USING QUANTITATIVE RISK ASSESSMENT (QRA) AND COST BENEFIT ANALYSIS (CBA) TO PRIORITIZE FIRE AND LIFE SAFETY RISK REDUCTION MEASURES IN OLD RAILWAY TUNNELS

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ABSTRACT

The cost of upgrading existing old railway tunnels, infrastructure and systems, some built over 100 years ago, to bring them into compliance with modern fire and life safety standards such as NFPA 130, is often very high. Modern rolling stock fire hazard has been reduced with the advent of fire-hardened passenger railcars with low fuel load, flammability and smoke emission and minimal fire propagation paths. The probability of a catastrophic event of "disabled passenger train on fire in the tunnel, requiring evacuation" during a typical 1- to 2-km trip between city subway stations, is very low. The scenario of a "passenger train on fire requiring evacuation" will more likely culminate at the station platform, where almost all trains on fire will arrive. The exception will be those rare combinations of events when a serious train fire occurs simultaneously during a train-disabling event such as collision, derailment, loss of traction power, loss of train propulsion or other wayside defect/obstruction in the tunnel. Excluding acts of terrorism and criminal arson, modern rolling stock fires are very likely to end up at the station platform where rescue operations will take place.

Old railway tunnels in urban areas, on the other hand, have a unique problem of occasional right-of-way (ROW) fires, of the "low" to "average" intensity, which pose a safety hazard to trains, required to stop in a congested, poorly ventilated tunnel, particularly if the incident cannot be resolved rapidly, and the train cannot move to the nearest station in a few minutes.

As in all risk analysis, the allocation of funds for, and prioritizing of capital projects and/or operating & maintenance procedures aimed at reducing fire and life safety risk in old railway tunnels while maximizing the risk reduction per Dollar spent, is best accomplished using analytical tools of quantitative risk assessment and cost benefit analysis.

This paper illustrates an example of application of quantitative risk assessment, using fault and event tree analysis, cost benefit analysis and other tools, to prioritize capital projects and operating and maintenance strategies, in reducing the risk to passengers from an initiating event of "train stopped in the tunnel section in the presence of right-of-way fire" in old railway tunnels.

1. INTRODUCTION

The cost of upgrading existing old railway tunnels, infrastructure and systems to bring them into compliance with modern fire and life safety standards such as NFPA 130, is often very high. For example, the life cycle cost of constructing, operating and maintaining an adequately-sized fan plant for a typical 1- to 2-km tunnel section between two adjacent stations of an existing railway may average US$ 30 million over a 40-year period. The cost may even be exacerbated when there is no sufficient space either underground or at the street level in a densely populated urban area to build an adequately-sized fan shaft and fan plant in the existing old infrastructure, or when a more costly configuration such as a horizontal fan shaft is required.
Old railway tunnels have their unique and diverse sources of fire on the right-of-way, in addition to the "traditional" fire risk associated with rolling stock combustible load, flammability and smoke emission. Some of the sources of right-of-way fires unique to old rail transit tunnels include:

- Debris and refuse on the right-of-way, which are partly introduced by homeless persons seeking shelter in the underground system; trespassers, vandals and others who litter the system under poorly-monitored and inadequately-secured tunnel access.
- Contractors’ activities and materials, including storage of flammable material on the right-of-way.
- Electrical cable fires on the tunnel walls resulting in heavy smoke and generally low heat release.
- Water leakage from the tunnel walls and ceiling onto the third rail, causing electrical arcing, insulator burning, debris, trash, grease, and wood ties igniting on the right-of-way.
- Water accumulation at the track level due to clogged/poor drainage, causing electrical arcing of the third rail, creating electrical ignition sources for flammable material on the right-of-way.
- Accumulation of steel dust on the right-of-way, providing electrical paths for third rail electrical arcing which, in turn, ignites flammable material on the right-of-way.

