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Recommendations for Testing Radar-Based Collision Warning Systems on Heavy Equipment

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	ft	foot
GHz	gigahertz	ft^2	square foot
kg	kilogram	gal	gallon
km/h	kilometer per hour	in	inch
m	meter	lb	pound
m^2	square meter	%	percent
ms	millisecond	°	degree

RECOMMENDATIONS FOR TESTING RADAR-BASED COLLISION WARNING SYSTEMS ON HEAVY EQUIPMENT

By Todd M. Ruff

ABSTRACT

Researchers at the National Institute for Occupational Safety and Health are investigating technologies that could be used to detect objects, small vehicles, and pedestrian workers that may be in the blind areas of haulage equipment used in mining and construction. A detection system that warns the equipment operator that there is an obstacle nearby could prevent collisions and save many lives each year. One popular technology for collision warning systems is radar. Several different types of radar have been tested in the laboratory and on mining equipment. Early in the study, questions arose concerning the best way to test radar systems. Many factors affect the performance of radar, including the size, shape, and composition of the object that is to be detected; the height of the radar antenna(s); and the relative motion of the radar system and/or object. This report discusses several different test procedures and test targets and recommends methods to determine how effective a radar system will be in detecting a person near heavy equipment.

INTRODUCTION

Researchers at the National Institute for Occupational Safety and Health (NIOSH) are investigating technologies that could be used to detect objects, small vehicles, and pedestrian workers that may be in the blind areas of large mining equipment. A detection system that warns the equipment operator that there is an obstacle nearby could prevent collisions and save many lives each year.

One popular technology to accomplish this is radar. There are several commercially available radar systems designed to monitor the blind areas around many types of vehicles. In this study, NIOSH researchers were interested in protecting workers around large haulage equipment used in surface mining and construction. Tests using several different types of radar systems have been conducted on several sizes of off-highway dump trucks (Ruff 2000, 2001). The purposes of these tests were to evaluate the effectiveness of each radar system in detecting objects and people and to determine best practices for installing the systems.

The detection zone of a radar system depends on many factors, including (1) the type and configuration of the radar antenna, (2) the size, shape, and composition of the object being detected, and (3) the mounting height and tilt angle of the radar antenna. These last two factors are variables that can be controlled by users. In the early stages of these evaluations, several issues with test procedures required some experimentation with radar mounting locations and different test objects to establish a standard test method.

The most common accidents involving collisions with mining or construction equipment involve pedestrian workers or smaller passenger vehicles. A radar system used to warn of collisions should be very good at detecting these two objects. The question then arose, "What should be used as a standard test object during evaluations of radar systems?" When comparing a radar system's ability to detect a person or a small vehicle, detecting a person will be more difficult due to a person's smaller size and greater variability. Thus, the ability of a system to detect a person is an important characteristic to evaluate. Many objects can be used to simulate a person, so the focus of the first task was to determine the best test object to use when defining the radar's detection zone for a person.

Of course, one option is to use an actual person for a test object, rather than an object that simulates a person. The second task then involved determining how a radar system's detection zone differed according to the size of person detected. These data were then used to determine a size range for a test person to ensure that the detection zone did not vary significantly when someone else conducted the same tests with a different person.

Finally, NIOSH researchers tested several different radar systems on many types of dump trucks. Observations were made regarding the variables involved when systems were mounted on actual heavy equipment and the effects of these variables on the detection zone and the reliability of the radar system. Some of the most significant variables involved (1) whether the engine was running or not, (2) whether the equipment was moving or stationary, and (3) the mounting location and orientation of the radar antenna. A summary of these observations and recommendations is included in this report along with a recommended test procedure.

DETERMINING EFFECTIVE TEST TARGETS

One obstacle that a collision warning system must detect is a person working near the equipment. To evaluate the effectiveness of a radar system in detecting a person, either the detection characteristics for an actual person must be evaluated or the detection characteristics of some object that accurately represents a person must be evaluated.

NIOSH researchers needed to find out what object would most accurately simulate the presence of a human, realizing that the most effective test target may turn out to be an actual person. To this end, the detection zones for several test targets were compared with the detection zone for an actual person using two different types of radar systems.

TEST TARGETS

Several test targets are commonly used to evaluate radar systems. Of these, corner reflectors and metallic spheres were evaluated because they are frequently used in radar testing and calibration. A test manikin has also been suggested as a test target by the Society of Automotive Engineers (SAE), which recommends the use of either a person or a manikin in a kneeling position to evaluate the detection zone of a collision warning system (SAE 1999). To show the potential for discrepancies depending on manikin composition, we compared the detection ranges for two types of manikins. Finally, in previous NIOSH tests, researchers used an actual person to determine the reliable detection zones for people, so the results from test objects are compared to the results for a person.

Trihedral corner reflectors are often used as a standard test target for evaluating radar (figure 1). The dimensions of the metallic reflector determine how much of the radar's signal is reflected back to the antennas. This reflection characteristic is also referred to as radar cross section (RCS) and depends on the composition, size, and shape of the object, as illustrated in figure 2. These dimensions must be calculated so that the RCS of the reflector equals the RCS of a person. A trihedral corner reflector with dimensions of 8.4 cm (3.3 in) on each side has been proposed in preliminary standards. The reflector must be attached to the end of a long plastic pole, which allows it to be positioned inside the radar beam while allowing the person holding it to remain outside the radar beam (tests must be conducted to assure that the plastic pole is not detected by itself). An advantage to this method is that the reflector is easily purchased or constructed, and it represents a repeatable target size. Also, with a proper pole or other rigging, it is theoretically possible to determine the vertical dimensions of a radar beam. One disadvantage is that a corner reflector is extremely directional, i.e., the amount of signal reflected back to the radar depends on the reflector's orientation (figure 2). Another disadvantage is the potential for radar signal reflection from the person holding the plastic pole.

Another standard test target is a metallic sphere. Again, the diameter of the sphere must be such that it reflects an amount of radar signal equivalent to what a person would reflect. According to Skolnik (1990), the RCS for an adult male ranges between 0.4 and 1.2 m^2 (4.3 and 12.9 ft^2), depending on radar frequency. After talking with radar system manufacturers, we used an estimate of 0.8 m^2 (8.6 ft^2) for the RCS of a man in a standing position. This resulted in a metallic sphere with a diameter of 1 m (39 in). The sphere must also be attached to some type of rigging or a plastic pole to allow the person holding it to remain outside the radar beam. Depending on the weight of the sphere, this may not be practical. Standard metal spheres constructed for radar calibration tests are available. However, for the size required in this application, the sphere would weigh approximately 26 kg (57 lb) and cost almost $5000. This is definitely not practical, so other options were investigated. Theoretically, both the vertical and horizontal beam dimensions can be determined using a sphere, and the magnitude of the reflected signal does not depend on orientation (figure 2).

The SAE standard for evaluating collision warning systems (SAE 1999: Discriminating Back-Up Alarm System standard J1741) allows the use of person or an anthropomorphic dummy or manikin. The manikin is to be the size of a small person (5th percentile female), as defined by SAE standard Human Physical Dimensions J833 (1989), dressed in a long-sleeved shirt and long pants, and placed in a kneeling position in the detection zone. No other specifications are given, which may result in variations in test results due to the different materials that are used in manikin construction. Sophisticated manikins, like those used in automobile crash tests, contain more metal parts than those used in department stores, for example, and this difference may affect detection, especially for radar. Also, while a manikin may be practical for initial evaluations, we suspect that these tests must be confirmed using a test object that more closely approximates the RCS of a human.

NIOSH researchers have been evaluating radar systems using a human test subject in a standing or walking position. An advantage to this is that the test results accurately represent the detection characteristics of an actual person and do not introduce the possible discrepancies associated with inanimate objects. The time requirements for tests using a person are short,

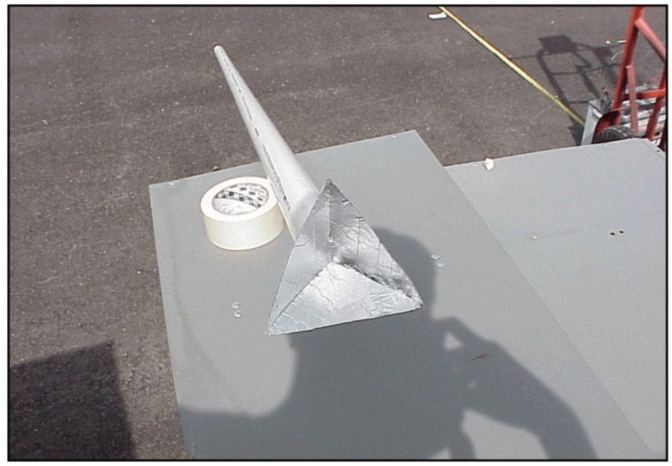

Figure 1.—Small trihedral corner reflector attached to PVC pipe.

