IF CRASC'15
III THIRD CONGRESS ON FORENSIC ENGINEERING
VI CONGRESS ON COLLAPSES, RELIABILITY AND RETROFIT OF STRUCTURES
SAPIENZA UNIVERSITY OF ROME, 14-16 MAY 2015

RISK ANALYSIS FOR SEVERE TRAFFIC ACCIDENTS IN ROAD TUNNELS

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THE ISSUE OF SAFETY IN TUNNELS

Mont Blanc Tunnel Fire **(1999)**
39 Fatalities
Italia (Courmayer) – France (Chamonix)
single – bore, bidirectional tunnel
Length = 11.6 km

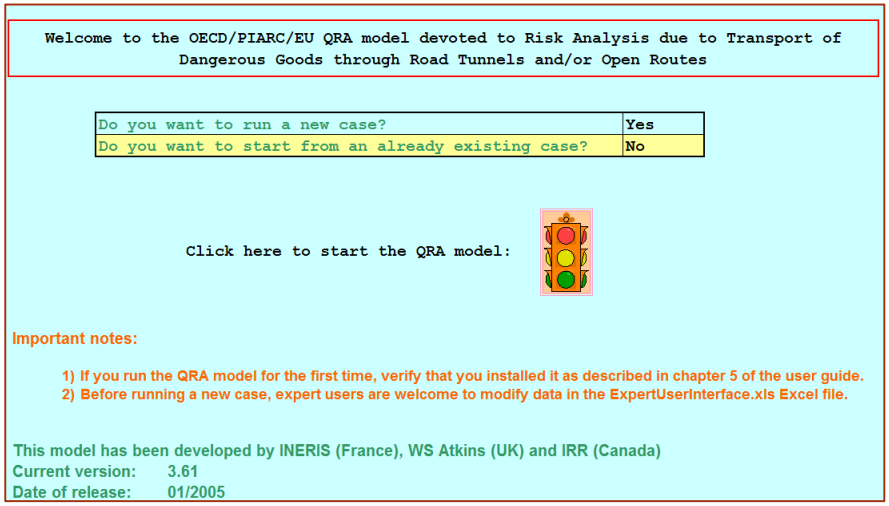
St. Gotthard Tunnel Fire **(2001)**
11 Fatalities
Switzerland (Göschenen) – Switzerland (Airolo)
single – bore, bidirectional tunnel
Length = 16,9 km

Frejus Tunnel Fire **(2005)**
2 Fatalities
Italia (Bardonecchia) – France (Modane)
single – bore, bidirectional tunnel
Length = 12,9 km

THE ISSUE OF SAFETY IN TUNNELS

Quantitative Risk Analysis ← **Directive 2004/54/EC** → **Objectives Parameters Requirements**

Transport of Dangerous Goods through road tunnels
OECD/PIARC/EU
Quantitative Risk Assessment Model



- **OECD** (Organisation of Economic Co-operation and Development)
- **PIARC** (World Road Association)
- **European Commission**
- France **(INERIS),** Canada **(WS Atkins)**, UK **(IRR)**

