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ACCIDENT RISK EFFECT: FUZZY LOGIC & SIMULATION BASED ANALYSIS

Sangyoub Lee
Research Associate, Construction Engineerign and Management, Purdue University, West Lafayette, Indiana, USA

Daniel W. Halpin
Professor and Head, Construction Engineerign and Management, Purdue University, West Lafayette, Indiana, USA

ABSTRACT
The construction industry has historically had a disproportionately high rate of disabling injuries and fatalities for its size and accident statistics have played an important role as prime indicator for measuring safety performance, however the current system of statistics collection is based upon post-accident analysis, which provides only factual information with no regard to any data prior to the occurrence of the accident. This study estimates the probability of accidents due to the fuzzy-based effect of the factors affecting safety performance. And the quantitative variation in productivity is simulated to incorporate the effect of the probability of accident, which can be demonstrated as a 3-dimensional relationship between probability of accident and extra duration resulting from accident. It is found that productivity is more affected by increased extra duration than by increased probability of accident, when the probability of accident is low. It can be inferred that less frequent fatal accidents causing longer delays are more critical to productivity than more frequent non-fatal accidents that result in shorter delays.

KEYWORDS
Construction Safety, Fuzzy Logic, Simulation, Accident Risk Effect

1. INTRODUCTION

The construction industry has historically had a disproportionately high rate of disabling injuries and fatalities for its size (Hinze, 1997). In 2000, the construction industry again recorded the highest number of fatal work injuries of any industry, although the total for the industry was down about 3 percent. This accounted for 19.5 percent of total fatalities in 2000 (increasing from one-sixth in 1995), which amounts to over three times its 6.6 percent share of total employment. Among the various efforts for accident prevention performed in construction, accident statistics have played an important role in measuring safety performance as well as in being an impetus for accident-prevention studies (Census of Fatal Occupational Injuries Staff, 1997). However, the current system of statistics collection is based upon post-accident analysis (Staley and Foster, 1996). These data provide only factual information regarding the post accident situation, but ignore conditions existing prior to occurrence of the accident. The purpose of safety assessment is to predict the safety performance expected on the proposed project by providing an objective prediction by the past safety record as well as a current-but more subjective-prediction by the current safety practices (Levitt and Samelson, 1993). In order to measure the risk of accident and its effect prior to the occurrence of accidents, the various approaches, mainly those of a quantitative and qualitative nature, may be considered. This study adopts (1) a fuzzy logic-based approach to estimate the fuzzy probability of accidents due to the qualitative performance of factors affecting safety, (2) a simulation-based approach to quantify the impact of accident risk on productivity, which provides the relationship between the variation in productivity and extra time duration resulting from an accident.

2. FUZZY LOGIC BASED ACCIDENT RISK ESTIMATION METHODOLOGY

Since the classical reliability theory generally fails to consider any information about the variables defined in linguistic terms, the linguistic variables and measures need to be translated into mathematical terms, and this can be achieved by using the fuzzy sets and system theory. The fuzzy logic systems can address the imprecision of the input and output variables directly by defining with fuzzy numbers and fuzzy sets, which can be expressed in linguistic terms (Tsoukalas and Uhrig, 1997).

2.1 Linguistic Variables defining Accident Risk

The linguistic variables defining the risk of accident in this study are '**C**' as the condition of the factors affecting safety performance, '**F**' as the frequency of occurrence of the C, '**AC**' as the adverse consequence resulting from the C, and '**R**' as the frequency level of the accident occurrence (Ayyub and Eldukair, 1989). The methodology for the accident risk estimation is based on the fuzzy set theory to translate the subjective terms of these four variables associated with the factors into mathematical measures. And the theory of probability is used to estimate the expected risk measures of the construction operations. In order to translate the linguistic value of these variables, the membership function of the linguistic grading scale needs to be developed.