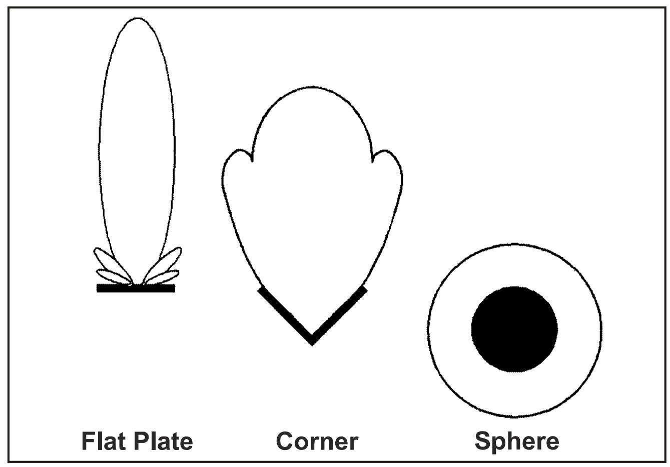

Figure 2 —Approximate radar cross-section patterns for different reflectors with relative magnitudes of reflected signal (U.S. Dept. of the Navy, 2001).

and the detection zone is easily determined by simply walking within the area of interest and recording the zone in which reliable detection occurred. A disadvantage to this method is that a person's height may slightly affect the results, depending on the mounting configuration of the radar antenna. Also, this method is effective in determining horizontal dimensions of the detection zone, but not vertical dimensions.

TEST DESCRIPTION

To determine the difficulties and effectiveness of each type of target, a test was conducted to determine the detection zones of the targets for two different radar systems that were made for heavy equipment. System 1 operates at approximately 13 GHz, and system 2 at approximately 6 GHz. The detection zones for the various objects were then compared to the detection zone for an upright (standing) person to determine whether the object was an accurate representation of a person.

The test area was a flat, empty, asphalt parking lot with dimensions of approximately 24 m (80 ft) wide by 46 m (150 ft) long. The radar system was mounted on a handcart (dolly) approximately 114 cm (45 in) high, powered by a car battery, and placed at one end of the parking lot (figure 3). A grid was laid out in front of the radar system with spacing between points of 0.76 m (2.5 ft).

First the detection zone for a person was determined by having a NIOSH researcher walk within the area of interest. The points at which the person was consistently detected by the radar were marked on the ground and recorded on a graph. A more detailed description of the test procedure can be found in the appendix.

Next, the corner reflector was tested. The reflector had dimensions of 8.4 cm (3.3 in) on each side and was mounted on the end of a 3-m (10-ft) long polyvinyl chloride (PVC) pipe (figure 1). The person holding the pipe then walked near, but not in, the detection zone for the person. The reflector was held out in the zone, and the points at which it was detected were marked on the ground and recorded on a graph. Several reflector orientations and heights were tested at each grid point to ensure accurate recording of the detection zone.

Two different reflective spheres were tested. The first sphere was made from easily obtained materials and was simple to construct. A 36-cm (14-in) in diameter playground ball was covered in aluminum foil, and the foil was secured using foil tape. The ball was then attached to the end of the PVC pipe using string (figure 4).

Because 36 cm (14 in) is too small to represent a person accurately and the foil did not provide a smooth surface, another larger sphere was needed to approximate the RCS of a person. One idea was to construct an approximation of a metallic sphere from a weather balloon spray-painted with conductive paint. The balloon had a final diameter of 91 cm (36 in). (It could have been inflated larger than this, but then it would not have fit through doors.) The 91-cm (36-in) size is a close approximation of the RCS of a person; however, the reflectivity of the conductive paint was not known. The balloon was then hung on the end of the PVC pipe (figure 5). Constructing this test target was fairly simple; however, the conductive paint is quite expensive ($400/gal). Care must also be taken in order to ensure that the paint does not peel off because of deflation or expansion or rough treatment during the test.

Figure 3.—Radar system mounted on dolly for testing.

Each sphere was tested by placing it in the potential detection zone and recording the point where it was consistently detected. The PVC pipe theoretically allowed only the sphere to be detected. The spheres were placed near the ground and as high as 2.1 m (7 ft) to ensure accurate recording of the detection zone.

Finally, two different manikins were tested to show the effects of manikin composition on the radar detection range. The first model (figure 6, left) is a crash test dummy similar to the newer Hybrid III 5th percentile female (the model number was not available). It is composed of a steel and aluminum frame with a vinyl skin (heavy manikin). The second manikin (figure 6,


Figure 4.—A test sphere with diameter of 36 cm (14 in).


Figure 5.—Ninety-one centimeter (36 in) in diameter weather balloon coated with conductive paint.

right) is a model used in accident reconstruction and is available from Atlanta Legal Photo Services (model 2047).[1] It is composed of a wire frame surrounded by a foam body (light manikin).

Only radar system 2 was available at the time of the manikin tests, so results may vary depending on the radar system. Our tests were conducted with the manikin in a sitting position because (1) the version of the SAE standard available to us at the time of the tests required the manikin to be in a sitting position, (2) it is impossible to put some manikins in a kneeling position, and (3) only the height for a sitting manikin is specified in the standard. (Results may vary slightly between kneeling and sitting due a difference in height). Each manikin was placed in a sitting position at various points directly in front of the radar along the centerline to determine the reliable detection range (figures 7 and 8). The height from the ground to the top of the manikin's head was 81 cm (32 in). Comparing the detection range of sitting manikins along the centerline was sufficient to show the effects of differing compositions.

Figure 6.—Test manikins.

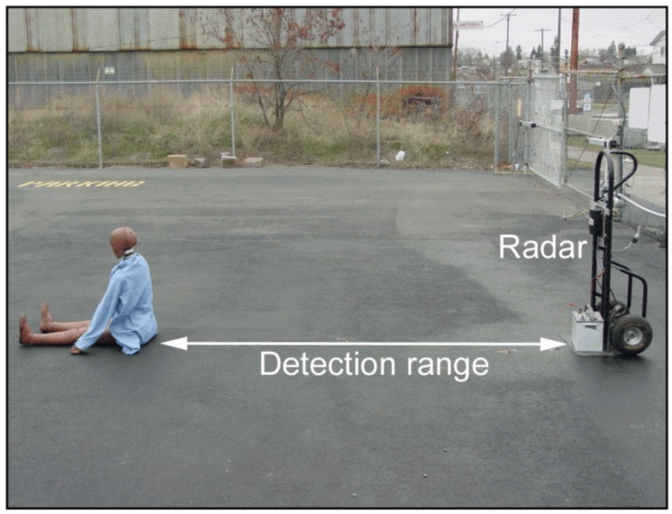

Figure 7.—Radar system 2 and heavy manikin.

Figure 8.—Radar system 2 and foam manikin.

TEST RESULTS

Radar System 1

Figure 9 shows the detection zones as recorded for a person, the trihedral corner reflector, and the 36-cm (14-in) in diameter sphere. The person used for this test was a NIOSH researcher who was 190 cm (6 ft, 3 in) tall and weighed 84 kg (185 lb). Test results using a different person may vary slightly (discussed below). The results show that the person had the largest detection zone, the corner reflector's detection zone was smaller, and the zone for the 36-cm (14-in) sphere was smaller yet.

Some difficulties were encountered when testing the corner reflector. Many times, while trying to find a detection point, it was not possible for the person to stay out of the detection zone. Thus, at many points within the potential detection zone, the person had to lift the pipe and reflector and move it out of the detection zone to determine if he were being detected. This was a time-consuming process. Also, detection of the corner reflector was sporadic and depended on orientation. The corner reflector had to be moved, tilted, and turned several times at each potential detection point to verify detection or no detection. Detection also depended on reflector height. With all these variables, many times the reflector was not detected in the same place twice. Repeatability was difficult to establish, and the outline sketched on the plot in figure 9 is a best estimate.

As mentioned earlier, the 36-cm (14-in) sphere was thought to be too small for this application. Figure 9 confirms this and shows that the detection zone was much smaller than that for a person. Also, it was difficult to establish the detection zone of

[1]Mention of specific products or manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

the sphere without walking into the detection area, thus causing erroneous results. Detection depended on height with this sphere, but not orientation. This test was conducted more quickly than for the corner reflector, and we decided to pursue further tests with the weather balloon that approximated a larger sphere.

Figure 10 compares the detection zone for a person with the zone for the balloon. The detection zones are roughly the same size. A few difficulties were seen in using the balloon , e.g., its detection depended on height. The zone was enlarged in a few places near the radar system if the balloon was raised 1.5 to 1.8 m (5 to 6 ft) off the ground. The results shown in figure 10 were for the balloon at roughly 1 m (3.3 ft) off the ground. Also, as the day progressed and the temperature rose, the balloon expanded, causing the conductive paint to crack and peel. While it was relatively simple to construct the reflective balloon with the correct equipment, a balloon may not be practical as a standard test target.

Radar system 1 was not available when the tests of the manikins were conducted. See the next section for the results using radar system 2.