PIARC/OECD QRAM OUTPUTS

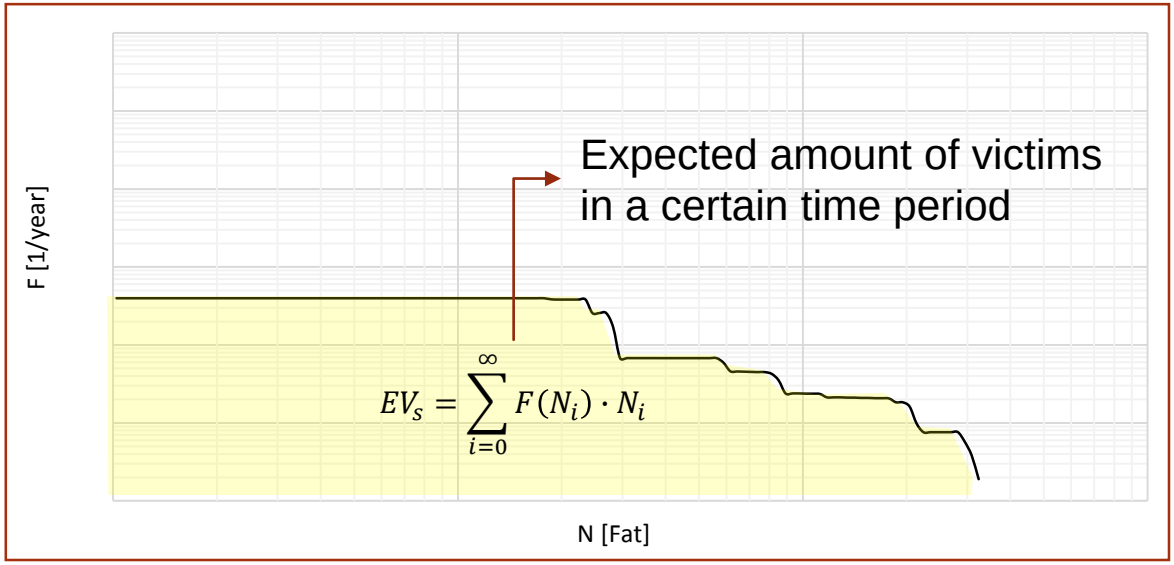
$$R = F \cdot C$$

F probability of occurrence / frequency

C extent of damage / consequences

- Fatalities
- Injured
- Destruction of buildings and structures
- Environmental Damage

PIARC/OECD QRAM → **Societal Risk**



The risk to which a group of people is subjected in case a scenario s occurs.

$$SR = F(N) \cdot N$$

The F-N diagrams may be applied to illustrate the **risk profile for a specific hazard** such as a fire in a road tunnel.

TUNNEL RISK ASSESSMENT PROCEDURE

Mean Data:

- Traffic
- Accident Frequencies
- Tunnel Geometry
- Tunnel Equipment
- .....

Risk Analysis

Data Collection

Data Preparation

Risk Calculation Using QRAM

Is Risk acceptable?

NO

YES

End

Additional risk reduction measures

Prevention Measures:

- Signs and road markings
- Lighting
- Traffic control
- Route geometry
- Prohibition of access to certain types of vehicles

Protection Measures:

- Monitoring
- Fires/Accident Detection system
- Ventilation system
- Emergency lighting
- Protection of escape routes
- System of emergency management
- Emergency Procedures

Risk Acceptability:

