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Human-machine interface safety in construction: Protecting workers and equipment

Romel C. Deloso, Mohammed A. Aldossary, Samuel Ojo. Aladesoyin, Feras K Alfosail *, Hashim B. Awami, Ahmed S. Ghamdi and Samir A. Nujaim

Project Management, Saudi Aramco, P.O. Box 5000, Dhahran 31311, Saudi Arabia.

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Abstract

The operation of heavy equipment on construction sites presents one of the most significant safety risks in industrial projects. In order to address these challenges and enhance both safety and efficiency within the Fadhili Increment Projects Department, a comprehensive Human-Machine Interface (HMI) safety system has been implemented. This multi-layer system integrates multiple advanced measures to enhance operational efficiency and improve personnel protection across all construction activities. First, a strict "No Foot-on-Ground" policy has been established to prevent personnel from entering active equipment zones, thereby reducing the risk of human-machine interaction during critical operations. Second, equipment alert technologies have been introduced to enhance real-time awareness for operators. Third, proximity warning alarm systems (PWAS) are used to alert workers and operators when they are in close proximity, helping to prevent potential collisions. Additionally, rear-view closed-circuit cameras (CCTV) systems have been installed on vehicles to improve visibility and support safer movement in complex environments. Finally, targeted hazard identification training has been provided to heavy equipment operators and flagmen, ensuring they are equipped to recognize and respond to potential risks. Combining advanced technologies with well-defined safety protocols, Fadhili team has set a new standard for construction safety and operational excellence within Saudi Aramco's project portfolio

Keywords: Construction Site Safety; Risk Mitigation; Machine Interface Design; Safety Protocols; Construction Equipment Operation

1. Introduction

One of the primary objectives for construction contractor during projects is to lead a business model that is able to incorporate effective occupational health, safety and environment leadership and protocols. This is critical to maintaining a HSE excellence culture, fulfilling stakeholders' expectations, and enabling employees to work safely and reach self-actualization. One of the main ways to achieve these objectives is through compliance with all relevant laws and regulations. Additionally, seeking to demonstrate respect for the society in which operations take place as well as working towards the goal of no accidents, harm to people, or damage to equipment. Additionally, formal effective risk management programs are in place to identify, evaluate, and manage HSE risks and the identification of the high-risk activities at an early stage during projects, because of many heavy equipment operations. Therefore, a "NO FOOT ON GROUND" policy has been adapted to mitigate the risks. In simple terms, the policy states that the inspector or responsible supervisor shall halt the operation of surrounding equipment to prevent any potential incident when it is necessary to inspect the area. To support this policy all personnel have been equipped with skills, training and knowledge to fulfill the requirements. In addition, measurement of the performance is conducted regularly to promote continuous improvement.

* Corresponding author: Feras K Alfosail.

Research shows:

- Equipment-related incidents account for over 25% of construction fatalities globally [1].
- Blind spots and proximity risks are primary contributors to struck-by incidents [2].

Moreover, in the event that such policy become impractical and not feasible, a Human/ Machine Interface (HMI) plan for heavy equipment operation is to be developed to mitigate potential risks and/or avoid negative factors to the human (Workmen) machines (Heavy Equipment) and environment and adjacent community concerning the traffic during construction activities. The plan includes control measures aimed at minimizing disruption and risk to others during heavy equipment operation in line with Safety Construction Manual (CSM) of Saudi Aramco [1]. In addition to the management plan, several aspects have been considered to enhance the effectiveness related to:

- Heavy Equipment Design and Safety Technologies Features
- Pre-Use Inspections & Maintenance
- Worksite Controls & Zoning
- Operator Qualifications & Training
- Personal Protective Equipment (PPE)
- Supervisory Oversight, Audits and Campaigns

By integrating these behavioral safety controls, sensor-based technologies and operational zoning strategies, organizations can minimize risks from human-machine interactions, ensuring compliance with safety standards and reducing incidents during heavy equipment operations. Further details to the aspects are provided in subsequent section of the article.

