Use of the Multiple Severity Method to Determine Mishap Costs and Life Cycle Cost Savings

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Abstract

The multiple severity method determines mishap risk by plotting the probability of a mishap with respect to all of the possible mishap severities, in terms of monetary units, using multiple point estimates or a cumulative distribution function. The results of the multiple severity method are displayed as a line on a probability vs. severity graph, where the line represents the continuous risk curve. The integral of the continuous risk curve is the life cycle cost of the risk. Program managers, to determine the acceptable cost for mitigating the risk, can then use the life cycle cost of the risk. Comparing the life cycle cost of the risk before and after mitigation and the cost of the mitigation itself results in the life cycle cost saving, or life cycle cost, of the mitigation strategy.

Introduction

The mishap risk normally uses the worst possible severity, as in MIL-STD-882C (ref. 1), or the most reasonable credible severity, as in MIL-STD-882D (ref. 2) and NAVSEAINST 5000.8 (ref. 3). Both of these methods fail to account for a spectrum of potential severities for a particular mishap. The possible severity outcomes for each mishap will follow a probability distribution and simply selecting any one severity with its associated probability will not fully characterize the mishap. When the probability of a mishap matches to only one severity outcome, this over estimation comes at the expense of not capturing the probability of any other outcome.

An example would be running a marathon. The worst possible mishap resulting from running a marathon is death. However, if only conditions leading to death were tracked as hazards, the hazards that could potentially lead to less severe mishaps would be overlooked. The multiple severity method would separate the risk of each severity arising from running the marathon and evaluate the component probabilities of each severity.

Combining multiple risks to report a total system risk presents a different problem. The multiple severity method solves this problem by assigning a Mishap Cost to each risk, which is a single dollar value. These individual mishap costs are easily summed-up to total system costs that include equipment damage, personnel injury, as well as environmental damage. More research is required to make this feasible; but it could provide a way to compare all mishaps regardless of system or harm category (injury, equipment damage, or environmental damage).

Objective

This methodology provides the system safety professional a quantitative risk report that allows managers to base mitigation strategies on a dollar value and to estimate life cycle cost savings of those mitigation strategies. The benefit is that hazard mitigations that cannot be justified by regulatory or risk acceptance requirements, could be justified from a life cycle cost savings prospective. This methodology could potentially show the cost benefits of safety rather than just the cost incurred by safety analyses.

Limitations

The Multiple Severity Method and derived Mishap Costs require detailed knowledge of the potential mishap and accurate probabilities of occurrence using methods such as fault tree analysis. The complexity of the method limits it to mitigation strategies not based on regulations or precepts, but on a cost benefit analysis to support a management decision. To combine risks to humans and the environment with equipment damage risks, a method needs to be created to estimate the equivalent monetary loss for humans and environmental risks similar to the way the insurance industry estimates these risks. Components of this methodology may be applicable to more qualitative assessments without the detailed cost analysis. Future efforts should focus on creating techniques to simplify the creation of continuous risk models and the Mishap Costs derived from them.

<u>Analysis</u>

Risk Contour Plots: Mishap risk is the combination of probability and severity for a particular incident or outcome as described in MIL-STD-882D (ref. 2). Figure 1 is a plot of severity, in US Dollars, versus probability with risk contours in which every point on the contour is the product of severity and probability (Severity($)*Probability = Constant Risk Contour dollar amount). Every point on a particular contour has the same Mishap Cost, for example, every point on the $10,000 risk contour has a Mishap Cost of $10,000.