The allocation of funds for projects and/or operating & maintenance procedures aimed at reducing fire and life safety risk in old railway tunnels while maximizing the risk reduction per Dollar spent, is best accomplished using analytical tools of quantitative risk assessment and cost benefit analysis. This is particularly useful in analyzing specific user-defined, well focused hazard scenarios including various operating options and failure recovery strategies in assessing the risk to passengers from fire and smoke conditions on the right-of-way in old railway tunnels.

This paper addresses an example of systematic application of quantitative risk assessment, using event tree analysis, in combination with other analytical tools, to quantify the baseline and residual risk to passengers when a train is stopped in a typical 1- to 2-km tunnel section between adjacent stations in the presence of right-of-way fire.

2. BASELINE CONDITION DATA

For the purposes of this example a "typical old railway tunnel" scenario is postulated including baseline operating parameters, empirical trains delay statistics and empirical fire incident statistics in the tunnel section. In this particular example, assume that the railway's fire incident reporting system and a detailed train delay database are available to develop all quantitative inputs into the fault and event tree analysis. Similarly, the existing emergency ventilation capability in each tunnel section is known. The empirical data available also provides the highest fire size in each tunnel section, which can be adequately handled by the emergency ventilation to provide tenable environment to detrained passengers on foot in the tunnel section.

An example of possible fire rating and severity categories that a railway might use in compiling fire statistics in its fire incident reporting system is shown in Table 1.
### Table 1: Example of Fire Severity Rating Categories for Fire Incident Reporting System

<table>
<thead>
<tr>
<th>Rating</th>
<th>Severity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very Low</td>
<td>No disruption to service; No damage to railway property; No reported injuries/fatalities due to fire/smoke; No discharge/evacuation of passengers; Fire self-extinguished or extinguished without Fire Department.</td>
</tr>
<tr>
<td>2</td>
<td>Low-Average</td>
<td>Delays to service 15 minutes or less; Minor damage to railway property (no structural damage); No reported injuries/fatalities due to fire/smoke; Discharge of passengers in station; Minor residual smoke present (haze). Heat Release Rate Indication: less than 150,000 BTU/hour.</td>
</tr>
<tr>
<td>3</td>
<td>Above Average</td>
<td>Delays to service greater than 15 minutes; Moderate to heavy damage to railway property; 4 or less reported injuries due to fire/smoke; Discharge of train or transfer of passengers to another train (not in station); Station/platform/train filled with smoke. Heat Release Rate Indication: from 150,000 to 6,000,000 BTU/hour.</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>Major delays in service [over one (1) hour]; Major structural repairs needed to repair railway property; 5 or more reported injuries or 1 or more fatalities; Evacuation of passengers to benchwall or roadbed; Mass evacuation of more than one train. Heat Release Rate Indication: greater than 6,000,000 BTU/hour.</td>
</tr>
</tbody>
</table>

For the purpose of this example, assume that the tunnel and vehicle combustible materials for a typical tunnel section are reviewed, inventoried, quantified and analyzed using a simulation for Heat Release and Smoke Release Rates. The purpose is to simulate a representative fire growth profile that will allow determination of Heat Release and Smoke Release rates as a function of time in the tunnel environment. In our example it can be concluded that:

- Other than as a result of vandalism/terrorism the likelihood of Severity 3 or 4 fire in a car is remote.
- A 1½-gallon gasoline fire results in full car involvement. For this example, acts of terrorism and criminal arson are excluded from consideration.
- A three-bag in-car trash fire, while producing smoke, does not result in full car involvement.
- A ½-gallon gasoline fire does not result in full car involvement.
- In low-ceiling tunnels (13 feet) 1 MW and greater wayside fires result in the horizontal smoke plume dropping to 8 feet from top of rail. This presents a hazard to evacuating passengers.
- The smoke plume from a 150,000 BTU fire does not drop to 8 feet, thereby not endangering evacuating passengers. Our conservative approach is to consider severity 2 wayside fires as posing hazard to detrained passengers in non-ventilated narrow and low-ceiling tunnels.
- A wayside fire does not propagate extensively.