Radar System 2

A second radar system built by a different manufacturer was tested to verify the results of previous tests. Figure 11 compares the detection zones for a person, the corner reflector, and the small sphere. The same difficulties were seen in these tests, and the differences in the detection zones for the various targets were significant. The detection zone for the small foil-covered sphere was, as expected, much smaller than the detection zone for a person. The detection zone for the corner reflector was also smaller than that of a person. Figure 12 compares the detection zones for a person and the large balloon. Again, the zones are similar with the exception that the sphere was detected 61 cm (2 ft) farther away than the person.

The tests of the manikins consisted of finding those distances at which the manikin was detected directly in front of the radar system (figure 7). Using the heavy manikin and a radar mounting height of 114 cm (45 in), the manikin was detected between 3.8 and 5.3 m (12.5 and 17.5 ft). It was not detected anywhere else along the centerline. The light manikin was not detected at any position.

This test was conducted again with the radar mounting height at 74 cm (29 in) to determine if the poor detection was due to the manikin sitting underneath the radar beam. For this test, the heavy manikin was detected between 0.76 and 7.6 m (2.5 and 25 ft). The light manikin was only detected at one point and that was directly in front of the radar at a distance of 0.76 m (2.5 ft). A final test was conducted with a small person in the same sitting position to compare the detection range between manikins and people. The person was detected from 0 to 7.6 m (25 ft), which was a very similar result to that for the heavy manikin.

CONCLUSIONS AND RECOMMENDATIONS FOR TARGETS

Test results show that trihedral corner reflectors are difficult to use as test targets. Detection of a corner reflector is highly dependent on the angle and orientation of the reflector relative to the incident radar signal. Moderate variations in the orientation of the reflector can result in its not being detected in areas where detection would be expected. The most practical method of testing a corner reflector is to mount it on a plastic pole so that a person can walk outside the potential detection zone while holding the reflector inside the zone. However, it is sometimes difficult to tell if the person is actually causing the alarm rather than the reflector. A less practical means of positioning the reflector would be to use rigging or lines that extended well outside the detection zone and that could be adjusted by a person or by moving the radar system. This would solve the problem of false detections of the person, but causes many other difficulties.

If a person is not used as the test target, the next best thing is a metallic sphere with a diameter of at least 91 cm (36 in). Unfortunately, a metallic sphere of this size is not affordable or practical for these tests. An approximation of a sphere using a weather balloon or rubber ball coated with conductive paint is feasible, but not very durable.

If a manikin is to be used as a test target, as recommended in the SAE standard, it must have a RCS similar to that of a human of the same size. In these limited tests, a high-quality crash test dummy that contains a steel and/or aluminum frame was a close representation of a human. However, this type of manikin is very expensive. The less expensive and lighter foam manikin used in these tests was not an accurate representation of a human and can not be used to evaluate radar. It may be feasible to use a foam manikin with clothes in evaluating other types of technology, such as ultrasonic or infrared sensors, but further tests are needed to verify this.

The SAE standard calls for the manikin or person to be in a sitting or kneeling position; however, most of our other tests involving people were conducted with the person standing. A standing person was used because walking through the detection zone is more practical and safer than sitting, especially when testing systems on actual equipment. Also, the most common position for a human on a work site and near equipment will be either standing or walking, not sitting. It is legitimate to require the detection of a sitting or crouching person, but this would be a most extreme case, much like detecting a person lying down. It is difficult for a radar system to detect a sitting person yet ignore rocks and ruts on the ground. These tradeoffs and safety concerns forced researchers to evaluate the most common position of a person near the equipment, which would be the standing position.

It was concluded that to determine a radar system's reliable detection zone for a person, an actual person should be used as the test target. However, this raised the question of what effects body type or height might have on the radar's detection zone. This is the subject of the next section.

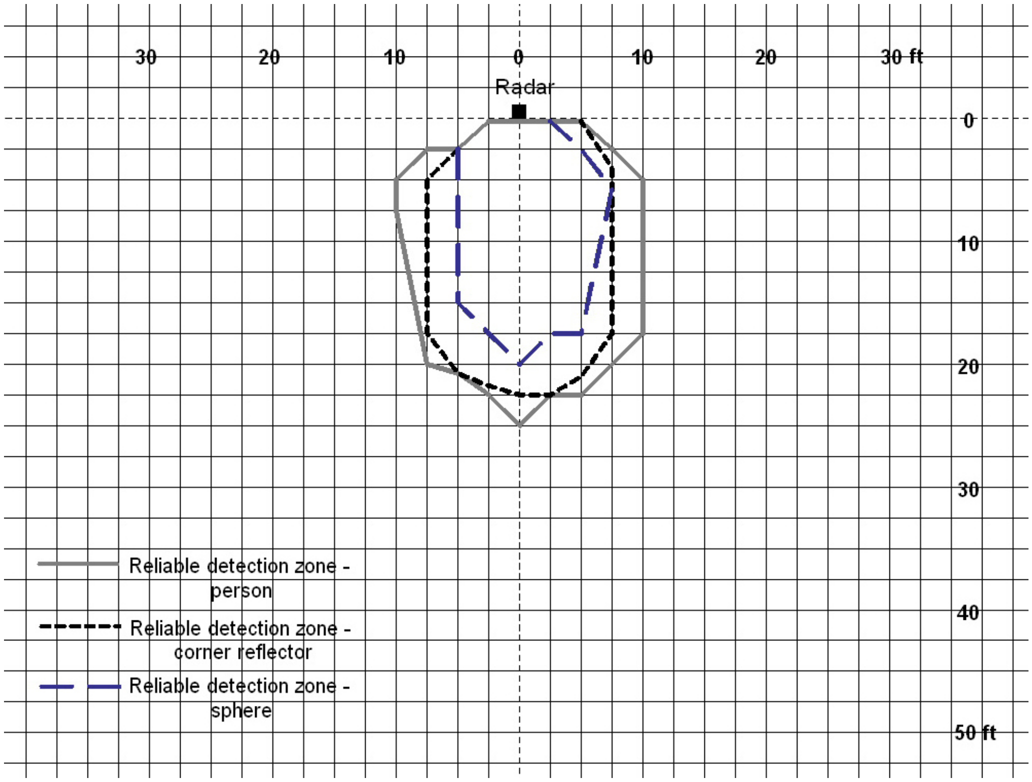

Figure 9.—System 1: Detection zones for person, corner reflector, and small sphere.

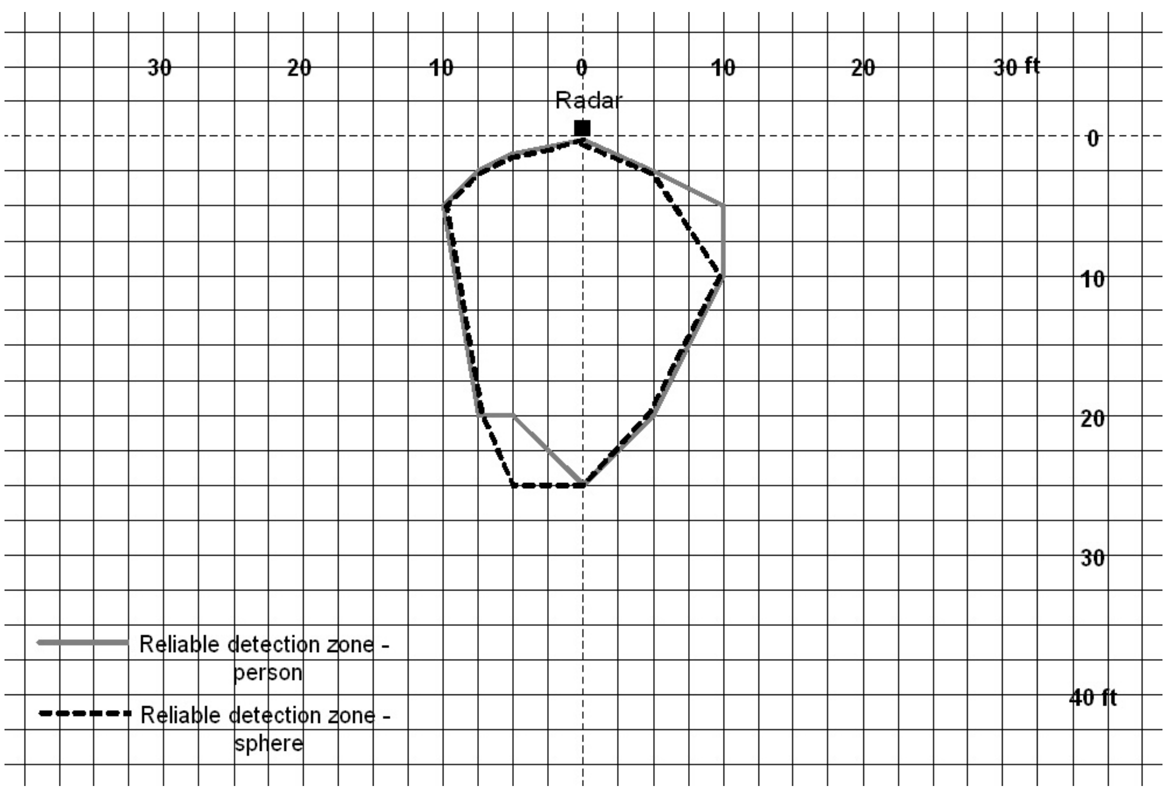

Figure 10.—System 1: Detection zones for person and large sphere.

