ACCIDENT PREVENTION STRATEGIES:
CAUSATION MODEL AND RESEARCH DIRECTIONS

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ABSTRACT

This paper presents an accident causation model that identifies the production system factors affecting the accident process, and proposes accident prevention strategies. The model builds on descriptive rather than prescriptive theories of work behavior and acknowledges the inevitability of exposures and errors. It also focuses on the operation as the level of analysis—that is, it focuses on the factors that influence the number of accidents during a construction operation.

The model first identifies the production factors that affect the frequency of hazards during a construction activity, and emphasizes the importance of task unpredictability. Then we examine how the production pressures and the tendency to minimize effort increase the workers’ efficient behaviors and their exposure to hazards, while safety efforts try to prevent such exposures. Finally, the model acknowledges that exposure to hazards only leads to accidents, if errors or changes in the situation “release” the hazard.

Based on this conceptualization of the accident process, the paper proposes accident prevention strategies that do not focus on compliance with safety rules: (1) reduce task unpredictability to reduce the frequency of hazards; (2) improve the work conditions to enable more productive behaviors without increasing the safety risk, and (3) develop error management strategies to prevent, trap and mitigate the consequences of errors. These strategies provide direction for safety research.

KEY WORDS

Safety, Accidents, Models

INTRODUCTION

The current approach to accident prevention is based on OSHA’s violations approach. This does not mean that companies focus only on preventing OSHA violations, but that the approach to safety emphasizes compliance with safety rules and procedures. This approach focuses primarily on prescribing and enforcing defenses—that is, physical and procedural barriers that reduce the workers exposure to hazards. It emphasizes management commitment to remove unsafe conditions, and workers’ training and motivation to prevent unsafe behaviors. Safety programs—such as training in hazard

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awareness, inspections, motivation, enforcement, penalties, etc., emphasize competency and liability, and attempt to increase compliance with the safety rules and/or increase the cost of non-compliance. The violations approach has contributed to the reduction of accident rates, but it also has important limitations.

- Production and cost considerations are in conflict with safety compliance. Short-term conflicts between safety and production are usually resolved in favor of production, as efforts for production have relatively certain outcomes and receive rapid and rewarding feedback (Reason 1990).
- The compliance approach focuses on reducing exposures to hazards. This is a limited view of accident causality, it focuses on liability and does not address the production system factors that generate the hazards and shape workers’ behaviors.

Better models of accident causation are essential for developing effective accident prevention strategies. Effective causation models need to explain the processes by which hazards are generated and released and identify the production system characteristics that generate hazards, shape the work behaviors and create preconditions for accidents.

This paper presents an accident causation model. The model takes an ‘activity-level’ perspective (as opposed to incident-level); it analyzes the steps of the accident process and identifies the production system factors that influence the type and frequency of hazards during an activity. The model is based on descriptive rather than prescriptive models of work behavior—it takes into account the actual production behaviors, as opposed to the normative behaviors that workers ‘should’ follow.

The model is based on previous research in the areas of accident causation (Rasmussen et al. 94, Rasmussen 97), human error (Rasmussen et al. 1981, Reason 1990) and construction safety (Hinze and Parker 1978, Jaselskis et al. 1996, Toole 2002, etc.), and review of several construction accidents that the authors were familiar with. Based on the model, the paper proposes strategies for accident prevention and suggests directions for future research.

MODEL OVERVIEW

Figure 1 shows the stages of the accident process and the main factors that influence the process and consequently the likelihood of accidents during a construction activity. The arrows indicate cause-effect relationships. The positive and negative signs indicate the direction of the relationship between the factors; a positive sign indicates that when the cause increases, the effect also increases. A negative sign indicates that when the cause increases, the effect decreases.

The characteristics of the task and work context, and the unpredictability of the task generate hazards. Workers may or may not be exposed to hazardous situations. Safety efforts to control conditions prevent exposures. Production pressures lead to efficient work behaviors (working fast, taking shortcuts, etc.) which increase production but also increase exposure to hazards. Safety efforts to control behaviors reduce efficient behaviors, and consequently exposures. Exposures to hazards create the potential for accidents, but do not necessarily lead to accidents. Errors and changes in conditions (such as mechanical failures) under conditions of exposure “release the hazard” and generate incidents. The release of a hazard (incident) may result in an accident (injury or fatality) or a “near miss” incident without injury, if the hazard is not trapped. Protective
measures (such as personal protective equipment) mitigate the consequences of an incident. The following section describes the model in more detail.

**Figure 1. Accident causation model**

**ACCIDENT CAUSATION MODEL**

**HAZARDS**

In this paper, a hazard is defined as a situation with the potential to cause injury, unless the worker can detect and avoid the hazard, without exposing themselves to a greater hazard. Figure 1 shows that the number of hazards during an activity depends on task characteristics and task unpredictability.