These conclusions are applied very conservatively in the development of fault and event tree analysis to determine the baseline risk in each tunnel section, particularly in assessing probability of fire propagation and risk to passengers on-board the vehicle, and in the tunnel for detrained passengers.
3. FAULT TREE ANALYSIS

Fault Tree analysis is a deductive ("top down") analysis for determining the combinations and logical relationships of various events, fault conditions, failures and human errors that could result in the occurrence of a user-defined undesired top event. A fault tree analysis begins with the definition of a top event and then determines through logical relationships (e.g., AND, OR, NOT, majority vote gates, etc.) the contributing factors to the top level undesired event.

A comprehensive, top-level undesired event identified as “Train passengers exposed to fire/smoke condition in the tunnel section, posing a hazard to passengers” is constructed to examine the key wayside and carborne events, fault conditions, failures and human actions, that may contribute to this top event, and calculate a frequency of occurrence in events per annum. The fault tree uses empirical data from the railway's own delay database and fire incident reporting system.

The fault tree addresses, among others, the frequency of occurrence of incidents in which a train comes to a stop in the tunnel. This encompasses train-disabling and non-disabling events from all causes during a station-to-station trip, while a fire and smoke condition ignites at the same time on the wayside or on the vehicle, posing hazard to passengers. The fault tree addresses the frequency of occurrence of tunnel wayside fires igniting during a short (<20 min.) or extended (>20 min.) train-disabling event in the tunnel section, posing hazard to train passengers.

Additionally, the fault tree quantifies the frequency of occurrence of a carborne fire bringing the train to a stop during a station-to-station trip. The fault tree also allows comparison of the frequency of train stoppages from all disabling and non-disabling causes, in the presence of fire/smoke conditions, when fire severity is not addressed. This is done to identify the predominant stoppages to be studied further in an event tree analysis, to quantify the total risk associated with the various possible outcomes of the railway's recovery strategies.

Key branches of the fault tree deal with the following key events:

- Passengers in car exposed to wayside smoke, posing a hazard to passengers (train stoppage <20 minutes, no passenger detrainment in the tunnel required)
- Passengers detrain in the tunnel under fire/smoke, posing hazard to passengers (stoppage >20 minutes, up to 2 hours)
- Train on fire in the tunnel section, posing hazard to passengers, consisting of 3 sub branches:
  - Train Collision or derailment ignites fire/smoke on the (disabled) train, posing hazard to passengers
  - A train-disabling fire erupts on a train while in the tunnel section, stopping the train, posing hazard to passengers
  - A disabled train in the tunnel section ignites on fire, posing hazard to passengers

The probability of occurrence and the frequency (in events per year) of a large, train-disabling carborne fire erupting and disabling a moving train during a 1- to 2-km station-to-station trip through a tunnel section, is very low (approximately $1 \times 10^{-4}$ event per annum). The probabilities associated with these scenarios exclude major acts of terrorism and criminal arson events. Fires resulting from negligence, mischief, small arson, and minor vandalism are addressed commensurately with the statistics recorded in the railway's fire incident reporting system and delay databases.

In our example, ignition sources on the vehicle give rise to less than three carborne fire and/or smoke incidents per year per tunnel section in a heavily traveled 2-km tunnel. In order for the carborne fire/smoke condition to culminate in a top level undesired event of "disabled train on fire in the tunnel section posing hazard to passengers", a series of multiple events, fault conditions and human errors must occur over a short time span of a station-to-station trip. Some of these required events and conditions include, for example, the following: if the fire already existed on the train during a previous station stop, it was not detected by the train crew prior to departure; or, the fire may have
erupted on the train after departure from the station; the ignition source must have sufficient fuel load to start and sustain a fire; the fire must have propagation paths to spread on the train from its point of origin; the fire is not extinguished by passengers or train crew at any stage; the fire spreads and disables the train's motive power and prevents the train from reaching the next station; the fire location, type and magnitude on the train pose hazard to passengers in the passenger compartment. Separately, the scenario of a passenger train derailment/collision resulting in fire, posing hazard to passengers, is also calculated in the fault tree. Consequently, the probability of a top-level undesired event of a disabled train on fire, posing hazard to passengers in a typical 1- to 2-km tunnel section would be very low (approximately $1 \times 10^{-4}$ event per annum). This excludes acts of criminal arson and terrorism.