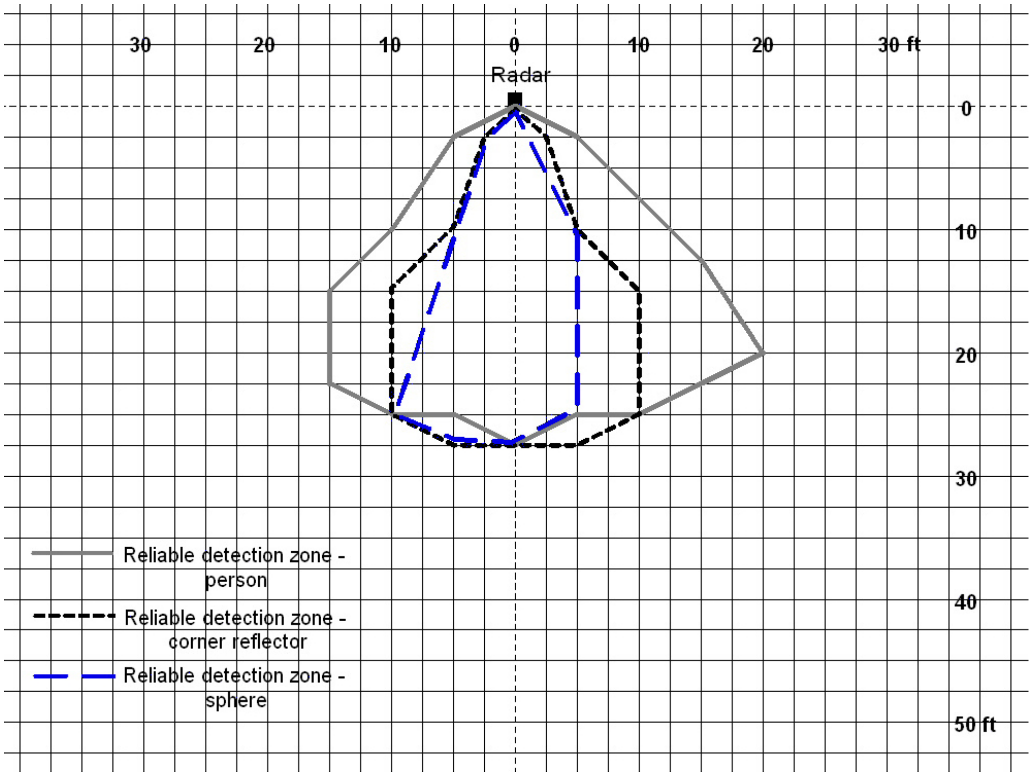

Figure 11.—System 2: Detection zones for person, corner reflector, and small sphere.

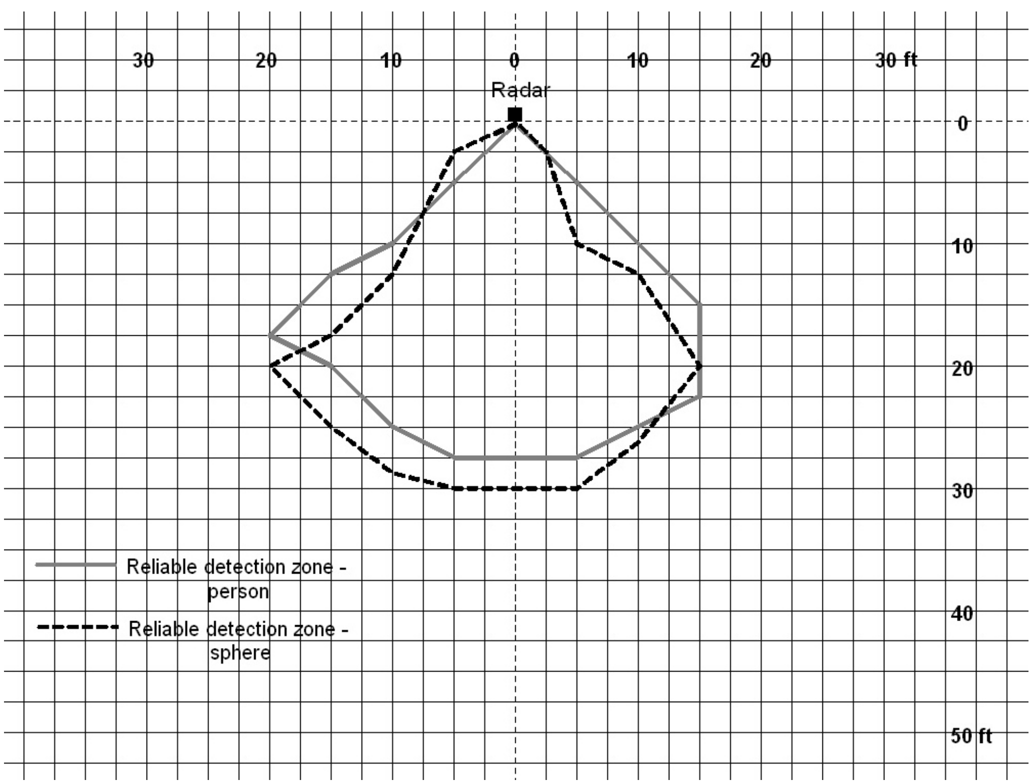

Figure 12.—System 2: Detection zones for person and large sphere.

EFFECT OF BODY TYPE ON RADAR DETECTION

To better understand the effects of body size on the detection zone for a given radar system, researchers compared the detection zones for three different-sized people. The same two radar systems were used for these tests. However, other variables were introduced in order to consider the effects of different-sized mining equipment. These variables involved mounting height and downward tilt of the radar antenna. Several different configurations were tried and compared.

TEST DESCRIPTION

These tests were conducted in the same parking lot as previous tests. For each radar system, three different mounting configurations were tested. The first configuration consisted of mounting the radar on a test frame at a height recommended by the manufacturer (approximately 114 cm [45 in]). The radar unit was not tilted at this height, but pointed straight out into the detection area (figure 13). The second mounting configuration had the radar at a height of approximately 264 cm (104 in) with 15° downward tilt (figure 14). The third configuration was at the same height, but with a 25° downward tilt. (The measurement of tilt angle is shown in figure 14.) The higher mounting location is similar to what would be needed if the radar were mounted near the light bar of a large off-highway dump truck.

In initial tests, three test subjects were used, and their physical attributes are listed in table 1. However, after the first few tests it was apparent that body weight was not a significant factor, and only persons 1 and 2 were used thereafter. All the persons tested were wearing cotton pants, a cotton shirt or jacket, and leather shoes. (Metal items such as glasses, belt buckles, and watches were removed at first, but then allowed after we determined that these items had no effect on the dimensions of the detection zone.)

The test subjects were chosen on the basis of their size differences. We wanted to use test subjects that were close to the 5th percentile female and 95th percentile male as described in the SAE standard J833–Human Physical Dimensions (1989). In this standard, the dimensions and weights of small (5th percentile female), medium, and large (95th percentile male) humans are given (table 2). Note that a medium person's attributes are not the same as the average U.S. height and weight, which is 160 cm (5 ft 3 in) and 61 kg (135 lb) for an adult female and 175 cm (5 ft 9 in) and 73 kg (162 lb) for an adult male (Droste and Dye, 1994).

The reliable detection zone for each person was determined by having one person walk toward the radar unit and place a marker where reliable detection began and where it ended (figures 15 and 16). After the edges of the detection zone were marked, the zone was recorded on a graph. Then the next person repeated the test. For more details, see the appendix.

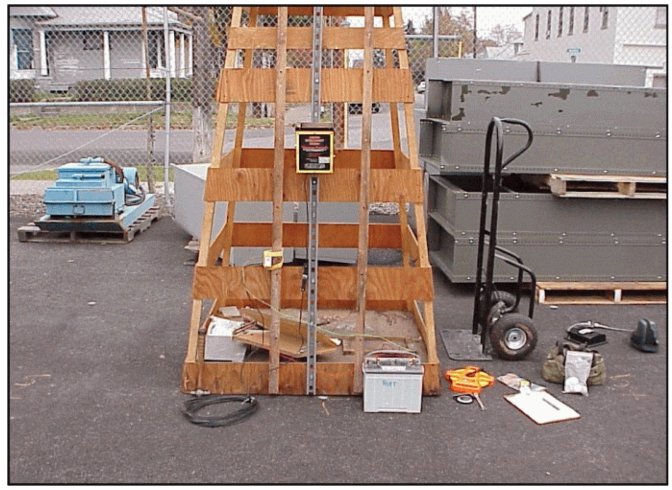

Figure 13.—Low mounting configuration for tests to compare people.

