

RISK COMMUNICATION

Peer-Reviewed

THE BEAUTY OF THE BOW TIE

Assessing & Communicating Risk

By Bruce K. Lyon and Georgi Popov



IT HAS BEEN SAID that beauty is in the eye of the beholder. In the context of risk assessment, this can be applied to the bow-tie analysis diagram. Its ability to effectively communicate an event's potential risks in one diagram can be described as beautifully simple. This is important considering the complexity of risks in many workplaces and organizations' desire to make sound and timely decisions.

Effective communication is paramount in the management of risk. A risk assessment without clear communication among decision-makers and stakeholders does not enable an organization to achieve its objectives. Through consistent and effective risk communications, decision-makers are kept better informed and are more confident in their decisions (Lyon & Popov, 2017). Without effective communication with stakeholders before, during and after the process, risk assessment results will likely sit on the shelf.

Risk and its components can be illustrated by the risk pathway model shown in Figure 1. In this example of a fall risk while working at height, the risk is derived from gravity, the risk source or hazard. Factors or conditions that can elevate the risk's potential, such as wind or surface conditions, are called "risk drivers." The exposures in this example are those working at height, as well as workers and property beneath the elevated work. Triggers are causes that initiate the incident, such as sudden movements that cause a loss of balance. This leads to an incident: a worker falling to a lower level. The consequences may include fatalities, severe injuries and damage to property. This linear model helps visualize and understand the nature of risk.

Like the risk pathway model, the bow-tie diagram provides decision-makers with a clear picture of the hazards, their risk pathways, existing controls and resulting consequences. In addition, it is easy to use and can be applied to almost any scenario. The bow-tie analysis method is described in International Organization of Standards (ISO) 31010-2019, nationally adopted by ANSI/ASSP/ISO/International Electrotechnical Commission (IEC), as "a graphical depiction of pathways from the causes of an event to its consequences."

KEY TAKEAWAYS

- **Bow-tie analysis is a simple method used to analyze and communicate risk pathways and controls for a selected hazard scenario.**
- **The benefits of the bow tie include its ease of use for most any scenario and its ability to clearly communicate the risks to decision-makers by providing a visual diagram or map of the scenario.**
- **The original hazard analysis method has evolved into more complex variations, such as the striped bow-tie risk assessment developed by the authors.**
- **The striped bow-tie method incorporates layers of control, risk reduction factors based on the hierarchy of risk treatment and risk summation estimation to assess a scenario's risk.**

FIGURE 1
RISK PATHWAY MODEL OF A FALL FROM HEIGHT

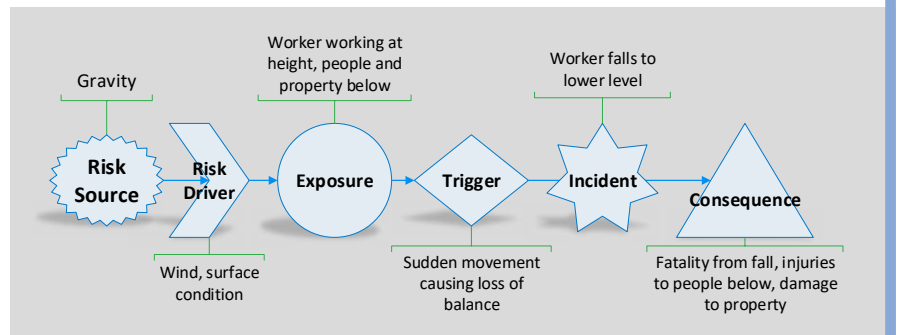
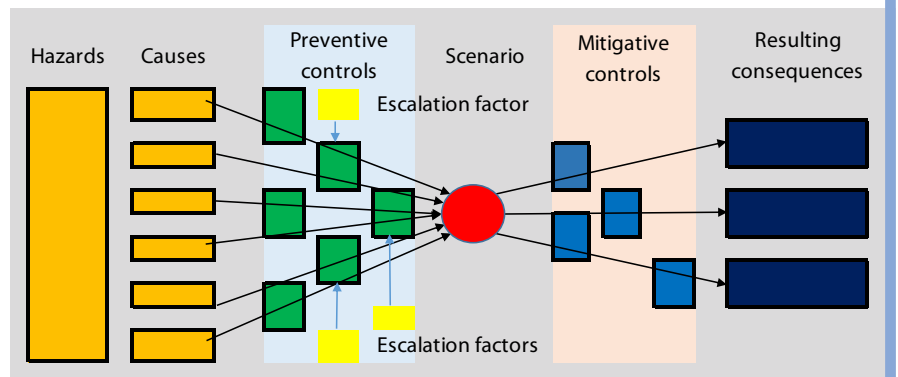


FIGURE 2
BOW-TIE DIAGRAM EXAMPLE



The traditional bow-tie analysis is a barrier-type model used to identify and communicate risk for a specific scenario. Its name is derived from the shape of the diagram created in the analysis, as shown in Figure 2. The bow-tie diagram illustrates the linkage between hazards, preventive barriers, mitigation controls and consequences. It provides a clear view of the existing barriers that prevent exposure to the hazards, as well as the reactive or mitigative measures in place to reduce the impact of the consequences in the event of exposure. This allows the barriers to be linked to specific tasks, procedures, responsible individuals and systems to effectively manage the risks. It also quickly makes it obvious where barriers may be missing or inadequate for a particular hazardous scenario.

