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AN OVERVIEW OF METHODS AND PARAMETERS TO EVALUATE DETECTION PERFORMANCE AND VALIDATION OF COLLISION WARNING AND AVOIDANCE SYSTEMS

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ABSTRACT

Between 2005 and 2021, a NIOSH internal review showed that haul trucks were involved in 54 incidents at surface mines in the United States. Haul truck collision warning and avoidance systems (CXS) can assist in preventing accidents at surface mines. CXS use technologies to detect people or objects and alarm to alert haul truck operators. Robust testing can help ensure that they detect objects without excessive false positive alarms. Testing and validation would increase confidence in and encourage implementation of a CXS. Researchers from the National Institute for Occupational Safety and Health (NIOSH) reviewed documents related to the evaluation and validation of CXS with two objectives: (1) to identify methods and parameters used to evaluate detection performance and (2) to identify gaps in CXS test methods and in detection performance. Stakeholders can use the findings from this research to guide implementation of CXS to improve safety at surface mines.

INTRODUCTION

In surface mining, there are inherent conditions and constraints that contribute to hazards in haul truck operation for the operators and other individuals in the surrounding environment. Environmental conditions such as dust, fog, or rain may prevent the operator from clearly locating surrounding equipment or workers. In addition to environmental concerns, the haul truck operator must overcome limited visibility because of the size of the haul truck. For example, a Caterpillar 777F haul truck measures 6.49 m (21.4 ft) wide, 10.5 m (34.7 ft) long, and 5.2 m (17.0 ft) high [**1**]. The operator's visibility of nearby objects is limited due to blind spots created by the machine's size and design. In addition, the haul truck has significant momentum when in motion, regardless if it is empty at 74,194 kg (163,568 lbs.) or loaded at 163,293 kg (360,000 lbs.) [**1**]. Therefore, the operator would need real-time information about the surrounding areas and adequate timely alerts to prevent accidents. From a review of MSHA fatality reports, we identified 54 incidents that involved haul trucks from 2005 to 2021 [**2**]. It is possible that a portion of these accidents could have been prevented with the use of a collision warning and avoidance system (CXS).

A CXS can exist in various configurations and incorporate different technologies to improve a haul truck operator's situational awareness of and ability to navigate their surroundings safely [**3**]. Commercially available CXS technologies include but are not limited to Radio Detection and Ranging (Radar), Light Detection and Ranging (LiDAR), Radio Frequency (RF), Global Navigation Satellite Systems (GNSS), and video cameras. A radar is a sensor that produces and discharges its own radio waves to determine location, speed, and angle of an object. LiDAR is a sensor that uses laser to locate objects in space [**4**]. Radio frequency (RF) uses time for the signal to propagate between the equipment fitted with RF sensors to determine the distance between them [**4**]. GNSS relies on satellite technologies to determine its position on earth. A CXS can use one technology or a combination of technologies to detect surrounding objects.

The collision warning system concept has three major aspects. First, the sensing element of these technologies can detect nearby objects or can provide localization information such as relative position and heading. The information from the sensing element is transmitted to the filtering and computing elements. Next, the filtering and computing elements would decide based on the information from the sensing element and the risk of collisions. Finally, the CXS would alert the operator whenever an object or person is in the vicinity of the haul truck [**4**]. According to ISO 21815-1, unlike a collision warning system, a collision avoidance system can intervene by braking or preventing motion [**46**].

CXS technologies present a great opportunity to improve haul truck safety in surface mining operations by detecting possible collisions before they can occur. The addition of CXS technologies can assist the drivers while navigating these potentially dangerous settings by providing timely detection to avoid collisions. Therefore, the object detection components of the CXS architecture become an item of interest for CXS validation [**5**]. For this reason, NIOSH researchers conducted a literature review to identify relevant documents related to test methods for evaluating the detection performance and validating CXS.

Because testing and validating CXS technologies is not widely standardized in the mining industry, an atmosphere of reluctance, uncertainty, and mistrust exists. A solid sense of trust could be established if there were standard methods to test and validate that a CXS functions as intended. Two types of tests that could be the foundation for trust in CXS technologies are identified. The first test should seek to test for false positives where there is no hazard present, and an alarm occurs. The second test should address false negatives where a hazard is present, but the alarm does not occur. These tests should be done in a standardized manner. If such standardized tests were developed, the mining industry and researchers would benefit from robust experiments to determine general performance and the effects of variables such as weather, road grade percentage, and mounting considerations.