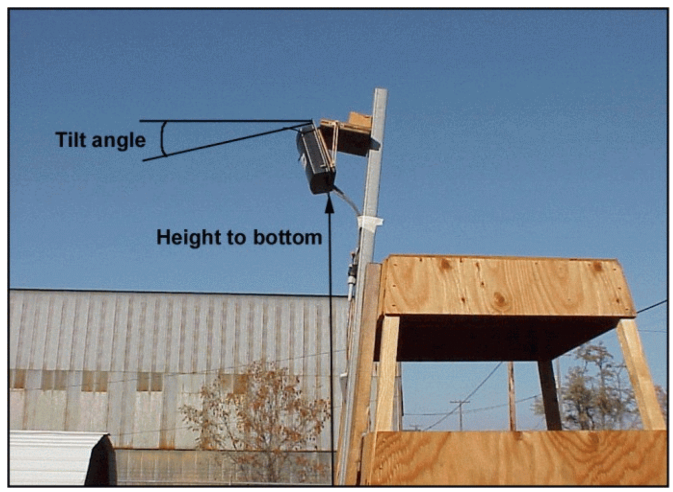

Figure 14.—High mounting configuration for tests to compare people.

Table 1.—Test subjects

Person	Gender	Height (with shoes)	Weight, kg (lb)
1	Female	160 cm (5 ft 3 in)	50 (110)
2	Male	190 cm (6 ft 3 in)	84 (185)
3	Male	190 cm (6 ft 3 in)	120 (265)

Table 2.—Human physical dimensions in SAE J833

	Height (with shoes)	Weight, kg (lb)
Small (5th percentile female)	155 cm (5 ft 1 in)	48 (106)
Medium (halfway between the two)	170 cm (5 ft 7 in)	73 (161)
Large (95th percentile male)	188 cm (6 ft 2 in)	96 (212)

Figure 15.—Determining detection zone for person 1.

Figure 16.—Determining detection zone for person 2.

TEST RESULTS

Radar System 1

The first radar system was mounted level at 107 cm (42 in) high on the test frame. The detection zones for persons 1 and 2 were determined first. Person 3 was then tested to determine if body weight would affect the detection zone for the radar system. The detection zone for all three persons is shown in figure 17 and was the same for all test subjects. Based on this result, person 3, being the same height as person 2, was no longer used in the tests.

The next test of system 1 was at a height of 267 cm (105 in) and a tilt angle of 15° downward. The detection zones for persons 1 and 2 are shown in figure 18. The outer range of the system was 7.6 m (25 ft) for both test subjects; however, the inner range did differ by 1.5 m (5 ft) because of the difference in the test subjects' heights. Figure 19 illustrates this effect. It shows that the outer range is not expected to change because approximately the same amount of the person's body is in the radar beam regardless of the person's size. The inner range varies because the shorter person is walking underneath the beam at a distance further from the radar. Note that the width of the left side of the detection zone varied by 0.76 m (2.5 ft) for each person. The exact cause of this is unknown, and the test subject's size could not be proven as the cause.

The last test of system 1 was at a height of 262 cm (103 in) and a tilt angle of 25° downward. The detection zones for persons 1 and 2 are shown in figure 20. The outer range of the system was 6.9 m (22.5 ft) for both test subjects, and the inner range differed by only 31 cm (12 in). This difference was expected because of the steeper beam angle for a 25°-radar tilt angle. Also of significance was the large change in overall detection zone dimensions for both people when comparing the low mounting position with the high mounting position.

Radar System 2

The second radar system was mounted level at 114 cm (45 in) high on the test frame. The detection zones for persons 1 and 2 are shown in figure 21 and are essentially identical. The outer range at this height was 8.4 m (27.5 ft), and detection occurred all the way up to the front of the radar unit.

The next test of system 2 was at a height of 267 cm (105 in) and a tilt angle of 15° downward. The detection zones for persons 1 and 2 are shown in figure 22. The outer range of the system was 7.9 m (26 ft) for both test subjects; however, the inner range did differ by 0.76 m (2.5 ft) because of the difference in the test subjects' heights. The width of the detection zone did not vary at the outer detection ranges, but began to narrow slightly as test subject 1 walked under the radar beam.

The last test of system 2 was at a height of 267 cm (105 in) and a tilt angle of 25° downward. The detection zones for persons 1 and 2 are shown in figure 23. The outer range of the system was 7.9 m (26 ft) for both test subjects; however, the inner range still differed by 0.76 m (2.5 ft) because of the difference in the test subjects' heights. Again, the width of the detection zone did not vary at the outer detection ranges but began to narrow slightly as the smaller test subject walked under the radar beam. Also note that, while the overall dimensions did change, the difference in detection zones between low mounting and high mounting were not as significant as when using system 1.

CONCLUSIONS

Based on these limited tests, the following conclusions can be made for these two radar systems.

- A person's height does not affect the maximum range or outer dimensions of the detection zone.
- A person's height does affect the dimensions of the detection zone for radar systems mounted higher than approximately 1.8 m (6 ft) above the ground, but only at locations near the radar unit where the test subject begins to walk under the radar beam. The difference in the dimensions of the inner detection zone did not exceed 1.5 m (5 ft) for the configurations and people tested. However, if a person is in a crouching or sitting position, the inner detection zone dimensions could vary significantly when

compared to the same person standing.

• In general, a person's height did not affect the width of the detection zone, except at close-in ranges where the test subject began to walk under the radar beam.

• In our limited tests, body weight did not appear to have a significant effect on the detection zone of a radar system.

• Mounting height and tilt angle do affect the dimensions of the detection zone. This effect is not the same for every radar system.

• Small metal items on the test subject, such as glasses, watches, or jewelry, do not appear to affect the dimensions of the detection zone.

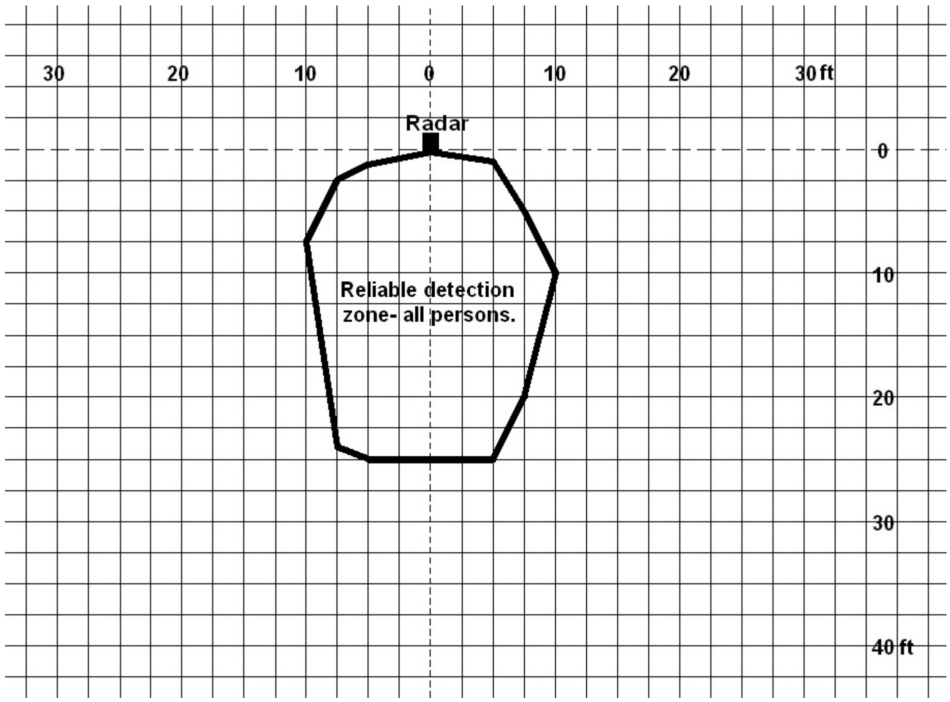

Figure 17.—Detection zones for persons 1, 2, and 3 and system 1 mounted low.

