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Evaluation of a radar-based proximity warning system for off-highway dump trucks

Todd Ruff *

National Institute for Occupational Safety and Health, Spokane Research Laboratory 315 E. Montgomery, Spokane, WA 99207, USA

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Abstract

A radar-based proximity warning system was evaluated by researchers at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health to determine if the system would be effective in detecting objects in the blind spots of an off-highway dump truck. An average of five fatalities occur each year in surface mines as a result of an equipment operator not being aware of a smaller vehicle, person or change in terrain near the equipment. Sensor technology that can detect such obstacles and that also is designed for surface mining applications is rare. Researchers worked closely with the radar system manufacturer to test and modify the system on large, off-highway dump trucks at a surface mine over a period of 2 years. The final system was thoroughly evaluated by recording video images from a camera on the rear of the truck and by recording all alarms from the rear-mounted radar. Data show that the system reliably detected small vehicles, berms, people and other equipment. However, alarms from objects that posed no immediate danger were common, supporting the assertion that sensor-based systems for proximity warning should be used in combination with other devices, such as cameras, that would allow the operator to check the source of any alarm.

Keywords: Proximity warning; Collision avoidance; Obstacle detection; Mining; Safety

1. Introduction

Researchers at the National Institute for Occupational Safety and Health (NIOSH), Spokane Research Laboratory, are studying technology that can help operators of off-highway surface mining equipment avoid collisions with other vehicles and workers, and avoid backing over the edge of a dump point (Ruff and Holden, 2003). Each year, an average of five fatalities occur in surface mines and quarries involving these types of accidents, accounting for 12% of all fatalities at these operations (MSHA, 1999–2003).

All of these accidents can be partially attributed to the lack of visibility from the cab of the equipment. For example, in September of 2003, two workers were killed and another injured when their van was run over by a 190 t capacity dump truck. The van had pulled up to the parked truck on the right side and stopped immediately in front of it to drop off supplies. Due to a miscommunication, the operator of the truck was not aware of the van's location. The truck pulled forward, crushing the van under its right front tire (Fig. 1). Of note was the fact that the dump truck had cameras installed on the front and rear; however, the camera system was in standby mode and no camera view was visible on the monitor at the time of the accident (Pyles et al., 2003).

Dump trucks are the most common type of equipment (58%) involved in these accidents (MSHA, 1999–2003). Fig. 2 shows the blind spots near a 50 t capacity off-highway dump truck commonly used in quarries and construction. While smaller than the trucks used in large surface mines, the configuration of this truck is very similar. The grey areas of the plot are where the operator cannot see the ground. The blind areas around larger trucks are even more extensive, with the front right blind area extending 18 m (60 ft) or more. It is evident that some method is required to monitor the areas that an operator cannot see directly.

* Tel.: +1 509 354 8053; fax: +1 509 354 8099.
E-mail address: ter5@cdc.gov.

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Fig. 1. Collision between haul truck and passenger van.

Systems to monitor blind areas near vehicles are available, but very few are designed specifically for mining equipment. Of those marketed for mining, the most popular are video camera systems. The obvious benefit of cameras is that they provide a view of blind areas. However, there are concerns that an operator could miss a potential collision because he or she did not check the video monitor before moving the truck. Furthermore, cameras do not provide an alarming function when an obstacle is in the path of the truck and in danger of being struck.

NIOSH researchers are studying sensor technology that can supplement cameras and provide a method for prompting the operator to check the video monitor. Sensor-based proximity warning systems provide an alarm when an object is detected, but they do not discriminate among objects and thus generate alarms that may not signify real danger. If too many alarms are generated that do not warrant extra caution, user confidence can decrease (Bliss and Acton, 2003; Breznitz, 1984).