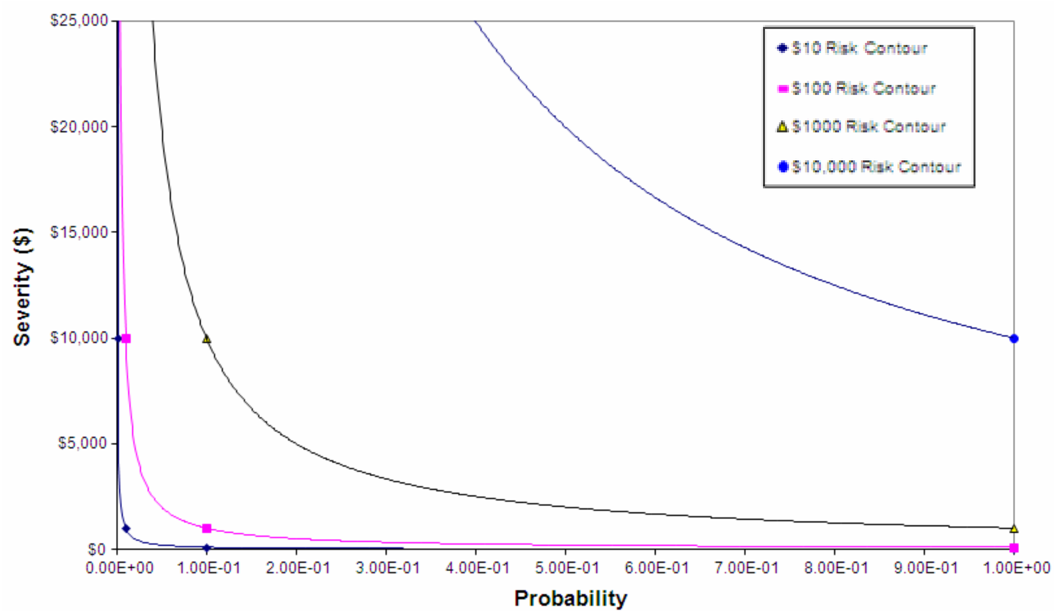

Figure 1 – Risk Contour Plot

When viewing the risk contours in a normal plot, as in Figure 1, the lines become asymptotic to the X and Y axes. By plotting them on a Log_{10}(severity) versus Log_{10}(probability) plot, as shown in Figure 2, the contours appear to be linear and the graph can be expanded to show the traditional risk area.

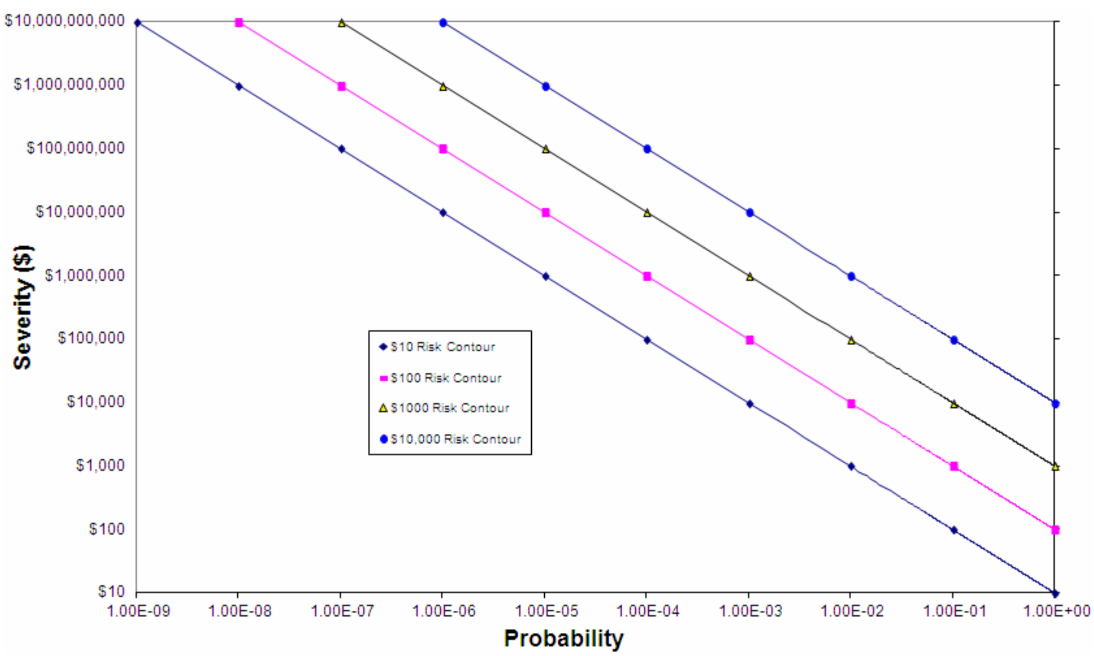

Figure 2 – Risk Contour Plot on Log_{10} Scale

Mishap Risk Assessment Matrix: The example mishap risk assessment matrix presented in MIL-STD-882D, Appendix A (ref. 2), and NAVSEAINST 5000.8 (ref. 3), was combined with a contour plot in Figure 2 to make the overlay shown in Figure 3. This figure shows that the color-coded risk levels of the MIL-STD-882D matrix do not necessarily contain equal risk throughout, as evidenced by each of the risk contours passing through two to three of the risk levels. The methodology presented in this paper could be tailored to the MIL-STD-882D matrix; however, for simplicity this paper will use an adaptation of this matrix as a basis for discussion.

