# RISK ANALYSIS OF TERRORISM ON U.S. CARGO TRANSPORTATION INFRASTRUCTURE

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In the past four years, national security has been a primary concern, initially regarding human health, and eventually including protection of sensitive infrastructure, the environment, and commerce from threats of terrorism. Safeguards employed have included change in policy, intrusion detection technology, increased surveillance, and improved intelligence. An innovative method of safeguarding cargo shipment exists as a technology currently reserved for limited and special applications: freight pipeline transhipment. Risk associated with this specialized form of U.S. infrastructure is developed as "what-if" scenario sequences. The severity of consequences is quantified by index numbers prescribed by the US Department of Home Land Security. Impacts of these hazards are then analyzed in more detail using a two-tier study, which focuses on the negative impact to human well-being, capital assets, and socio-economic stability. The risk assessment includes acceptability factors which are based on the incremental acceptable risks derived from revealed preference concepts. In summary, the risk assessment for terrorism on the infrastructure involves: (1) the evaluation of terrorism hazards to human health, the environment, and commerce; (2) terrorism activity scenario development; (3) risk estimation for different terrorist activities; and (4) risk acceptability analysis for the matrix of potential consequences. Most terror risk to infrastructure in the U.S. is immediately deemed unacceptable by society. However, in this study, it is found that when appropriate threat deterrent technologies are employed, risk acceptability can be achieved; whereas malicious threats to conventional surface transportation systems may remain indefinitely unacceptable, even given enhancement of security policies and safeguard measures.

Keywords: Fatalities, Infrastructure, Risk, Socio-economic and Terrorism

## INTRODUCTION

Subsequent to the September 11$^{th}$, 2003 attacks on the United States, significant national concern focuses on the effectiveness of safeguard measures protecting critical infrastructure (adopted from USDHS, 2004). Documented within are results and methodologies of a vulnerability study executed to analyze the risk of terrorism on tubular freight systems in the United States and abroad. Such systems utilize linear electric induction motors to convey capsulated cargo between fixed endpoints within pipeline structures. Though the concept of transporting freight through pipelines is relatively new, and currently limited to special applications, the process represents a viable alternative to conventional strategies, by eliminating uncertainties associated with highway congestion and rail logistics. Such inherent hidden qualities have attracted 'new thinking' and consideration, regarding transport of vital and/or hazardous products, especially in sensitive or densely populated areas. Using the risk modelling strategy outlined in this study, accidental and intentional malicious hazards,

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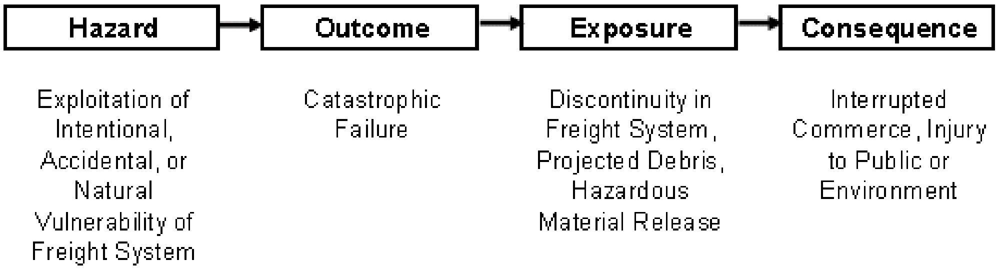
that have potential of resulting in transportation incongruence, are analyzed to predict the probability of negative impacts to human health, environmental well-being, and commerce. The causal relationship presented in **Figure 1** illustrates how vulnerabilities of a freight pipeline system might be exploited to result in such negative consequences.

**Figure 1:** Conceptual Model of Generalized Risk Pathway




## IDENTIFICATION OF HAZARDS

Identification of hazards is derived from data for conventional freight transportation systems. Although a degree of subjectivity was required during establishment of analogous risk pathways between pipeline and conventional systems, historical data proved to be a valuable resource for identification of terror-threats, and severity of those threats, during prediction analyses. Pipeline construction, operation, maintenance, rail system statistics, linear induction motor technology, and historical and experimental freight pipeline system information was used to identify hazards and potential exposure groups. Causal factors considered in the model include: misalignment of guideway, destruction of track, sabotage of electrical or mechanical controls, flooding, intrusion to include excavation, flash fires, or any combination of these dangers. The potential and real economic, environmental, and safety hazards associated with freight pipeline failure are identified in **Table 1**.