The bow-tie diagram combines a simplified fault tree analysis on the left-hand side to analyze causation of a hazardous scenario or event and a simplified event tree analysis of the resulting consequences on the right-hand side (Popov et al., 2016). The analysis focuses on the barriers or controls between the causes and risk, and the barriers or controls between the risk and the resulting consequences. Figure 2 provides a visual layout of the bow-tie diagram pathways.

The Origins of Bow-tie Analysis

The origins of bow-tie analysis are unclear. One of the earliest documented uses is found in course notes from a lecture on hazard analysis at the University of Queensland, Australia, in 1979 (Gill, 1979; Gower-Jones et al., 1996; Ministry of Defense, 2018). Then, in 1988, following the Piper Alpha Platform disaster, the oil and gas industry was under great pressure to improve

efforts in systemic hazard analysis and risk assessment of their operations. This led to the development of the bow-tie methodology. The Royal Dutch/Shell Group was one of the first companies to effectively integrate bow-tie analysis into its business practices, which became a company standard for analyzing and managing risks and soon was adopted by others in the industry.

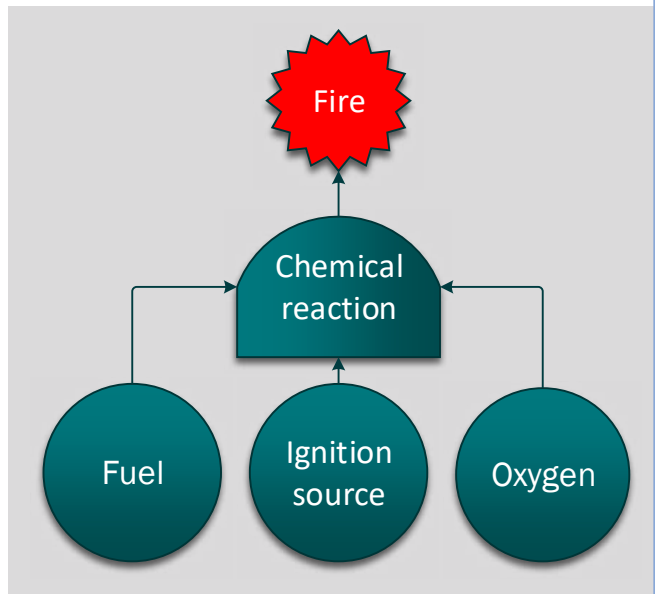
The method has since spread to other industries, including aviation, healthcare, military and defense, mining, chemical, maritime, and financial analysis. Examples of bow-tie analyses have been published by governments and industry associations, including the U.K., France, Australia, New Zealand, the European aviation industry and the U.S. Federal Aviation Administration. More recently, the bow-tie method has grown in popularity among U.S. organizations due to its ease of use and clarity in communicating risk. One reason for its spread is that it provides a big-picture view

of a process or system to effectively describe risk exposures and controls that would otherwise be difficult to explain.

Fault Tree Analysis

Fault tree analysis (FTA) is used to identify and analyze factors that can contribute to a specified undesired event or “top event.” Causal factors of the event are identified, organized and represented pictorially in a tree diagram, which depicts their relationship to the top event as shown in Figure 3. The causal factors identified in the FTA can be associated with component failures, human errors or any other pertinent factors that lead to the defined top event. It uses basic symbols for the “failure,” “causes,” “and” gates, and “or” gates. “And” gates are used for failures that result from a combination of causes, while “or” gates are used for a single-point failure where only one of the causal factors is needed to cause the top event (ASSP, 2020).

FIGURE 3
FAULT TREE ANALYSIS
DIAGRAM FOR FIRE



Event Tree Analysis

Event tree analysis (ETA) is used to analyze the top event and resulting consequences. Like FTA, it is a graphical method that represents the mutually exclusive sequences of events that could arise following an initiating event according to whether or not the various systems designed to change the consequences function. The tree can be quantified to provide the probabilities of the different possible outcomes (ASSP, 2020).

The ETA diagram starts with the initiating event, with lines connecting to each control. For each control, lines connect its success or failure to the resulting consequence, as shown in Figure 4. Probability of failure or success can be assigned to each control by expert judgment, from data or from individual FTAs (ASSP, 2020).

Bow-Tie Methodology

The beauty of a bow-tie analysis is its ability to provide a clear, visual road map of how hazards are managed and risks reduced. As with many methods, it is best performed with a group of knowledgeable stakeholders to provide different perspectives and operational insights.

The first step in developing a traditional bow-tie diagram is to define the hazardous scenario or top event to be analyzed. Once defined, the potential hazards and their causes are identified and placed on the left side. Any existing preventive barriers are then identified and placed in the path of the arrows from the hazards to the top event. The anticipated consequences are identified and placed on the right side of the top event.

Any reactive or mitigating controls are placed in the path of the arrows from the top event to the individual consequences. For both preventive barriers and mitigating controls, any escalating factors or conditions that could reduce their effectiveness should be identified and placed next to the associated control.