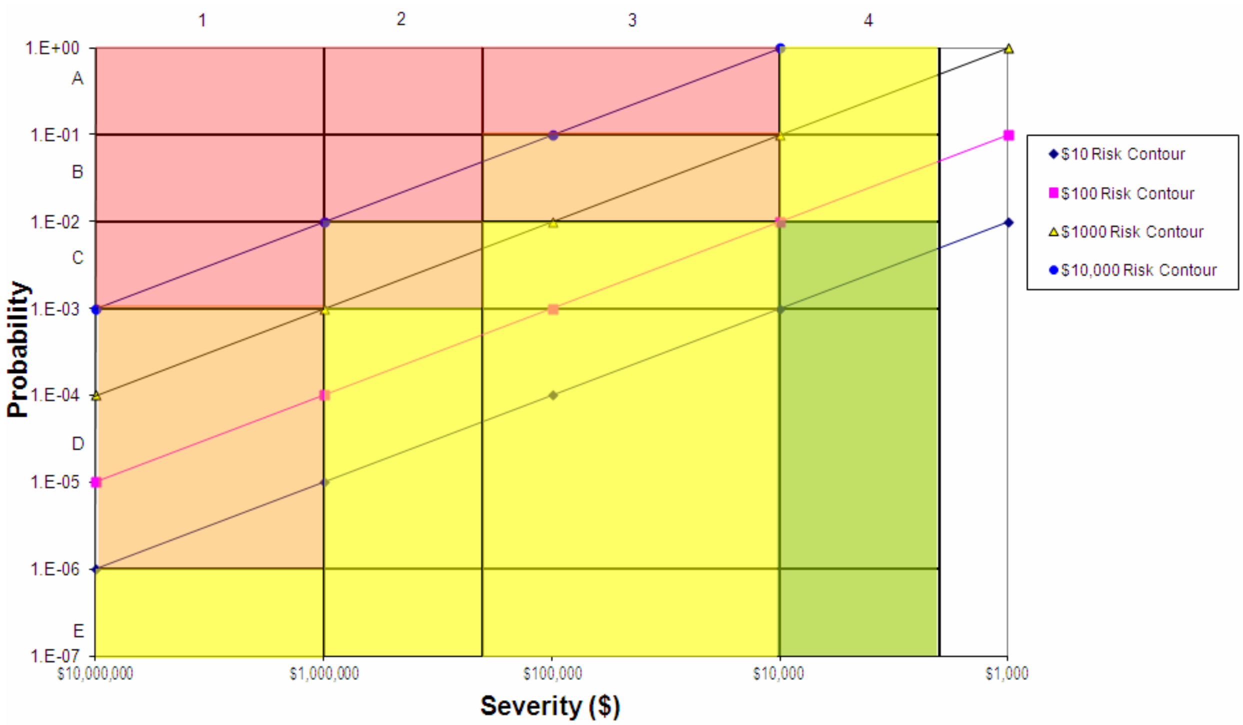

Figure 3 – MIL-STD-882D Example Mishap Risk Assessment Matrix on Log_{10} Scale with Risk Contours

The matrix presented in Figure 4, which transposes the MIL-STD-882D matrix with adjusted severity and probability categories, will be used for the remainder of this discussion. This matrix is plotted using log based probability and severity categories and is transposed to provide the severity on the vertical axis.