**Task characteristics** include: (a) the task technology (the work method, materials, tools, equipment, and actions needed to perform the task) and (b) the task context, that is the physical conditions and surrounding activities. Different activities involve different hazards. Furthermore, the same activity performed under different conditions (housekeeping conditions, heavy equipment traffic, overhead activities, etc.) also involves different hazards.

**Task unpredictability** means that the work cannot be completed as planned; the scope of the task may be different than expected and planned for, the conditions under which the task is to be performed are different than expected, or appropriate resources may be missing (information, tool, material, manpower, skills, etc.). Unpredictability leads to unplanned tasks and unexpected situations, and increases both the likelihood of hazardous situations, and the production pressures.

Unpredictability generates hazardous situations because the resources (tools, manpower, skills) or safety measures required to do the task safely may not be available
for the unexpected tasks or conditions. For example, the crew planned for a 6’ ladder, but some locations require an 8’ ladder. Workers’ errors may also create unpredictable hazards; for example, a worker may set up an unsafe scaffold thus creating a hazard for himself and other workers. Even if a crew performs safety pre-task planning, the plan will be inadequate if the task is unpredictable. Furthermore, unpredictable tasks and conditions require increased effort, more movement of workers and equipment, increased material handling, increased need to improvise, more out-of-sequence tasks, and more confusion.

Unpredictability increases workload and production pressures, because it generates urgent interruptions that have to be resolved fast or they can disrupt production. Resolving the interruptions takes time and reduces the time available for the planned task. As a result, task unpredictability generates ‘urgent/last minute’ problems and creates temporarily ‘peaks’ of production pressures, even if the overall activity is not under particular schedule pressure.

The task characteristics and unpredictability generate two types of hazardous situations: (a) predictable situations due to the nature of the task and surrounding, and (b) unpredictable situations due to uncertainty task and environment. The frequency of unpredictable situations depends on the effectiveness of production planning.

EXPOSURE TO HAZARDS

Workers may or may not be exposed to the hazards. Safety efforts to control conditions and behaviors reduce exposures, while efficient work behaviors may increase the likelihood of exposure.

Safety efforts to control conditions include physical barriers that isolate hazards and prevent exposure (e.g., trench protection, barricades, etc.) For the predictable hazards, management can plan and set up the required defenses. Management attitude and commitment to safety influence the availability of resources and effort. However, for unpredictable hazards, there is greater likelihood that defenses will not be in place.

Efficient work behaviors. Production pressures and workload drive workers to adopt more efficient work behaviors (Rasmussen et al. 1994) (such as working faster, taking shortcuts, or working without the required safety equipment), as the workers try to accomplish higher production by spending less time and/or effort on each work item. Workers take shortcuts or exert excessive effort to reduce the time to perform a task. Such efficient work behaviors are typically considered ‘risk-taking’ because they bring the workers closer to the ‘boundary of loss of control’ (Rasmussen et al. 1994). But, from the perspective of the worker, it is not risk-taking—experienced professionals develop shortcuts and tricks-of-the-trade as efficient ways to perform the work. Such shortcuts may be more dangerous for less experienced workers, or under particular conditions. Such behaviors often are established trade practices that may violate prescribed procedures—they are ‘routine violations’. Such dangerous-but-efficient work behaviors increase productivity, but also increase exposure to hazards. As shown in Figure 1, when production increases the production pressures are reduced and so is the need for dangerous-but-efficient behaviors.
**Safety efforts to control behaviors** include training in safety rules and procedures, incentives and motivational campaigns such as safety culture and value-based safety, enforcement and punishments, and behavior-based safety. One important limitation of this approach is that it conflicts with production pressures and the tendency for efficient work behaviors and requires continuous pressures (Rasmussen et al. 1994).

Strategies to reduce exposures also include alarms and warnings such as spotters, backup alarms, high visibility safety vests, etc. The effectiveness of such warning measures is limited. Blackmon and Gramopadhye (1995) found that the effectiveness of backup alarms is low because of the general noise level of the jobsite, the operators’ reliance on the alarms, and reduced attention.

**INCIDENT**

Exposures to hazards create the potential for accidents, but do not necessarily result in accidents. A worker working at high elevation near an unprotected edge will not necessarily fall. For an accident to occur, the hazard must be released. The release of the hazard is the critical event at which there is loss of control of the hazard (loss of control of equipment or tool, loss of structural stability, etc.). Human errors and changes in conditions can trigger the release of hazards. Table 1 lists examples of typical exposure to hazard scenarios found on construction sites, and possible subsequent scenarios of the release of hazards.