LITERATURE REVIEW METHOD

Our method was to review published documents from various databases that evaluated CXS performance, implementation, or effectiveness. Using 13 electronic databases, we reviewed CXS-related documents from industries where CXS technologies are most to least prevalent such as automotive, mining, construction, and agriculture. To help narrow our search for relevant documents, we used a list of keywords related to CXS and heavy equipment. For example, we used keywords like "collision," "avoidance," "object detection," "vehicle-to-vehicle (V2V)," "vehicle-to-infrastructure (V2I)," and "vehicle-to-everything (V2X)". We used the following criteria for our search: (1) be published between 2000–present, (2) be in the English language, (3) be a peer-reviewed article, conference proceeding, government agency publication, or standard, and (4) include information regarding field and laboratory tests, simulation related to CXS technologies, or a combination of simulation and field test validation. The following sections summarize the literature review findings regarding CXS testing methods and relevant parameters.

RELEVANT LITERATURE

Automotive

For the automotive industry, NIOSH researchers identified three approaches to test and validate CXS systems: static/ dynamic, scenario-specific, and computer-aided modeling or simulation-based. For the static/dynamic approach, there were two portions depending on the state of the ego vehicle (term in the automotive industry used to define the subject vehicle with all the sensors): static and/or dynamic. On the static portion, researchers positioned the static ego vehicle—the vehicle equipped with CXS—at a selected origin and moved the target objects or vehicles at various distances and orientations with respect to the ego vehicle and recorded the target's coordinates when an alarm occurred. For the dynamic portion, the roles were reversed; the researchers moved the ego vehicle toward the remote objects (which were static) to observe the coordinates of the moving vehicle when a CXS alarm was triggered. For the scenario-specific approach, the researchers conducted field or track tests based on specific scenarios or configurations of vehicle interaction. Usually, researchers selected specific scenarios with high likelihood of incidents observed from crash incident databases. Generally, for this type of approach, the researchers allowed both the ego and the target vehicle to be in motion in a controlled setting such as a test track. For the third type of approach, computer-aided modeling, the researchers relied mainly on computer-aided simulation to model pertinent scenarios and validated or tuned their models based on field testing results of the first (static/dynamic) or second approach (scenario-specific) or both. Researchers in the automotive industry applied all three approaches in a controlled environment. In these approaches, they used input parameters like relative speed, distance, position, decelerations, or orientations to then measure outputs that demonstrate the performance of the CXS, such as false positive and negative detections, true positive (an alarm is generated at an unsafe distance) and negative detections (no alarm is generated at an unsafe distance), and onset timing. We will discuss the findings of all three approaches in the paragraphs below.

Automotive researchers used the static/dynamic approach to assess four critical sets of measures for CXS. One set of tests examined the coarse capabilities and limits of a CXS. These rough capabilities and limits included detection range and range accuracy, relative speed, and speed accuracy. Researchers used the static/dynamic approach to evaluate performance of three radars when the field-of-view was overlapped [**6**]. These evaluations were usually carried out in ideal conditions with specific requirements such as the exclusion of foreign objects not related to testing [**7-10**]. The second set of tests examined the calibration of [**11**] and behavior of CXS sensors in different configurations. The third set of tests focused on CXS field response for imminent collision hazards using known grid points. Lastly, researchers generally used this approach to assess the likelihood of response per zone, the longitudinal and lateral distance at the alert onset [**57**]. For example, researchers used alert onset timing to calculate time-to-collision (TTC) to evaluate last-second braking and last-second steering judgment of test participants [**12**]. We found in some cases that researchers also used this approach as a baseline for the scenario-specific approach and/or computer-aided model approach [**19**].