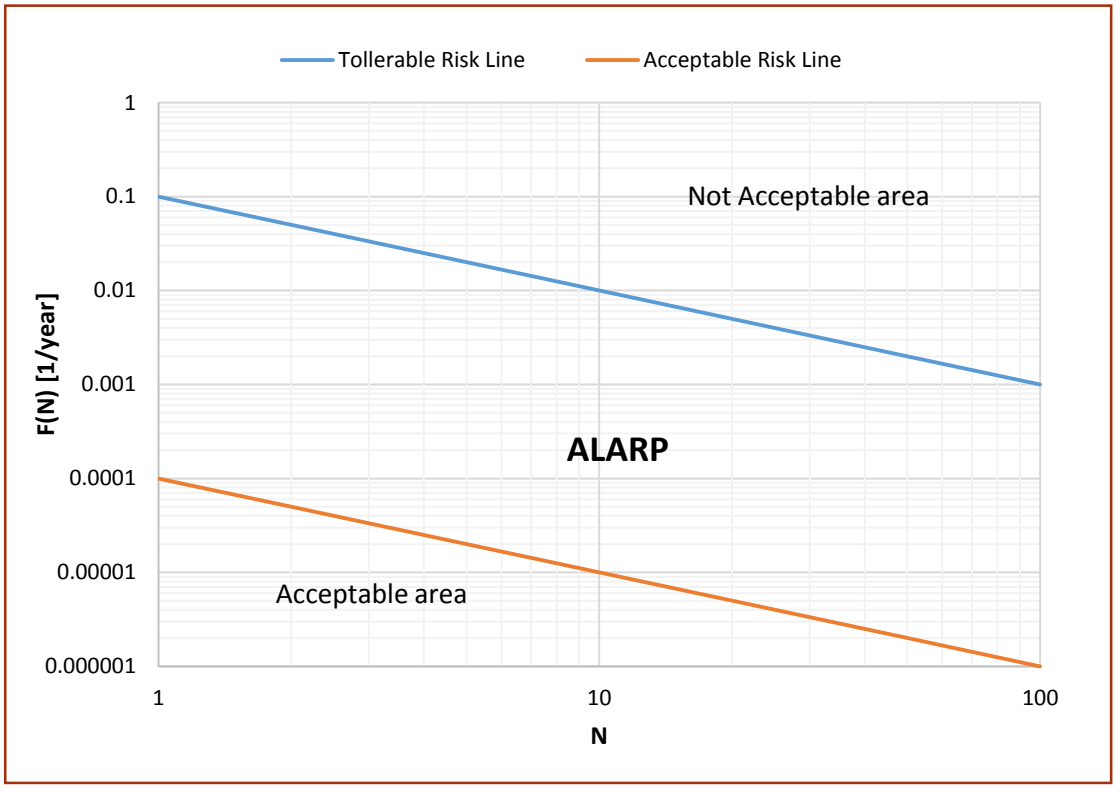
- Absolute criteria
- Relative criteria

SOCIETAL RISK ACCEPTABILITY CRITERIA

Absolute Criteria

$$EV_s \leq EV_{limit}$$

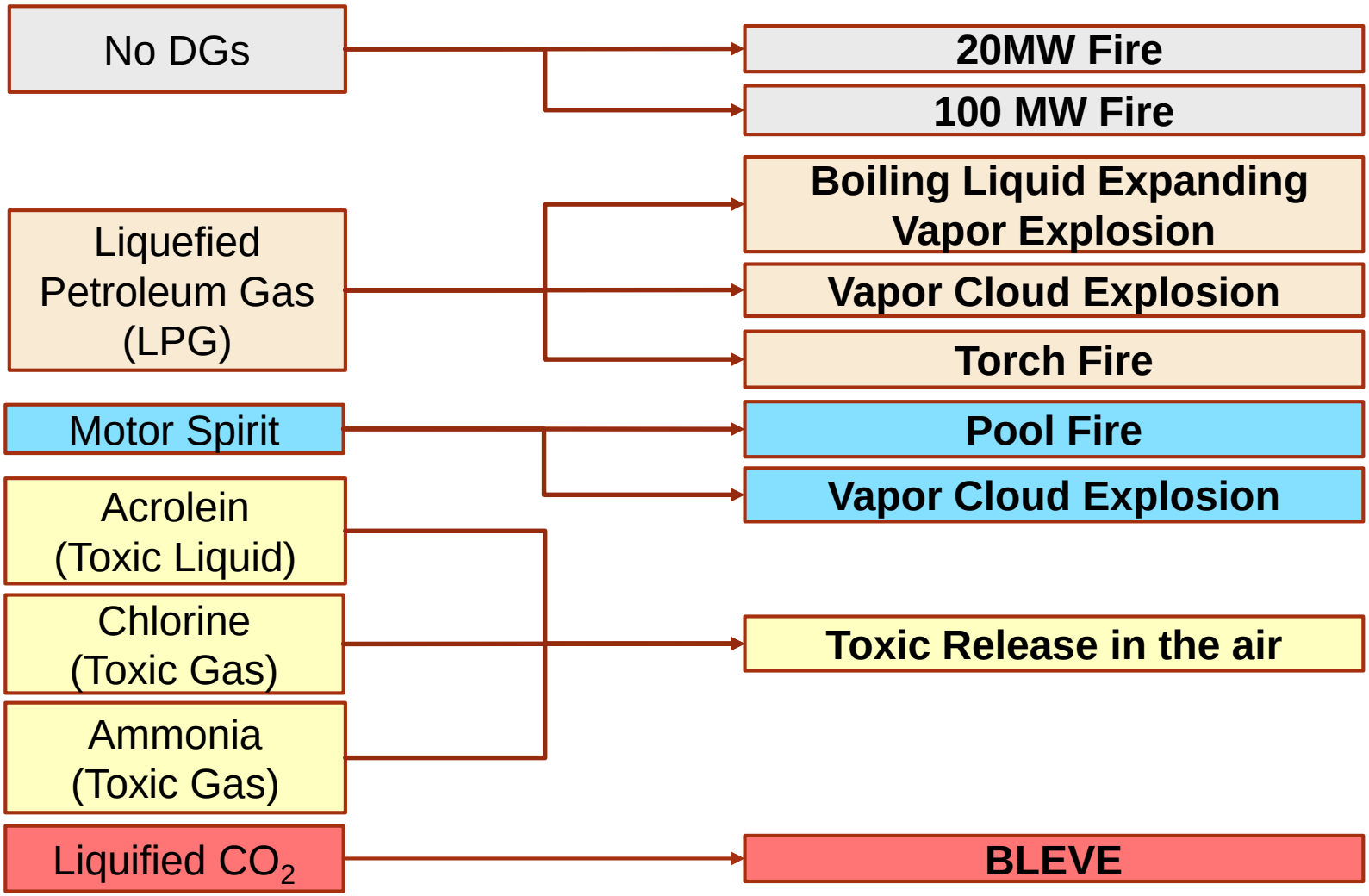
As Low As Reasonably Practicable



ALARP area:

- prevention and/or mitigation actions must be taken to reduce the risk, as far as reasonably practicable
- **Cost – Benefit Analysis**

