

An investigation into chemical tanker offloading and loading processes: Do they protect against the full range of predicted human error types?

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Abstract: A recent analysis of over 1600 hazardous chemical incidents found that 65% were attributed as being either exclusively or partially due to human errors. Previous studies into understanding human error causes have concentrated on retrospectively analysing these incidents and categorising the initiating cause against human error taxonomies such as Reason's model of unsafe acts or Rasmussen's Skills, Rules and Knowledge (SRK) classification. This study investigates industry understanding and practice prior to an incident occurring by interviewing engineering and operations staff of high hazard chemical plants that perform the common task of tanker loading or offloading.

Engineering and Operations personnel at 10 top-tier COMAH sites were interviewed to compare their perception of human error problems and existing barriers present on their loading/ offloading operation with the predicted errors and protection proposed by theoretical human error models and regulatory or industry guidance. Because of the scarcity of literature on the pre-incident perception of engineers and operators involved in tanker operations, knowledge elicitation from the practitioners was employed to identify and examine their underlying ideas, assumptions and conceptualisations of the task. Semi-structured interviews took place at the engineers or operators workplace where they described the loading/ unloading process, any mistakes that might be made and what barriers were in place to prevent them. The interviews were recorded and transcribed into a data analysis package where template analysis was used to analyse the results. The template was based on the HSE model of human failure types and each error type was augmented with any academic, regulatory or industry guidance recommended for preventing the error. Any themes in the interview text relating to the human error types or recommended prevention methods were logged to develop a picture of the engineers and operators understanding.

The study showed that while many of the recommended practices to prevent human error are in common use, there is a reliance on the competency and integrity of the individual and examples where this barrier failed were readily available. The checking of critical steps was generally weak, however the removal of time pressures and distractions to guard against omissions and lapses was pro-actively managed by the majority of participants and there were a number of examples of good practice that could easily be adopted by all companies to improve their operations.

Introduction

The human contribution to incidents arising out of routine operations and maintenance activities has been the subject of academic and regulatory interest for many years. The extent of the problem is highlighted in a recent analysis of 1632 hazardous chemical incidents in China (Zhang and Zheng, 2012) where 65% of incidents were categorised as being either exclusively or partially due to human errors.

Regulators (HSE, 1999) and industry groups (EI, 2001) have sought to improve this situation in the UK by producing guidance describing the theory behind the causes of human error, proposing methodologies to analyse operations or maintenance tasks and identifying appropriate barriers to protect against the errors.

This study concentrates on a common type of operations task within the process chemical sector; the loading or offloading of product to or from a tanker. Engineering and Operations personnel were interviewed to compare their perception of human error problems and existing barriers for the loading/ offloading operation with the predicted errors and mitigation proposed by theoretical human error models

Previous Studies

Research into analysing the amount of human error present in operations and maintenance tasks have found between 45% and 80% of critical accidents have been attributed to human error (Pheasant, 1991, p181, Reason, 1990, p186, Reason & Hobbs, 2003, p1), and an estimate of up to 80% of all accidents at work is quoted by the UK Health and Safety Executive (HSE, 1999) as being attributable to the actions or omissions of people.

More specific research focusing on the Process Chemical sector, including the tanker operation, is less widely performed. However, studies available for this sector (Zhang & Zheng, 2012, Nivolianitou, Konstandinidou & Christou, 2006, Konstandinidou, Mivolisntiou, Markatos & Kiranoudis, 2006, Löwe, Kariuki, Porcsalmy, Fröhlich, 2005) show a slightly smaller range of between 45% and 65%, although categorisations of the error types are not standardised.

Specifically for tankers and loading/ offloading, a study of 242 storage tank incidents (Chang and Lin, 2006) showed that maintenance error was the second most frequent cause of accidents (13%), closely followed by operations error (12%), with overfilling being the most common operator error. A review of chemical truck filling (Lu & Wu, 2012) found 30% of all plant human errors were associated with the truck filling process, and two other studies found that about 14% of all human errors occurred during the loading/ offloading process (Löwe, Kariuki, Porcsalmy, Fröhlich, 2005, Konstandinidou, Mivolisntiou, Markatos & Kiranoudis, 2006)