Researchers wanted to determine how often a radar-based proximity warning system would alarm and what objects would cause alarms during normal dump truck operations. These data could then be used to determine whether a combination of cameras and radar would provide a more effective solution than either system by itself. The radar system described in this article monitored the front and rear of an off-highway dump truck; however, only data from the rear radar system was collected, as described in Section 2.5. The

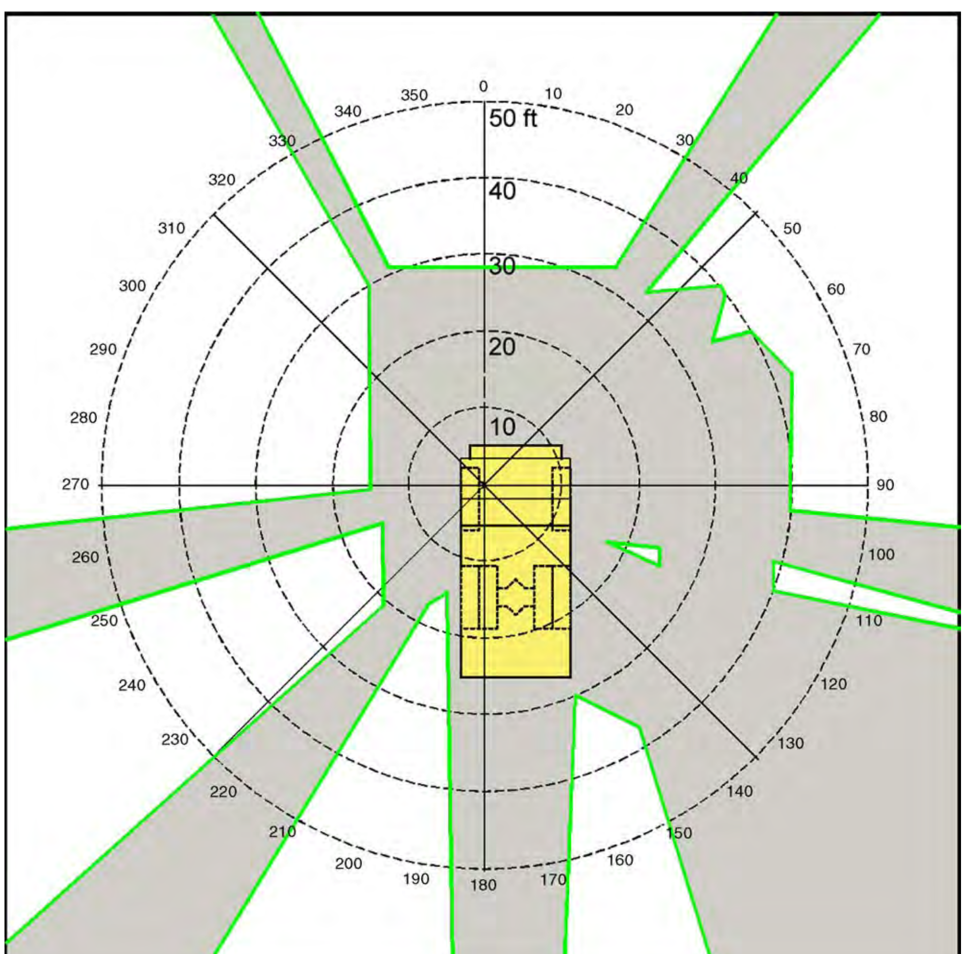

Fig. 2. Blind areas, in grey, for a 50 t haul truck.

analysis of alarms applies only to reverse movements of the dump truck for this discussion.

2. Methods

2.1. Radar and camera systems

After completing a survey of available technologies for proximity warning on construction and mining equipment, the heavy duty preview radar system from Preco Electronics, Boise, ID,[1] was chosen for field tests at a surface mine. This radar system is packaged and marketed for off-highway earth-moving machinery. The system uses pulsed radar to sense the presence of and determine the distance to an object within the radar beam. An alarm display is mounted in the cab of the truck and has both audible and visual warnings. A series of LEDs light up in succession and the warning tone changes frequency to indicate distance to an object. Originally, the system consisted of one radar antenna per alarm display, but the detection area for one antenna was not adequate for large equipment. After suggested modifications were made during the course of the tests, the latest preview system now allows multiple antennas to be networked to a single alarm display. This allows the system to monitor blind spots at the front and rear of the mining equipment.

A camera system consisting of one camera mounted on the rear axle of the truck, one camera mounted on the front of the truck and a video monitor in the cab was also installed on the truck to provide the operator with a visual check of the front and rear blind areas. The camera view automatically switched between front and rear, depending on gear selection.

