Hazardous Material Transportation through tunnels – A risk assessment framework

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UH
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The Mont Blanc Tunnel

- major trans-Alpine transport route
- borders of France and Italy
- length 11,611 m
- single gallery with a two-lane dual direction road
- 35% freight transport to north Europe
- 1.1 million vehicles per year
The accident
March 24 1999

10:46 am - ignition in a tractor refrigerated trailer carrying 9 tons of margarine and 12 tons of flour
10:52 am first signs of smoke
10:53 am explosion
The tunnel interior after the incident
The cost

- 41 persons dead
- structural & mechanical damages
- tunnel closed for three years
The Tauern Tunnel

• part of A10 Tauern Autobahn (Austria)
• important north-south route through the Alps
• connects Germany, Italy, and Slovenia
• length 6,400 m
• single bidirectional tube
• ADT 14300 veh, 20% trucks
The accident

May 29 1999, 5:00 am
The tunnel interior after the incident
The cost

• tunnel closed for 3 months
• remedial works cost USD 6.5 million
• lost toll fees USD 19.5 million
More accidents

China tunnel explosion in Hunan province 'kills 20'

An explosion in a road tunnel being constructed in central China has killed at least 20 people, state media say.

The blast occurred in a tunnel on the road linking Yanling and Rucheng in Zhuzhou city in Hunan province.

It took place as a vehicle carrying explosives was being unloaded, state media quoted local authorities as saying.

Lax building rules and poor safety standards mean such accidents are far from uncommon in China.

Four workers had been pulled out of the tunnel, including one in a critical condition, AFP reports, citing state media.
## Tunnels in Hawaii

<table>
<thead>
<tr>
<th>Island</th>
<th>Route</th>
<th>Tunnel name</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oahu</td>
<td>John A. Burns Freeway (Interstate H-3)</td>
<td>Tetsuo Harano (twin tunnels)</td>
<td>5165 feet (eastbound)&lt;br&gt;4890 feet (westbound)</td>
</tr>
<tr>
<td>Oahu</td>
<td>John A. Burns Freeway (Interstate H-3)</td>
<td>Hospital Rock (twin tunnels)</td>
<td>354 feet (eastbound)&lt;br&gt;353 feet (westbound)</td>
</tr>
<tr>
<td>Oahu</td>
<td>Queen Liliuokalani Freeway (Interstate H-1 -- eastbound lanes only)</td>
<td>Middle Street</td>
<td>393 feet</td>
</tr>
<tr>
<td>Oahu</td>
<td>Likelike Highway (state route 63)</td>
<td>Wilson (twin tunnels)</td>
<td>2813 feet (eastbound)&lt;br&gt;2775 feet (westbound)</td>
</tr>
<tr>
<td>Oahu</td>
<td>Pali Highway (state route 61)</td>
<td>Pali No. 1 and No. 2 (pair of twin tunnels -- two in each direction, one after the other)</td>
<td>1080 and 497 feet (eastbound)&lt;br&gt;1000 and 500 feet (westbound)</td>
</tr>
<tr>
<td>Oahu</td>
<td>none (access to inside of Diamond Head crater)</td>
<td>Kahala</td>
<td>&lt;0.1 mile?</td>
</tr>
<tr>
<td>Oahu</td>
<td>none (access to inside of Diamond Head crater, currently closed to public but may be reopened)</td>
<td>Kapahulu</td>
<td>&lt;0.1 mile?</td>
</tr>
<tr>
<td>Kauai</td>
<td>none (private, used by bicycle and other tour groups with permission of McBryde Sugar Plantation)</td>
<td>Kipu-Mahaulepu</td>
<td>2200 feet</td>
</tr>
<tr>
<td>Maui</td>
<td>Honoapiilani Highway (state route 30)</td>
<td>Olowalu</td>
<td>318 feet</td>
</tr>
</tbody>
</table>
What are hazardous materials

- Class 1: explosives
- Class 2: gases
- Class 3: flammable liquids
- Class 4: flammable solids, combustion-liable, flammable gases-liable, self-reactive
- Class 5: oxidizing and organic
- Class 6: toxic and infectious
- Class 7: radioactive
- Class 8: corrosive
- Class 9: miscellaneous
Legal framework

- International regulations – Accord Dangereux Routier (ADR) since 1957
  - Classification
  - Vehicle
  - Securing
  - Packaging
  - Drivers
- National regulations / restrictions
- European directive 2004/54/EU
Scope