1) DANGEROUS GOODS AND ACCIDENT SCENARIOS



2) SCENARIO PHYSICAL EFFECTS

Thermal Effects

- Fires
- VCEs
- BLEVEs

Radiative Heat Flux

q_r [kW/m^2] = f(d)

which is experienced by the receiver per unit area

Pressure Effects

- VCES
- BLEVEs

Side-on Blast Overpressure

ΔP_s [bar] = f(d)

Wave Positive-phase

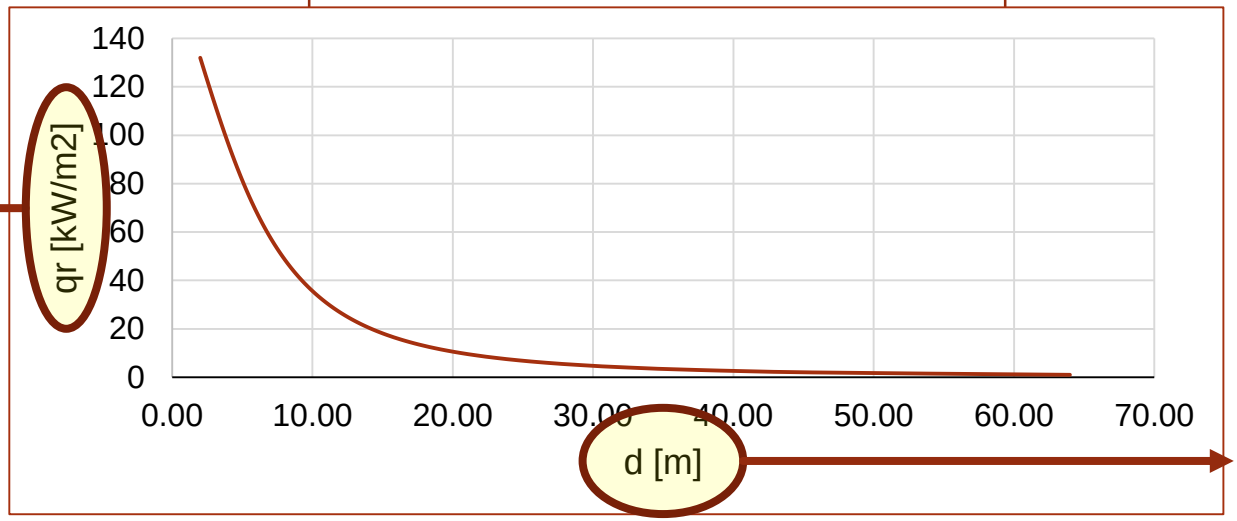
t_+[bar] = f(d)