2.2 Fuzzy Relation between Variables

The major linguistic variables for the accident risk estimation are the variable C and variable F. The total effect of all factors' condition, C_i, '**E**,' is determined by taking the fuzzy union of the membership function, $U_{C \times AC}$ (c_i, ac_j) = min $[U_C (c_i), U_{AC} (ac_j)]$, combining the condition, C_i, and the adverse consequences, AC_j. Similarly, the total effect of the frequency of occurrence of the C_i, '**T**,' is also developed by taking the fuzzy union of $U_{F \times R}$ (f_j, r_k), combining the frequency of occurrence of the C_i, F_j, and the frequency level of the accident occurrence, R_k. And it estimates the risk of accident due to the effect of the variable F. The standard fuzzy relation, '**K**,' between the adverse consequences, AC_j and the frequency level of the accident occurrence, R_k is developed based on fuzzy condition statements represented by 'if AC_1, then R_1, else if AC_2, then R_2 … else if AC_n, then R_n'. The fuzzy composition relation, '**M**' between E and K, $U_{E \circ K}$ (c_i, r_k) = max$_{Ci}$ (min $[U_E (c_i, ac_j), U_K (ac_j, r_k)]$), is developed to estimate the risk of accident due to the effect of the variable C. Finally, a subjective estimate of the risk of accident can be determined by considering the joint effect of the condition of factors and the frequency of occurrence of the condition based on the joint membership function defined by $U_{M, T}$ $(c_i, f_j)(r_k)$ = min c_i $[U_M (c_i, r_k), U_T (f_j, r_k)]$ (Ayyub and Eldukair, 1989).

3. DATA ACQUISITION

For the identification of safety factors and the acquisition of data for the grading scale and the linguistic measure of variables, the 35 experts were consulted by the interview survey, including 15 safety directors in corporate construction who provide management perspectives and 20 respondents such as project manager, superintendent, and foreman who provide field perspectives. Management perspectives have an average of 21.3 years of experience in the construction industry and 15.7 years of experience in the area of trench construction, while field perspectives have an average of 23 years and 17.3 years in each of areas, shown as in Table 1.

Table 1: Experience of Consulted Experts for Data Acquisition

Perspectives		Management	Field	Total
The number of experts		15	20	35
Experience	In construction	21.3 yrs	23 yrs	22.3 yrs
	Only in trench	15.7 yrs	17.3 yrs	16.6 yrs

3.1 Safety Factors Identification

Many factors affecting the safety of construction operations might cause accidents leading to consequences ranging from hospitalization to death. As the accidents in construction operations usually occur due to the interaction and integration of the several types of event, the effect of these factors on the safety needs to be assessed and controlled. In this study, the factors affecting safety performance in trench operation are identified, since trench operation is statistically regarded as one of the most hazardous types of work in the U.S. construction industry. The survey revealed the three most important safety factors in trench operation to be 'Training for trenching,' 'Supervision,' and 'Pre-planning.'

3.2 Data for Grading Scale

The survey asked the experts to fill out the questionnaire asking the primary value of the grading scale (e.g. good, moderate, and poor) depending on each of the linguistic variables (e.g. condition), which intends to translate the linguistic value of variables by their own level of belief. In order to establish a general numerical guideline for condition related safety factors, given extremely poor condition has a value of 0 and extremely good condition has a value of 10, questionnaire asked the respondents to assign an appropriate numerical value for poor-moderate-good, then the value for small-medium-large in a guideline for frequency level of occurrence (condition), and for small-medium-severe in a adverse consequence, finally for high-low in a frequency level of occurrence (accident). The grading scales of all survey respondents are analyzed in order to define the membership functions for primary values, which address the completeness of the element, $x_i \,|\, U_A(x_i)$, where $U(x_i)$ is the membership function of the element x_i, as shown in Table 2.