Planning the transportation of hazardous material (hazmat) to minimize the associated risk due to incidents and material releases

Long term sustainability requires risk minimization in any infrastructure system
Objectives

- Estimation of the risk associated to the transportation of hazmat through tunnels
- Identification of alternative routes
- Comparison of risk on alternative routes
- Examination of the impact of measures for minimizing risk along tunnels
Methodology

- **Step 1**: Tunnel analysis
  - Negligible zone
  - Intolerable zone

- **Step 2**: Tunnel is open to hazmat transportation
  - Tunnel restriction advised

- **Step 3**: Identify alternative routes
  - Tunnel route analysis
  - Alternative routes analysis

- **Step 4**: Are there alternative routes with a lower risk than the tunnel route?
  - Yes
  - No

- **Step 5**: Identify alternative routes

- **Step 6**: Specify measures for tunnel and that minimize risk index

- **Step 7**: Promote alternative route of lower risk
Risk assessment

• For the quantification of risks, 4 stages are implemented
  – **Stage 1**: identification of possible scenarios and estimation of the probability of their occurrence
  – **Stage 2**: estimation of the impact area of the exposure
  – **Stage 3**: estimation of the impacted population
  – **Stage 4**: estimation of the number of fatalities and their frequencies
The procedural model

Risk source release model
- Accident probability
- Release frequency
- Release probability

Population exposure model
- Release: Vapor, Liquefied vapor, Liquid
- Dispersion: Minor dispersion, Dense vapor dispersion, Major dispersion

Dispersion of vapor cloud
- Pool
- Pool vaporization

Inflation
- Yes

Fire
- Vapor cloud inflation
- Major fire
- Pool of fire
- Yes

Explosion
- Vapor cloud explosion
- BLEVE

Dose
- Major poisoning
- Thermal radiation
- Hyper-pressure
- Particles

Consequence model
- Fatality index
- Risk index model
  - Individual risk (IR)
  - Societal risk (SR)
Risk source release model

• Estimated figures:
  – The probability of involvement in a road accident
  – The possibilities of each impact scenario, based on the size of the release (event tree)
Road accident index

\[ F_{tdg} = F_{accid} \times X_{tdg} \times L \times N \]

- \( F_{tdg} \) = frequency of accidents of the specific type (per year)
- \( F_{accid} \) = frequency of road accidents (per year/veh-km)
- \( X_{tdg} \) = proportion of vehicles of specific type
- \( L \) = length (km)
- \( N \) = volume of vehicles (per year=ADT*365)
Scenarios

- Hot BLEVE (Hot Boiling Liquid Expandable Vapor Explosion)
- Cold BLEVE (Vapor cloud explosion) or flash fire
- Toxic gas leakage
- Pool fire
BLEVE
FLASH FIRE
POOL FIRE

Thermal Pool Fire Test at Sandia National Laboratories

Placing a package 40 inches above a pool of burning fuel for 30 minutes at 800 degrees Celsius or (1475 degrees Fahrenheit).
# Event tree assumptions

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Quantity</th>
<th>Leakage size (mm)</th>
<th>Leakage rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bottled liquid gas BLEVE</td>
<td>50 kg</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Benzene pool fire</td>
<td>28 tn</td>
<td>100</td>
<td>20,6</td>
</tr>
<tr>
<td>3</td>
<td>Benzene vapor cloud explosion</td>
<td>28 tn</td>
<td>100</td>
<td>20,6</td>
</tr>
<tr>
<td>4</td>
<td>Chlorion leakage</td>
<td>20 tn</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>Containerized liquid gas BLEVE</td>
<td>18 tn</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Containerized liquid gas vapor cloud explosion</td>
<td>18 tn</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>7</td>
<td>Containerized liquid gas fire</td>
<td>18 tn</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>Containerized ammonia leakage</td>
<td>20 tn</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>9</td>
<td>Containerized acroleine leakage</td>
<td>25 tn</td>
<td>100</td>
<td>24,8</td>
</tr>
<tr>
<td>10</td>
<td>Encapsulated (in tubes) acroleine leakage</td>
<td>100 lt</td>
<td>4</td>
<td>0,02</td>
</tr>
<tr>
<td>11</td>
<td>Containerized Carbon dioxide BLEVE or over-pressure burst</td>
<td>20 tn</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Event tree