Toxicity Effects

- Fires (smokes)
- Toxis Releases in air

Concentration

C [ppmv] = f(d)



Effect Intensity

Distance from the epicentre

3) PHYSIOLOGICAL EFFECTS

Pressure

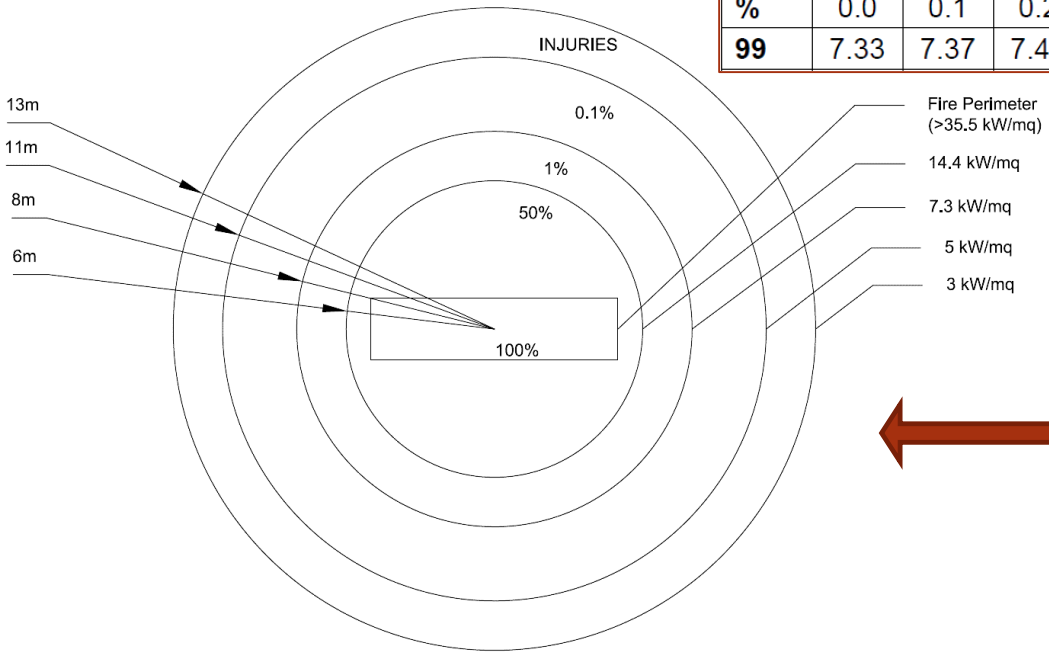
Toxicity

Thermal

$$Pr_j = a + b \ln\left(E_j \cdot t_{exp,j}\right)$$

%	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

Finney, 1971



Probit Transformation

$$Ratio = f(\mathrm{Pr}) = \int_{-\infty}^{Pr-5} e^{\left(-\frac{1}{2}u^2\right)} du$$

4) PROBABILITY OF OCCURRENCE OF THE SCENARIOS

Frequency of occurrence of the scenario s on the section i in a year [scen/year]

$$f_{s,i} = P_{s,i} \cdot f_{acc,i} \cdot (TH_i \cdot L_i \cdot 24 \cdot 365 \cdot 10^{-6})$$