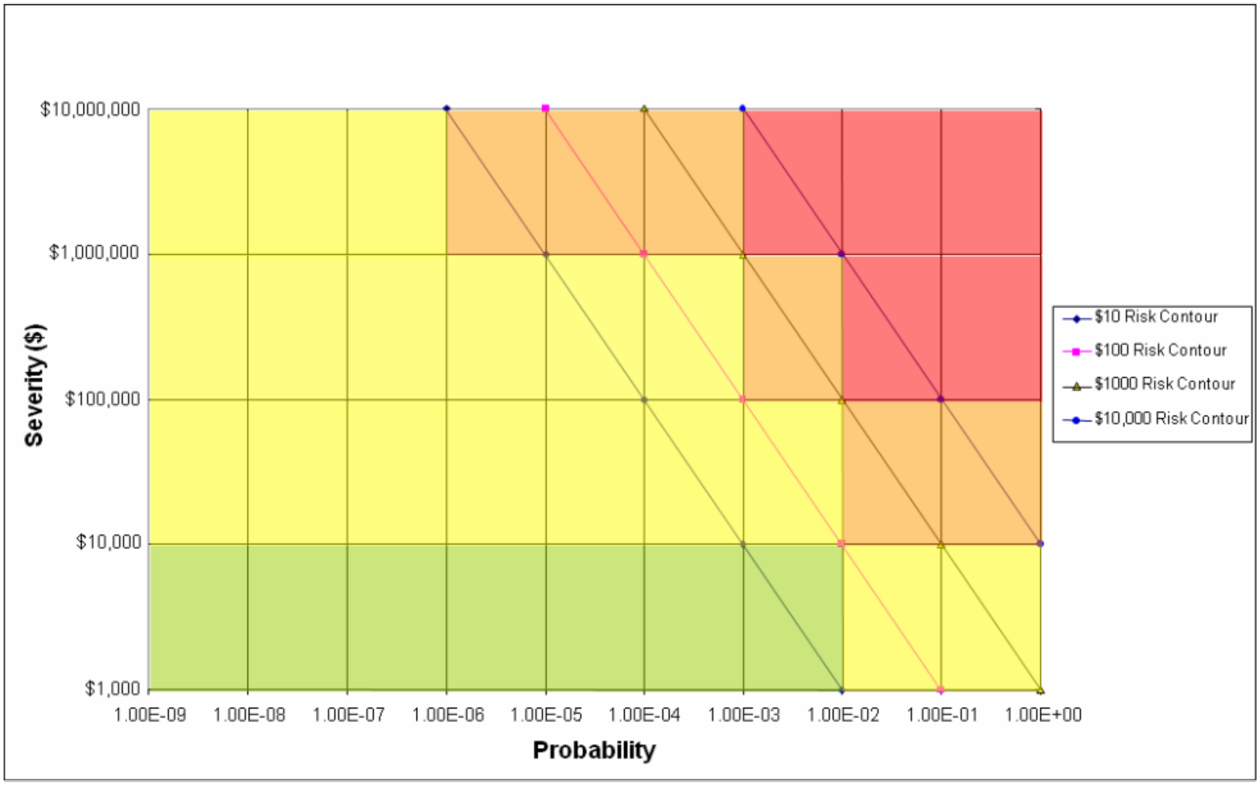

Figure 4 – Modified MIL-STD-882 Risk Assessment Matrix Used in Analysis with Risk Contours

Multiple Severity Method: The multiple severity method is a technique in which each risk is assessed by first deciding which severity outcomes are possible for the risk and secondly determining the probability of a mishap occurring for each of those severities.

When a risk is identified, the probability of a severity 1 mishap occurring can be determined and followed by the other severities. A severity 5 category can be added for near misses; in that, an event occurs which could have resulted in a mishap, however no loss was incurred. Alternatively, if the probability of the mishap occurring is known, such as mean time to failure, the probability percentage of that mishap resulting in each of the severity categories can be determined and multiplied by the overall mishap probability. In either case, the sum of the probabilities for each severity sum to the probability of the mishap occurring at all.

Table 1 shows an example of the multiple severity method being used to categorize the risk of running the London Marathon based on 23 years of data as presented (ref. 4). The severity categories were assigned for instructional purposes and further research is required to model the severity of injury and death, as well as environmental damage, in dollar amounts.

Table 1: London Marathon Injury Statistics, 1981-2003

Severity Category	Definition of Category	Probability of Occurrence (ref. 4)	Multiple Risk Indices
Severity 1	Death ($1,000,000-$10,000,000)	1: 67,414 (D_2)	$1D_2$
Severity 2	Hospital Admission ($100,000-$1,000,000)	1:10,000 (D_1)	$2D_1$
Severity 3	Contact With a Hospital Emergency Department, not admitted ($10,000-$100,000)	1:800 (C)	3C
Severity 4	Contact with St. John's Hospital Ambulance Service, not sent to Emergency Department ($1,000-$10,000)	1:6 (A)	4A
Multiple Severity Method Risk: $1D_2$ {$1D_2$, $2D_1$, 3C, 4A}			

The result of using this method is a mishap risk that is reported as the highest risk of all of the severities, which is not necessarily the highest severity outcome, followed by the severity/probability combinations for each severity in braces. An example would be for the London Marathon statistics shown in Table 1, the resulting risk, using the multiple severity method would be $1D_2$ {$1D_2$, $2D_1$, 3C, 4A}, where $1D_2$ is the risk with the highest Mishap Cost, as shown in Figure 5.