**Table 1:** Summary of the Identified Hazards by Terrorism

| Identified Hazards | Infrastructure Damage | Environmental or Sensitive Security Areas Damaged | Injury to Population |
|---|---|---|---|
| Tube Rupture | X | X | X |
| Intrusion (including excavation) | X | X | X |
| Adjacent Pipeline Leak | X | X | X |
| Sensor Malfunction | X | -- | -- |
| Electro-Mechanical Failure | X | -- | -- |
| Capsule Collision | X | -- | X |
| Pipeline Damage (short circuit) | X | -- | X |
| Hazardous Material Spill | X | X | X |
| Flash Fire | X | X | X |

A brief narrative, describing how the probability for each threat event listed in **Table 1** was calculated, is provided below. Probabilities range from 0 to 1 and describe the likelihood of occurrence, with smaller numbers representing events less likely to occur. For example, a risk value of 0.01 is likely to occur 1 time out of 100.

**Freight Pipeline Rupture**
A compromise in the integrity of the pipeline structure poses the threat of catastrophic explosion and/or release of potentially hazardous contents to the environment, which may include urban areas. Approximately 500,000 miles of natural gas and oil pipelines exist in the United States, in which 454 rupture accidents were reported in 1989 (DOT, 1992). Based on existing data, the frequency of occurrence of tube freight pipeline rupture can be conservatively estimated to be 0.00091 for each mile of freight pipeline per year.

**Terrorist Intrusion**
Malicious infringement into the operating envelope of the freight pipeline is possible via structures designed for operation, maintenance, and repair. Threats posed by unauthorized access might result in vandalism, arson, damage to structural integrity of the pipeline shell, damage to the propulsion system, or catastrophic explosion. In the United States approximately ½ of all adverse pipeline incidents are caused by a third-party intrusion (USDOT, 1992). An approximate 30 annual pipeline damage incidents are incurred by mechanical equipment, such as backhoes and bulldozers. In pipeline transportation systems, hazardous material is typically shipped in tamper resistant and sealed containers. It is conceived that by implementing additional current safeguard technologies, unauthorized access and construction accidents can be further and significantly reduced. If half the 30 annual incidents are attributed to unauthorized intrusion, the frequency of occurrence can be conservatively estimated at 0.00045 for each mile of pipeline per year.

**Freight Pipeline System Adjacent to Human Population**
Accidental or malicious release of hazardous materials shipped within pipelines can have potential adverse effects on adjacent populations via drinking water and airborne pathways. Injured human groups can include operation and service personnel, construction workers, third-party contractors, and the civilian populous. An estimated rate of 0.01 per incident is assigned to the public as the potential exposure group.

**Sensor Failure**
Sensors are used to detect flooding, guideway misalignment, intrusion, and pipeline leaks. The average failure rate for electrical hardware is 0.0086 per year. With increased innovation and sophistication in threat sensing technology, which has been motivated by awareness and collateral damage incurred by terrorist activity, sensor failure is estimated to be improved five folds at 0.043.

**Electro-Mechanical Failure**
Based on records of rail equipment and train accidents attributed to electro-mechanical failure, the failure rate of the freight pipeline systems, in protected environments attributed to intentional threat activity, is estimated to be one percent of conventional train systems. The estimated rate for such failures is 0.0002 for each mile per year.

**Capsule Derailment and Capsule Collision**
Freight pipeline systems, designed to convey capsules through close-fitting ducts, often with only one inch of clearance, are vulnerable to any of several malicious derailment strategies. Given derailment occurrence of one time, per 100 years, per 400 miles of high-speed ground-level guideway systems; the frequency of occurrence of such a derailment is estimated to be 0.00025 for each mile per year.

**Guideway Short-Circuit**

Risk of pipeline flooding and guideway short-circuit is inherent in subsurface freight systems where the groundwater elevation sometimes exceeds the elevation of tunnel inverts. Electrical systems in the tunnel, such as power catenary lines, motors, and control wiring, are vulnerable to water damage. Probability of a guideway short-circuit, as a direct or indirect result of terrorist activity, is estimated to be 0.5.