Traffic of HGVs passing through the section i in one hour **[veh/h]**

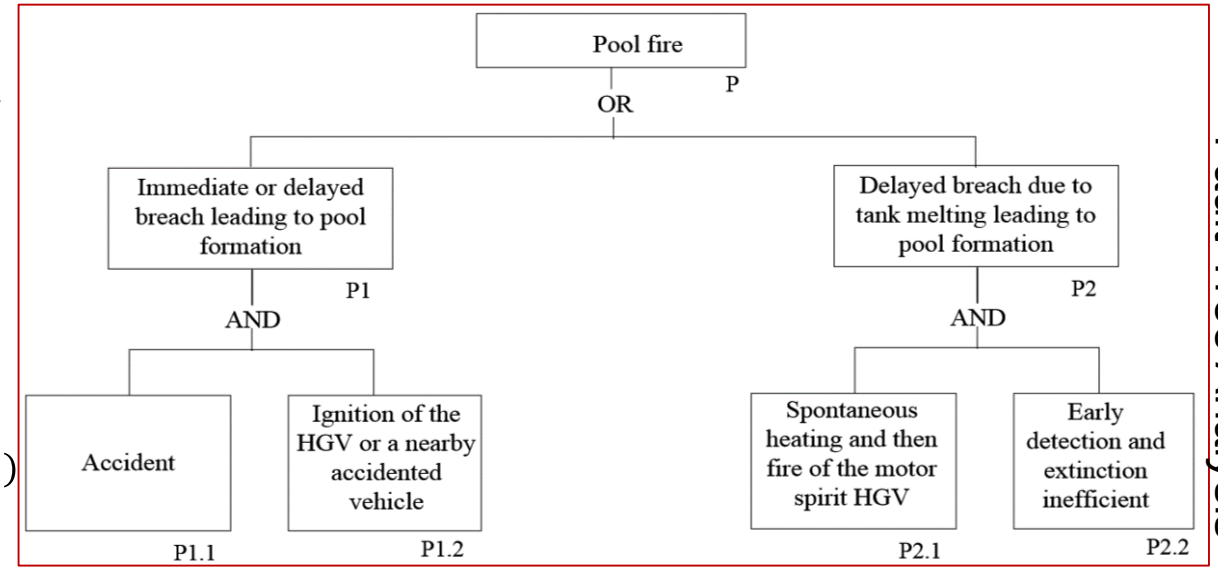
Annual frequency of accidents involving HGVs on the section i **[acc/(MVkm*year)]**

$$f_{acc,i} = \frac{HGV_{acc,i}}{TH_i \cdot L_i}$$

- HGV/h
- % DG-HGV
- DGs types
- Accidents/year

Conditional probability that scenario j occurs once an accident implying an HGV has taken place on the section i

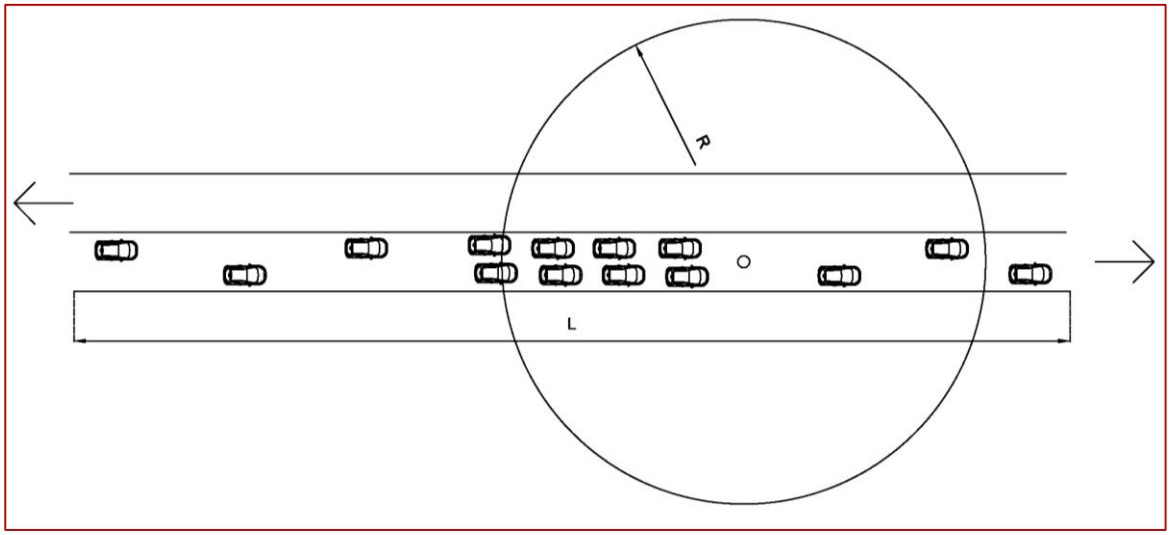
$$\mathbf{P} = (\mathbf{P1.1} \cdot \mathbf{P1.2}) + (\mathbf{P2.1} \cdot \mathbf{P2.2})$$