Bow-tie analysis can be applied in any industry and to any scenario or event. Bow-tie diagrams can analyze previous incidents, current situations and anticipated future events. A major benefit is that a bow-tie diagram can be readily understood at all levels, from C-suite executives and managers to engineers, operations personnel and other stakeholders.

FIGURE 4
EVENT TREE ANALYSIS DIAGRAM FOR FIRE



For all its strengths, the bow-tie analysis does have limitations. The traditional method is generally limited to qualitative descriptions with no risk scoring ability. It is not generally useful in complex situations, particularly where estimation of risk is important. However, it can be modified and combined with more detailed risk assessment methods.

Constructing a Bow-Tie Diagram

To construct a traditional bow-tie diagram, the FTA and ETA are combined in a horizontal layout with the top event in the center, as presented in Figure 5. The FTA is placed on the left side with the hazards and preventive barriers, while the ETA is placed on the right side with the mitigation measures and consequences. It is important to understand that measures on the left (FTA) are designed to prevent the event from occurring, while measures on the right (ETA) are taken to reduce the impact of the consequences.

A few prerequisites should be in place as part of the organization's risk assessment process. First, the risk criteria and context for the project should be established as stated in ISO/IEC 31010 and ASSP TR 31010. Risk criteria may include the organization's defined acceptable level of risk, risk factor definitions for levels of likelihood and severity, and stated response actions for risk levels to achieve as low as reasonably practicable, as well as various risk assessment methods for identifying hazards and risk sources, analyzing risk, and evaluating risk. Second, the risk context should be established, including the scope, purpose and objectives of the effort. It is useful to apply the SMART (specific, measurable, attainable, relevant and time-based) concept when developing written scope, purpose and objectives for the project. Part of the context will also include identifying qualified team members to participate in the assessment, including various departments such as risk management, production, quality, maintenance, end-users and others that have knowledge or may be affected.

Steps for Conducting a Conventional Bow-Tie Analysis

The traditional bow-tie analysis process consists of the following steps:

1) **Select and define the hazard scenario.** A significant and plausible hazard scenario (top event) is selected for analysis and placed in the center knot of the bow-tie diagram. The selected scenario should be well-defined with a description of the event, systems and processes involved; where and when it occurs; and elements associated.

2) **Identify hazards.** Hazards that can lead to the selected scenario are identified and listed on the far left side of the diagram. Hazard identification can be conducted using a variety of methods, including brainstorming, checklists, preliminary hazard analysis, failure mode

and effect analysis, hazard and operability study, what-if, and checklist methods, among others.

3) **Identify causes or triggers.** For each hazard, potential causes or triggers that could lead to the event are identified. This may require research, review and brainstorming by an experienced team to adequately identify potential causes or triggers. Causes are listed in the second column on the left side of the diagram with linkage to the associated hazard and the scenario.

4) **Identify preventive controls.** Existing controls or barriers designed to prevent release or exposure to the hazard are identified and added to the diagram between the cause and the scenario. Preventive measures may include elimination, substitution, minimization, simplification, passive (e.g., fixed guards, enclosures, permanent barriers) or active (e.g., presence-sensing devices, limit switches, ventilation) engineering controls, administrative measures and PPE.

FIGURE 5 SIMPLE BOW-TIE ANALYSIS DIAGRAM FOR FIRE

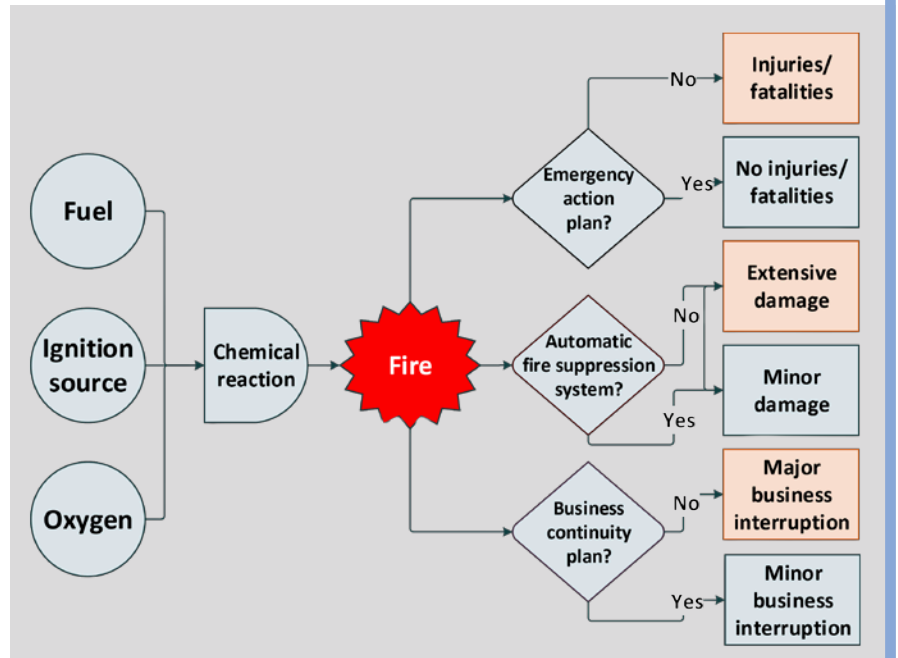
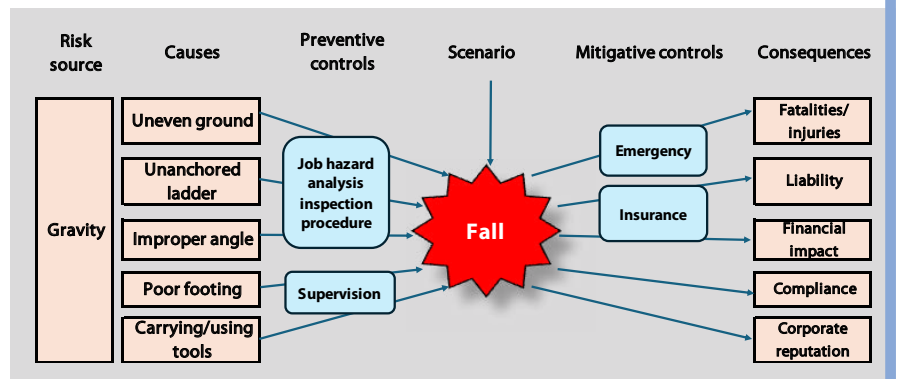