**Freight Container Damage**

Freight in pipeline conveyance systems is typically shipped in containers protected by a system of safety measures that is four levels deep. Integral precautions for insurance of delivery and protection of human health and the environment include: individual tamper resistant freight containers, the transhipment capsule that carries packages, the pipeline shell, and the thickness of backfill material that covers the pipeline. The likelihood of freight damage is contingent on failure of the containment system, and collateral damage is dependent on the hazardous characteristics of the product, including: the product's degree of ignitability, corrosivity, reactivity, and toxicity. To the modern terrorist, pipelines and containers known to transport hazardous materials are more likely targets of malicious activity. The estimated rate of a hazardous material spill, then, is 0.5 per incident.

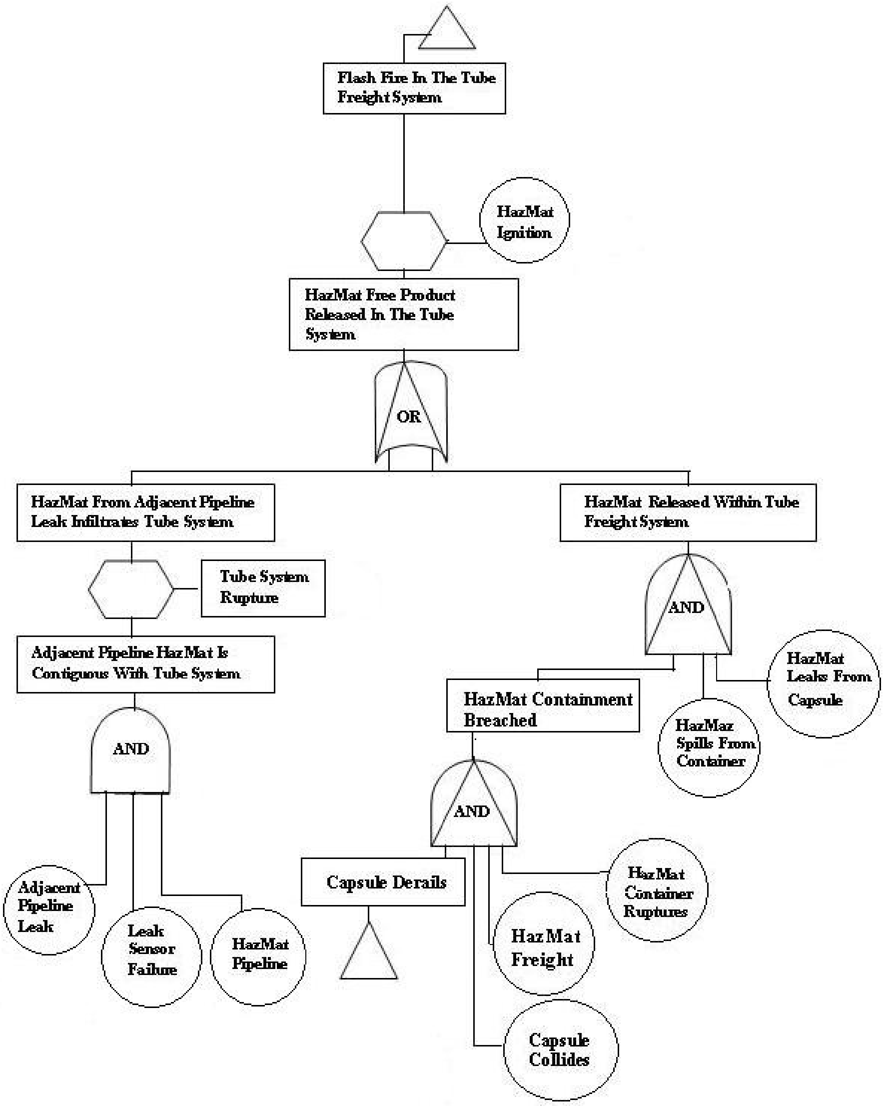
**Ignition of Flammable Cargo**

Probability for the occurrence of fire in subsurface freight pipelines is typically less than that for ground level or elevated transportation systems; given that oxygen supply is intrinsically limited by air handling equipment. In natural fires caused by faulty electrical equipment or sparking rails, fuels are rapidly consumed, intra-pipe oxygen is exhausted, or smouldering fires are extinguished prior to damage of significant magnitude. Malicious activity involving arson is likely to be larger in scale, however, and may include intentional release of liquid or gaseous fuel supplies, if not explosives. The probability of fire is conditional on successful intrusion, leaking cargo, rupture, and sensor failure. The estimated rate of cargo ignition is 0.5 per incident.