The fault tree analysis, using the railway’s empirical data, also provides comparative frequencies of occurrence for the train stoppages from disabling and non-disabling causes, in the presence of fire/smoke condition in the tunnel section. These comparative frequencies of occurrence, which do not address fire severity, are used to identify the predominant frequency of train stoppage in the presence of fire, to be studied as an initiating event using an event tree analysis to quantify the risk.

4. EVENT TREE ANALYSIS

Event tree analysis quantifies total risk of multiple outcomes stemming from a single event. The event tree begins with a user-defined initiating event and develops a range of multiple outcomes by progressing through a series of possible scenarios (“decision events”). Event tree analysis is a highly suitable tool for quantitative risk assessment in its ability to produce results that combine in a single analysis the frequency of occurrence and consequence (severity) of multiple events and provide a total risk

Thus, the event tree technique complements the fault tree by addressing a spectrum of possible outcomes, rather than a single top-level undesired event. Each event tree outcome lends itself to risk assessment through its severity (consequence) and frequency of occurrence.

4.1 Selecting an Initiating Event

In our example, using a typical 1- to 2-km, old railway tunnel in an urban rail transit system with high volume of operations, the initiating event is: “Train stopped from all causes and fire/smoke condition in the tunnel section”.

Using the railway's empirical data, the fault tree analysis conducted provides comparative frequencies of occurrence for the various initiating events in which a train comes to a stop in the tunnel section in the presence of fire/smoke condition. The frequencies shown in Table 2 represent an example for a busy 2-km tunnel section, with crossovers and 171,000 train trips per year. The comparative frequencies of occurrence in Table 2 do not address the severity of the fires. Namely, the fire severity distribution likely to be encountered during the train stoppage is addressed separately.
Table 2: Comparative Frequencies of Initiating Events: Train Stopped from all Causes in the Tunnel Section in the Presence of Fire and Smoke Condition (Fire Severity not Addressed)

<table>
<thead>
<tr>
<th>Initiating Event Description</th>
<th>Frequency (events per annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train stopped for more than 20 minutes, and a wayside fire/smoke condition occurs in the tunnel section</td>
<td>$1.28 \times 10^{-2}$</td>
</tr>
<tr>
<td>Train stopped for 20 minutes or less, and a wayside fire/smoke condition occurs in the tunnel section</td>
<td>$3.42 \times 10^{-2}$</td>
</tr>
<tr>
<td>Disabled train on fire in the tunnel section</td>
<td>$9.25 \times 10^{-4}$</td>
</tr>
<tr>
<td>Non-disabled train procedurally stops in front of tunnel right-of-way (ROW) combustible material on fire when the train moves through the tunnel section</td>
<td>3.53</td>
</tr>
</tbody>
</table>

The fault tree indicates that the initiating event of "Non-disabled train procedurally stops in front of tunnel combustible material on fire when the train moves through the tunnel section" is the most frequent occurrence in our example of a 2-km, old railway tunnel in an urban environment. In a typical 1- to 2-km, old railway tunnel, the frequency of occurrence may be 4,000 to 5,000 times greater than that of the initiating event "Disabled train on fire in the tunnel section". This does not address the severity of the fire during the train stoppage or its effect on train passengers.