Researchers in the automotive industries used the scenario-specific approach to test the performance of CXS technologies using typical collision hazards that a vehicle operator could encounter during routine operations. These collision hazards included: civil structures [**13**], sudden stopping of target vehicles [**14**], vehicle crossing at an intersection, and pedestrian intruding in the path of the ego vehicle. The aim of this approach was to assess CXS response when these collision hazards were imminent. For example, Tiernan et al. assessed the response of a CXS in a range of specific scenarios that involved two vehicles crossing at an intersection [**15**]. They assessed CXS response when collision hazards were present and then absent. When the threat was present, they looked for the vehicle to generate a true positive alert. Because the system also had autonomous braking capabilities, they also observed if the CXS initiated braking when collision hazards were imminent. Similarly, researchers in the automotive industry evaluated a semi-truck equipped with autonomous emergency braking (AEB) for straight line and cut-in scenarios using a range of speeds. They aimed to investigate the reduction in reaction time between volunteer drivers and the AEB system [**16**]. While the measurement methods are not described, AEB could be a critical factor for a CXS. This study also investigated the effect that surface conditions and payload may have on braking performance in terms of stopping distance.

NIOSH researchers found that the scenario-specific approach had real-world benefits and challenges. For benefits, the second approach—scenario specific—presented an opportunity to test for false/true positives. For example, Schratter et al. tested for the false/true positive response of CXS systems with autonomous braking capability in two scenarios [**17**]. One scenario required braking intervention, and the other did not. They labeled any braking in the scenario that did not require braking as a false positive reaction of the CXS. It seems that there are some challenges in terms of measuring and validating the relative position of both vehicles while they are in motion at a relatively high speed. Ahmed-Zaid et al. studied two GPS relative positioning methods for a V2V CXS: real-time kinematic (RTK) and single point (SP). Researchers in the automotive industry found GPS positioning using RTK was better than using the SP method [**18**].

NIOSH researchers found that the computer-aided modeling approach was an extended approach of the scenario-specific approach or static/dynamic approach and, in one case, both. Researchers in the automotive industry typically select specific scenarios to test and use the results as a baseline to generate data for the computer simulation. In the simulation-based approach, Van Auken et al. modeled scenarios, sensors, and vehicle dynamics [**19**]. Using this approach, Carpenter et al. assessed the performance of CXS by analyzing different sensor combinations without adding extra time or cost [**7**]. Another research article discussed algorithm development to investigate the decision making of a CXS [**20**]. The researchers subjected the algorithm to 30 different simulation scenarios and validated the algorithm by conducting field tests.

Automotive-related Standards

CXS end-users can rely on standards and articles to address safety concerns within their own operation, but different terminology can be used throughout the various documents. This can lead to misinterpretation of the information and result in the improper implementation of a safety system or imprecise application of a test procedure. Therefore, a consistent vocabulary is crucial when developing documents containing information regarding safety systems. SAE J2944 focuses on providing and encouraging the use of common terms and definitions for safety system performance measures [**21**]. Since safety systems may range from zero- to full-driving automation, a classification of the roles and responsibilities of both the driver and system for the various levels of driving automation allows an end-user to understand the expectations when implementing such a system [**22**]. For example, Tables 1 and 2 in SAE J3016 detail the roles of the user and automation system for dynamic driving tasks and responses for the six levels of driving automation [**22**]. Understanding these roles for the system being used will improve a system's capability of fulfilling its intended safety functions by reducing risk. Aside from understanding the roles and common terminology, an end-user may benefit greatly from knowledge of sensors used in a CXS [**3**]. SAE J3088 covers operating principles, strengths, performance factors, limitations, and applications for an extensive list of sensors and technologies. Additionally, automotive researchers discuss specific CXS detection capabilities and requirements [**23**, **24**]. Lastly, SAE J3116 provides comprehensive details regarding a test manikin intended to represent a pedestrian [**25**]. Overall, these documents provide a solid knowledge base and should be referenced when implementing or testing a safety system.

Mining

From the documents that NIOSH researchers reviewed, researchers in the mining industry seemed to apply the three previously mentioned approaches—static/dynamic, scenario-specific, computer-aided modeling — to test the detection performance of CXS. One key organization in CXS validation, the Australian Coal Industry's Research Program (ACARP), funded research to develop, implement, and evaluate the effectiveness of CXS on surface mining haul trucks. Their researchers developed a proximity detection system (PDS) validation framework [**4**]. They divided the framework into two tiers based on two failure modes. Tier 1 testing deals with the object detection performance of a PDS, while Tier 2 validates the intelligence layer. Tier 1 has four parts: field-of-view validation, dynamic variables testing, noise variables testing, and site terrain variables testing.