**Flash Fire Probability**

The probability of a flash fire occurring within the confines of a freight pipeline structure is determined by the combined events of a hazardous material spill and successful ignition of flammable materials, given that both are caused by terrorist activity. Logic that defines the concept used to determine the probability of a flash fire is presented as the fault tree in **Figure 2**. The resultant probability of flash fire by initiated by terrorism is 0.01.

**Figure 2**: Flash Fire Fault Tree




# RISK ANALYSIS

## Risk Index Matrix

The U.S. Department of Homeland Security (USDHS) classifies risk, in matrix format, based on asset criticality coupled with vulnerability (**Table 2**). Published are value ranges used to determine asset importance, and threat frequencies used to classify vulnerabilities.

Using this strategy, risk to essential assets (1) with extremely high vulnerability (A) is of paramount concern and is unacceptable. The far extreme of the spectrum is represented by non-vital assets (4) with low vulnerability (D), toward which little concern is expressed.

***Table 2:*** *Risk Index Matrix*

| | Asset Criticality | | | |
|---|---|---|---|---|
| **Asset Vulnerability** | **Essential, (1)** | **Critical, (2)** | **Important, (3)** | **Unimportant, (4)** |
| Extremely High (A) | 1A | 2A | 3A | 4A |
| High (B) | 1B | 2B | **3B** | 4B |
| Medium (C) | 1C | **2C** | **3C** | 4C |
| Low (D) | **1D** | **2D** | 3D | 4D |

From the USDHS Risk Indexing strategy, frequencies for different classes of collateral damage threats are presented in **Table 3**.

**Table 3:** Severity of Damage vs Risk Index

| Severity Of Consequences | Frequency Of Occurrence | Risk Score* |
|---|---|---|
| Catastrophic Damage | 0.0091 | 1A |
| Critical Damage | 0.0001 | 2B |
| Important Damage | 0.0095 | 3A |
| Negligible Damage | 0.0100 | 4A |

* US Department Of Homeland Security

As categorized by the USDHS, **Table 4** presents probabilities for different classes of human threats.

**Table 4:** Public Health Injury

| **Severity Of Consequences Public** | Frequency Of Occurrence |
|---|---|
| Catastrophic Injury | 4.5E-5 |
| Critical Injury | 4.5E-4 |
| Marginal Injury | 9.1E-8 |
| Negligible Injury | 4.5E-3 |

## Risk Acceptability

Between two ends of the USDHS Risk Index spectrum are marginally acceptable categories 1D, 2C, 2D, 3B, and 3C, which require management decision. Factors influencing final decision include: cost to secure, asset value, threat to human life, and perceived risk. Human health is paramount regarding categorization of risk, especially when seeking approval from public stakeholders and policy-makers. The matrix index adopted by U.S. Department of Homeland Security, as shown in **Table 2**, serves as a first tier in risk assessment, providing valid foundational risk classification. The matrix is not designed to determine ‘acceptability’ or make decisions regarding. Methods utilized in the following analysis are ideally suited for marginal USDHS Risk Index classes requiring decision management.

## Methodology

The following steps were implemented during construction of the risk models, as applied to **Table 1** terror threats: (1) define risk pathway, (2) build a logical event tree, (3) construct a probabilistic fault tree, (4) calculate estimated risks for each pathway, (5) determine risk referents using Rowe’s methods, and (7) compare risks for acceptability. Probabilities associated with non-routine events, conditional probabilities, and failure probabilities for key subsystems are shown in **Table 5.** Items in this table represent event nodes on the master fault tree used to determine risks for each pathway leading from hazard to consequence.

**Table 5:** The resultant failure probability of key systems by terrorism

| Hazard | Category | Probability |
|---|---|---|
| Terrorism Intrusion | Non-Routine | 1.0E-3 |
| Intruder Damages Guideway | Non-Routine | 0.39 |
| Contiguous Water Damage | Conditional | 0.095 |
| Hazmat In Tube Freight System | Conditional | 0.22 |
| Ignition Of Flammable Material | Conditional | 0.39 |
| Electromagnetic Damage | Conditional | 1E-04 |
| Adjacent To Env. Sensitive Area | Conditional | 0.095 |
| Adjacent To Population Center | Conditional | 0.01 |
| Worker Exposure | Conditional | 0.095 |
| Guideway Short-Circuit | Component | 0.39 |
| Adjacent Pipeline Leak | Component | 4.5E-3 |
| Sensor Failure | Component | 0.043 |
| Mechanical-Electrical Failure | Component | 1E-2 |
| Derailment | Component | 2.5E-4 |
| Freight Pipeline Collision | Component | 0.01 |
| Hazmat Spills | Component | 0.5 |
| Hazmat Leaks From Capsule I | Component | 0.5 |
| Rupture | Component | 9.1E-3 |