The predominant statistical reason for a rapid transit train to stop in the presence of fire/smoke condition in an old urban railway tunnel occurs when a train procedurally stops due to tunnel right-of-way (ROW) fire. This predominant occurrence constitutes an initiating event which can evolve and develop into multiple scenarios and outcomes, dependent on multiple decision events, culminating either in train recovery (i.e., the train reaches the nearest station) or passenger evacuation. The multiple scenarios, their outcomes, probability of occurrence, consequence (severity), and resultant risk to passengers stemming from the initiating event, are addressed in a quantitative risk assessment using the event tree analysis.

While it is obvious that additional event trees can be constructed to quantify additional risk stemming from additional initiating events, our example illustrates a risk assessment process for a case of initiating event: "Train stopped in the presence of right-of-way (ROW) fire/smoke in the tunnel section". The following sections describe a proposed event tree analysis and risk assessment to quantify the risk for this initiating event.

### 4.2 Baseline Risk

Risk is defined as the product of the severity of the event (expressed in our example as loss value in US Dollars), and the frequency of the event (in events per annum). Baseline risk is calculated in the event tree analysis using prevailing conditions and operating strategies before implementation of any corrective action. The event tree, shown in Table 3, begins with the initiating event and its frequency of occurrence (in events per year) and progresses from left to right with columns addressing the series of decision events, each shown with its probability of failure, “Q”. A null branch indicates an "inert" branch with no success or failure implications on the outcome, based on the sequential logic of the preceding events/columns. The right side of the event tree developed for this example terminates with multiple outcomes, each defined by its severity (consequence) and frequency of occurrence. Probability calculation for the decision events is accomplished using a variety of analytical tools such as fault trees, mathematical/ Boolean Algebra modelling, fire/smoke modelling programs, etc.
4.2.1 Decision Events

The following decision events are used in the event tree as possible scenarios/events that can develop from the initiating event and the probability of each is calculated. "Q" values shown in Table 3 represent the probability of failure (unavailability) of each decision event:

- **Traction power available in the tunnel section when a train is stopped**
  
  Once the train has stopped in the tunnel in the presence of a ROW fire incident, the probability that at the same time and place the traction power will be lost is calculated.

- **Train propulsion available**
  
  This attribute is concerned with the probability that an incident train, which procedurally stopped in front of a ROW fire, will lose its propulsion/motive power at that time and place.

- **Train rescue route clear**
  
  This attribute is concerned with the probability that a train, which procedurally stopped in front of a ROW fire in the tunnel, will have a clear route to continue either forward to the next station, or back to the previous one.

- **Enable/clear train rescue route**
  
  The probability that a train rescue route that is initially blocked will remain blocked is calculated by addressing issues such as: the clearing of short red signal delays, re-assessment of forward move through the fire location based on ROW fire severity and obstruction ahead, timely recovery from delays ahead, and clearing blockage behind the incident train.

- **Train moved forward to nearest station**
  
  As depicted in the event tree, the successful outcome of this event is to move forward to the nearest station and the failed outcome is to resort to the complex and time-consuming move back to the previous station (depending on the type of signaling system). The probability that the incident train moved forward given the availability of rescue route(s) is calculated.

- **Bring rescue train when traction power is available**
  
  Bringing a rescue Electric Multiple Unit (EMU) is an event that may occur when the incident train rescue route can not be cleared (depending on tunnel configuration and number of tracks, and whether it is possible to bring a rescue EMU on adjacent track in the same tunnel), or if the incident train does not have its motive power, but traction power is available and another rescue train can be brought on the same track. The probability of this event is calculated in this column.

- **Interior train environment tenable**
  
  This event quantifies the probability that during the train delay and recovery operation, which did not require passenger detrainment in the tunnel, the interior train environment remained tenable, in the face of ROW fire. The tenability of the car interior environment during a ROW fire/smoke condition depends on several factors: the intensity of fire/smoke, tunnel configuration, the availability of tunnel ventilation, the length of time spent in the environment and the air-tightness of the car to smoke penetration. The availability and timely deployment of fire suppression is also considered in quantifying success/ failure probability for this event.