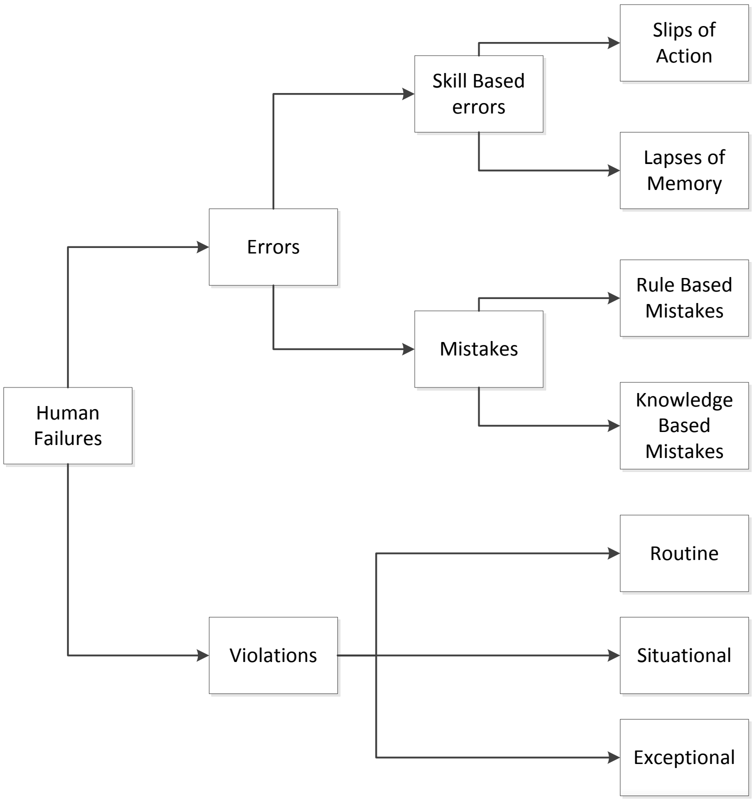
Theoretical background to human error types

There are a small number of human error models that have been used to analyse incidents and develop guidance within the high hazard community.

Rassmussen's (1982) Skill, Rule and Knowledge model of human performance (SRK) defined three basic error types: skill based slips (lapses), rule or knowledge based mistakes. The integration of both slips and mistakes was proposed by Reason as a Generic Error Modelling System in his influential textbook on human error (Reason, 1990, p61). By differentiating between rule-based mistakes and knowledge-based mistakes, the model aligns with Rasmussen's SRK classification and enables distinctions between conscious, problem solving errors and errors in activities that take place as part of automatic behaviour. Within high hazard industries, this model did not completely explain the human errors observed during incident analysis, leading Reason to include the distinction between SRK errors and violations in his model of unsafe acts (Reason, 1990, p207).

The Reason model of unsafe acts continues to be used with little modification and forms the basis for a number of regulatory and industry guidance documents (HSE 1999, EI 2009). These guides not only educate the industrial user base in human error theory, they also document potential barriers that may be implemented to protect against the different error types (HSE, 2013).

Figure 1 - Types of Human failure (from HSE, 1999)



There have been several studies using the SRK or Reason framework to analyse operational and maintenance type tasks. Reason (1990) discusses three studies which showed that skilled based errors were the most frequent at an average of 61%, 27% for rule based and 11% for knowledge, Hobbs and Williamson (2003) found that operations staff operated in the skilled mode for 65% of the time, 31% in rule based mode and 4% in knowledge mode. A study of 22 error reports concerning petroleum loading and unloading operations (EI, 2009) found 73% of errors were slips/ lapses, 9% mistakes and 18% violations. These studies give us an indication of the proportion of time operations staff spends in each human performance level.

This study classifies the potential problems and barriers perceived by engineers and operators of tanker loading/ offload systems against the HSE model of human error types (HSE, 1999) and compare their perceptions against the predicted errors and suggested mitigation actions suggested by theoretical human error models, regulator/ industry guidance and published studies.

Methodology

Previous studies into understanding human error causes in the process chemical sector, and particularly tanker loading/ offloading, have concentrated on retrospectively analysing incidents and categorising the initiating cause (Chang & Lin, 2006, Lu & Wu, 2012, Kariuki & Löwe, 2006, EI 2009).

Because of the scarcity of literature on the pre-incident perception of engineers and operators involved in tanker operations concerning the potential for human error and the reasons for existing barriers, knowledge elicitation from the practitioners was employed in this study to identify and examine their underlying ideas, assumptions and conceptualisations of the task.