Table 2: Primary Grading Scales for Four Variables

<table>
<tr><td rowspan="3">C</td><td>Good = [0.6|0.28, 0.7|0.75, 0.8|0.94, 0.9|1.0, 1.0|1.0]</td></tr>
<tr><td>Poor = [0.0|1.0, 0.1|1.0, 0.2|1.0, 0.3|0.91, 0.4|0.47, 0.5|0.19, 0.6|0.13, 0.7|0.06]</td></tr>
<tr><td>Moderate = [0.2|0.09, 0.3|0.53, 0.4|0.81, 0.5|0.88, 0.6|1.0, 0.7|0.72, 0.8|0.25, 0.9|0.06]</td></tr>
<tr><td rowspan="3">F</td><td>Large = [0.3|0.25, 0.4|0.25, 0.5|0.35, 0.6|0.66, 0.7|0.98, 0.8|1.0, 0.9|1.0, 1.0|1.0]</td></tr>
<tr><td>Small = [0.0|1.0, 0.1|1.0, 0.2|0.94, 0.3|0.78, 0.4|0.31]</td></tr>
<tr><td>Medium = [0.2|0.22, 0.3|0.69, 0.4|1.0, 0.5|0.94, 0.6|0.88, 0.7|0.59, 0.8|0.03]</td></tr>
<tr><td rowspan="3">AC</td><td>Severe = [0.3|0.06, 0.4|0.09, 0.5|0.19, 0.6|0.44, 0.7|0.84, 0.8|1.0, 0.9|1.0, 1.0|1.0]</td></tr>
<tr><td>Small = [0.0|1.0, 0.1|1.0, 0.2|0.94, 0.3|0.69, 0.4|0.34, 0.5|0.13, 0.6|0.9]</td></tr>
<tr><td>Medium = [0.2|0.34, 0.3|0.69, 0.4|1.0, 0.5|0.91, 0.6|0.81, 0.7|0.56, 0.8|0.16]</td></tr>
<tr><td rowspan="2">R</td><td>High = [1|1.0, 0.1|1.0, 1.E-02|0.66, 1.E-03|0.38, 1.E-04|0.06]</td></tr>
<tr><td>Low = [0.1|0, 1.E-02|0.13, 1.E-03|0.34, 1.E-04|0.72, 1.E-05|1.0, 1.E-06|1.0]</td></tr>
</table>

The defined grading scale can be extended by the effect of linguistic hedges for the translation of high and low levels of linguistic measures. The translation of linguistic hedges such as 'very' and 'fairly' into fuzzy sets may be assumed to be very = CON (A) = $[U_A(x_i)]^2$, and fairly = DIL (A) = $[U_A(x_i)]^{½}$, where $U(x_i)$ is the membership function of the element x_i, and CON and DIL are the concentration and the dilation operations, respectively (Tsoukalas and Uhrig, 1997). For example, the grading measure of the variable C can be shown as following in Table 3 and Figure 1.

Table 3: Grading Scales for Variable C

	Value	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	Very Good (VG)	0	0	0	0	0	0	0.53	0.87	0.97	1.00	1.00
	Good (G)	0	0	0	0	0	0	0.28	0.75	0.94	1.00	1.00
	Fairly Good (FG)	0	0	0	0	0	0	0.08	0.56	0.88	1.00	1.00
C	Moderate (Mod)	0	0	0.09	0.53	0.81	0.88	1.00	0.72	0.25	0.06	0
	Fairly Poor (FP)	1.00	1.00	1.00	0.95	0.68	0.43	0.35	0.25	0	0	0
	Poor (P)	1.00	1.00	1.00	0.91	0.47	0.19	0.13	0.06	0	0	0
	Very Poor (VP)	1.00	1.00	1.00	0.82	0.22	0.04	0.02	0.00	0	0	0

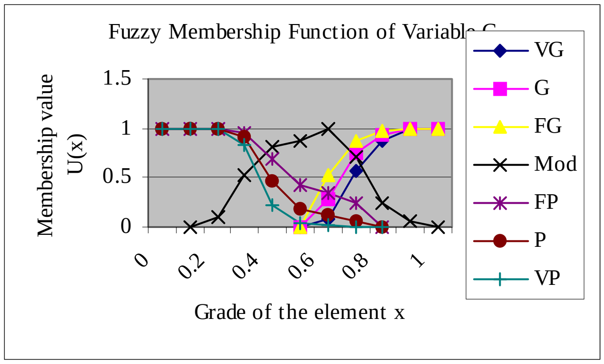

Figure 1: Diagram of Grading Scales for Variable C

Grading scales including the above membership function for variable C are working as a tool for translating each level of linguistic answers.

3.3 Data for Linguistic Measure

To develop the probability of accident, the survey also asked the questions for linguistic answers depending on each condition of variables, for example, when the condition of the safety factor is very poor, 1) what is the frequency of occurrence of the very poor condition? 2) then what is the adverse consequence of the very poor condition? 3) finally what is the frequency level of the accident occurrence?. These questions are asked in each of the condition levels (e.g. 'Very poor,' 'Poor,' 'Fairly poor,' 'Moderate,' 'Fairly good,' 'Good,' and 'Very good') of the three safety factors in two main activities of the trench operation: 'Excavation' and 'Pipe-installation.' As stated earlier, these answers are translated using grading scales developed earlier. The analysis of survey data indicates that 'Very poor' condition of factors in excavation and 'Poor' condition in pipe-installation turn out to be the most probable values of variable C.

