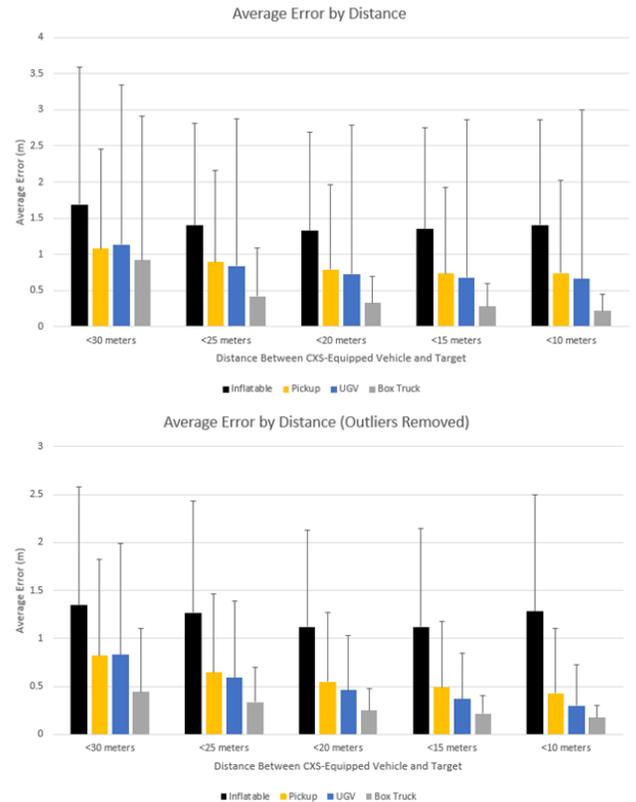
FIGURE 7: AVERAGE ERROR (WITH AND WITHOUT OUTLIERS) FOR EACH OF THE FOUR TARGETS.

The box truck had the lowest mean detection error, while the inflatable had the highest. Although the UGV had a slightly lower average error than the pickup truck, its variance was much higher. The pickup truck, along with the inflatable, displayed the largest variance. Figure 7 shows the error in bar graph form. Error bars are added to show one standard deviation above the mean. As expected, the error tends to decrease as the vehicle approaches the target. The average error for each target was within one standard deviation of the detection error of the pickup truck, with the exception of the inflatable truck under 10 meters with outliers removed.

4.2 Curved Path
Tests with the CXS-equipped vehicle traveling in a curved path towards the pickup truck and the box truck were conducted. Figure 8 shows the radar detections for all 10 trials that were completed for each target, and Tables 5 and 6 show the statistics for the curved path tests. The target was outside the detection zone of the radar until the CXS-equipped vehicle turned to face the target towards the end of the curved path, so there were fewer true detections of the target than with the straight path tests. For much of the tests, the radar reported the object detection distance to be around 12 m (39.4 ft) until the CXS-equipped vehicle was less than 4 m (13.1 ft) from the target. It is difficult to conclude whether those detections were a misreported distance of the intended target or if the radar was picking up another object such as the ground or a guardrail. Even for the small range where detections were most accurate, the box truck appears to display a greater detection accuracy than the pickup truck. This is consistent with the results from the straight path tests. The box truck data formed a stronger

linear relationship between radar distance and actual distance. The data from the pickup truck was more scattered. The radar mostly reported a slightly larger distance than the ground truth within 3 meters of the pickup truck. In real-world applications, the target object being closer than the reporting of the CXS could be problematic, although differences of a few meters might be insignificant when considering the scale of a haul truck. When traveling in a curved path, the target did not enter the detection zone of this particular radar until below 4 m (13.1 ft). Future studies could test different radar-based CXS or other technologies that could better detect targets in the collision path of a vehicle while turning.