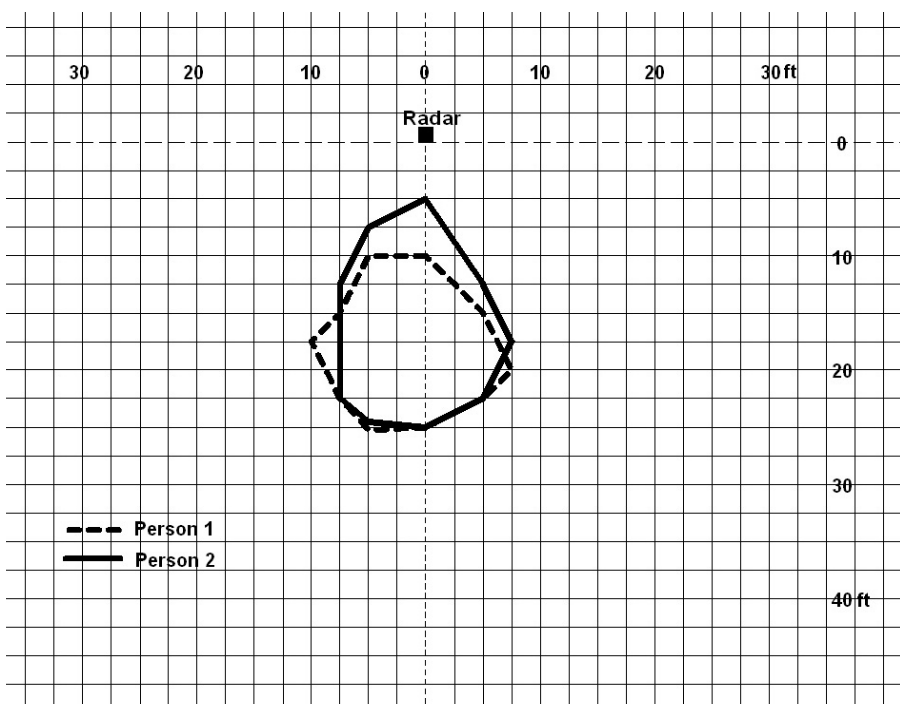

Figure 18.—Detection zones for persons 1 and 2 and system 1 mounted high (15° tilt).

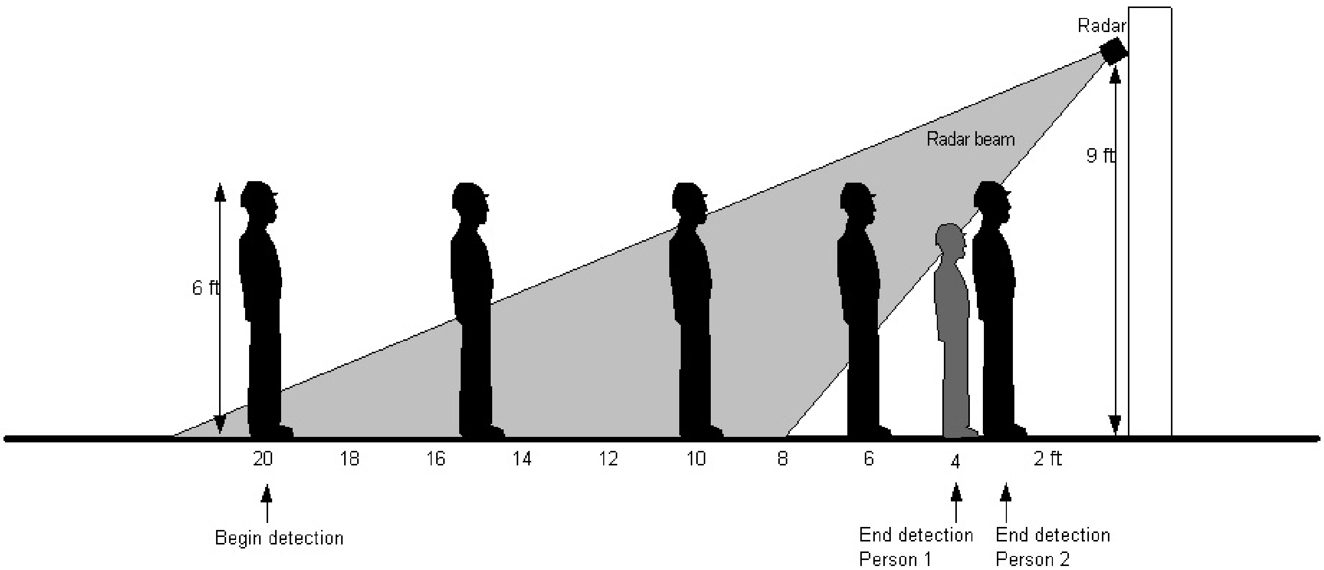

Figure 19.—Example of differences in inner detection ranges.

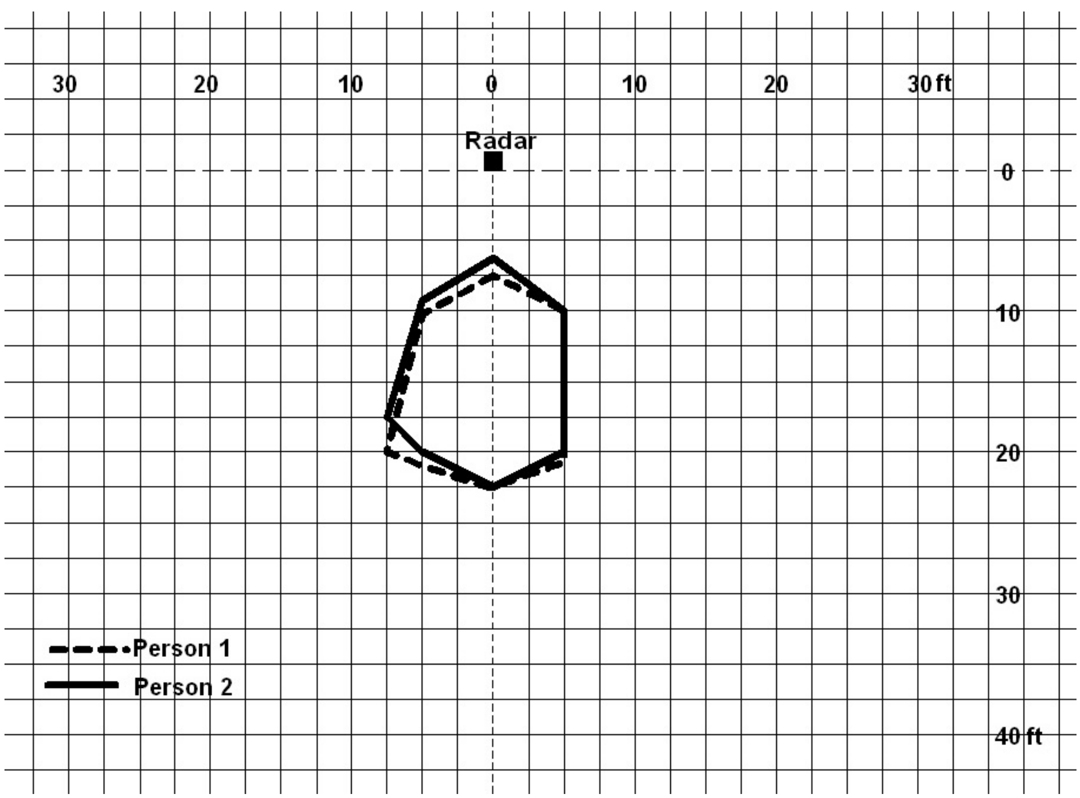

Figure 20.—Detection zones for persons 1 and 2 and system 1 mounted high (25° tilt).

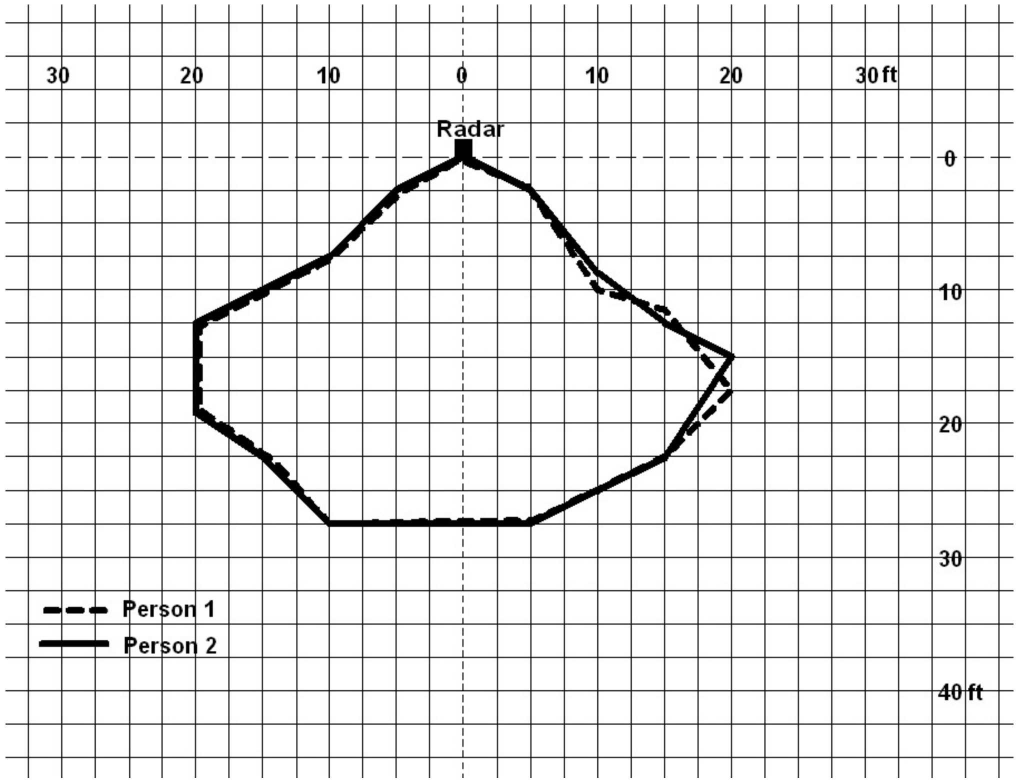

Figure 21.—Detection zones for persons 1 and 2 and system 2 mounted low.