Table 3: Most Probable Values of Condition and Associated Variables

Activities	C		F	AC	R
In Excavation	Very poor condition of	Training	Very large (33%)	Very severe (43%)	Very high (57%)
		Supervision	Very large (37%)	Very severe (57%)	Very high (60%)
		Pre-planning	Large (37%)	Severe (33%)	Fairly high (40%)
In Pipe-installation	Poor condition of	Training	Large (43%)	Severe (47%)	High (37%)
		Supervision	Large (43%)	Severe (47%)	High (47%)
		Pre-planning	Large (27%)	Fairly severe (30%	Fairly high (37%)

The most probable values of the linguistic measures in variables, C, F, AC, and R can be calculated into a probability of accident, which predicts a risk of accident by current safety performance using the fuzzy set model described in next section.

4. ACCIDENT RISK – PROBABILITY OF ACCIDENT

In above Table 3, when the value of the variable C in the factor 'Training' is 'Very poor' in excavation activity, the associated variables such as F, AC, and R have values of 'Very large,' 'Very severe,' and 'Very high,' respectively. And the other factors, 'Supervision' and 'Pre-planning,' have also values in each of associated variables. Based on the joint effect of the values of variables C and F: $U_{M,\,T}\,(c_i,\, f_j)(r_k) = \min c_i\, [U_M\,(c_i,\, r_k),\, U_T\,(f_j,\, r_k)]$, the fuzzy joint membership function integrating the effect of the each variable can develop the fuzzy probability. In order to measure the joint membership value for each level of probability, the membership value for each level of variable R, $P_f = 10^{-n}$ is developed by evaluating six matrices for the joint relation: $P_f = [10^{-1}\,|\,0.507,\, 10^{-2}\,|\,0.507,\, 10^{-3}\,|\,0.357,\, 10^{-4}\,|\,0.422,\, 10^{-5}\,|\,0,\, 10^{-6}\,|\,0]$. The probability mass function of Pf can be developed according to Zadeh (1968): P (P_f =

10^{-1}) = 0.507 / (0.507 + 0.507 + 0.357 + 0.422) = 0.283, P ($P_f = 10^{-2}$) = 0.283, P ($P_f = 10^{-3}$) = 0.199, P ($P_f = 10^{-4}$) = 0.235, P ($P_f = 10^{-5}$) = 0, and, P ($P_f = 10^{-6}$) = 0. The mean value of the probability of accident, P_f, can be calculated: $N_E = -6\times0 - 5\times0 - 4\times0.235 - 3\times0.199 - 2\times0.283 - 1\times0.283 = -2.3868$. Thus, the expected value of the probability of accident in excavation activity is estimated at $10^{-2.3868}$ or 0.0041, which means 0.41%.
And the probability mass function for the pipe-installation activity of Table 3 is also developed and the mean value of the probability of accident, P_f, can be calculated: $N_P = -6\times0 - 5\times0 - 4\times0.247 - 3\times0.252 - 2\times0.251 - 1\times0.251 = -2.4957$. Therefore, the expected value of the probability of accident in pipe-installation activity is estimated at $10^{-2.4967}$ or 0.00319, which means 0.319%. This study shows the excavation activity has bigger probability of accident than the pipe-installation activity.

5. SIMULATION OF ACCIDENT RISK EFFECT

This paper explores a quantitative approach to incorporate the effect of the risk of accident by measuring variation in productivity attributed to delays resulting from non-fatal accidents in underground hydraulic shoring trench operations. A simulation model using MicroCYCLONE is developed in order to show the sequence of hydraulic shoring trench operations and measure the productivity of it. At this juncture, a brief explanation of MicroCYCLONE simulation is presented.