Participants

Engineering and operations staff from ten companies based within a 30 mile radius participated in the research. All companies operate top tier COMAH sites; these are the higher lever classification of chemical sites within the UK Control of Major Accident Hazards regulations (COMAH, 1999) and their operations include either offloading or loading hazardous materials into or from tankers.

The participants were selected by convenience sampling given constraints including availability, permission to participate and individual circumstances. The participants were all male and held either management/ engineering or operational roles with an average of over 20 years' experience in the high hazard process chemical sector. All participants have designed, supervised or operated a tanker load/ offload involving high hazard chemicals. A small number of the participating companies had performed some form of human factor analysis, generally Hierarchical Task Analysis (HTA), and this was noted as an additional attribute. A coding system was utilised to preserve the anonymity of the companies taking part.

Table 1 –Participant attributes

Code	Role	Experience (Yrs)	Discipline	Task	HF Study
Chemical 1	Chief Engineer	15	Manager/ Engineering	Offload	Yes
Chemical 2	Day Supervisor	9	Operations	Loading	No
Chemical 3	Snr Improvement Engineer	15	Manager/ Engineering	Offload	Yes
Chemical 4	Shift Manager	17	Manager/ Engineering	Loading	No
Chemical 5	Site Process Engineer	20	Manager/ Engineering	Offload	Yes
Chemical 6	Process Technician	40	Operations	Offload	No
Chemical 7	Plant Manager	9	Manager/ Engineering	Offload	No
Chemical 8	Process Technician	28	Operations	Loading	No
Chemical 9	HSE Support Officer	10	Operations	Offload	No
Chemical 10	Production Manager	40	Operations	Offload	No

The sample size (N=10) was constrained by available participants with the desired task and industry background. The principle of theoretic saturation may be used to define an end point for a qualitative research study, where the researcher continues to collect and analyse data until no new categories develop (Willig, 2008, p37). However where convenience sampling is used, theoretic saturation may not be possible. Guidelines for estimating the sample size required to reach saturation vary; Guest, Bunce and Johnson (2006) report that after 12 interviews, new themes emerged infrequently. Romney, Batchelder and Weller (1986) calculated that samples as low as 4 participants can provide accurate results providing the participants possess a degree of expertise about the subject matter, the higher the average competency of the sample, then the smaller the sample required. The participants of this study were all experienced in high hazard process plants and particularly the loading/ offloading task. During this study, no new categories were identified after the first three interviews, suggesting that the sample size was sufficient for the study.

Data collection

There are several methods described in standard texts for collecting field data to be used in qualitative analysis such as observation, transcripts from semi-structured interviews, diaries and narratives (Coolican 2009, Wilson & Corlett 2005, Parker 2004). To enable the participants to discuss their thought processes (Willig, 2008, p23), semi-structured interviews were selected for this study.

Each interview lasted between 30 minutes and an hour and was conducted at the place of work of the participants. The data was collected by individual semi-structured interviews undertaken by a single interviewer who was a TüV Certified Functional Safety Engineer[1] with over 30 years' experience in the process chemical sector. This assisted in establishing credibility with the interviewees and the understanding of the subject matter being discussed.

The method of data collection was audio taping which was later transcribed into a Word document. The use of a single interviewer overcomes some of the documented disadvantages of semi-structured interviews concerning reliability and training (Coolican, 2009, p152). The semi-structured interview started with the interviewer setting the scene with an open-ended question. To ensure all aspects of human error were discussed, a number of supporting prompts based upon the HSE model (HSE, 2013) were crafted and introduced if the topic was not covered by the participant. The interview transcripts were imported into the QSR NVIVO 9 software package to enable analysis of the data.

Data Analysis

To analyse the large quantity of rich data resulting from the semi-structured interviews, template analysis (King, 2004a, King, 2004b) was utilised. This methodology initially develops a list of codes, the template, that represent themes occurring in textual data. Template analysis is a form of thematic analysis, which in contrast to a more traditional method such as discourse analysis, allows the researcher to infer broader assumptions, relationships and meanings beyond the verbatim conversation and experiences of the participant and elicit their experiences, meanings and realities (Braun and Clarke, 2006).