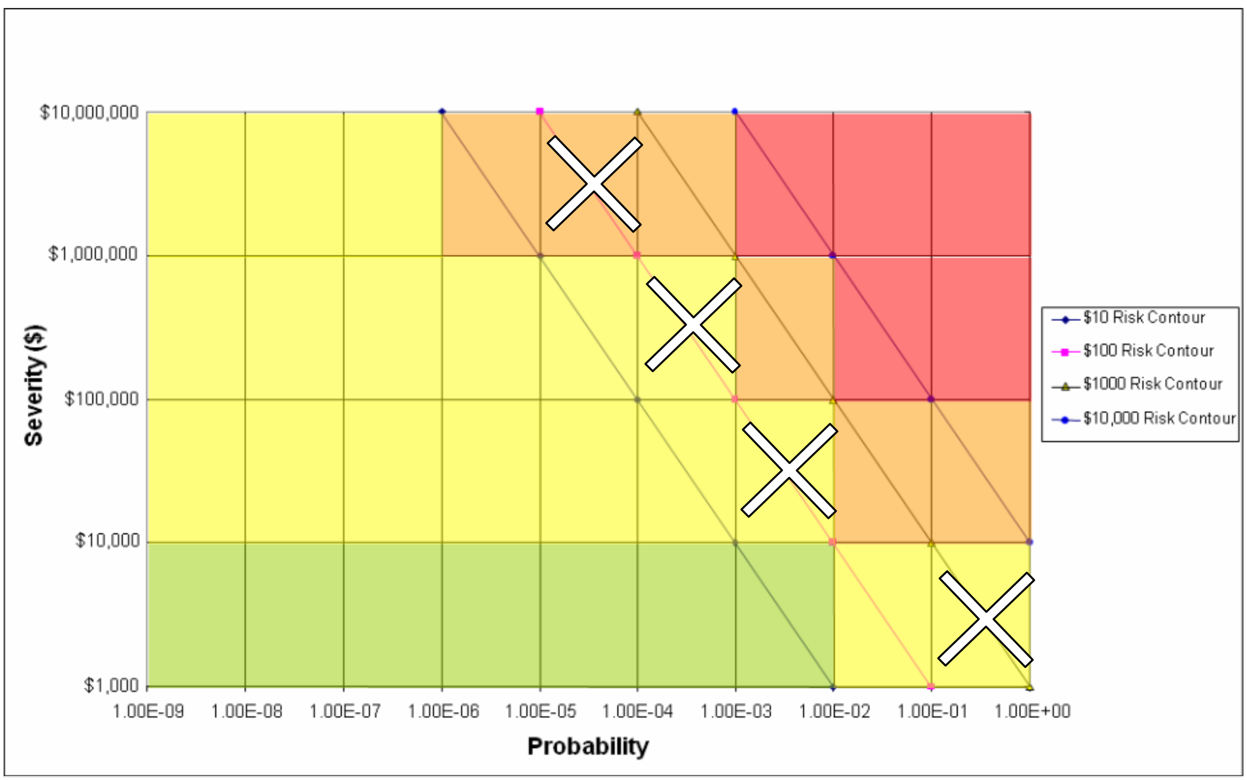

Figure 5 – Risk of Running the London Marathon

The multiple severity method can provide the system safety engineer with a greater insight into the risk associated with a system and provide a vehicle for communicating that insight to safety managers. This method also helps to identify low consequence outcomes of risk so that they are not overlooked when mitigations are employed, which only mitigate the highest consequence outcomes.

Mishap Cost: A risk is the combination of severity and probability of a mishap occurring. If the severity and probability are multiplied together, the value of the risk at that point is determined. This practice is similar to the capital asset pricing model in financial risk management. The risk contours presented earlier show collections of points that have the same risk, which when put into financial terms, will be referred to as Mishap Cost hereon. Typically, mishap risk is given as one severity and one probability. Using such a model to determine the Mishap Cost would grossly underestimate the true Mishap Cost of the risk. The multiple severity method provides a better model in an attempt to provide a more realistic value to the risk presented, due to the fact that more than one specific outcome is possible as a result of a mishap.

To provide the best possible model for mishap risk, a continuous model should be used in which every possible severity outcome has an associated probability. This model can easily be created using the multiple severity method and creating a regression line between the multiple point estimates the method yields. Another approach would be to use a cumulative distribution function that fits similar mishap data and applies it to the multiple severity method model, which would be an area for further research. The continuous mishap risk line can then be used for the mishap valuation.