<table>
<thead>
<tr>
<th>Release size</th>
<th>Inflation time</th>
<th>Domino effects</th>
<th>Impact scenario</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$P_{rel,l}$</td>
<td>$P_{dom} \mid P_{rel,l}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.0217$</td>
<td>$0.10$</td>
<td>$\Sigma 1$: BLEVE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{ign,l} \mid P_{rel,l}$</td>
<td>$0.20$</td>
<td>$\Sigma 2$: Pool Fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{ign,d} \mid P_{rel,l}$</td>
<td>$0.10$</td>
<td>$\Sigma 3$: Flash Fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{ign,nd} \mid P_{rel,l}$</td>
<td>$0.10$</td>
<td>$\Sigma 4$: SAFE</td>
</tr>
<tr>
<td>$P_{rel,s}$</td>
<td></td>
<td>$P_{ign} \mid P_{rel,s}$</td>
<td>$0.10$</td>
<td>$\Sigma 5$: Pool Fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{ign,nd} \mid P_{rel,s}$</td>
<td>$0.90$</td>
<td>$\Sigma 6$: SAFE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_{rel,no}$</td>
<td>$0.938$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Sigma 7$: SAFE</td>
<td>$93.8000%$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Total$</td>
<td>$100.0000%$</td>
<td></td>
</tr>
</tbody>
</table>

**Accident of road tanker**
The procedural model

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Population exposure model

• Dose reaching the population, depending on the distance from the source
  – Thermal radiation \( (q') \)
  – Hyper-pressure \( (p_0) \) (in case of BLEVE)
  – Toxic vapor as concentration \( (c) \) of CO
  – High temperature \( (T) \)
Thermal radiation ($q''$) may be created from a pool fire, or flash fire or BLEVE that is the consequence of the explosion of a boiling liquefied expandable vapor.

$$q'' = f (Ff, mh', \Delta Hc, x)$$

where:

$q''$ = thermal radiation (W/m$^2$)

$Ff$ = percentage of thermal radiation that comes from the flame (%)

$mh'$ = burning rate (kg/s)

$\Delta Hc$ = burning energy (J/kg)

$X$ = distance from the center of the fire (m)
Hyper-pressure (po) (in case of BLEVE) ..

created during the BLEVE

\[ p_s = \frac{808 \cdot [1 + (z/4.50)^2]}{[1 + (z/0.048)^2]^{1/2} \cdot [1 + (z/0.32)^2]^{1/2} \cdot [1 + (z/1.35)^2]^{1/2}} \]

where:

\(P_s\) = hyper pressure (Pascal)

\(z\) = relative distance (m/kg\(^{1/3}\))
Hyper-pressure (po) (in case of BLEVE)

\[ z = \frac{x}{W^3} \]

where:
- \( z \) = relative distance (m/kg\(^{1/3}\))
- \( x \) = distance from source (m)
- \( W \) = TNT equivalent (kg)

\[ W = \frac{n.m.E_c}{E_{cTNT}} \]

and
- \( m \) = mass (kg)
- \( n \) = explosion performance indicator (in %, the empirical value of 0.03 is being used)
- \( E_c \) = burning energy of the material (J/kg)
- \( E_{cTNT} \) = burning energy for TNT (J/kg, the value of 4.6 \( \cdot \) 10^6 J/kg is being used)
Smoke temperature

\[ T_g(x,t) = T_o + \left[ T_{g,o}(\tau) - T_o \right] e^{\frac{-h \cdot P \cdot x}{\rho_o \cdot u \cdot A \cdot C_p}} \]

where:

- \( T_g(x,t) \) = Average smoke temperature at point \( x \) and time \( t \) (K)
- \( T_{g,o}(\tau) \) = Average smoke temperature in the middle of the pool fire (\( x=0 \)) at time \( \tau \)
- \( \tau \) = Time required for the heat transfer from the center of the pool fire in distance \( x \) (s) (\( \tau = t - (x/u) \))
- \( T_o \) = Initial air temperature (K)
- \( h \) = Heat transfer component (W/m²·K)
- \( P \) = Average perimeter of area (case of tunnel) (m)
- \( X \) = Distance from the center of the pool fire (m)
- \( T \) = Time from the start of the fire (sec)
- \( \rho_o \) = Air concentration (=1,2 kg/m³)
- \( U \) = Average air speed (m/s)
- \( A \) = Average surface (case of tunnel (m²))
- \( C_p \) = Air thermal capacity (kJ/(kg·K))
Gases concentration