Fault Tree Analysis

5) SOCIETAL RISK INDICATORS

Number of Victims



t_{sce} Occurs the accident scenario

t_{barr} Delay for stopping approaching traffic

t_{jam} min (t_{sce}, t_{barr}).

Road Users Density in a Traffic Jam [users/m]

$$N = \{(R \cdot D_{RUJ}) + [(R - L_{jam})] \cdot D_{RUF}\} \cdot \%LETH$$

Road Users Density in a Fluid Traffic [users/m]

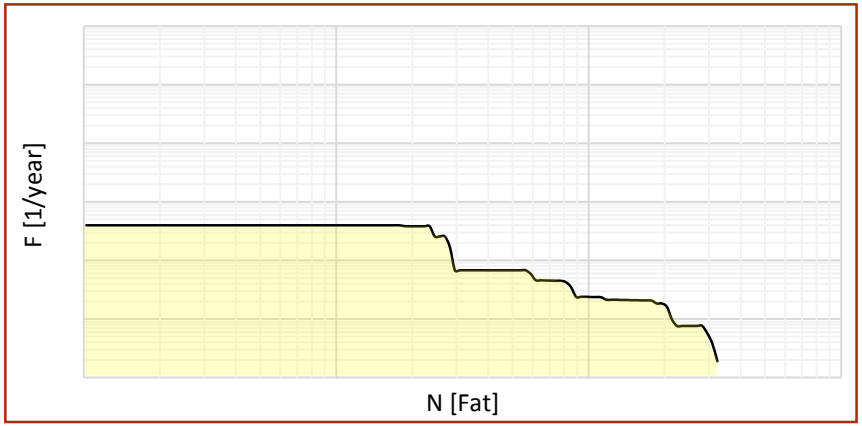
6) SOCIETAL RISK INDICATORS

F-N curve construction

Each scenario s may appear as different events E_i depending on:

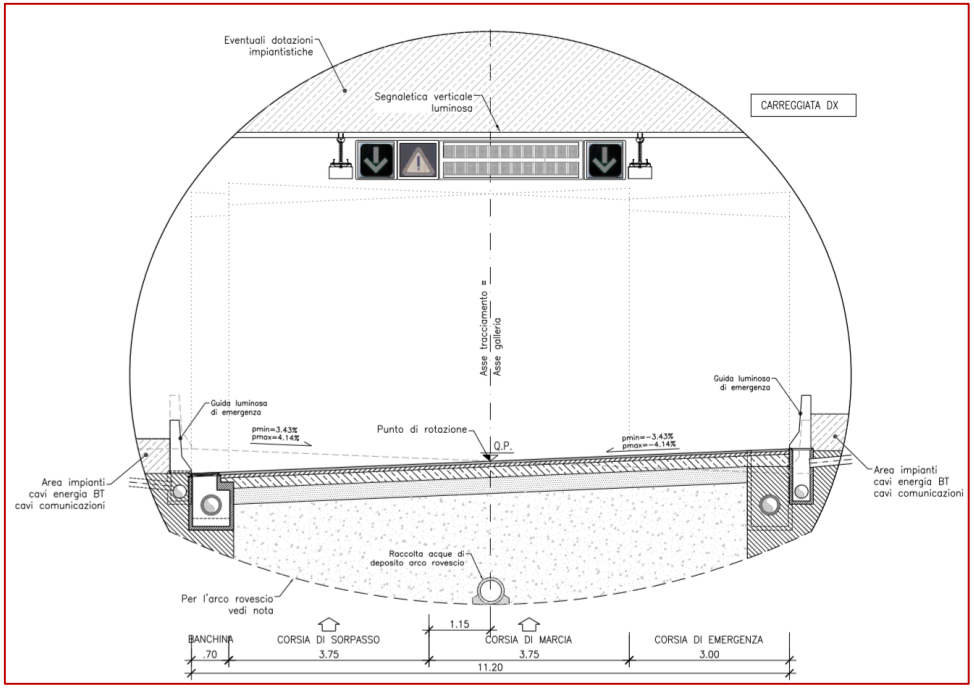
- the section of the path being considered (section i)
- the accident location on the section
- the traffic direction (A, B)
- the reference period of the day (QUIET, NORMAL, PEAK)
- ....