The continuous mishap risk line, which is a function of severity in terms of probability, can be integrated from the minimum probability to the highest probability, resulting in the total Mishap Cost. Equation 1 shows this integral where S is the severity and p is the probability.

$$\text{Mishap Cost} = \int_{pmin}^{pmax} S\,dp \text{ for } S = f(p) \quad (1)$$

Figure 6 shows an example of the continuous mishap risk line in which the multiple severity method was used. The definite integral is most easily determined by evaluating the line in four segments using the equations shown on the chart. More research could be used to determine the exact equation for these lines; however, these equations were used to show equal risk (power function with power of -1) in the severity category. The area under the line represents the result of the integral, which is the mishap cost.

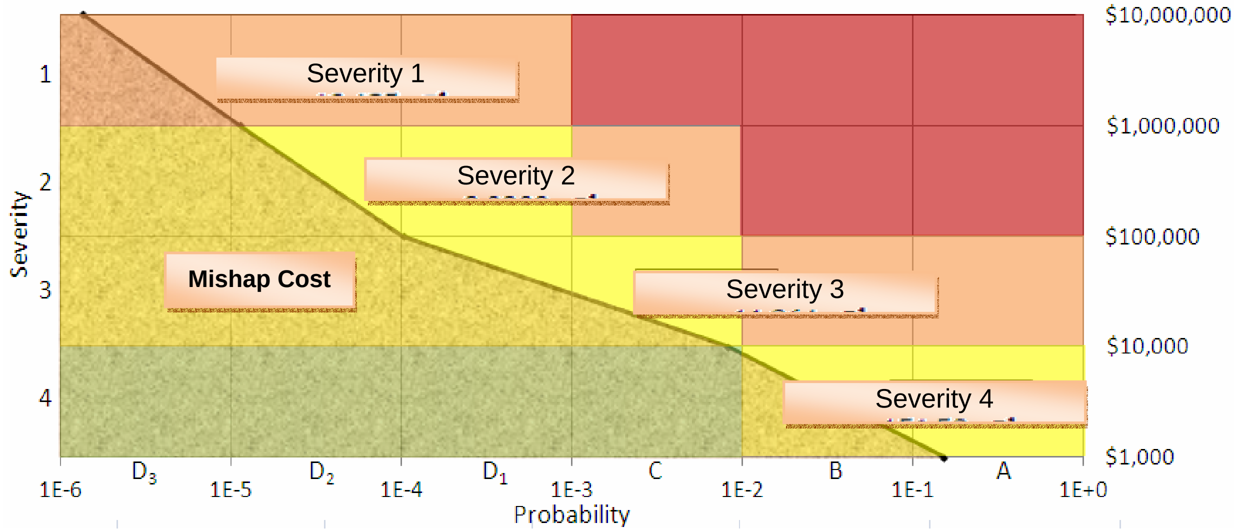

Figure 6– Example Initial Mishap Cost

The equations for the lines in Figure 6 are shown in the continuous mishap risk column in Table 2 below which is the probability density function of the risk. The integral of this line is shown in the mishap cost column and is the cumulative distribution function of the risk. The result of the integrals are shown in mishap cost column which estimates the life cycle cost of the risk in each of the severity categories.

Table 2: London Marathon Mishap Cost Analysis Before Mitigation

Severity Category	Continuous Mishap Risk (Probability Density Function)	Mishap Cost Integral (Cumulative Distribution Function) $\int_{pmin}^{pmax} S\,dp$	Resulting Mishap Cost
Severity 1	$S_1=13.485p_1^{-1}$	$\$13.485 \int_{10^{-5}}^{10^{-4}}$	$31.05
Severity 2	$S_2=9.0909p_2^{-1}$	$\$9.09 \int_{10^{-6}}^{10^{-5}} p_2^{-1}\,dp =$	$20.93
Severity 3	$S_3=11.364p_3^{-1}$	$\$11.36 \int_{10^{-5}}^{10^{-3}} p_3^{-1}\,dp =$	$26.17
Severity 4	$S_4=151.52p_4^{-1}$	$\$151.52 \int_{10^{-3}}^{10^{-2}} p_4^{-1}\,dp =$	$348.89
		Total Mishap Cost Per Runner: Total Mishap Risk Per Marathon:	$427.04 $13,800,000

Summing the individual mishap costs for each severity yields the total mishap cost of $427.04 as shown in equation 2. This value can be interpreted to be the amount of money it is worth to mitigate the risk, per runner, or equivalently, it can be interpreted as the cost of the risk if no further mitigations are implemented. This value may seem low in this case; however, if 32,300 runners run the race as in 2002 and 2003, the total mishap cost reaches $13.8 million, justifying further mitigation.

$$\text{Total Mishap Cost} = \sum_{Sev\,1}^{Sev\,4} MC_i = \$31.05+\$20.93+\$26.17+\$348.89=\$427.04 \qquad (2)$$

It is worth noting that no one entity in the London marathon shoulders this risk. Some of the resulting lost work time maybe shouldered by individuals and companies while the healthcare costs are mainly shouldered by the individuals and the government. Liability waivers would be a possible financial mitigation for the city; however, if this were a military run, the military would be liable for most or all of these costs.