## Risk Referent Model

The second tier in the risk acceptability analysis is developed based the on the risk referent model, proposed by Bill Rowe (Rowe, 1977). Rowe utilizes prospect theory to modify risk acceptability, by incorporating public perception of threats. His basis includes factors based on degree of volunteerism, severity of outcome, cost benefit balancing, and controllability. In general, the public is more tolerant of voluntary risk than involuntary risk, the public accepts higher risk when it feels it is in control of the hazard, and the same number of fatalities may be viewed as 'more acceptable' when distributed over several accidents, rather than resulting from a single less-frequent incident. Natural risks are generally considered more acceptable than man-made risks.

The risk referent modelling approach includes four phases:

- Determine appropriate risk classification scheme based on revealed preference
- Determine an absolute risk reference for each class in the scheme, (Table 6)
- Using the risk reference as a base, calculate the risk referent using appropriate proportionality and derating factors.
- Compare the estimated risk from the fault tree analysis with the risk referent to determine acceptability

The referent defines a risk acceptability limit. This value is based on the risk reference, modified by cost, benefit, volunteerism, and severity of potential consequences. If the estimated risk from the fault tree analysis is within, or less than, one order of magnitude of the calculated referent, it is considered acceptable. The referent is determined from the following equation:

$$\textit{Risk Referent} = \textit{Risk Reference} \times F_1 \times F_2 \times F_3 \qquad \textit{Eq. 1}$$

Step one (1) then, involves selection of the risk reference. If, for example, our intent is to prevention death by explosion from an intentionally malicious act on a freight pipeline system, we would select a 'Man Triggered, Involuntary Act'. The risk reference for this class, form **Table 6**, is 1E-5. This value is the primal risk limit we, as humans, feel comfortable subjecting ourselves to. We can read this as, 'we do not wish to subject ourselves to any danger, intentionally caused by another, that has the probability of causing death to more than 1 person out of 10 thousand per year.' This is still a risk class, however, and does not account for the other factors that customize the value for tubular freight systems.

**Table 6:** Summary of Risk Reference

| | Classes of Consequences | | |
|---|---|---|---|
| **Risk Classification** | **Fatalities per Year** | **Immobility Cases/Year** | **LER* (Years)** |
| Man Originated | | | |
| Catastrophic | | | |
| Involuntary | 2E-7 | 1E-6 | 6E-4 |
| Voluntary | 4E-6 | 4E-6 | 6E-3 |
| Man Triggered | | | |
| Ordinary | | | |
| Involuntary | 1E-5 | -- | 0.03 |
| Voluntary | 1E-3 | -- | 2.00 |

* Life Expectancy Reduction

We must then multiply the risk reference value by the first two factors, $F_1$ and $F_2$, which represent represent the degree of voluntarism and the inherent bias to accept or reject the risk based on indirect benefit/cost balance (see **Table 7** and **8**).

**Table 7:** Proportionality Factors ($F_1$)

| Factor | Involuntary Risk | Regulated Voluntary |
|---|---|---|
| Proportionality Factor (F1) | 0.01 | 1.00 |

**Table 8:** Derating Factor ($F_2$)

| Cost / Benefit Balance Factor | Involuntary Risk | Regulated Voluntary |
|---|---|---|
| Favorable | 1.0000 | 1.00 |
| Marginally Favorable | 0.1000 | 0.20 |
| Indecisive | 0.0100 | 0.10 |
| Marginally Unfavorable | 0.0010 | 0.02 |
| Unfavorable | 0.0001 | 0.01 |

The third factor, $F_3$, is an aggregate discounting factor reflecting four considerations associated with the controllability of risk as determined by $F_3 = C_1 \times C_2 \times C_3 \times C_4$, where: $C_1$ = control approach, $C_2$ = degree of control, $C_3$ = state of implementation, and $C_4$ = control effectiveness.