2.2. System installation

The camera and radar systems were mounted on a Caterpillar 793B 260 t capacity dump truck (Fig. 3) at the Phelps Dodge Morenci Inc. copper mine in Morenci, AZ. Two radar antennas were mounted on the rear axle of the truck (Fig. 4) and two were mounted on the front bumper. The rear-mounted antennas required a special bracket so the antennas could be mounted without welding on the axle casing. The rear antennas were also angled in toward each other approximately 15° so that their beams crossed, providing a wider detection area behind the rear dual tires.

The radar alarm display was mounted in the cab on a center console just forward and to the right of the operator's seat. For the final system, a single alarm display indicated the presence of objects either to the rear or in front of the truck, depending on gear selection.

[1] The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of specific products and manufacturers does not imply endorsement by NIOSH.

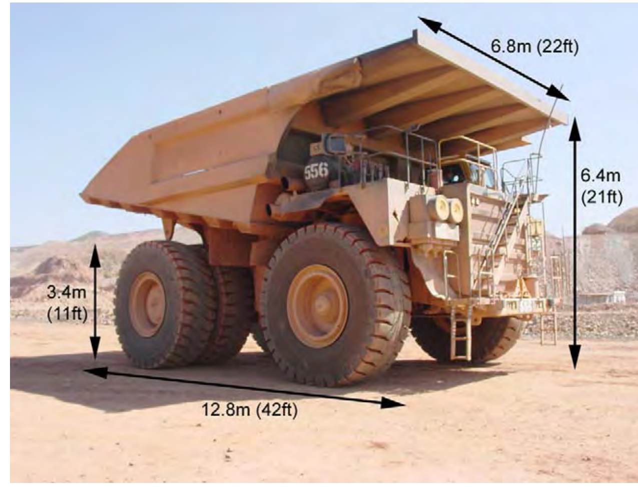

Fig. 3. Caterpillar 793B haul truck.

The camera system consisted of two cameras, one above the rear axle (Fig. 4) and one on the front deck railing. The video monitor was located in the cab above the passenger door. A control box allowed input from a reverse signal so that the correct camera view was displayed depending on travel direction.

2.3. Detection areas

To determine the dimensions of the radar detection areas, a plot was made for the detection of a standing person, as shown in Fig. 5. For reasons of safety, these plots were made with the truck stationary and a person walking towards the truck. The locations where the radar detected the person were then marked on the ground and later plotted on a graph. Note that the rear detection area does not cover the immediate area near the rear tires of the truck. Early tests showed problems with the radar generating false alarms due to detection of the tires. For these tests, the radar system was calibrated to ignore the tires, but this caused a person within 3 m (10 ft) of the rear axle

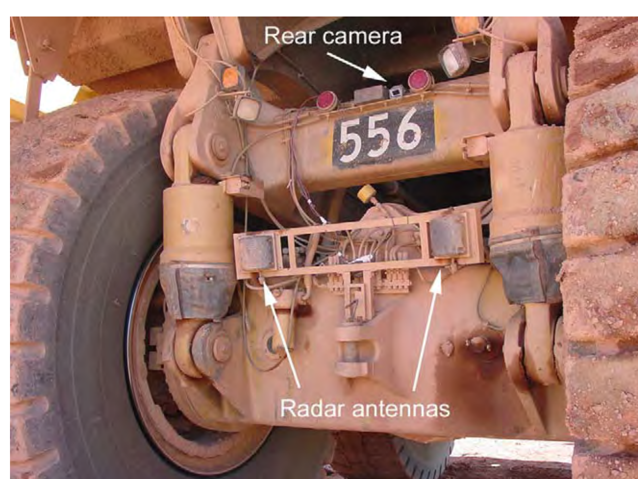

Fig. 4. Radar and camera mounting positions.