5.1 MicroCYCLONE Simulation

MicroCYCLONE is a micro-computer based on simulation program designed specifically for modeling and analyzing site level processes, which are cyclic, and uses a symbolic graphic format for simulation of construction processes. MicroCYCLONE is based on classical networking techniques and it uses the modeling concepts of CYCLONE (CYCLic Operations Network) format, which has become the basis for a number of construction simulation systems with the simplification of simulation modeling process using a symbolic graphic format. The identification of resource units associated with a construction operation, the elemental work tasks with their related duration, and the resource unit flow routes through the work tasks are the basic rationale for the modeling of construction operations (Halpin, 1990). For a detailed discussion of MicroCYCLONE and its application, the reader can refer to ‘Planning and analysis of construction operations’ (Halpin and Riggs, 1992).

5.2 Simulation with Probability of Accident

The productivity simulation is based on different combinations of the probability of accident and resultant delays by accidents, which are restricted to non-fatal accidents requiring the short break for hospitalization. The simulation model for this study is modified from the original model of the hydraulic shoring system (Abraham and Halpin, 1999). The size of a trench is different, depending on the project site, the standard trench size of 6ft × 8ft × 20ft is considered for this study. Most of the activities consisting of trenching process, such as excavation, pipe-installation, and backfill activity may possibly result in an accident. In this study, these activities are assumed to have two possible outcomes: One resulting in an accident, and one not resulting in an accident. The probability of accident developed earlier in excavation and pipe-installation are 0.41% and 0.319% respectively. Since these are around 0.4 %, it is assumed that the probability ranges from 0.1% to 1% by 0.1%, and extra duration by concomitant delay ranges from 30 minutes to 300 minutes in increments of 30 minutes.

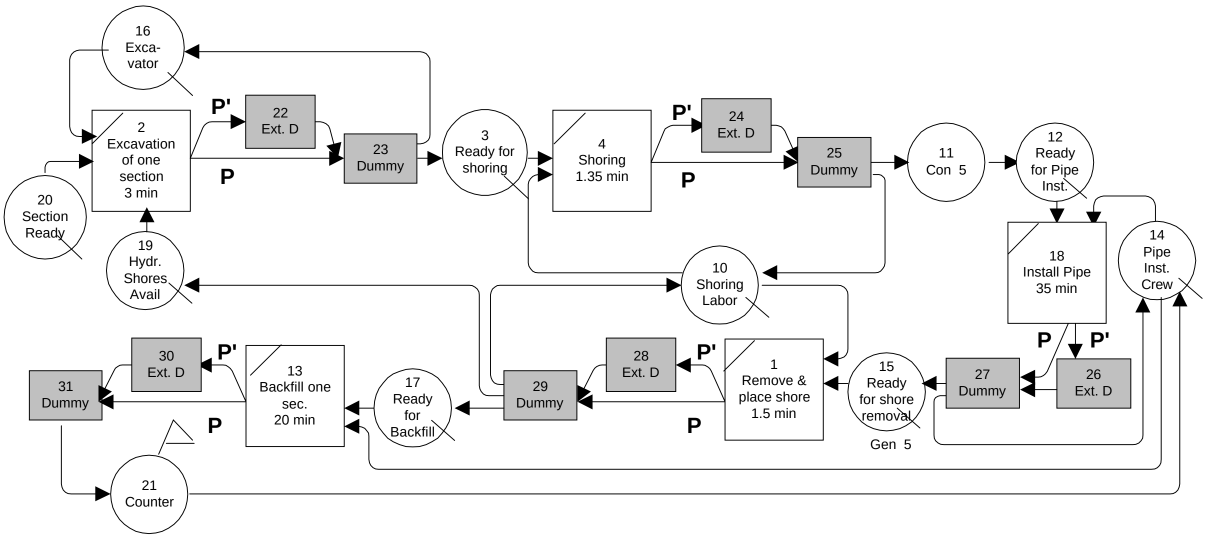

Figure 2: CYCLONE Model of Trench Operation with Accident Risk

For the identification of a cycle number of a converged point, the model was simulated from the cycle number 200 up to 3000 and showed convergence after 2400 cycles. Thus, the productivity after 2400 cycles can be regarded as an indication of the most appropriate cycle value for simulation. The Figure 2 shows the simulation model considering the accident risk, where P' is the probability of an accident occurrence, whereas P is the probability of a non-accident. Productivity was simulated based on a combination of the probability and delayed duration and the simulated productivity is expressed in feet per hour (ft/hr). The original productivity with no probability of accident is 8.79ft/hr and the results of simulation for productivity are shown in Tables 4 and 5.