**Table 9:** Controllability ($F_3$)

| **Control Approach, C1** | **Degree of Control, C2** | **State of Implementation, C3** | **Basis for Control Effectiveness, C4** |
|---|---|---|---|
| Systematic Control | Positive | Demonstrated | Absolute |
| 1.0 | 1.0 | 1.0 | 1.0 |
| Risk Management System | -- | -- | -- |
| 0.8 | -- | -- | -- |
| Special Design | Level | Proposed | Relative |
| 0.5 | 0.5 | 0.5 | 0.5 |
| Inspection and Regulation | Unchecked | -- | -- |
| 0.3 | 0.3 | -- | -- |
| No scheme | Uncontrolled | No Action | None |
| 0.1 | 0.1 | 0.1 | 0.1 |

Based on the scenario of maliciously inflicted catastrophic failure on a tubular cargo system, which could potentially result in subsequent death and interrupted commerce, derating factors $F_1$ and $F_2$ are 0.01 and 0.0001, respectively. $F_3$ is determined as follows; $F_3 = C_1 \times C_2 \times C_3 \times C_4$, where $C_1 = 0.3$; $C_2 = 0.3$; $C_3 = 0.5$ and $C_4 = 0.5$. See **Table 9** for components of the controllability factor.

**Table 10:** Risk Referent Matrix for Human Injury

| **Risk** | *Probability of Human Fatality* | **Severity Dept. Of HS** | **Reference** | **F1** | **F 2** | **F3** | **Referent** |
|---|---|---|---|---|---|---|---|
| Destruction Of Pipeline System via Terrorism (Public) | 4.65E-08 | Catastrophic, (2) | 1.0E-05 | 0.01 | 0.01 | 0.0225 | 2.24E-12 |
| Explosion Within Pipeline System (Workers) | 3.9E-05 | Critical, (10) | 4.0E-04 | 1 | 0.1 | 0.0225 | 9.0E-9 |

By comparing the estimated probability of all potential human injury cases versus the risk referent values shown in **Table 10**, it is realized that human injury caused by terrorism on freight pipeline systems is unacceptable to the US public. However, with the implementation of some systematic safeguard policies and the installation of stronger deterrent structures, the probability of human injury cases can be reduced from 4.5E-9 and 4.5E-8 for the general populous and freightline workers, respectively. Meanwhile, $F_2$ and $F_3$ can be increased to 1.0 for both injury cases with the implementation of better awareness and inclusion of the public in policy setting. Consequently, risks referents become 1.0E-07 and 4.0E-4 for the public and workers, respectively. This indicates potential approval and acceptance of risk-reduction strategies by both affected groups.

**Risk Acceptability for Other Modes of Freight Transportation**

Using the same approach, it has been found that the probability of catastrophic human injury by terrorism to the public on the other surface transportation modes will be as high as 5x10-4. The risk referent is found to be 1.0x10-14. Meanwhile, with innovative security policies and structural safeguards, the probability of catastrophic injury can be reduced to 1.0x10-4 and the risk referent becomes 2.5x10-12. This determination yields that terror threats to conventional shipping methods might remain unacceptable indefinately.

## CONCLUSION

Severity of consequences and frequency of occurrence for each fault were determined using a first tier categorical risk indices determined from the U.S Department of Homeland Security guidelines. For model calibration, marginally acceptable hazards, and application of risk perception, it was necessary to develop scenarios and implement substantiated risk modelling strategies that yield sound acceptability limits. To accomplish this, risk pathways were identified regarding intentional malicious acts on tubular freightlines. Pathways were developed into a logical event tree, in which, probabilities were assigned at event nodes, forming a probabilistic fault tree. Occurrence frequencies were estimated from analogous transportation system statistics. The fault trees utilized Boolean logic to calculate estimated risks for fault scenarios. Risks associated with the freight pipeline system, evaluated using the risk model, were found to be more sensible than those assigned using the USDHS risk index method.

In summary, human injury risk associated with tubular freightlines that are subject to terrorist attacks were found to be ‘not acceptable’, based on operational policy applied to existing pipelines in the U.S. However, after implementation of systematic safeguard policies and installation of stronger deterrent structures, unacceptability regarding risk to human injury by terrorism on freight pipeline system can easily be reversed. Meanwhile risks associated with terrorism to other freight carrying modes may remain unacceptable indefinitely. Significant advantages of freight pipeline systems, in terms of fortification and deterrence from terrorist assault, are exhibited over conventional cargo transhipment methods.

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