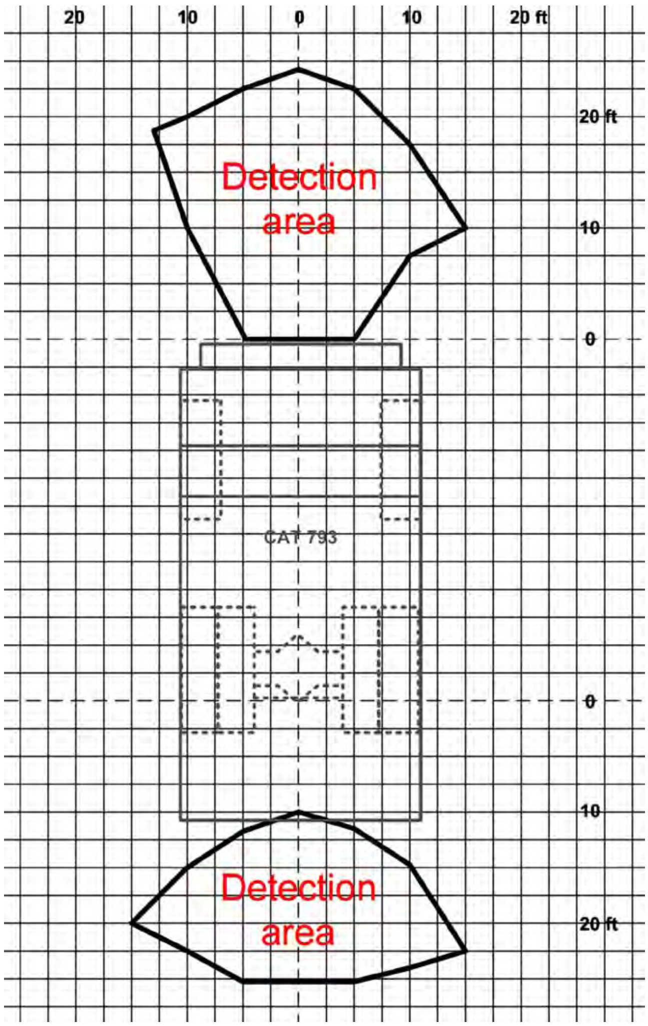

Fig. 5. Radar detection areas for a person.

to be missed. The height of the radar antennas also contributed to this problem because a person could walk underneath the radar beam when close to the antennas. While the rear detection area was not ideal, a trade-off must be made between close detection and false alarms from tires or other structures protruding from the truck. The outer range of the detection area was not affected by these limitations and a person was detected out to 7.6 m (25 ft) away from the truck's axle.

Collisions most often involve a passenger vehicle, so the rear detection area for a van was also determined. This was done by moving the dump truck in reverse toward the empty van, which was parked perpendicular to and centered on the rear centerline of the dump truck. The dimensions of the van's outer and midrange detection areas were similar to those of a person, but close detection near the rear dual tires was not verified due to safety concerns. It is expected that close detection would be better for a van than a person due to the larger size of the van and its increased reflectivity. This was true in earlier tests with a passenger vehicle and a single antenna system (Ruff, 2001).

The radar detection area for a person and the camera field of view (FOV) were then compared using video footage. It was important that the radar detection area was totally contained within the camera's FOV so that the cause of radar alarms could be verified by the operator and by researchers. Fig. 6 shows the rear camera view with the detection area overlain on the video. This plot also allowed an estimate of the distance between the back of the truck and objects in the camera's FOV during data analysis. Distances from the centerline of the truck are marked in 1.5 m (5 ft) increments on the longitudinal lines. Distances from the axle are marked along the centerline.

2.4. Data collection system

Researchers wished to determine what types of objects were detected by the radar system and how often the system would alarm during the course of normal operations. To do this, video footage from the rear camera was recorded on a digital video recorder. The recorder also saved the time and duration of all radar alarms from the rear system. When the video footage was reviewed, the recorder software overlaid text on the video to signify that an alarm had occurred. Fig. 7 shows a screenshot of the recorder viewing software. The "radar" text on the upper right of the video indicates that an alarm was occurring during that segment.

2.5. Test description

Video and radar alarms from the rear-mounted systems were recorded for 7 days while the truck was in use during normal operations, which consisted mainly of the load/haul/dump process and occasional parking maneuvers for break time or truck maintenance. Video and radar alarms were recorded only when the truck was in reverse and started immediately after the reverse gear had been selected. Because of data storage limitations, data from the front of the truck were not collected and may be the subject of a later study.