2. Heavy Equipment Design and Safety Technologies Features

Saudi Aramco in projects and operations outlines comprehensive requirements aimed at ensuring structural integrity, operational safety, and long-term reliability—particularly in demanding industrial environments. The design of the equipment has specific standards to ensure safe and compliant use across its onshore and offshore facilities. In particular, the design and operation of the heavy equipment must meet the requirements of OSHA standards, international standards, and the relevant General Instructions (GIs) of Saudi Aramco. The design of the equipment includes load test verification to ensure that equipment such as cranes are rated for the load capacities. For construction sites, additional safety mitigation measures have been adapted to reduce and manage the risks associate with human / machine interface. These measures include some of the latest safety feature and technological advancement:

- An audible reverse alarm that is at least 10 dB above ambient noise enough to alert any nearby worker or personnel
- Enhance visibility by
 - Install rear view closed-circuit cameras. The rear view camera has the to view the area behind the equipment to a distance of at least ten (10) meters. This allows the operator to navigate and maneuver easily even at congested site locations. The utilization of such system enhances the visibility of the on-ground personnel and eliminates the blind spots and support the decision-making of the heavy equipment operator. Additionally, some cameras have additional capabilities to utilize colors identifying hazards around the vehicle using colored display and operator in low light environments. Figure 1 shows how the rear-view camera system is able to demonstrate to the heavy equipment operator the presence of a personnel at the worksite in a blind spot zone.



Figure 1 Rear View Camera System on Excavator

- Use of proximity warning alert system (PWAS). The PWAS has the functionality to detect personnel located at the rear of the equipment up to 6 meters, to a distance of at least six (6) meters of the equipment with the installed Display and activate an alarm notifying the equipment operator of a hazard. Refer to the figure 2 showing the distance covered by the PWAS on heavy equipment vehicles. The utilization of the PWAS system in heavy equipment can reduce the occupational fatalities in construction sites by 11% [3].



Figure 2 Rear View Camera System on Excavator

- Mounting high-visibility lighting to address low-visibility areas
 - Equip all heavy equipment with easily accessible emergency shutdown switch and the need to have dual controls and operators for some heavy equipment such as manlifts where lower controls can be override-capable for emergencies complying with ANSI/SIA A92.2 requirements
 - Deploying flagger assisted equipment alert technology. This technology focuses on identifying hazards and threats that the heavy equipment operator is an aware of but the flagman does. This allows the flag man to activate the alarm wirelessly in the cabin suspending the operations activity when endangered. This device is utilized in addition to the audible whistle that is utilized for spotting purpose as shown in figure 3.



Figure 3 Flagman Wireless Alert System for Heavy Equipment

- Heavy equipment vehicles have been equipped with automatic vehicle locator (AVL) to monitor the road speeds and proximity of vehicles in the field from each other

2.1. Pre-Use Inspections & Maintenance

To ensure effectiveness of the HMI plan, an additional safety layer is included by conducting the required inspections on the site and the equipment. The equipment components are inspected daily for any leaks, damaged hoses or wiring, and functionality of the alarms, lights and reservoirs. In addition, Saudi Aramco employs periodic inspection certification programs for heavy equipment ensuring the operation of the equipment in accordance with manufacturer specifications and easy identification with clear door number on the equipment. The other safety aspect is to verify the site condition which include properly compacted foundations, float pads must be appropriate and in good condition. Based on the conducted inspections, the only approved equipment shall be permitted for operations at Site.

Moreover, the inspections carried out on the heavy equipment are supplemented with the maintenance performed on each equipment conducted in accordance with the manufacturer schedule and as recommended by Saudi Aramco standards. This process includes documentation and ensuring that all vehicle logs are completed and up-to-date. The documents are finally maintained in Company controlled archive for verification purposes.

2.2. Worksite Controls & Zoning

Extending the “NO FOOT ON GROUND” into the HMI plan is mainly obtained by defining appropriate zones and establishing controls at worksite. This includes three categories pedestrian/vehicle separation, Flagman for low visibility, and safe approach distances.