Box truck
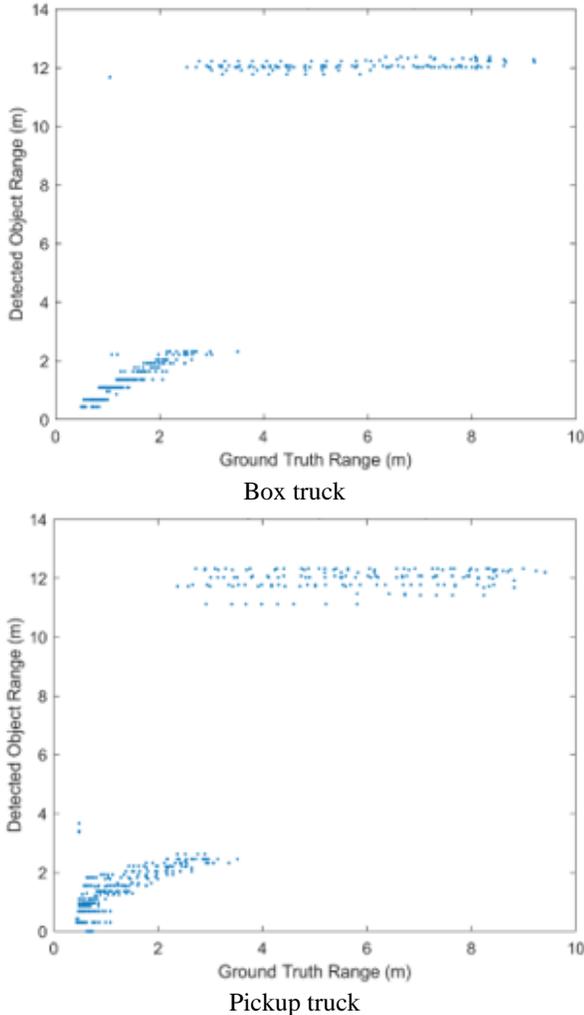
Pickup truck

FIGURE 8: AGGREGATED 10 TEST RESULTS FOR BOX TRUCK AND PICKUP TRUCK (CURVED PATH).

TABLE 5: AVERAGE ERROR AND STANDARD DEVIATION (IN METERS) FOR THE CURVED PATH TESTS.

Target		Total	< 5 m
Pickup	Mean	1.762	1.158
	Std Dev	2.179	2.459
Box Truck	Mean	1.637	1.116
	Std Dev	2.966	2.785

TABLE 6: AVERAGE ERROR AND STANDARD DEVIATION (IN METERS) WITH OUTLIERS REMOVED FOR THE CURVED PATH TESTS.

Outliers Removed		Total	< 5 m
Pickup	Mean	1.180	0.313
	Std Dev	1.968	0.309
Box Truck	Mean	0.950	0.095
	Std Dev	2.030	0.102

5. LIMITATIONS

This study involved the testing of one radar system's capability of detecting different targets in specific environmental and experimental conditions. Future studies may explore the impact of adverse weather conditions such as precipitation, dust, or fog on the accuracy of the measurements made by the radar system. Due to time and resource constraints, ten trials for each target were conducted. More trials could further verify the results collected in this study. Additionally, future research could investigate more targets that could be used in place of common objects found at mines. These tests could be repeated with other radar systems or different technologies such as LiDAR, RFID, electromagnetic, GPS, or camera-based CXS. Different roadway conditions, more complex paths, varied backgrounds, and variable speeds could also be explored.

6. CONCLUSION

This study investigated the ability of a radar system to detect different targets that represented a light vehicle that could be encountered at a mine site. Data was collected for a CXS-equipped vehicle traveling in a straight path and curved path towards a stationary target. Radar alarm events were recorded, and GNSS data was used as ground truth. Four targets (i.e., a box truck, a UGV, an inflatable truck, and a pickup truck) have been tested and ten trials were conducted for each target and path. Analysis shows that the box truck had the lowest detection error, followed by the UGV, pickup truck, and inflatable truck, in that order.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Reference to specific brand names does not imply endorsement by the National Institute for Occupational Safety and Health.

REFERENCES

[1] J. Homer, J. Bickson, C. DeGennaro, M. Girman. *Analysis of U.S. Surface Mining Haul-Truck-Related Fatalities,*

SME Annual Meeting. Preprint 22-085. Society for Mining, Metallurgy & Exploration. Salt Lake City, UT. Feb. 27– March 2, 2022.