\[ C = Y_G \frac{M_a}{M_G} \frac{Q(\tau)}{m_a H_c} \]

where:
- \( Y_G \) = Amount of the gas that is produced per amount of material burned (kg/kg)
- \( M_a \) = Air molecular weight (g/mol)
- \( Q(\tau) \) = Thermal energy rate (W)
- \( M_G \) = Gas molecular weight (g/mol)
- \( m_a \) = Gas mass flow rate (kg/s)
- \( H_c \) = Burning energy (J/kg)
Smoke

where:
$F_{heat} = \frac{\int_{0}^{t_{exp}} dt}{60 \cdot e^{\left(5\cdot2^{-0.027\cdot T}\right)}}$

where:
$F_{heat} = \text{Dose of thermal radiation} \ (%)$
$t_{exp} = \text{Exposure time} \ (s)$
$T = \text{Smoke temperature} \ (^{0}C)$

$F_{toxicity} = \int_{0}^{t_{exp}} \frac{C}{90} \, dt$

where:
$F_{toxicity} = \text{Toxicity dose of CO} \ (%)$
$t_{exp} = \text{Exposure time} \ (s)$
$C = \text{CO concentration} \ (%)$
The procedural model

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Consequence model

Number of fatalities (N)

\[ N = D_P \times [0.95 \times A_{90} + 0.7 \times (A_{50} - A_{90}) + 0.3 \times (A_{10} - A_{50})] \]

where \( D_P \): population density
Population risk contours
The procedural model

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  - Societal risk (SR)
Risk index model
The case of Attica Motorway
Restrictions applying

• Restricted traffic of road tankers through the tunnels of Mavri Ora, Zefiri, Vrilissia and ring road of Imitos
• Restricted traffic of other HazMat (excluding road tankers) through the tunnels of Liossia and Aharnes
• No restrictions for the tunnels of Elefsina, Metamorfosi and Iraklio
The assumptions

- Vehicle capacity 35m$^3$
- Type of release:
  - Small → 500 lt
  - Large (all 6 compartments) → 5541 lt
The results
# After the analysis

<table>
<thead>
<tr>
<th>tunnels</th>
<th>regulation</th>
<th>result</th>
<th>actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 tunnels</td>
<td>No</td>
<td>Negligible risk</td>
<td>None</td>
</tr>
<tr>
<td>Elefsina</td>
<td>No</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td><strong>Mavri ora</strong></td>
<td>Total restriction</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td>Liosia</td>
<td>Only road tankers</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td><strong>Zefiri</strong></td>
<td>Total restriction</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td>Aharnes</td>
<td>Only road tankers</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td>Metamorfosis</td>
<td>No</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td>Iraklio</td>
<td>No</td>
<td>ALARP</td>
<td>Measures</td>
</tr>
<tr>
<td><strong>Vrilissia</strong></td>
<td>Total restriction</td>
<td>Intolerable risk</td>
<td>None</td>
</tr>
<tr>
<td><strong>Imitos</strong></td>
<td>Total restriction</td>
<td>Intolerable risk</td>
<td>None</td>
</tr>
</tbody>
</table>
Mavri Ora: main route and diversion

Graph showing the frequency of events (F) in relation to the number of fatalities (N) for different risk levels (Intolerable Risk, English ALARP, Dutch ALARP, Negligible Risk) with and without tunnel. The graph illustrates that the risk is lower with a tunnel compared to without.
Measures

- Design, maintenance: geometry, alignment, illumination, equipment, materials, purpose-built drainage system for HazMat
- Motorist mitigation: emergency exits
- Traffic management: speed/time regulation, control, enforcement, traffic diversion plans
- Emergency management system: monitoring, communication
Mavri Ora tunnel with measures

Graph showing risk assessment with frequency versus number of fatalities for different measures:
- Traffic diversion
- Drainage
- Drainage and traffic diversion

Risk categories:
- Intolerable Risk
- Dutch ALARP
- English ALARP
- Negligible Risk
Summing up

- Road accidents involving hazmat are rare but have a high impact
- Community and road safety sustainability requires a low risk
- Risk methodology for impact assessment
- Implementation in a case study
- Six tunnels in negligible, seven in ALARP, two in intolerable zones
- Mitigation measures for tunnels to minimize risk
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