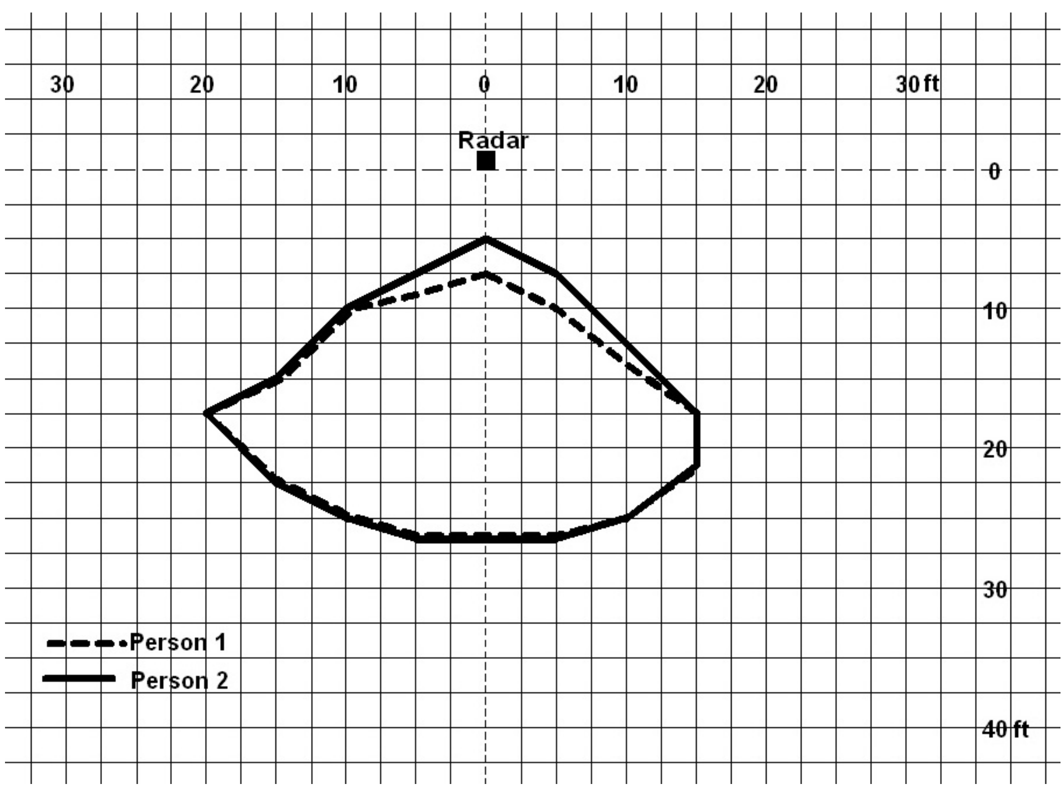

Figure 22.—Detection zones for persons 1 and 2 and system 2 mounted high (15° tilt).

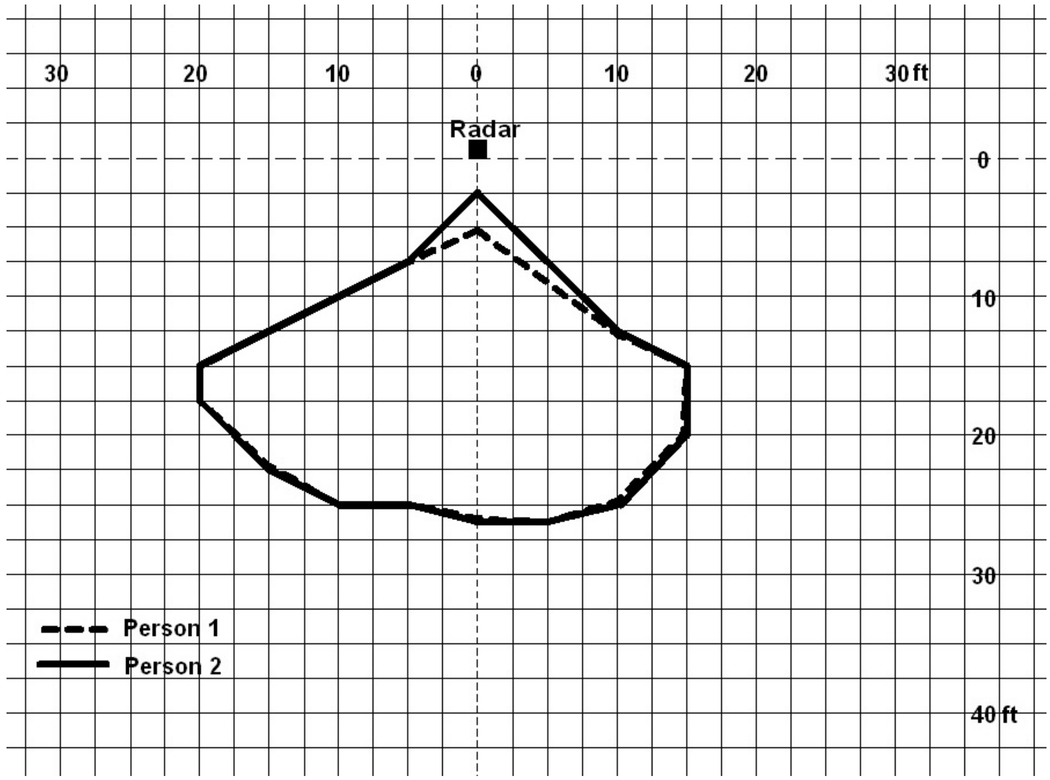

Figure 23.—Detection zones for persons 1 and 2 and system 2 mounted high (25° tilt).

RECOMMENDATIONS FOR TESTING SYSTEMS ON HEAVY EQUIPMENT

Based on the above test results and other tests conducted on surface mining and construction equipment, the following general recommendations are made concerning the evaluation and implementation of radar-based collision warning systems. Most manufacturers will provide a data sheet or description of the detection characteristics of their radar system; however, it is important to verify the operation of the radar system on the actual equipment on which it will be used. Information on false alarm rates, mounting locations, and detection zones for a person and a smaller vehicle will be critical in making a decision on the effectiveness of a collision warning system prior to final installation on equipment used in actual production.

INITIAL EVALUATIONS ON HEAVY EQUIPMENT

• Radar systems should be mounted at approximately chest height for the best detection. *Justification:* This height allows the best detection of a standing person because a significant portion of the body is within the radar beam, even at close distances. Lower mounting heights may result in false alarms from detecting the ground. Higher mounting locations will require the radar antenna to be tilted downward in order to improve close-in detection. This decreases the maximum range of the radar detection zone and may increase false alarms.

• After installing a collision warning system according to the manufacturer's instructions, the equipment should be moved in reverse (or forward for front-mounted sensors) in an area with no obstacles or people to determine if false alarms occur. The ground surface should be typical of actual working conditions. *Justification:* Tests have shown that false alarms may result from the detection of rotating tires or other components of the equipment itself. Also, some systems malfunction because of the vibration of the equipment, shocks from shifting gears, or braking suddenly. False alarms may also be generated from the detection of irregularities in the ground surface such as ruts or rocks. After conducting these tests, adjustments to system settings and the mounting configuration may be necessary. If these adjustments do not eliminate false alarms, the system may not work on that particular piece of equipment or in that particular environment.

• The reliable detection zone for a person should be determined by having a person walk toward the stationary, but running, equipment. *Justification:* A person walking into the blind area of a stationary machine is a common hazardous condition, and the system must be able to detect this. Tests have shown that an actual person should be used to conduct these tests because other test objects, such as radar reflectors or manikins, may have different detection characteristics. It is also recommended that several, close-in detection points be tested with the person in a crouching position so that the limitations of the radar in detecting a sitting or crouching person can be understood and conveyed to equipment operators. The equipment should have the engine running to verify that vibration will not affect operation of the radar.

- The reliable detection zone for a person should be verified by moving the equipment toward a stationary standing person. This must only be done at test grid points where it is safe, i.e., points that provide sufficient stopping distance when the person is detected or when the person or spotter indicates that detection has not occurred where expected. Radios must be used so that the person can communicate with the equipment operator, and a spotter must be in an area where the operator can see hand signals. These tests should be conducted with the person standing so that his or her movement is not restricted. *Justification:* Tests have shown that the detection zone for some radar systems decreases in size when the equipment moves toward the person as a result of vibration or speed sensitivity.
- A person of average height (175 cm ±8 cm [5 ft 9 in ±3 in]) should be used to determine the detection zone for a person. The person should wear clothing typical of that work site. *Justification:* The detection zone does not change significantly for persons of slightly differing heights. However, the zone may be different for persons on two extremes of height, i.e., a 160-cm (5-ft, 3-in) person versus a 190-cm (6-ft, 3-in) person. Testing with an average-sized person will give a good indication of system performance.
- The reliable detection zone for a smaller vehicle, such as a pickup truck, should be determined by parking the smaller vehicle at various points in the potential detection zone and moving the equipment toward it. *Justification:* A smaller vehicle parked in the blind area of the equipment is a common hazardous condition, and the system must detect this. Also, previous tests have shown that the detection range for a pickup truck can be as much as three times greater than the range for a person (Ruff 2000). Operators should be made aware of the potential for significant differences in detection zones for different objects.