FIGURE 6 BOW-TIE DIAGRAM OF A FALL FROM A LADDER



5) **Identify escalating factors.** Conditions, factors and failure modes that could escalate the hazard or reduce the effectiveness of existing controls are added to the hazard linkage in the diagram. Judgment is needed to determine which factors present a real weakness and potential for escalating the hazard.

6) **Identify consequences.** Should the event occur, the resulting consequences are identified and listed on the right side of the bow-tie diagram. Linkage lines are then drawn radiating out from the event scenario to each consequence. Consequences should be defined as credible worst-case effects without mitigation.

7) **Identify mitigating controls.** Existing controls for reducing the impact of each consequence are identified and placed between the scenario and the consequence. Examples of mitigating controls might include fire suppression or sprinkler systems to mitigate fire spread, secondary containment to contain a liquid chemical spill or release, an emergency response plan and a fall arrest system to reduce injury severity during a fall.

An example of a constructed bow-tie diagram for common work practice using a ladder is provided in Figure 6 (p. 39).

Striped Bow-Tie Risk Assessment

While the conventional bow-tie method has many benefits, it does have some limitations. These include lack of a risk scoring mechanism, lack of differentiation of risk treatments and their effectiveness, and inability to allow estimation of combined risks or risk summation. Recognizing the limitations of the traditional bow-tie method, the authors developed the striped bow-tie risk assessment model in 2016 to communicate risk-based information to decision-makers. The striped bow-tie model incorporates a risk scoring system, use of risk-reduction factors for controls and simplified layers of control analysis approach to address risk summation.

Risk Scoring System

As a risk assessment method, the striped bow-tie model usually uses a two-factor risk scoring system with severity of consequence (S) multiplied by likelihood of occurrence (L). Like other risk assessment methods, it requires an established risk criteria including defined risk categories for severity and likelihood, and a risk matrix as shown in the example in Figure 7.

Control Factor Risk Reduction Formula

To conservatively factor in risk reductions for risk treatments and controls, a control factor risk formula is used, as shown in Table 1. The formula uses risk reduction multipliers according to the hierarchy of risk treatment levels based on their expected effectiveness and reliability levels for both preventive controls and mitigating controls. These risk reduction multipliers are estimates and are partially based on a risk reduction scale presented in ANSI B11.0-2020, Figure 4.2, and the concept of safety integrity levels (SILs) from the chemical process safety industry and IEC 61508 (IEC, 2010). SILs are a measure used to represent the relative level of risk reduction provided by a safety instrumented function. The SIL system categorizes such safety functions' reliability and performance requirements, with higher SILs indicating greater safety and a lower likelihood of dangerous failures (IEC, 2010).

A control factor risk reduction table uses risk reduction multipliers that represent the level of anticipated risk reduction based on relative effectiveness and reliability. For example, in Table 1 the authors use a 0.1 multiplier for the elimination of a hazard, which reduces the risk level by 90%. The 90% reduction is used to account for potential residual risks that may remain, as well as possible unintended secondary risks created by its removal. On the lower end, administrative measures would have a 0.9

FIGURE 7
RISK CRITERIA & MATRIX EXAMPLE

Incident outcomes					Likelihood of occurrence				
Severity	Severity rating	Health effects (people)	Property damage	Environment impact	1 Very Unlikely	2 Unlikely	3 Possible	4 Likely	5 Very Likely
Extreme	5	Death or permanent total disability	Catastrophic damage	Significant impact	5	10	15	20	25
High	4	Permanent partial disability; hospitalizations of three people or more	Severe damage	Significant, but reversible impact	4	8	12	16	20
Moderate	3	Injury or occupational illness resulting in one or more days away from work	Significant damage	Moderate reversible impact	3	6	9	12	15
Minor	2	Injury or occupational illness not resulting in a lost work day	Moderate damage	Minimal impact	2	4	6	8	10
Insignificant	1	First aid only or no injuries or illnesses	Light damage	No impact	1	2	3	4	5
Risk level actions									
Catastrophic			15 - 25	Operations not permissible, take immediate action					
High			9 - 14	Remedial action required, high priority					
Moderate			5 - 8	Remedial action suggested					
Low			1 - 4	Remedial action discretionary					

multiplier, reducing the risk by 10%. The authors emphasize that these are only estimates and that users may want to adjust the multipliers up or down to meet their own needs. It is important to consider the control's possible failure modes and escalation factors when applying risk reduction factors to avoid overestimating their effectiveness and reliability.