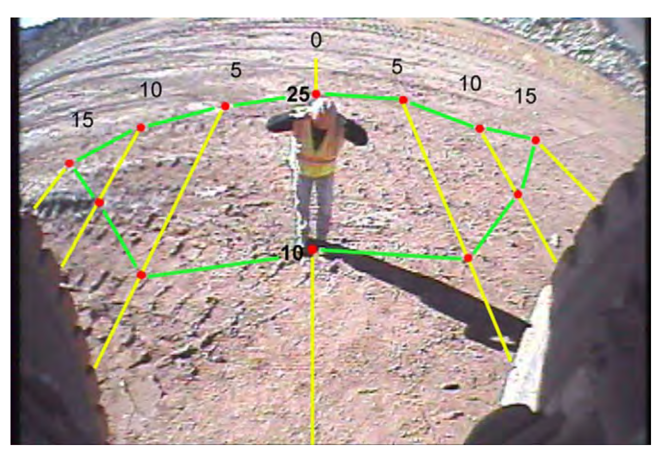

Fig. 6. Rear radar detection area as seen from video monitor (distances in ft).

Fig. 7. Screen shot of video viewing software.

3. Results

3.1. Data analysis

While reviewing the 7 days of video footage, the following items were recorded manually: date and time of reverse movement of the truck, the activity of the truck (loading, dumping, parking), the alarm type based on what was visible in the video during the alarm (true, false, missed—defined below) and a description of what was visible in the video.

3.2. Alarm definitions

A radar alarm was considered true if an object larger than approximately 30 cm (12 in.) high was inside the area contained in the detection area of the radar. An alarm was considered false if no object larger than 30 cm (12 in.) high was present inside the detection area. False alarms included detection of ruts, small dirt berms, small rocks or foliage. Missed alarms occurred when a large object was within the radar detection area, but no alarm was generated.

True alarms contain the subset of nuisance alarms. Nuisance alarms are defined as those alarms from objects of which the operator is already aware and there is little or no risk associated with the situation. Nuisance alarms are partially determined from context because the truck operator's awareness is assumed. For example, backing to a rock pile in the loading area presents little risk because: (1) the truck tires may strike the rock pile without causing damage; (2) the truck cannot over-travel the rock pile; (3) the operator is positioning the truck while moving at a slow speed and is aware of the rock pile. On the other hand, detecting the berm at a dump point is not considered a nuisance alarm, even if the driver is aware of the berm. Backing to a dump point requires extra caution, and over-traveling the berm, in most cases, would result in the truck going over the edge of a high embankment.

Table 1
Radar alarm data

Event	Quantity	Percentage
Reverse movements of truck	618	
Total alarms	580	
True alarms	478	82 of all alarms
False alarms	102	18 of all alarms
Nuisance alarms	243	42 of all alarms (51 of true alarms)
Missed alarms	0	
Reverse movements with no alarm	38	

3.3. Data

Using the above definitions, Table 1 summarizes the number and types of alarms recorded.

4. Discussion

4.1. False and nuisance alarms

During the 7-day test, the truck was moved in reverse 618 times. Ninety-four percent of the time an alarm was generated during reverse movement, but only 235 alarms (41%) actually required immediate action or extra caution from the truck operator. The high number of alarms that do not in reality represent dangerous situations, which include false and nuisance alarms, will create problems if operators lose confidence in the system and start to ignore alarms altogether (Bliss et al., 1995; Breznitz, 1984; Sorkin, 1988).

Thus, a trade-off exists between adequate sensitivity for detecting objects near the truck and the probability of false alarms (Parasuraman et al., 1997). Sensor manufacturers have an understandable propensity toward alarming because of the potentially high cost of a missed detection (Bliss and Acton, 2003). If an object as small as a person must be detected, then other objects, such as ruts or rocks, may be detected also. Nuisance alarms are inevitable because maneuvering is required near objects that are not in danger of being hit.

False alarms affect more than an operator's trust of the radar system. Kerstholt and Passenier (2000) showed that people perform less accurately in the event of a real disturbance when there was a known probability of false alarms. They also took more time to diagnose a disturbance, which could have significant impact in the outcome of a potential collision. Bliss and Dunn (2000) showed that alarm responses can be further degraded when the response requires high workload levels. For example, in the case of proximity warning for mining equipment, numerous false alarms and the effort required for verification may affect the operator's willingness to recheck mirrors or a video monitor, much less leave the cab to check personally on the source of the alarm.