CONSIDERATIONS FOR RADAR SYSTEMS IN A PRODUCTION SETTING

Radar systems provide an alarm in the cab of the equipment when an object or person has been detected. Existing systems only provide an approximate distance to the object on the alarm display, usually by activating a series of lights. The size or type of object and the exact location of the object are not displayed. Also, multiple objects may be detected, but the alarm display can only provide one alarm. This may mean that an object is being "masked" by another larger object, e.g., a person standing between the equipment and a wall may be hit if the operator sees the wall and thinks that it is the only cause of the alarm. Because of the characteristics of existing radar systems, it is recommended that the operator verify the cause of an alarm before moving the equipment. This can be done through direct sight, mirrors, or cameras.

For large equipment, visual verification would require exiting the cab and walking around the equipment if no other means are available. Mirrors could be used in some situations, but they, too, have limited visibility and cannot provide a view directly behind the equipment. Alternatively, a camera system that provides a view of the blind areas, including the detection zone of the radar system, could be used to verify the cause of any alarm. While radar is effective in detecting people and other large objects, false or ambiguous alarms can be common. Until radar systems are improved, a combination of radar with video cameras is recommended for most large equipment.

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APPENDIX: TEST PROCEDURE

This test procedure describes the method a system manufacturer would use for determining the characteristics of collision warning systems employed to detect obstacles near mining and construction equipment. Final verification of detection characteristics at mine or construction sites would require the methods described earlier.

DEFINITIONS

Collision Warning System. A system consisting of a sensor and an alarm display that detects nearby objects and provides a warning to the equipment operator.

Obstacle. An object that must be detected by the collision warning system. For these tests, the obstacles should consist of either a person or a passenger-type vehicle.

Sensor. The part of the system that senses nearby objects, e.g., radar antenna.

Alarm Display. The part of the system located in the cab of the equipment to provide a visual and/or audible alarm indicating that an obstacle is in the system's detection zone.

False Alarm. An alarm indicating the presence of an obstacle in the detection zone of the collision warning system when no obstacle exists, or an alarm from any object that is a significant distance away from the expected detection zone.

Reliable Detection Zone. The area in which an obstacle is detected 100% of the time.

Sporadic Detection Zone. The area in which an obstacle is detected some of the time but not always, i.e., less than 100% detection, but more than approximately 10%.

Recorded Detection Zone. A plot of the detection zones transcribed on graph paper with a grid spacing of either 1 m or 2.5 ft.

TEST OBSTACLES

The collision warning system must detect the obstacles that are most commonly involved in collisions, i.e., pedestrian workers (persons) and smaller passenger/utility vehicles such as trucks or vans.

Person

For tests to detect a person in the detection zone of a collision warning system, a person should stand or walk in the area of interest near the sensor. The person should be 175 cm ±8 cm high, including shoes.

Smaller Vehicle

For tests to detect a smaller vehicle in the detection zone of a collision warning system, a passenger-type vehicle that is typical at mine sites in the geographical area should be parked or driven in the area of interest. At a minimum, one orientation for the vehicle should be tested in which the vehicle faces the sensor.

TEST METHOD

Test Area

The test area should be an open space on flat terrain with a dry sand and/or gravel base. No rocks, foliage, or debris larger than 8 cm in diameter should be in the test area. No objects should be within approximately 50 m in the sensing direction of the collision warning system, i.e., 50 m of clear area should lie behind the equipment to establish a rear sensing zone. No large objects should be within 25 m of both sides of the collision warning system. All personnel, except whoever is conducting the test, should remain in an area where they will not be detected by the collision warning system.

Sensor Mounting Locations

General testing of the collision warning system can be performed on a mobile test stand, but to claim that the system will work on a specific piece of equipment, the system must be mounted and tested on that equipment. For forward sensing, the sensor should be mounted on the front bumper or grill according to the manufacturer's instructions. For rear sensing, the sensor should be mounted on the rear bumper area. If this is not possible, as with large off-road trucks, it can be mounted near the light bar or on the rear axle. Other locations may be acceptable, depending on the collision warning system's installation instructions.

PROCEDURE

False Alarms

Tests of the collision warning system should start with no obstacles near the system, as defined in the section entitled "Test Area." With the potential detection zones totally clear, the equipment should be moved at slow speed (less than 8 km/h) in the direction of sensing for approximately 15 m to determine the frequency of false alarms. If false alarms occur, the cause of the alarms should be determined, if possible, and noted, e.g., "System detected the ground" or "Detected rotating tires." The system should then be adjusted or relocated so false alarms are at a minimum in a clear test area. The system settings and mounting location when false alarms are at a minimum should be recorded.

Obstacle Detection

The detection zones for the collision warning system should be determined by placing the obstacle at various distances and locations behind the stationary equipment (with the engine running) according to a test grid pattern. Test points in the potential detection zone should be defined by a grid with a spacing of no more than 1 m between test points. Detection at each grid point should be determined by recording whether or not an alarm is activated when the obstacle moves toward the sensor in a line parallel to the long axis of the equipment. For a person, movement toward the sensor should be at a slow walking speed (less than 6 km/h). For a smaller vehicle, movement toward the sensor should be less than 8 km/h.

Note: The detection zone must be verified for a moving piece of equipment by allowing the person or small vehicle to remain stationary at several points at the far edge of the detection zone and moving the equipment slowly toward the obstacle. The equipment may continue backing for several meters, but must be stopped before it reaches an unsafe distance to the obstacle. Any discrepancies over 30 cm between (1) detection zones for moving equipment and a stationary obstacle and (2) stationary equipment and a moving obstacle must be noted.

The following steps summarize the test procedure for a person (for the small vehicle tests, simply substitute a vehicle for a person). The starting position for the person should be in front of the sensor portion of the collision warning system, but at a distance well outside the potential detection zone.

1. Starting on the centerline of the equipment (0-m line) and outside the detection zone, begin the test by walking toward the sensor. Place a marker on the centerline where detection occurs and the alarm is activated.
2. Back up until the alarm stops. Walk toward the sensor again to verify the position of the first detection point. Repeat this step until a consistent detection point is determined. If there are points where the alarm is not consistent (sporadic detection), mark the first point where this occurs with a different-colored marker.
3. Continue walking toward the sensor along the 0-m centerline. Verify that the alarm remains on while walking along the entire line. Place a marker where detection stops and the alarm is not activated. The alarm may be activated up to the point directly in front of the sensor. In this case, place the marker at this point.
4. Walk out of the detection zone to the initial starting point.
5. Move from the 0-m centerline to the next grid line (1 m) and repeat steps 2 through 4 along this line.
6. Repeat these steps along each line until detection does not occur at any point on the lines.
7. Move to the other side of the centerline and repeat the above steps to determine the detection zone for that side of the centerline.
8. Record the position of the markers as described in section 5.
9. Verify the detection zone for moving equipment by allowing the person to stand at the points of the detection zone farthest away from the collision warning system. Using a spotter and radios, signal the equipment operator to move slowly forward a few meters. Then signal the operator to move slowly in reverse. Record the distance to the equipment when the alarm detects the stationary person and the alarm is activated.
10. Stop the equipment at a safe distance from the person. Have the operator move the equipment back to the starting position.
11. Conduct the test again for the next detection point on the next grid line. Repeat until the outer edges of the detection zone are verified. Record any discrepancies greater than 30 cm between this test and the test using the stationary equipment and walking person.

Detection Zones

The reliable detection zone should be recorded as the area in which the obstacle is detected 100% of the time. The obstacle must be detected and an alarm must be generated immediately (<200 ms) after the equipment starts moving toward the stationary obstacle or after the obstacle moves toward the stationary equipment. The sporadic detection zone should be recorded as the area in which the obstacle is detected less than 100% of the time, but more than approximately 10% of the time. Less than 10% detection should be considered outside both detection zones, but may be noted as a false alarm.

RECORDING DATA

False Alarms

False alarms should be noted when testing the collision warning system as described above in the section on "Detection Zones." Possible causes of any false alarms and optimum mounting configurations to minimize false alarms should be noted.

Detection Zones

The reliable and sporadic detection zones should be recorded on a graph with a 1-m or 2.5-ft grid that approximates the general shape of the detection zone as seen from a top view. The general shape of the detection zone can be estimated by interpolating between tested points.

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