<table>
<thead>
<tr>
<th>Hazard Description</th>
<th>Exposure to Hazard</th>
<th>Release of Hazard (Incident)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unprotected edge</td>
<td>Working near an unprotected edge</td>
<td>Worker slips and falls</td>
</tr>
<tr>
<td>(work context)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saw with dull blade</td>
<td>Operating saw</td>
<td>Saw jams and kicks back</td>
</tr>
<tr>
<td>(under-maintained tool)</td>
<td>with dull blade</td>
<td></td>
</tr>
<tr>
<td>Material handling</td>
<td>Lifting material</td>
<td>A muscle exceeds functional limit</td>
</tr>
<tr>
<td>(task characteristic)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surrounding activities</td>
<td>Working under another crew</td>
<td>Object falls and hits worker</td>
</tr>
<tr>
<td>Unsecured power source</td>
<td>Working without lock out-tag out</td>
<td>Another worker turns on the power</td>
</tr>
</tbody>
</table>

**Errors.** Errors are unintended actions that fail to achieve their intended outcome. Reason (1990) identifies three types of errors: slips and lapses (unintentional loss of control), mistakes (selection of incorrect course of action) and perceptual errors (actions that result from misinterpretation of the actual situation). Huang and Hinze (2003) found that misjudgment of a hazardous situation was a significant factor in over 30% of fall accidents.

Not all errors release hazards. An error will have no safety consequences if there is no exposure to a hazard—e.g., errors made in flight simulators are inconsequential, while other errors are ‘trapped’ and control is recovered before the hazard is released. However, when a worker is in proximity to a hazard, there is very small tolerance for error. At that point, a small error or even a normal variation of action may release the hazard. If the
worker(s) detects the error soon enough to ‘trap’ the error and recover control, then the release of the hazard is prevented.

**Error inducing factors.** The likelihood of errors depends on the task demands (complexity, dynamism, pressures), the environment, and the workers’ capacity to do the task, distinguish boundaries, and trap errors. According to Rasmussen et al. (1981), causes of human “malfunction” include external events (such as distractions, component failures, or the physical environment), excessive task demands (due to task characteristics and situation), performance shaping factors (such as work load, skills and stress factors), reduced capacity (due to fatigue, etc.), or intrinsic human variability.

**Changes in conditions.** When a worker is exposed to a hazard, the hazard may be released not by a human error, but by changes in the work conditions, such as mechanical failures of tools and equipment, trench collapse, etc. In other words, the worker’s behavior may be appropriate, but the situation changes. Changes in conditions are often sudden and do not allow time to react and recover control or avoid the hazard.

**INJURY**

With regard to the consequences, an incident may result in an injury (or fatality) or it may be a ‘near miss’. Injury accidents include traumatic injuries, ergonomic injuries (overexertion or repetitive types), or occupational illnesses and diseases.

If the worker can react fast enough to avoid the hazard or interrupt the flow of events (trap the error or recover control), then the injury can be avoided. The ability to react depends on the speed of the hazard release—when the loss of control is very sudden, there is no time to react. Workers’ experience and situational awareness are critical in anticipating failure and taking appropriate action. The magnitude of injury also depends on situational factors that may aggravate or mitigate the injury (including the individual’s tolerance, and luck).

**Protective measures** such as personal protective equipment, are ‘the last line of defense’ and can mitigate the consequences of an incident.

**RESEARCH DIRECTIONS FOR ACCIDENT PREVENTION**

Current safety practices focus on preventing workers’ exposures to hazards with efforts to control conditions and behaviors. Based on the accident process described in this paper, we identify three other strategies for accident prevention:

1. **Reduce the number of hazardous situations by reducing work unpredictability.** Current approach to safety (compliance) prescribes specific defenses for each hazardous situation, but does not influence the number of hazardous situations generated.

2. **Reduce the safety risk of efficient behaviors.** Rather than constraining the productive behaviors with a set of rules, this strategy focuses on addressing the factors that make the efficient behaviors unsafe.

3. **Develop error management practices and skills.** Exposures and errors are unavoidable. We need to increase the workers ability to avoid, trap and recover from errors under conditions of exposure.
REDUCE UNPREDICTABILITY

This strategy focuses on reducing the number of hazardous situations due to unpredictability. The model proposes that unpredictable situations are more likely to result in exposures and accidents because (a) defenses are not planned ahead of time, (b) create high production pressures which increase exposures, and (c) increase the likelihood of errors.

The primary means for reducing unpredictability is increasing the reliability of planning. Ballard and Howell (1998) proposed the use of the Last Planner System ® for production control which requires development of high quality work assignments. This ensures that the necessary resources (including manpower with the appropriate skills), directives and pre-requisites for an activity are available and the work can be completed as planned.

Research is needed to increase understanding of the effect of task unpredictability on exposures and accidents. However, there is some evidence that task unpredictability may be a significant factor in accidents. A recent study found that projects that used the Last Planner System ® had accident rates about 45% lower than projects that did not use it. Both groups of projects were performed by the same contractor, were of similar nature, and used same safety practices (Thomassen et al. 2003).