Table 4: Variation by Extra Duration

Min	0.2%	0.4%	0.6%	0.8%	1.0%
0	100%	100%	100%	100%	100%
30	99.7%	99.4%	99.0%	98.6%	98.2%
60	99.3%	98.7%	97.8%	97.0%	96.0%
90	98.9%	97.8%	96.2%	95.0%	93.4%
120	98.2%	96.6%	94.2%	92.4%	90.1%
150	97.5%	95.3%	92.3%	89.9%	87.0%
180	96.9%	94.2%	90.4%	87.5%	84.2%

Table 5: Variation by Probability of Accidents

Min	60min	120min	180min	240min	300min
0	100%	100%	100%	100%	100%
0.1	99.8%	99.1%	98.3%	97.6%	96.8%
0.2	99.3%	98.2%	96.9%	95.6%	94.3%
0.3	99.1%	97.4%	95.6%	93.7%	91.9%
0.4	98.7%	96.6%	94.2%	91.9%	89.8%
0.5	98.4%	95.7%	92.6%	89.8%	87.0%
0.6	97.8%	94.2%	90.4%	86.9%	83.5%

Table 4 shows the productivity variation rate of different probabilities by the change of concomitant extra duration by 30 minutes, whereas Table 5 shows the productivity variation rate of different extra durations by change of accident probability by 0.1%. In Table 4, when the extra duration is as low as 30 minutes, it does not make any significant effect to the productivity, even though the probability of accident is high. On the other hand, as shown in

Table 5, though the probability of accident is as low as 0.1%, it impacts more significantly on the productivity. Thus, every relationship of the probability of accident to productivity variation and extra duration can be integrated into a 3-dimensional surface model for a more definite identification of the three relational factors (see Figure 3).

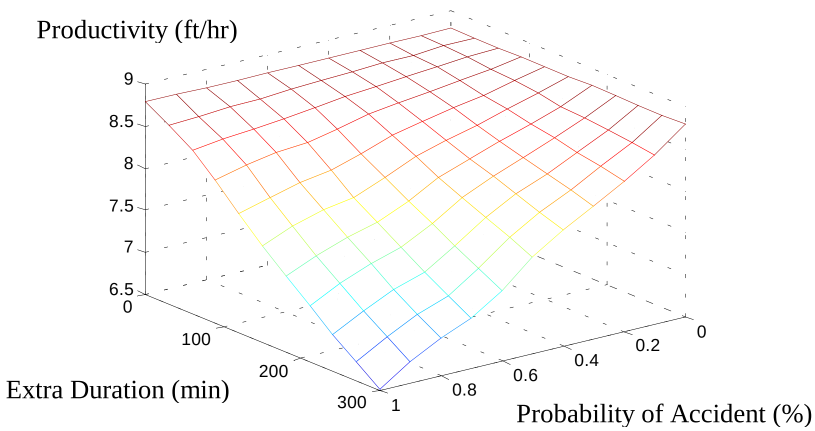

Figure 3: 3-Dimensional Productivity Variation Diagram

By comparing with above Figure 3, and Tables 4, 5, it is noted that the productivity is affected more by the extra duration than by the probability of accident especially, when the probability of accident is low. It can be therefore inferred that less frequent fatal accidents causing longer delays are more critical to productivity than more frequent non-fatal accidents resulting in shorter delays.

6. CONCLUSION

This study discusses the estimation of the probability of accident in trench operation as a risk of accident due to the fuzzy based effect of the safety factors prior to the occurrence of accidents. The quantitative variation in productivity attributed to delays resulting from probability of accident is simulated to incorporate the effect of the risk of accident on productivity. This study focuses on one major aspect of accident effect, namely, the demonstration of the relationship between the variations in productivity and the delays resulting from accident situations. It also discusses the development of a system to analyze variations in productivity as they relate to different combinations of accident probabilities and resultant delays. Research findings indicate that the productivity is affected more by the extra duration than by the probability of accident especially, when the probability of accident is low. It can be inferred that less frequent fatal accidents causing longer delays are more critical to productivity than more frequent non-fatal accidents that result in shorter delays. Not only will this method help to evaluate the risk of operation, but will also reflect the level of accident effect.

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