For Pedestrian/Vehicle Separation:

- The area shall be clearly segregated marked for pedestrian-only and vehicle-only zones
- Use barricades, signage, and floor markings to enforce separation and no-entry/parking zones

For Flagman:

- Trained spotters wearing high-visibility vests must assist operators in blind spots
- Flagman are maintaining direct communication using colored flags
- Flagman shall ensure that a distanced is maintained between heavy equipment and any nearby structure

For Safe Approach Distances:

- An example of this is to install goal posts at ≥ 25 meters from power lines to warn operators of safe distances in accordance with Saudi Aramco safety requirement
- Figure 4 demonstrate an example of worksite zoning. The segregation of the zones reduces personnel exposure to dangers at the construction site. In addition, the installation of physical barriers enforces compliance. Lastly, the flagman acts as a dynamic control.



Figure 4 Worksite Zoning Layout

2.3. Operator Qualifications & Training

The training and certification is another safety aspect for the HMI plan. The training addresses the need to have qualified personnel and competent to demonstrate that the areas that have the necessary knowledge and skills to safely and properly perform their assigned work. In addition, all personnel are required to receive documented training for assigned, based on job classification and training needs analysis, before being permitted access to the work site.

On that basis, the training includes:

Certification Requirements:

- Operators must hold valid Saudi Arabian government licenses and/or certifications per Saudi Aramco recommended GIs for specific equipment (e.g., cranes, excavators)
- Non-certified equipment operators must undergo documented training, testing, and written authorization from their Contractor

Hazard Awareness Training:

- Basic HSE orientation
- Training must include lessons from past incidents
- Operators are trained to recognize low-visibility zones, use flagman, and respond to alarms/hazards

Based on the completion of the safety matrix for heavy equipment operator certification, the Company ensures Compliance with the Saudi Arabian Qyadati program.

In general, training integrates incident-based learning, hazard recognition with equipment-specific certification. Researches have shown that training improves the ability of the workers to identify hazards accurately by 20% to 30 % [4].

2.4. Personal Protective Equipment (PPE)

Personal protection equipment (PPE) is considered an important safety layer when considering the implementation of the HMI plan. Although PPEs are required by any personnel working at construction site, specific requirements are addressed for operators and nearby personnel and flagman:

- High-visibility clothing (ANSI/ISEA 107 compliant). This is identified by the fluorescent vest used by the flagman
- Color coded/marked hard hats (ANSI Z89.1), flags, safety glasses, and hearing protection
- Full-body harnesses with lanyards for aerial work platforms and manlifts (anchored to approved points)
- The use of the marking with color coding, in addition to the reflector vest ensure that flagman or spotters are properly identified with increased visibility to the operator.

2.5. Supervisory Oversight & Audits

The last safety aspect in the HMI plan is to perform the check and balance. This is carried out by auditing requirements with associated responsibilities as per the plan’s responsibility matrix. The activities include daily, weekly and monthly verifications to ensure operators have valid certifications and equipment is inspected and to ensure that unauthorized personnel maintain visibility and communicate with operators (e.g., direct eye contact). Additionally, inspection examples include:

- Weekly focused inspections (e.g., SBOIs, PSIs) and management safety walk-throughs with HSE officer
- Audit compliance with HMI plans and address deviations (e.g., expired inspection stickers)
- In addition, safety campaigns and awareness programs with demonstrations are conducted to ensure all safety guidelines and HMIP requirements are addressed to all workers.

3. Conclusions

The proposed HMI system demonstrate the following:

Table 1 Summary of Proposed HMI System

Strengths	Limitation	Future Enhancement
Multi-Layer Redundancy Integration of Technology + Behavior Alignment with International Standards	Dependence on human compliance Technology cost Environmental constraints (dust, heat)	AI-Based predictive safety Wearable smart PPE Autonomous Equipment Integration

By Integrating the requirements in the HMI plan, the organizations under construction can minimize risks from human-machine interactions, ensuring compliance with safety standards of Saudi Aramco, improving the operational efficiency and reducing incidents during heavy equipment operations.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare no conflict of interest to be disclosed.

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