- **Supervised evacuation by railway or fire department**
  
  In our example, assume that the railway strives to reach a decision whether to evacuate a train within 20 minutes from the onset of an incident of “disabled train during a ROW fire and smoke condition”. Review of empirical fire and smoke incident reports would indicate that generally, the Fire Department and railway supervisory personnel are at the scene within less than 20 minutes.
The probability that the evacuation will be supervised by railway staff or Fire Department personnel can be calculated based on tunnel location, physical characteristics and railway emergency response data.

- **Tunnel environment tenable during evacuation**
  
  This attribute quantifies the probability of having a tenable tunnel environment for evacuating passengers on the ROW. The tenability of the tunnel environment during a fire/smoke condition for detrained passengers depends on several factors: the intensity of fire/smoke, tunnel configuration, availability of ventilation, length of time spent in the environment, and the health and mobility of the evacuees. The availability and timely deployment of fire suppression is also considered in quantifying success/failure probability for this event.

- **Minimal walking hazards present**
  
  The probability of having minimum walking hazards, is calculated as a function of emergency walking surface condition and lighting conditions in the tunnel section, as they affect tripping hazard and injuries during a full train evacuation in the tunnel.

### 4.2.2 Severity

The severity of each outcome on the event tree branches is determined as the worst credible mishap in accordance with levels of severity (consequence), including intermediate levels of severity. In selecting the severity for each branch on the event tree, a comparative assessment is made, within each branch and among the various branches (rows), of the severity implications of success and failure of the decision events along each path. These reflect the worst credible mishap (in equivalent fatalities, major and minor injuries, converted to US$) arising from passengers exposure to hazards (including time of exposure), based on the success or failure of the decision events along each branch.

Severity (consequence) categories include negligible (-), negligible, marginal (+), critical (-), critical, catastrophic, and catastrophic-multiple. Each severity (consequence) category has an assigned loss value associated with it, in accordance with the railway's accepted risk assessment guidelines. The loss value associated with each consequence (severity ranking) represents a wide range of possible combinations of injuries and fatalities, using United States Department of Transportation guidelines for “value of life,” “value of severe injury,” “value of minor injury,” and reflects the worst credible consequence that could result.

### 4.2.3 Frequency

The frequency of occurrence of each outcome from each branch is calculated by multiplying the frequency of the initiating event by the probabilities of success or failures of the decision events along each path from left to right for each row outcome. Frequency is expressed in events per year.

### 4.2.4 Total Baseline Risk in the Tunnel Section

For each possible outcome (each row), the severity (consequence) loss value is multiplied by the frequency of occurrence to yield the risk value expressed in Dollars per year. All risks are then summed from all rows to yield a total risk value to the railway for the subject tunnel section for this initiating event.

Table 3 depicts an example of event tree analysis, calculating the baseline risk (before implementing mitigation measures) of possible train recovery or evacuation when the train stops in the presence of a ROW fire in a sample 2-km tunnel section. The various outcomes stemming from the initiating event are investigated using 10 decision events, and the resultant baseline risk is quantified in US$ per year.
Tunnel Environment

Traction Power is Available in Train Rescue Route

Enable/ Clear Train

Train Moved Forward

Bring Rescue Train Interior Train

Supervised Evacuation

Calculation of Risk

Train Propulsion Tenable during Hazards Present Available Clear to Nearest Station when TP Available Environment Tenable by Railway or FD

Table 3: Example of Event Tree Analysis - Baseline Risk Assessment of Possible Train Recovery or Evacuation for a ROW Fire in a Sample 2-km Tunnel Section.