[2] M. Wharry. *Collision Avoidance Systems and Collision Warning Systems, Reducing Surface Mobile Equipment Accidents Through Technology – Mine Safety and Health Administration (MSHA) Powered Haulage Initiative,* MSHA Annual Training Resources Applied to Mining (TRAM) Conference. Oct. 9-11, 2018.
https://www.msha.gov/sites/default/files/events/Collision%20 Warning%20TRAM%2010_3_2018.pdf.

[3] National Institute for Occupational Safety and Health (NIOSH). *Mining Project: Validating Collision Warning and Avoidance System Detection Performance for Surface Mining Haul Trucks.*
https://www.cdc.gov/niosh/mining/researchprogram/projects/p roject_collisionwarningdetection.html.

[4] J. Bickson, C. Zhou, Y. Zhang, J.R. Srednicki, J. Carr, M. Girman, J.A. Galanko, C.R. DeGennaro, B. Lambie. *Testing of Ground Truth Instruments for Use in Evaluating Haul Truck Collision Warning and Avoidance Systems*, SME Annual Meeting. Preprint 24-083. Society for Mining, Metallurgy & Exploration. Phoenix, AZ. Feb. 25–28, 2024.

[5] T.M. Ruff. *Test Results of Collision Warning Systems for Surface Mining Dump Trucks,* Report of Investigations (National Institute for Occupational Safety and Health); 9652; DHHS publication; no. (NIOSH) 2000-120. 2000.
https://stacks.cdc.gov/view/cdc/6395.

[6] T.M. Ruff. *Application of radar to detect pedestrian workers near mining equipment,* Applied Occupational and Environmental Hygiene. **16**(8): p. 798-808. 2001.
https://doi.org/10.1080/10473220118943.

[7] T.M. Ruff. *Advances in Proximity Detection Technologies for Surface Mining Equipment,* 34th Annual Institute on Mining Health, Safety and Research. Salt Lake City, UT. 2004.
https://www.cdc.gov/niosh/mining/works/coversheet1656.htm l.

[8] T.M. Ruff. *Evaluation of a radar-based proximity warning system for off-highway dump trucks,* Accident Analysis and Prevention. **38**(1): p. 92-98. 2006.
https://doi.org/10.1016/j.aap.2005.07.006.

[9] T.M. Ruff. *Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment,* Report of Investigations (National Institute for Occupational Safety and Health); 9672; DHHS publication; no. (NIOSH) 2007-146. 2007.
https://stacks.cdc.gov/view/cdc/8494.

[10] T.M. Ruff. *Overview of Proximity Warning Technologies and Approaches,* NIOSH Workshop on Proximity Warning Systems for Mining Equipment. 2010.
https://www.cdc.gov/niosh/mining/userfiles/workshops/proxi mityworkshop2010/ruff-niosh-pdworkshop2010-508.pdf.

[11] T.M. Ruff. *Recommendations for Testing Radar-Based Collision Warning Systems on Heavy Equipment,* Report of Investigations (National Institute for Occupational Safety and Health); 9657; DHHS publication; no. (NIOSH) 2002-135. 2002.
https://stacks.cdc.gov/view/cdc/9496.

[12] SAE International. *J1741: Discriminating Back-Up Alarm System Standard,* 1999.
https://www.sae.org/standards/content/j1741_199906/.

[13] International Organization for Standardization (ISO). *ISO 16001: Earth-moving machinery — Object detection systems and visibility aids — Performance requirements and tests,* 2017.
https://www.iso.org/standard/63688.html.

[14] International Organization for Standardization (ISO). *ISO 3411: Earth-moving machinery — Physical dimensions of operators and minimum operator space envelope,* 2007.
https://www.iso.org/standard/38911.html

[15] S. Grandone, D. Gunasinghe, I. Greyvensteyn. *ACARP C26028: PDS Validation Framework: Phase 3,* Australian Coal Industry's Research Program (ACARP). 2021.
https://www.acarp.com.au/abstracts.aspx?repId=C26028.