When using template analysis, it is common to identify some "a priori" themes in advance of the analysis (King, 2004b). The initial template of priori codes should be developed from the interview topic, including the questions, probes and prompts used during the interview (King, 2004a, p259) and for this analysis the basic human error type classification (HSE, 1999) could have been used as an initial template, however some authors believe that this classification requires training and experience to ensure consistency (Gordon, 1998). To counter this argument and assist the researcher in consistently interpreting the text and attributing it to the template codes, the mapping of the simpler human error categories developed for HEI/ FTA methods (CCPS, 1994, p192) against the SRK model provided by Gordon (1998), was utilised. This enabled a hierarchical template to be developed with generic error types supported by examples of barriers. This effectively created a 'word model' of barriers to assist in the consistent tagging of text against priori codes.

Figure 2 – Initial Template / Priori Codes

Inadvertent / Error
- Action error / skill based error / checking error
  - Slip & Memory lapse
    - Consistent design/ colours
    - Checklists and reminders
    - Independent cross check of critical tasks
    - Removal of distractions and interruptions
    - Sufficient time for task
    - Warnings and alarms to detect errors
- Thinking error
  - Rule based mistake/ retrieval failure/ communication failure
    - Plan for all 'what ifs', start-up, shutdown.
    - Regular drills/ exercises for upsets/ emergencies
    - Clear overview/ mental model
  - Knowledge based mistake / selection error / planning error
    - Diagnostic tools/ decision making aids (flowcharts, job aids)
    - Competencies
    - Organisational learning

Deliberate error / violation
- Routine/ Situational/ Exceptional
  - Improve risk perception
  - Promote understanding of consequences (why you do this)
  - Increase likelihood of getting caught
  - Effective supervision
  - Eliminate reason to cut corners
  - Improve attitudes/ organisational culture

Once the template was constructed, the researcher worked line by line through the set of transcripts and attributed sections of text with one or more codes in the initial template. To further assist with consistency of interpretation, the line by line analysis was conducted after all interviews had been transcribed and as a contiguous activity over two days. In the course of the analysis, themes emerged that did not fit with an existing code, and the template was extended to accommodate these new codes. The NVIVO software package was used to generate a number of reports by theme to assist the researcher in interpreting the data.

[1] A competency and accreditation scheme for safety practitioners widely accepted within the process sector

Results

Table 2 – Summary of participant references by theme

Theme	No. of sources	No. of references
Inadvertent / Error	10	167
Action error/ skill based error / checking error	10	104
Slip & Memory Lapse	10	104
Consistent design / colours/ photos/ drawings	8	11
Checklists & reminders	10	24
Independent cross check of critical tasks	10	30
Removal of distractions and interruptions	9	14
Sufficient time for the task	9	17
Warnings and alarms to detect errors	7	8
Thinking Error	10	63
Rule based error / retrieval failure / communication failure	10	16
Plan for all 'what ifs', start-up, shutdown	1	1
Regular drills / exercises for upsets / emergencies	9	11
Clear overview / mental model	4	4
Knowledge based mistake / selection error / planning error	10	47
Diagnostic tools / decision making aids (flow charts, job aids)	1	2
Competencies	10	31
Organisational learning	9	14
Deliberate error / violation	10	28
Routine / Situational / Exceptional	10	28
Improve Risk Perception	1	2
Promote understanding of consequences (why you do this)	5	8
Increase likelihood of getting caught	7	9
Effective Supervision	2	3
Eliminate reason to cut corners	4	5
Improve attitudes / organisational culture	1	1
Physical or Instrumented Protection	10	26
One person does the task 'most' of the time	3	3
Last step in task	5	7

The line by line analysis of the interview transcripts, which total nearly 30,000 words, extracted 231 references against 21 individual themes, and during the analysis three additional themes were added to the initial template.

The most prominent individual themes perceived by the participants as providing protection against error were competencies (training), independent checking, use of checklists (including procedures) and a new theme, the use of physical or instrumented protection. These will be discussed in depth in the following sections.

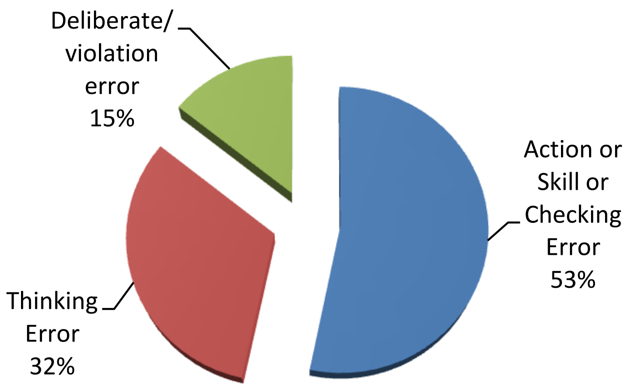
With reference to the human error types shown in the HSE model (HSE, 1999), the most prominent themes where protection is provided were skill based errors, followed by thinking errors and finally, violations. This may be expected as the offloading/ loading tasks are performed regularly, and participants will become 'skilled' in the task after they have been trained and deemed as competent.