Calculating Multiple Harm Hazards: In MIL-STD-882D (ref. 2), mishaps are segregated into categories of Personnel Injury or Death, Damage to Equipment, or Environmental Damage. Many mishaps are capable of falling in to more than one of these categories. In the paper An Improved Use of MIL-STD-882D Mishap Risk Index as Applied to Multi-Risk Mishaps, David R. Sadler (ref. 5), highlighted the difficulty in assessing a hazard when multiple “harm categories” can result from a single hazard. Often these hazards are treated as three separate hazards to avoid the difficulty in combining these harm categories. The multiple severity method can be used to calculate each harm category separately and the resulting Mishap Costs can then be added to get the full cost of the hazard. In addition to multiple harm categories, this method can be used to provide assessments that go beyond the scope of the MIL-STD-882 matrix and incorporate multiple fatality mishaps and equipment damage beyond $1M, such as the loss of a ship or other capital asset.

A limitation of this method is that dollar values need to be assigned to personnel injury and environmental damage. Simply applying a single cost of human life or environmental damage does not take into account the specific risks associated with the hazard such as multiple fatalities, and remediation costs for specific environmental damages. Further research in this area could provide a system in which these values can be applied. One possible way in which a value can be applied to personnel injury hazards would be to calculate the replacement cost of personnel and then use a multiplier to factor in less tangible costs, such as damage to reputation, image, production, availability, and so on. For environmental damage, previous remediation and abatements costs could be used to approximate the cost associated with specific environments mishaps. These dollar amounts will change over time based on inflation and could be linked to a price index or indices such as the Producer Price List.

Calculating the Risk of a Top Level Mishap and the Total System Risk: Currently, it is difficult to determine the risk of the Top Level Mishap and the total system. This difficulty often leads to reporting the number of hazards or Top Level Mishaps at each risk level. Similar to the technique used to calculate the risk of multiple harm hazards, the multiple severity method can be used to calculate the Mishap Cost for all of the Risks associated with a Top Level Mishap or even an entire system. This would provide a single dollar value to capture the entire risk the system, or Top Level Mishap represents. These Mishap Costs would then enable system safety managers to compare Top Level Mishaps and even various systems to each other to compare the risk. This comparison could help guide the outlay of resources to address the risks in a more methodical and cost efficient manner.

Calculating Life Cycle Cost Savings Using the Multiple Severity Method: The multiple severity method can be used to calculate the life cycle cost of a risk in the form of the Mishap Cost. If a mitigation strategy is proposed, the risk can be reassessed and the Mishap Cost after mitigation can be determined along with the cost of the mitigation strategy. These three values can then be combined using equation 3 to determine the lifecycle cost savings (or cost increase) associated with the mitigation strategy.

Life Cycle Cost Savings/Increase = Original Mishap Cost – Cost of Mitigation – Mishap Cost After Mitigation (3)

This lifecycle cost savings can be used as a metric to gauge the effectiveness and worth of a mitigation strategy or even a system safety program. The savings amount could prove to be most useful during an Analysis of Alternatives of mitigation strategies.

For the London Marathon example, shown in Figure 6, a hypothetical mitigation costing $100,000, such as filling in potholes on the race route, yields a reduced mishap risk. The risk of death during a marathon is generally related to heart failure, however, the Severity 2-4 mishaps generally result from ankle, knee, and foot injuries. By filling in potholes, in this example, the probabilities of a mishap resulting in a severity of 2, 3, or 4 was decreased by ten percent resulting in the residual mishap risk shown in Figure 7.