Steps for Constructing a Striped Bow-Tie Risk Assessment

The basic process for constructing a striped bow-tie risk assessment is the same as a traditional bow tie, with several additional steps.

1) **Select and define the scenario.** In this example, the scenario event is combustible dust explosion.

2) **Identify the hazard.** The primary hazard that, if uncontrolled, can lead to the hazardous event is identified using risk identification methods such as checklists, preliminary hazard identification, HAZID/RISKID, Pareto analysis and other methods listed in ASSP 31010 and placed in the far left side of the diagram.

3) **Identify causes and triggers.** The potential causes that can lead to the scenario event are identified and listed in the second column on the left side of the diagram.

4) **Estimate inherent risk for hazard causes.** Using a separate method such as preliminary hazard analysis, failure mode and effects analysis, or the modified

TABLE 1
CONTROL FACTOR RISK FORMULA

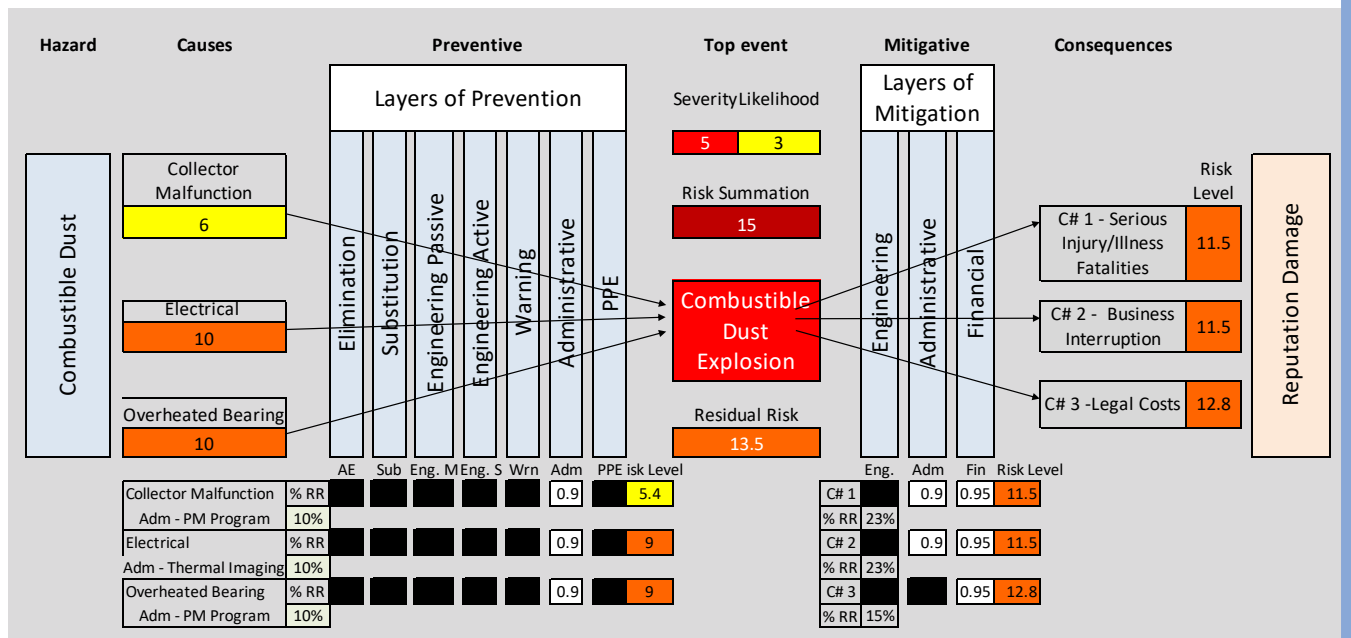
Preventive controls (left side of bow tie)	Multiplier	Mitigating controls (right side of bow tie)
Elimination	0.1	-
Substitution	0.4	-
Engineering - passive	0.6	-
Engineering - active	0.7	Engineering
Warning	0.8	-
Administrative	0.9	Administrative/warning
PPE	0.95	Financial
No controls	1	No controls

Note: Formula is Severity x (likelihood x control factor) = risk

FIGURE 8
INHERENT RISK ASSESSMENT

Risk source	Cause	Potential incident	Inherent risk			Top event	Combined risks		
			Severity	Likelihood	Risk level		Severity	Likelihood	Risksum
Combustible dust	Dust collection malfunction	Dust buildup	2	3	6	Combustible dust explosion	5	3	15
Combustible dust	Ignition from electrical	Explosion	5	2	10				
Combustible dust	Ignition from overheated bearings	Explosion	5	2	10				

FIGURE 9
STRIPED BOW-TIE MODEL FOR COMBUSTIBLE DUST EXPLOSION



layers of control analysis shown in Figure 8 (p. 41), the identified hazard causes are analyzed to estimate their inherent risk level (risk level without any controls). The inherent risk level scores for each hazard cause are put into the second column of the striped bow-tie model as shown in Figure 9 (p. 41).