4.2. Alarm presentation

These test results and conclusions from previous studies caused researchers to reconsider the design of the audible functions of the radar display. The audible alarm, as tested, provided continuous pulses that changed pulse frequency as an object came closer to the truck—the nearer the object, the faster the pulses. Driver feedback indicated that this was annoying, especially when the majority of alarms did not signify danger. Driver feedback consisted mainly of researchers finding the audible functions of the alarm display disabled at the end of the shift and some anecdotal evidence.

In the surface mining application, it could be argued that the radar system's alarms should be used to primarily prompt an operator to check a video monitor that shows a corresponding camera view. The alarms rarely merited an immediate braking action. After the operator is prompted to check the video, then he or she can make a determination as to the need for braking action, continuing to reverse with extra caution, or continuing to reverse with no added concern. The importance of providing redundant information is supported by Bliss and Acton (2003) in a study of automobile collision warning systems where low alarm reliability caused test subjects to rely heavily on the rear-view mirror to verify alarms. Another consideration is the fact that off-highway dump trucks are not often operated in congested areas and the probability of a collision is low. According to Parasuraman et al. (1997), the probability that an alarm represents a true condition is of vital importance to the operator and must be reflected in the alarm design.

Researchers worked with the sensor manufacturer to modify the alarms to more accurately reflect the fact that they should cause the operator to check the video monitor. The goal was to further grade the warning as described by Sorkin (1988) while considering the low probability of the need for immediate braking, i.e. instead of a continuous audible alarm when an object is detected, the alarm now sounds a series of three fast pulses only once. No additional audible alarm is generated until the object enters the zone closest to the truck, at which point the audible pulses become continuous again. Ideally, the closest zone would be within 0–4.6 m (15 ft) of the rear axle, which would require modifications to the current radar detection area. The LED's of the visual display would function as normal, always indicating the distance to an object anywhere in the detection area. Tests are currently being conducted to determine if this is an acceptable alarm scheme.

Other types of alarm presentations may also be studied. For example, a synthesized voice warning that simply states "check video" one time after an object enters the detection area may be examined. It may also be beneficial to integrate the radar's visual alarms and distance readout with a camera view so they can be simultaneously displayed on the video monitor. This may simplify the alarm response task and eliminate the need for an additional display enclosure.

Additional research is needed to understand the effects of the increased workload on an operator that comes from having to monitor both proximity warning alarms and video information. Legitimate concerns have been expressed as to whether an operator may become overloaded with information. Bliss and Dunn (2000) have shown that a combination of low alarm system reliability and increased alarm response workload may further degrade response frequency and reaction times. However, benefits may result from combining radar with cameras on surface mining equipment if the additional task of checking the monitor can be kept as simple as possible. Integrating the radar alarm into the video display and placing the video monitor in an intuitive and convenient location may help reduce workload.

5. Conclusions

In reviewing the MSHA fatality narratives of collisions involving mining equipment, researchers estimate that all but one of the fatalities could have been avoided if a reliable system for monitoring the blind areas had been installed (MSHA, 1999–2003). The single case in question involved a person lying underneath the equipment when it was moved. NIOSH is studying available technologies that can be used to assist equipment operators in monitoring blind spots. Modifications to existing sensor and camera systems have been recommended based on test results.

This study showed that an available radar system successfully detected objects in the rear blind areas of a large, off-highway dump truck and could be used to help avoid collisions with smaller vehicles, workers on foot or other obstacles. Because of numerous alarms that did not represent immediate danger, a visual method of monitoring the blind areas, such as video cameras, should be added so an operator can check the source and urgency of any alarms. Also, the audible alarming functions of the radar system must be redesigned to convey context-appropriate warnings to decrease the chance that alarms would be ignored.

Cameras have been a popular means of monitoring blind spots, but a recent accident and the fact that they do not provide an alarming function have raised concerns about their effectiveness. The combination of cameras and radar shows potential for overcoming the drawbacks of each single system by itself. A more comprehensive study to determine the effect that these technologies may have on accident rates over a longer term was outside the scope of this work, but may be the subject of future research.

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