Discussion

This study compared the potential human errors and barriers perceived by engineers and operators of tanker loading/ offloading processes at ten top-tier COMAH sites with those predicted by theoretical human error models and published research.

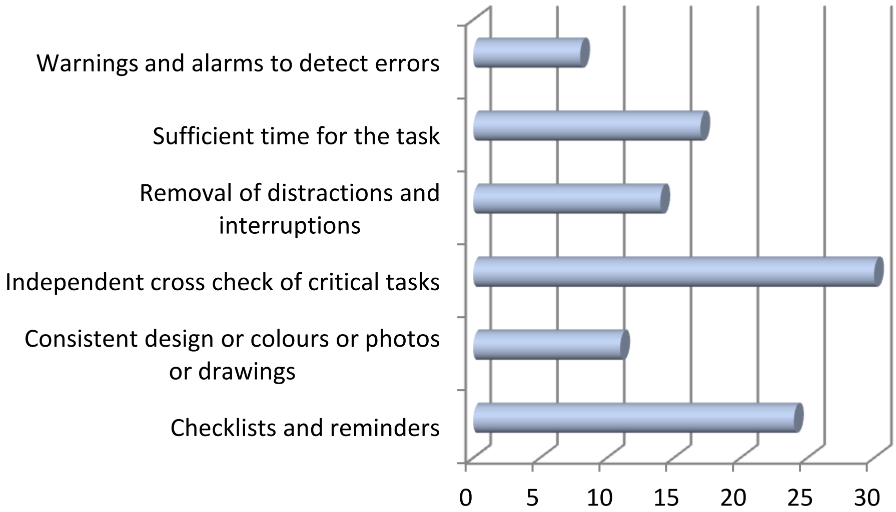
In common with other studies using similar classifications (Reason, 1990, Hobbs & Williamson, 2002, Hobbs & Williamson, 2003, EI 2009), protection against skill based errors was most prominent followed by thinking and violations.

Figure 3 – Distribution of Participant Themes



Representation across the barriers to skilled errors suggested by the template was unevenly distributed in the survey, with independent checking being the most prominent. While this is a recommended error reduction strategy in industry and regulatory guidance (HSE, 1999, CCPS, 1994, p220), detailed examination revealed that much of this was checking product details when they came to site. Only one site had an independent check of connections with another staff member before product loading/ offloading, however several sites admitted that the driver may perform an informal and unrecorded cross check while staff personnel perform the task. Formalising this check would be a simple improvement for many of the participants.

Figure 4 – Participant Barriers to Skill Based Errors



While performing a skill based task, omission of a step or memory lapse has been found to be one of the largest forms of human errors (Reason, 1990, p184, Hobbs & Williamson, 2003). The recommended way of managing this error is using checklists (Reason & Hobbs, 2003, p126, HSE, 1999, p13, HSE, 2013). Within the study, checklists and reminders were the second most reported barrier, however they were not rigorously used by the majority of the participants and the best examples came from those who had previously performed human factor studies. There were several examples of checklists being completed before or after task completion.

Closely related are the issues of distraction/ interruption of the operations staff or time pressures while performing the loading/ offloading (Reason & Hobbs, 2002, p45 & p65, Hobbs & Williamson, 2003). Several of the participants scheduled 'slots' for deliveries, so that there was plenty of time to perform the task before the next tanker arrived and the majority of participants stated that the operator was dedicated to the loading/ offloading task and would stay with the tanker for the duration of the task. The participants also reported that the slots were designed to avoid shift handovers and all companies who employed 'slots' reported that they would not start a loading/ offloading operation if it would go over the shift boundary. These tended to be the companies who were dealing with the most hazardous chemicals and these measures are in line with industry and regulatory recommendations (EI, 2011, HSE, 2013).

Another form of omission arose as a new theme during the analysis, the failure to complete the last step in the task after the main goal has been accomplished, for example putting the 'cap' on the hose. Research (Reason, 2002) suggests that this is the most common form of omission in a skilled task. Providing cues or reminders to mitigate these errors is difficult (Chung & Byrne, 2008) and the only absolute solution is to design the activity out. All of the participants who mentioned this issue relied upon checklists or individual competence to mitigate this error.