5) Connect hazard causes to scenario event. To link hazard causes to the event, lines are drawn from each hazard cause to the scenario event, forming the left side of the striped bow tie.

6) Identify and enter preventive controls. On the left side of the diagram, existing preventive control measures for each hazard cause are identified. Preventive controls are entered in the appropriate box below each “stripe.” When identifying the preventive barriers, the hierarchy of risk treatment model (Figure 10) is used. The preventive control stripes or options include: 1) elimination, 2) substitution, 3) multiple engineering controls, 4) single engineering control, 5) warnings and alarms, 6) administrative measures, and 7) PPE.

7) Estimate risk levels with preventive controls. Using established risk criteria like the example shown in Figure 7 (p. 40), the current-state risk level for each hazard cause is estimated. Control factor (CF) multipliers (Table 1, p. 41) are built into an Excel tool that automatically factors in the estimated risk reduction, producing the risk level shown in Figure 9 (p. 41). The Excel tool also produces a percent of risk reduction (%RR) achieved from added control measures using the formula:

$$\frac{\text{Original Risk Score} - \text{CF Risk Score}}{\text{Original Risk Score}} = \%RR$$

8) Identify consequences. On the right side of the striped bow-tie diagram, the consequences resulting from the scenario event are identified and listed. Lines are drawn out from the event, connecting to each consequence, on the right side of the diagram.

9) Identify and enter mitigating controls. Existing measures designed to mitigate consequences once the hazard event

occurs are identified and listed between the scenario event and the resulting consequence. The layers of protection include engineering, administration and financial. On the right side of the diagram, mitigative measures are entered in the appropriate box below the stripe as shown in Figure 9 (p. 41).

10) Determine the mitigating controls risk score. For each consequence identified, existing mitigating controls are analyzed and scored using the CF multiplier formula in Table 1 (p. 41), which are automatically calculated in the Excel tool. Fewer mitigative control options are available to reduce impact from events after they occur, and these are grouped into three categories (engineering, administrative/warning and financial/insurance). To calculate the percentage of risk reduction, the hazard cause with the highest risk level is used for all resulting consequences. The mitigating control risk reduction formula used is:

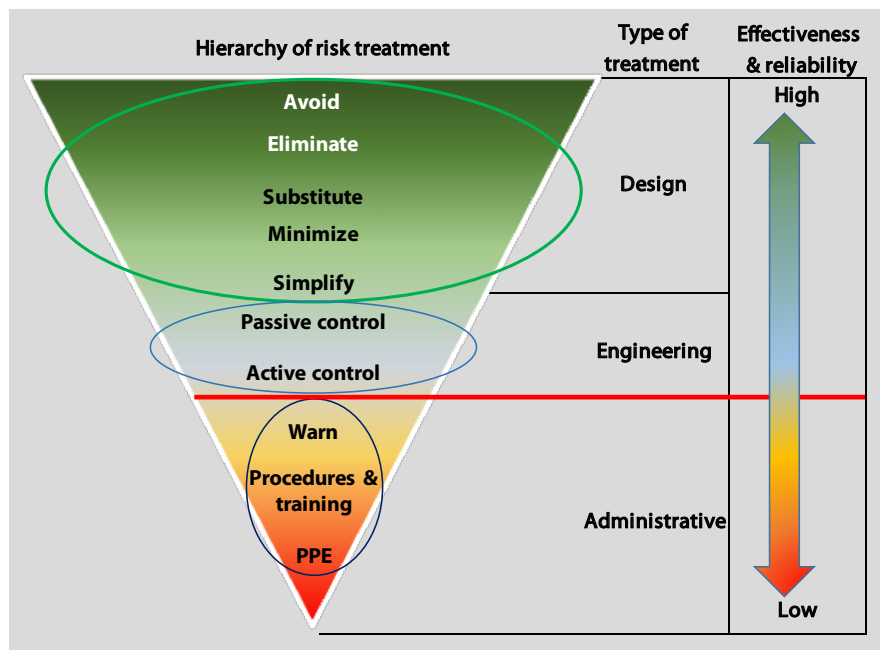
$$\frac{\text{Highest Original Risk Score} - \text{CF Risk Score}}{\text{Highest Original Risk Score}} = \%RR$$

To demonstrate the effectiveness of the bow-tie method as a risk communication tool, the following case study is presented.

Case Study

A large, national service organization operating a large fleet of passenger and small pickup trucks experienced a substantial increase in automobile incidents over a three-year period. Of particular concern was the high number of serious incidents, including head-on collisions. These increases caught the attention of the insurance carrier underwriters, as well as the chief financial officer (CFO) and chief executive officer (CEO) of the company. The organization’s risk management team and the authors discussed these concerns, ways to assess and communicate the risks, and possible solutions.