Using the first portion of the static/dynamic approach, ACARP-funded researchers discussed how to measure the detection zone around a haul truck [**26**]. In this setting, the haul truck was static while the target object—a light vehicle or person—was moving. They conducted two variations of static tests depending on the target object. In one variation, they allowed the light vehicle to move in a straight line at three different speeds in different orientations. In the other variation, a person walked at a normal pace and stopped at the alert onset or at the designated stopping zone. For the dynamic portion, ACARP-funded researchers conducted tests where the target vehicle started at a predetermined position and traveled in an arc or straight path. These researchers used this approach to conduct noise variable testing. Noise variable testing involves the target object in the vicinity but off the path of the ego vehicle. These target objects can interfere with the accuracy measurement but represent no immediate collision risk for the haul truck. In addition, ACARP-funded researchers used the first approach for field-of-view validation. The goal of the field-of-view validation was to measure the detection zone of the PDS using a target object at a series of pre-surveyed points with respect to the haul truck and compare that to the user specifications.

Using the scenario-specific approach, the ACARP-funded researchers identified six incident-prone scenarios, dynamic variables, and cases that are critical for CXS detection performance evaluation [**4**]. They concluded that it was unsafe to test all six scenarios. For example, the intersection and void tests have a higher risk of collision or fall that could injure the operator. For this reason, they recommended computer-aided modeling to mitigate the risk in these scenarios. They discussed the possible use of the scenario-specific approach to determine the effect of site terrain variables on the PDS's immunity against slopes gradients and high walls. In each of these tests, there are many factors involved that make testing every possible combination impractical. For that reason, the researchers drafted a plan using Taguchi orthogonal arrays to reduce the number of runs for a given number of factors while maintaining an appropriate level of scientific rigor. For example, a test that includes 7 different variables would require 128 runs to cover every permutation. With a Taguchi design, the same test can be completed in only 8 runs. In addition, they discussed the specific-scenario approach for dynamic variable testing of the different vehicle interaction scenarios outlined in Earth Moving Equipment Safety Round Table (EMESRT) PR-5A [**27**]. The variables in this test included speed, lateral off-sets, separation distances, and heading [**4**]. The PDS is tested against four scenario classes, which were condensed from the PR-5A L1-L7 scenarios. In addition, they proposed four cases for the four test scenarios to assess alert onset using the scenario-specific approach, including: 1) a clear positive case, a scenario where two vehicles are clearly headed for interaction, 2) an edge positive case, a scenario where two vehicles are headed for interaction but marginally misjudged clearance, 3) a clear negative case, a scenario where two vehicles are clearly not headed for interaction but passing head-on with sufficient clearance, and 4) an edge negative case, a scenario where two vehicles are not headed for interaction but only marginally.

To assess correlation between simulation and testing, ACARP-funded researchers modeled the conditions of previously conduced field tests of two types of CXS: a radio frequency tagging system and a continuous wave Doppler radar system [**28**]. At the time of the report, the Doppler radar system was still in the prototype phase, while the tagging system was in the process of being introduced to a mine in Australia.

Outside of ACARP, several documents from the OneMine database **[29-35]** covered the three stated approaches to testing and validating CXS technologies. For example, researchers in the mining industry applied the static/dynamic approach to assess detection performance of CXS technologies in field or laboratory conditions using the SAE J1741 standard [**36**]. In the reviewed documents, the controlled testing essentially consists of evaluating perceived detections while moving a target between grid points or moving the vehicle in a known and controlled manner with a static target at the grid points [**31-35**]. Further testing evaluated a system when installed on a machine to examine the performance and limitations during actual operation [**29-35**]. Test results of these studies included reliable and sporadic detection zone outlines and false detection insight [**31-35**]. In addition, researchers in the mining industry proposed the concept of developing computer-generated test grids that may be used for simulation **[23, 37-39**]. The information provided in these studies can be used to validate position data prior to and during CXS performance tests.