Operators would be expected to perform at the thinking or rule based level on multi-product plants where selection or routing decisions have to be made. These require an accurate mental model of the equipment and process to be developed. Few participants described activities to develop the mental model; one example was to physically walk the route through to the tank. Although recommended in industry guidance (EI, 2009), only one participant mentioned verbalising the task and discussing what-if-scenarios with the driver in advance of the task to rehearse and reinforce the process. These are both examples of good practice that could easily be adopted by more companies to improve the development of mental models.

At the knowledge level, competencies dominated the participants' responses. The main techniques quoted were training and procedures. A number of companies described more advanced methods of training including formal accreditation of their trainers and assessors (NVQ based) and the use of Activity Based Learning schemes involving theory, practical and formal assessment activities. All participants who specified advanced forms of training cited regulatory pressure as driving the improvements.

A new theme relating to individual performance emerged during the analysis, 'one person doing the task most of the time'. All companies who reported that they had a group of people who were accredited to perform the loading/ unloading but had one person who performed the task most of the time also reported that 'we don't have many incidents, but when we do it is always the stand-in'. The non-regular performer of the task has slipped down the performance levels in the SRK model to the 'Rule' level and requires different or more detailed procedures or job aids to successfully complete the task (Hobbs & Williamson, 2002). None of the participants who experienced this problem considered that different operators perform at different levels and may require additional job aids even though it is recommended in industry guidance (EI, 2011, HSE, 2013). It would be relatively simple to provide a more detailed procedure for reference by the non-regular performer, supplemented by a simple checklist for the skilled, regular performer.

For the violation theme in the template, increasing the likelihood of getting caught and promoting understanding of the consequences were the most regular items quoted by participants. The use of spot checks or inspections is recommended in industry guidance (EI, 2009) and there was evidence that these activities are being increasingly introduced by many companies and are being used as opportunities for coaching and training rather than punishment, which has been shown to be the one of the most beneficial methods of reducing violating behaviours (Reason, 2008, p60).

The extensive use of instrumented or physical systems to provide warnings, take emergency action or dictate the order of tasks is common within the chemical sector and driven by regulatory response to incidents or industry guidance (Buncefield, 2008, API, 2005). These systems were cited by nearly all participants as providing the ultimate protection from human errors.

Conclusions

This study was successful in identifying that while many of the methods and practices recommended for protection against theoretical human error types are in common use, there is a reliance on the competency and integrity of the individual and examples where this barrier failed were readily available.

All sites were top-tier COMAH registered, and some of the requirements of this legislation have an impact upon control of potential human errors. Competency and training methods were reported as being improved, with formally qualified trainers and assessors being introduced and computer based theory complimenting the traditional practical training. This improvement is attributed to regulatory interest and pressure which is expected to increase. The minority of companies who still rely upon basic watch and be watched methods to provide training without any supporting theory, procedures or job aids may find the regulators expecting improvements in their practices.

There were a number of examples of good practice that could easily be adopted by all participants in the study. These include: -

- Providing different levels of detail in job aids for the same task. None of the participants appreciated that different operators may be at different levels of the SRK human performance model, and operators who perform a task infrequently, although qualified as competent, will require different jobs aids than the regular, skilled performer. This is a message that needs to be communicated to engineering and operations staff for improvement.
- The use of the driver to provide an independent check of the connection. In general, checking of critical steps was weak, checking the paperwork was cited by all participants, but few companies had independent checks of the key, final connection. Drivers are often available to verify the activity and it would be a simple improvement to formalise this as a signed check.
- The removal of time pressures and distractions to guard against omissions and lapses. This was pro-actively managed by most participants with the introduction of set time slots for tankers enabling the scheduling of a dedicated operator for the duration of the loading/ offloading task. This practice addresses several common causes of skilled-based errors identified in previous post-incident studies.
- Talking through the task with the driver, discussing what is to be done and agreeing actions to be taken in the event of a failure. This would improve communication, develop the mental model and formalise the independent check of the critical connection steps.
- Regular management spot-checks where non-compliance does not result in punishment, but initiates a positive discussion about the task and the reasons behind the actions improves both knowledge and understanding of the consequences of violations is performed by a small number of companies, but has been shown to be particularly effective in reducing violating behaviour.

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