FIGURE 10
HIERARCHY OF RISK TREATMENT



The team performed a fleet loss analysis and determined that the leading hazardous event for serious and fatality-related losses was head-on collisions. For the head-on collision events, identified hazard causes included distracted driving, impaired/fatigued driving, speeding, vehicle failure, and weather and road conditions. For each of these causes, numerous risk controls were reviewed, as were possible consequences resulting from these fleet losses. Using the ANSI/ASSP Z15.1 Safe Motor Vehicle standard, the authors proposed a list of available preventive controls and mitigative controls, including the following:

- Purchasing vehicles equipped with built-in lane departure and blind spot alarms, crash protection design, auto emergency braking, air bag systems, electronic stability control, occupant restraints and traction control system
- Incorporating fleet safety engineering and technology, including drive mode technology (phone), telematics, fatigue monitoring, daytime running lights, and snow tires and chains

FIGURE 11
QUALITATIVE STRIPED BOW TIE, CURRENT STATE

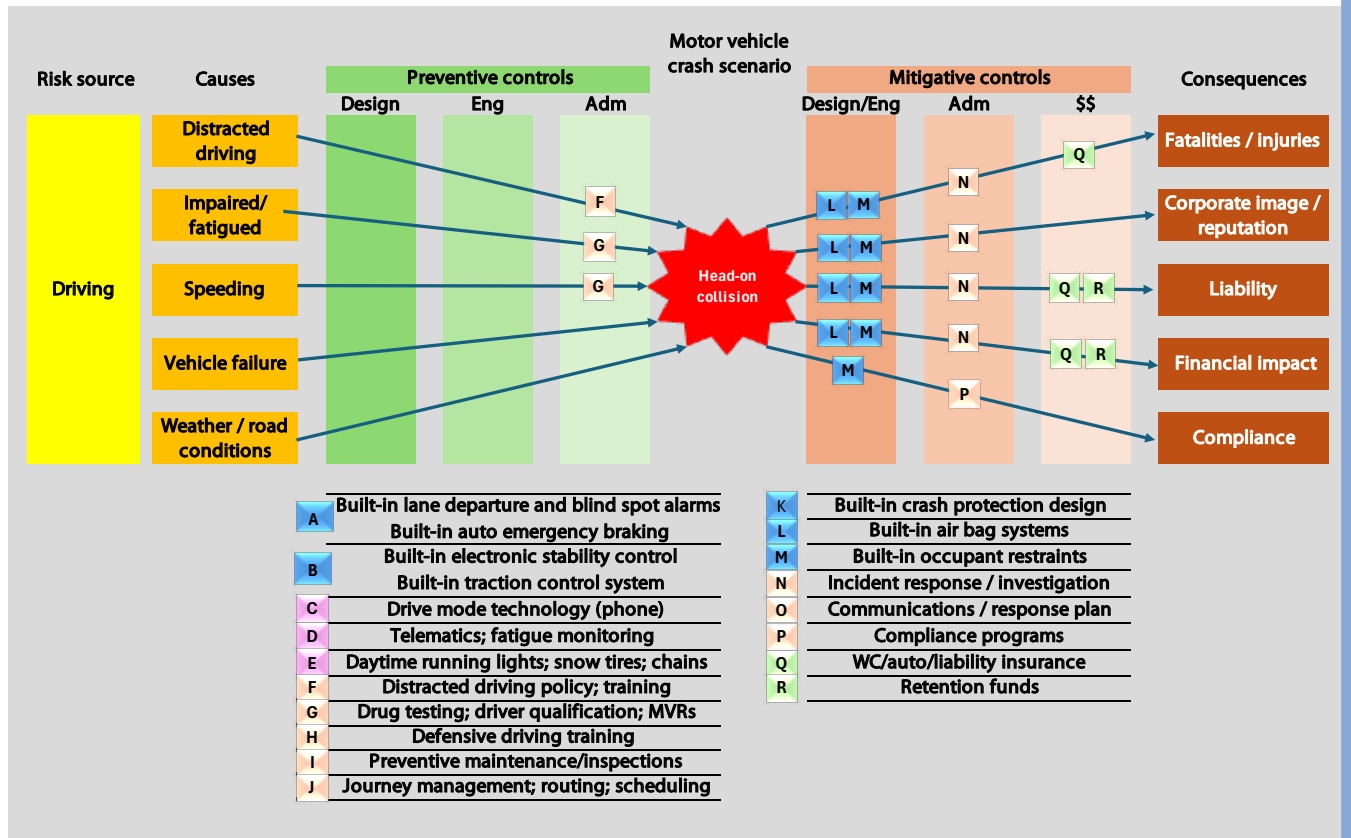
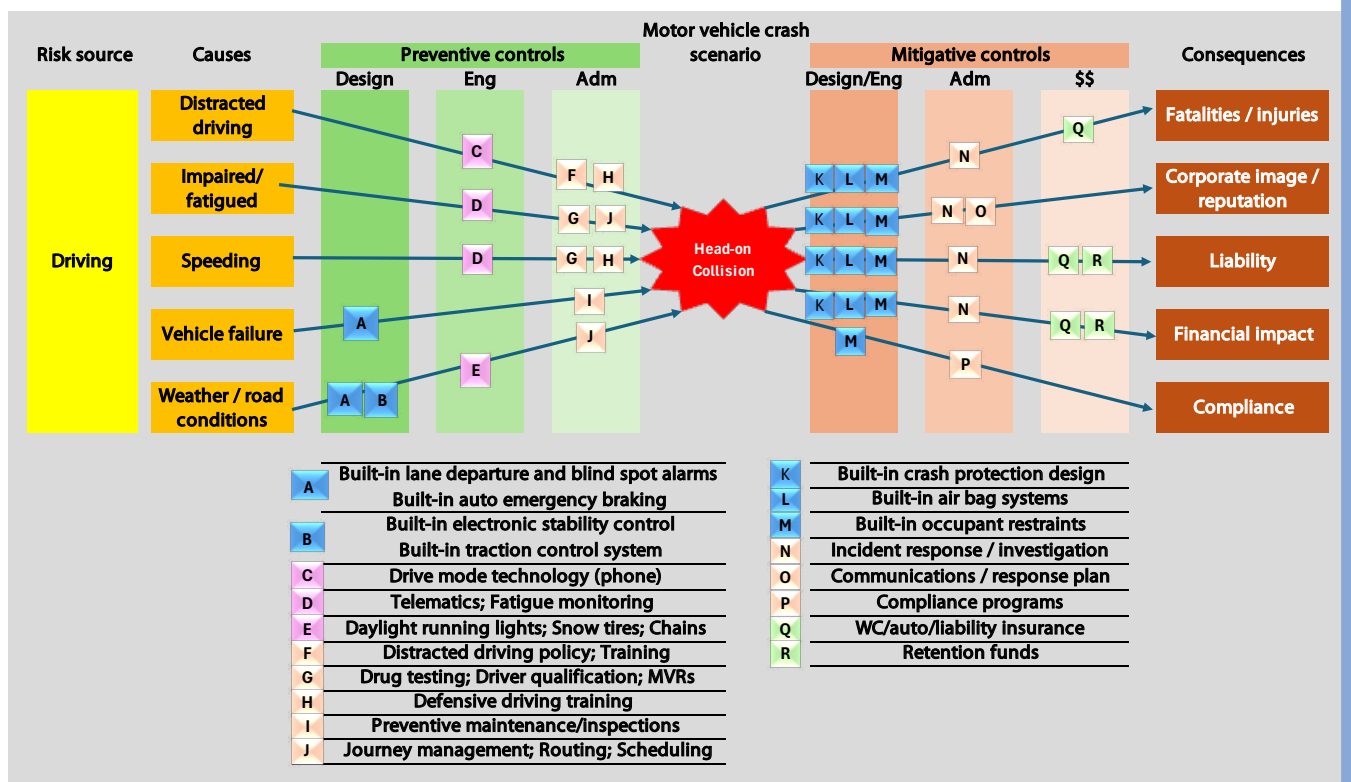