Table 2. Effect of Last Planner on accident rate.

<table>
<thead>
<tr>
<th>Project Characteristics</th>
<th>Projects using Last Planner</th>
<th>Projects not using Last Planner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Hours</td>
<td>305,604</td>
<td>580,371</td>
</tr>
<tr>
<td>No. of accidents</td>
<td>12</td>
<td>41</td>
</tr>
<tr>
<td>Incident rate*</td>
<td>7.85</td>
<td>14.13</td>
</tr>
</tbody>
</table>

* Incident rate is the number of injuries in a year per 100 full time workers.

REDUCE SAFETY RISK OF EFFICIENT BEHAVIORS

Current safety efforts to control behaviors are in conflict with efficient work behaviors. Instead of asking how can we keep workers from acting in more efficient ways (because they increase exposure to hazards), this approach focuses on “how can we make it safe for workers to work more efficiently?” so that efficient behaviors do not increase exposure to hazards.

Figure 2 proposes a relationship between task conditions, work behaviors, and accidents. The curve indicates the limit of loss of control. The figure illustrates that when task conditions become more complex, dynamic and unpredictable, the efficiency of the work behavior must be reduced for the work to remain safe.
In a simple example, the safe speed on a road (for a specific driver and vehicle) depends on the condition of the road, the visibility, the traffic load, etc. To safely increase the speed, we need to create conditions that reduce the likelihood of loss of control. This may include increasing visibility around curves, widening the road, reducing the potholes and obstacles, etc. Increased task predictability supports efficient behaviors and reduces the safety risk. It is also important to stabilize the work conditions and prevent sudden deterioration of conditions when workers are at a point of high efficiency.

Under this approach, one should focus on efficient behaviors that involve a significant safety risk (such as establish trade practices that are considered unsafe), and examine how we can change the task or the conditions, so that the same behaviors are safe. For example, the safe procedure for a task requires two workers. However, the establish trade practice involves only one worker doing it (so that the other worker does something else and the task moves faster). We need to investigate how we can change the task so it can be done safely by one worker.

This strategy would reduce the conflict between efficiency and safety. Control of safety would focus on securing the appropriate conditions, rather than controlling the workers’ behaviors.

A limitation of this approach is that safety may be improved only temporarily because workers will adapt their behaviors to compensate for attempts to improve system safety, and maintain the same level of perceived control (Rasmussen 1997). However, increased efficiency will reduce production pressures and the exposures to hazards.

**DEVELOP ERROR MANAGEMENT ABILITY**

This approach accepts that exposures and errors are unavoidable even in a “well defended” work environment and focuses on practices to minimize errors and their consequences under conditions of exposure.

In construction warning measures (backup alarms, spotters, etc.) are used to increase awareness of hazards when the workers cannot be isolated from the hazards, e.g., when
need to work under power lines, or when working near heavy equipment. However, these mechanisms have limited effectiveness (Blackmon and Gramopadhye 1995).

Error management is a set of strategies that enable the workers detect and correct errors before onset of consequences. Error management provides a set of error countermeasures with three lines of defense: (1) Error avoidance. (2) Error trapping to prevent it from propagating. (3) Error mitigation to reduce the consequences of those errors which occur and are not trapped.

Aviation was the first sector to develop error management strategies to reduce accidents due to ‘pilot error’ (Helmreich et al. 1999). In aviation, Crew Resource Management (CRM) is “an active process by crewmembers to identify significant threats to an operation, communicate them to the pilot and carry out a plan to avoid or mitigate each threat”. CRM has been adopted by other high-risk operations where effective work performance requires coordinated action—such as hospital operating teams, oil platforms and power plant control centers.

CRM emphasizes the key non-technical skills that affect crew interaction and operational safety and includes concepts such as team building, briefing strategies, situational awareness, stress management, and crew communication and decision-making.

CONCLUSIONS AND RECOMMENDATIONS

The paper developed a model of the accident process and identified key production factors affecting the process and the outcome. This main differences from previous construction accident causation models are the following. First the proposed model takes an activity-level perspective, and identifies production factors affecting the frequency of hazards and the likelihood of exposure. Second, the model is based on descriptive rather than prescriptive models of work behaviors and accepts the unavoidability of exposures and errors. Finally, the model proposes three directions for accident prevention that are not based on the mentality of “compliance with safety rules.” These strategies do not conflict but can complement the compliance approach.

The model and the proposed strategies provide directions for accident prevention research. First, the propositions of the model should be considered hypotheses for testing. Second, research is needed to investigate the feasibility and potential of the proposed strategies. Research is needed to:

- increase understanding of the effect of task unpredictability on exposures and accidents.
- examine if it is feasible to reduce the safety risk of efficient behaviors with changes in the task and the conditions.
- develop error management strategies for construction operations.

REFERENCES