<table>
<thead>
<tr>
<th>New Number</th>
<th>Frequency of Initiating Event (events per YR.)</th>
<th>Q= Probability of failure (fraction of 1)</th>
<th>Risk = Conseq. x Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Negligible(-)</td>
<td>$1,000 2.95E-02 $2,935.89</td>
</tr>
<tr>
<td>2</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Critical(-)</td>
<td>$3,000,000 1.636E-03 $4,906.83</td>
</tr>
<tr>
<td>3</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Negligible(-)</td>
<td>$500 5.85E-02 $2,927.21</td>
</tr>
<tr>
<td>4</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Critical</td>
<td>$5,000,000 1.303E-02 $183.08</td>
</tr>
<tr>
<td>5</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Negligible(-)</td>
<td>$500 4.679E-01 $467.91</td>
</tr>
<tr>
<td>6</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Critical</td>
<td>$5,000,000 3.262E-05 $163.08</td>
</tr>
<tr>
<td>7</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Negligible(-)</td>
<td>$500 9.331E-03 $466.53</td>
</tr>
<tr>
<td>8</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Critical</td>
<td>$5,000,000 5.198E-06 $25.99</td>
</tr>
<tr>
<td>9</td>
<td>3.53 Success 0.9949518 Success 0.9988787 Null</td>
<td>0.0096 Null Null Null Negligible(-)</td>
<td>$500 2.798E-02 $1,393.94</td>
</tr>
</tbody>
</table>

W= Frequency in events per year. Q= Probability of failure (fraction of 1)
Table 3: Example of Event Tree Analysis - Baseline Risk Assessment of Possible Train Recovery or Evacuation for a ROW Fire in a Sample 2-km Tunnel Section.

<table>
<thead>
<tr>
<th>Event Number</th>
<th>Frequency of Initiating Event [events per YR.]</th>
<th>Train Populaiton Available</th>
<th>Train Rescue Route Clear</th>
<th>Train Rescue Route Failed</th>
<th>Train Moved Forward to Nearest Station</th>
<th>Brin Rescue Train when TP Available</th>
<th>Interior Train Environment Tenable</th>
<th>Supervised Evacuation by Railway or FD</th>
<th>Tunnel Environment Tenable during Evacuation</th>
<th>Minor Walking Hazards Present</th>
<th>Calculated Risk</th>
</tr>
</thead>
</table>
| 32           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 33           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 34           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 35           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 36           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 37           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 38           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 39           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 40           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 41           | 3.53 Success 0.004016                         | Failure                     | Success 0.145209         | Success 0.00045499 Null   | Failure                              | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 42           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 43           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 44           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 45           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 46           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 47           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 48           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 49           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 50           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 51           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 52           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 53           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 54           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 55           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  
| 56           | 3.53 Failure 0.0050482                        | Null                        | Null                      | Null                      | Null                                 | Null                           | Failure                      | Null                             | 1.0000 Failure                   | Null                           | $2.763E-03  

Cumulative Sum: 3.53
Total Risk: $218,273
4.2.5 Total Baseline Risk in all Tunnel Sections

The event tree analysis is repeated for each tunnel section and the baseline risk from the postulated initiating event is calculated for each tunnel section in the underground system.

4.2.6 Prioritize Tunnel Sections in Descending Order of Baseline Risk

All the railway’s tunnel sections analyzed are prioritized in descending order of baseline risk. This enables the railway to identify a group of high-risk tunnel sections based on the railway’s risk acceptance criteria, and prioritize all tunnels for implementation of mitigation measures.

4.3 Residual Risk, Risk Reduction, Life Cycle Cost, Cost Benefit Analysis and Implementation of Proposed Mitigation Measures

Each proposed mitigation measure such as a capital project or an operating & maintenance (O&M) strategy/procedure is investigated for risk reduction potential. The mitigation measures are initially considered “competing” against one another, and are considered for implementation singly, assuming other competing projects and O&M strategies are not implemented. Risk reduction for each candidate mitigating measure is measured individually from the same common baseline risk level. For each proposed mitigation measure, a residual risk (i.e., the risk after implementation of the mitigation measure) is calculated using the event tree analysis in the tunnel section(s) in which it is proposed to be implemented. The incremental reduction in risk (expressed in US$ per year) is calculated as the difference between the baseline and residual risk, yielding the annual "benefit" Bi for each mitigation measure i.