FIGURE 12
QUALITATIVE STRIPED BOW TIE, FUTURE STATE



- Implementing fleet safety administrative policies and training, including distracted driving policy and training; drug testing and driver qualification; motor vehicle records reviews (quarterly); defensive driving training; preventive maintenance schedules and inspections; and journey management, routing and scheduling

- Mitigative design or engineering controls, including vehicles with crash protection design, air bag systems and occupant restraints

- Mitigative administrative actions, including immediate incident response and investigation procedures, corporate communication policy and up-to-date compliance program

- Mitigative financial measures, including adequate insurance coverages and limits, and in-house retention funds

As the team further investigated the numerous causes, controls and other factors, it became apparent that the issue was somewhat complicated to explain. With this information, the authors suggested using a qualitative striped bow-tie analysis diagram to provide a broad picture of the causes, controls and consequences for head-on collisions, as well as opportunities to strengthen controls where gaps existed.

By completing the striped bow-tie diagram with the identified causes, existing controls and consequences, the team was able to produce a graphic showing the existing gaps in their controls (Figure 11, p. 43), which were primarily on the preventive side. As stated in ANSI/ASSP Z590.3-2021, Prevention through Design, it is well recognized that prevention efforts provide the greatest risk reduction, while mitigative controls have only limited effects.

In a 30-minute meeting, the team presented their findings using the striped bow-tie diagram and briefly described the analysis process. When they were shown the current state (Figure 11, p. 43), senior management were able to see that gaps existed in their fleet safety efforts. The CFO and CEO had not been aware of these weaknesses and asked what could be done to improve fleet safety results. Showing the future state (Figure 12, p. 43) diagram, the team discussed the need for the additional preventive controls listed. This led to further discussion by senior management on the need to develop an action plan and assign responsibility for investigating these measures. The simple and clear approach of the bow-tie diagram allowed all stakeholders and decision-makers to understand the problem and possible solutions. As a result, senior management was able to identify priorities for investment in safer preventive controls in their fleet operations.

Conclusion

The beauty of the bow-tie diagram method is its ability to provide management and other stakeholders with a 30,000-ft overview of a hazardous scenario event, communicating its risk. It allows decision-makers to visualize the relationship between hazards and their causes, preventive controls, the event scenario and the mitigation measures to limit their consequences. The method is versatile and can be used in analyzing and communicating risks for all types of scenarios and in all industry settings. The striped bow-tie model addresses the limitations of the conventional bow-tie model by incorporating a risk scoring system and use of risk reduction factors for controls and simplified layers of control analysis approach to address risk summation. The bow tie's simple, logical approach of analyzing preventive barriers as well as mitigative measures to reduce an event's impact makes it a valuable risk assessment tool for the EHS professional. **PSJ**

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