Mining-related Standards

For the mining industry, NIOSH researchers identified nine CXS-related standards from the International Organization for Standardization (ISO). ISO develops and publishes technology-related standards covering various industries to improve safety through standardization of practices. Within ISO, there are two sub-committees of the Earth-moving Machinery Technical Committee that publish machine-safety-related standards: TC127/SC1, which covers test methods related to safety and machine performance, and TC127/SC2, which addresses safety, ergonomics, and general requirements. We identified four standards related to testing and validating CXS performance published under SC1 and five under SC2 (see Table 1).

Table 1. Relevant ISO standards.

SC1	***SC2***
ISO 5006:2017	ISO 9533:2010
ISO 14401-1:2009	ISO 17757:2019
ISO 14401-2:2009	ISO/DIS 21815-1
ISO 16001:2017	ISO/DIS 21815-2
	ISO/DIS 21815-3

Among the relevant standards published under SC1, ISO 16001 addresses technology aimed to improve visibility around mobile equipment, specifically through object detection systems and visibility aids [**40**]. This standard outlines some advantages and disadvantages when considering CXS device selection and specifies requirements and test procedures to evaluate the general technology-specific performance of these devices. These include test procedures and performance requirements for radar, ultrasonic systems, electromagnetic signal systems, and camera-based systems using the static/dynamic approach. The output parameters discussed in these test procedures include detection range, detection zone (width and distance), detection time, and target differentiation (human and other object) for camera-based systems.

The remaining relevant standards under SC1 address the operator's direct and assisted field-of-view surrounding large mobile equipment. In mining and other industries that require the use of large mobile equipment such as off-road haul trucks, collision-related accidents result from a lack of visibility where the operator does not have a complete view of the surrounding area. ISO 5006 provides standard methods to determine the operator's field-of-view [**41**]. Information provided in this standard considers human physical characteristics of the operator and persons within proximity of the machinery. This includes haul trucks used in surface mining. This standard also provides performance criteria for determining acceptable levels of visibility based on machine dimensions. ISO 14401 defines test methods and performance criteria for mirrors that supplement an equipment operator's rear field-of-view [**42**, **43**]. The standard specifies that the field-of-vision provided by rear-view mirrors must include defined areas to the left and right sides of a machine including outer ground contact points of the rear tires for haul trucks. Combined, ISO 5006 and 14401 provide standard test methods and criteria addressing an operator's field-of-view and field-of-vision for machinery. These standards provide an objective means for defining areas with limited or inadequate visibility and implementing mirrors for improving an operator's vision of surrounding equipment.

Relevant standards developed under SC2 address audible warning devices as well as autonomous and semi-autonomous equipment and those related to collision warning and avoidance [**44-48**]. Of these standards covered by SC2, ISO 9533 is on the basic end of the technology spectrum [**44**]. This standard covers performance criteria and test methods for evaluating machine-mounted backup alarms and horns used to warn those in the vicinity of mobile equipment. SAE International also provides a test method for qualifying backup alarms for off-road mobile equipment within SAE J1741 [**36**]. ISO 21815 is a standard for collision warning and avoidance systems that is under development. To date, the first edition for parts 1 and 2 of this standard are available [**46, 47**]. Part 1 covers general requirements including performance, system classification, and test procedures. Within Part 1, general performance requirements are deferred to existing standards, including ISO 13766 for electromagnetic compatibility, ISO 12100 for risk assessment, and ISO 16001 for object detection [**40**, **49, 50**]. Additional criteria are defined for system classification that encompass various types and combinations of condition-based system capabilities. Taking haul trucks for example, those described within Part 1 are, but not limited to, take-off inhibition, maneuvering speed, and travel speed. Part 1 also more clearly defines the similarities and differences between visibility aids, object detection systems, collision warning systems, and collision avoidance systems. Here, the primary difference between CXS types is that these systems include some degree of risk level assessment prior to providing a warning or interventional action. The approach for Part 1 includes the specific use-case requirements that are not technology specific [**46**]. Part 2 of ISO 21815 pertains to standardized communications for CXS, referencing the SAE communication network standard for heavy-duty vehicles (J1939) [**47**, **51**]. Risk areas and levels covered by CXS will fall under Part 3 of ISO 21815[**48**]. This standard is currently under development and unavailable for public view. Both object detection systems and CXS utilize automation enabling technologies. Autonomous and semi-autonomous mobile mining machines used at surface operations are specifically addressed by ISO 17757 [**45**].