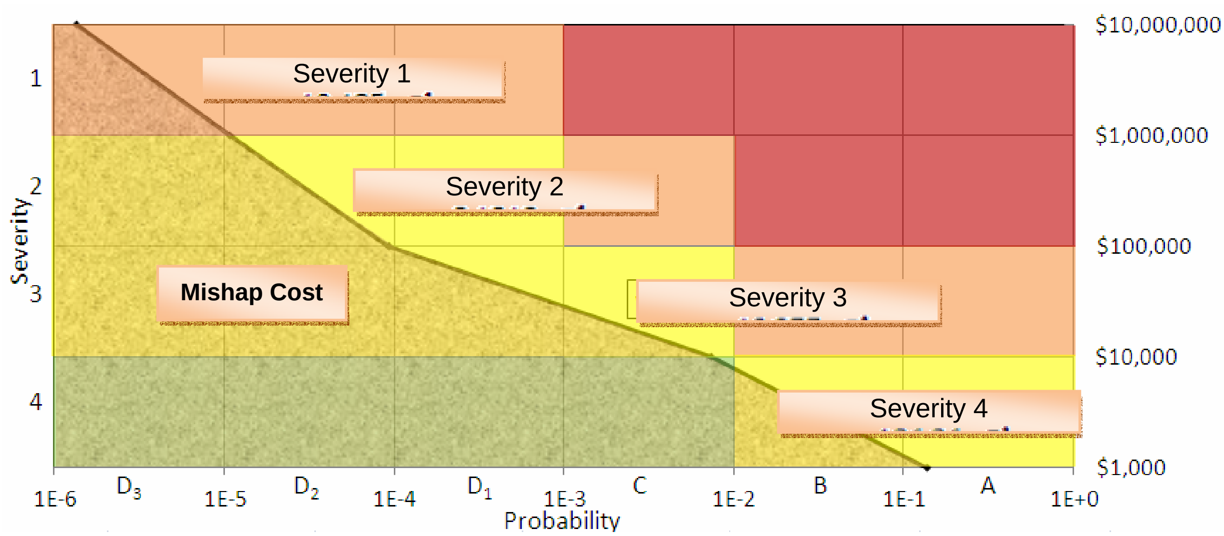

Figure 7 – Example Final Mishap Cost After Mitigation

By filling in potholes, mishap data presented in table 2 is reduced to the mishap data in table 3. Given the $100,000 cost of the mitigation and the initial mishap cost of $13.8M and the residual mishap risk of $12.5M , the life cycle cost savings of this mitigation are calculated using equation 3 and result in a mishap cost savings of $1.2M.

Table 3: London Marathon Mishap Cost Analysis After Mitigation

Severity Category	Continuous Mishap Risk (Probability Density Function)	Mishap Cost Integral (Cumulative Distribution Function) $\int_{pmin}^{pmax} S dp$	Resulting Mishap Cost
Severity 1	$S_1=13.485p_1^{-1}$	$\$13.485 \int_{10^{-5}}^{10^{-4}}$ □	$31.05
Severity 2	$S_2=8.1818p_2^{-1}$	$\$8.1818 \int_{10^{-6}}^{10^{-5}} p_2^{-1} dp =$	$18.84
Severity 3	$S_3=10.227p_3^{-1}$	$\$10.227 \int_{10^{-5}}^{10^{-3}} p_3^{-1} dp =$	$23.55
Severity 4	$S_4=136.36p_4^{-1}$	$\$136.36 \int_{10^{-3}}^{10^{-2}} p_4^{-1} dp =$	$313.98
		Total Mishap Cost Per Runner: Total Mishap Risk Per Marathon:	$387.42 $12,500,000

Results

The multiple severity method could be useful in assessing certain risks that could result in a spectrum of severity outcomes through the Mishap Cost. The Mishap Cost establishes a single variable, money, to characterize risk. The benefit of using monetary values is that it allows all harm categories to be assessed together to provide managers with the most accurate summation of the system safety risk. These monetary values also provide a mechanism for differentiating between the risks of one or multiple fatalities, which the current MIL-STD-882 approach lacks.

Discussion

The limitations of this method are that it requires more work on the part of the system safety engineer and it may require cost estimation skills by the system safety engineer and program management. In some cases, the added work and cost estimation skills could result in substantial life cycle cost reductions by the prevention of mishaps through mitigation strategies implemented based upon Mishap Cost estimations. Before this method can become practical, additional research needs to be conducted into the costs associated with human life and environmental damage, as well as multipliers to account for less tangible losses experienced after a mishap. Additional research may yield a more user-friendly version of the method using software or look-up tables.

Conclusions

The multiple severity method allows the system safety engineer to combine multiple risks and assign Mishap Costs, to each risk. These individual Mishap Costs are easily summed-up to total system Mishap Costs that could include equipment damage, personnel injury, as well as environmental damage, if a cost estimate for each is developed. These costs can be used to justify the expense of risk mitigations and one day could be used to estimate life cycle cost reductions based on various mitigation strategies. This analysis could ultimately be used to make decisions that reduce the financial risk resulting from mishap risk and show the monetary saving of safety mitigations.

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Biography

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