Similarly, for each proposed mitigation measure i, a total life cycle cost (including initial procurement, annual operating and maintenance, and disposition cost), is calculated over the life of the system. The LCC is expressed in present worth value in US$, and is calculated in the tunnel section(s) in which the measure is proposed to be implemented. The LCC is annualized to yield the annual life cycle cost Ci for mitigation measure i.

A benefit-to-cost (B/C) ratio is calculated for each capital program or O&M strategy/procedure, based on the annualized benefit and LCC for mitigation measure i.

The list of recommended capital projects and O&M strategies/procedures are rank-ordered by their benefit-to-cost (B/C) ratio.

Once the competing mitigation measures have been subjected to cost benefit analysis and rank ordered, they are to be applied incrementally, in their ranked order in the railway’s high-risk tunnel sections and throughout the entire underground system, as applicable. The primary goal is to reduce the unacceptable risk in each of the high-risk tunnel sections to a lower level acceptable to the railway. The level of unacceptable risk is specified in the railway’s hazard risk assessment matrix and acceptance criteria. A secondary goal is to apply the O&M strategies and select capital projects to all tunnel sections, to reduce risk in all tunnel sections, as long as the benefit-to-cost ratio is greater than 1, or when systemwide implementation is mandated for effectiveness.

The multi-step process integrating quantitative risk assessment (QRA) and cost benefit analysis (CBA) is summarized schematically as follows in Figure 1:
5. CONCLUSIONS FOR MITIGATION MEASURES IN OLD RAILWAY TUNNELS

1. Proactive projects and O&M strategies/procedures that reduce fire/smoke risk by lowering the likelihood of a fire starting or spreading are preferable to response and/or reactive projects or procedures that provide equivalent risk reduction or benefit-to-cost ratio.

2. Operational and Maintenance strategies/procedures to reduce fire/smoke risk are generally less costly and faster to implement than are capital projects. O&M strategies, however, require ongoing management oversight to assure their effectiveness. Generally, capital programs and design measures should have a higher precedence over O&M strategies/procedures.

3. Most O&M strategies/procedures have to be implemented systemwide to be effective, but frequency and intensity of procedural corrective actions may vary among tunnels.

4. Examples of non-ventilation capital programs to be implemented in old railway tunnels include: Procure and operate vacuum trains to remove flammable materials, trash, debris and steel dust from the ROW; Secure unused areas that attract homeless people. Seal or remove potential occupancy areas and secure potential means of access; Install linear heat detection, train holding lights, and fire alarm control panels in high-risk tunnel sections with no line of sight between stations; Install standpipe systems in high risk tunnel sections; Improve track walking surfaces and upgrade emergency exits and tunnel lighting in high risk tunnel sections; Upgrade signaling and communications systems to enhance train recovery strategies during ROW fire/smoke incident.

5. Examples of Operating and Maintenance strategies/procedures to be implemented in old railway tunnels include: Revise the railway’s policy and procedures to permit trains to proceed through minor smoke conditions on the right-of-way; Improve maintenance of the underground system by expanding inspection responsibilities of drainage, structural, track, power, lighting, signal, and electrical personnel and by improving maintenance practices and housekeeping; Increase thermal inspections of the wayside, and vehicle electrical systems and components, by use of thermal imagers mounted on the Track Geometry Car and by hand-held thermal imagers used by inspection personnel; Reduce the presence of homeless persons and intruders into the underground system by expanding inspection responsibilities, improving maintenance and housekeeping, and adding security; Increase debris clean-up and removal of hazardous materials through expanded inspection programs, improved maintenance and housekeeping, and improved contractor oversight; Expand the leak repair program through increased inspection and maintenance.

6. Additional examples of proactive recommendations include: Establish a Fire/Life Safety Committee; Review, and revise as necessary, emergency procedures and rules; Improve evacuation procedures and related wayside conditions; and expand and improve safety training.