Construction and Agriculture

NIOSH researchers reviewed relevant documents and standards regarding construction equipment to determine what test method, parameters, and measures were used to test or validate CXS. CXS technologies seem to be more prevalent in the construction industry than the agricultural industry. This might be the result of differences between vehicle interactions in both industries. Construction equipment is frequently used in low visibility applications—either due to the equipment backing up, swinging around, negotiating blind corners, or operating in inclement weather. Thus, proximity detection of equipment and personnel are of interest to the industry to prevent collisions. Of particular interest are testing methods used to determine the effectiveness of CXS.

Using the static/dynamic approach, Jo et al. performed tests to determine the field of coverage of an excavator's radio-frequency identification (RFID) based system [**52**]. They tested multiple approach angles and recorded the distance when an alarm occurred after conducting a temperature cycled test. The aim of the temperature cycle test was to assess the robustness of the system when subjected to cyclical temperature changes within an air environment. SAE J1741 discussed used the static/dynamic approach for three separate inadvertent detection tests for false positives. The first involved placing a test body outside of the detection zone. The second involves placing a sheet of 12-mm-thick plywood at twice the full detection zone distance along the machine's centerline, moving it left, and then moving it right. The third test simulates the effects of curbs and stones using five cinder blocks placed with their long edges parallel to the machine's detection zone centerline. The system is deemed to have passed the inadvertent detection test if the object was detected in fewer than 10% of tests. In addition, construction industry researchers provided pedestrian target recommendations for this type of test [**36**]. The relevant parameters related to the static/dynamic approach include machine size, sensor mounting requirements, detection zone, and detection time.

Previous NIOSH research examined CXS systems on trucks where the primary concern was preventing back-over accidents [**53**, **54**]. The testing was aimed mostly at system performance in severe environmental conditions (rain, snow, and mud) and secondarily at sensor locations that would maximize the field of view (FoV). The collision warning technologies used in these systems were radar, ultrasonic, and/or vision, and the parameters tracked during these tests included sensor location, FoV, range, vehicle speed, sensor response time, range reduction due to severity of conditions, and nuisance alarms. NIOSH researchers discovered some challenges in implementing the tested CXS in a congested work environment and during winter months. The sensor-based system generated nuisance alarms more often in a congested workplace. In contrast, the camera based CXS were a more passive method of monitoring. However, camera-based systems were not as effective in winter weather as in warmer temperatures due to snow and grime build-up. The combination of both sensor and camera based CXS might offer some advantages.

The CXS-related documents that NIOSH researchers reviewed in the agricultural sector had minimal instructions on detection performance and system validation. However, we reviewed an ISO standard that establishes procedures for testing the accuracy of positioning and guidance systems in agriculture [**55, 56**]. It is also important to note that while useful, only testing the accuracy of a GPS is insufficient to validate a CXS. The tests found in ISO 12188 could only supplement other tests that are more specific to the ability of a CXS to prevent collisions. However, for a CXS to be effective, its GPS needs to have a certain level of accuracy, and these standards provide methods for making those measurements.

LIMITATIONS

The search strategy used in this literature review may not have provided all the available documentation related to testing methods and validation of CXS technologies. In addition, we did not have access to the manufacturers' research and documentation because it is proprietary and mostly undisclosed.

CONCLUSIONS

NIOSH researchers reviewed and documented the different approaches to test and evaluate detection performance of collision warning and avoidance systems (CXS). Our review included documents from the automotive, mining, construction, and agricultural industries to observe testing methods, parameters, and measures, and to assess gaps in terms of testing and validation methods concerning detection performance. We identified several research gaps that we consider topics for further investigation or update. These research gaps included: test methods for false positives, standard test/simulation methods and procedures, design of experiments, clear assessment of CXS limits and capabilities, the effects of environment (e.g., sun glare on a camera-based system), the performance of CXS at dump points or drop-off hazards, and test methods and procedures for target recognition-based systems. We found that existing standards lay the groundwork for testing; however, there are gaps in terms of validating actual CXS performance. The identified research and frameworks afford a great deal of insight, but significant work is still needed to address gaps for CXS validation with respect to real-world performance.

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. Mention of any company or product does not constitute endorsement by NIOSH.

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