Scenario "s"			
Event	Event Frequency	Fatalities	Cumulative Frequency
E_i	f_i	N_i	F_i
[-]	[1/year]	[Fat]	[1/year]
E_1	f_1	N_1	$F_1 = f_1$
E_2	f_2	N_2	$F_2 = f_1+f_2$
E_3	f_3	N_3	$F_3 = f_1+f_2+f_3$
E_4	f_4	N_4	$F_4 = f_1+f_2+f_3+f_4$
...	...	...	...
E_n	f_n	N_n	$F_n = f_1+f_2+f_3+f_4+...+f_n$

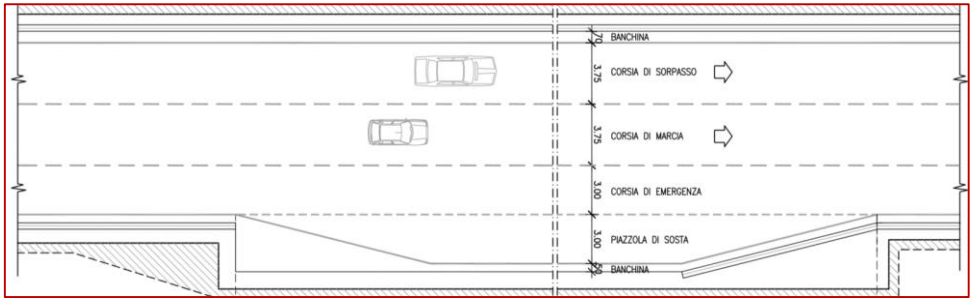


$$EV_s = \int_1^{+\infty} F(N)\, dN$$

THE ST. DEMETRIO TUNNEL



(Central Design Management ANAS S.p.A.)



Natural Tunnel

TWIN BORE TUNNEL,
ONE DIRECTION PER BORE

Polycentric Circular Section
Traditional Excavation

Catania – Syracuse (E45), ANAS s.p.a.
2007-2009, Pizzarotti & C. S.p.A. Parma

Height from the Roadway to the Inner Wall	8.06	[m]
Road Platform Width	11.2	[m]
Cross Sectional Area	87.31	[m^2]

		Bore in direction SOUTH (Syracuse)
portal of entry	[km]	4+800
portal altitude above sea level	[m]	10642
portal of exit	[km]	7+695
portal altitude above sea level	[m]	19242
Length	**[km]**	**2895**
maximum longitudinal slope	[%]	0.32
minimum longitudinal slope	[%]	0.32
average longitudinal slope	**[%]**	**0.32**

		Bore in direction NORTH (Catania)
portal of entry	[km]	7+698
portal altitude above sea level	[m]	19273
portal of exit	[km]	4+750
portal altitude above sea level	[m]	10480
Length	**[km]**	**2949**
maximum longitudinal slope	[%]	-0.32
minimum longitudinal slope	[%]	-0.32
average longitudinal slope	**[%]**	**-0.32**

C. Di Santo
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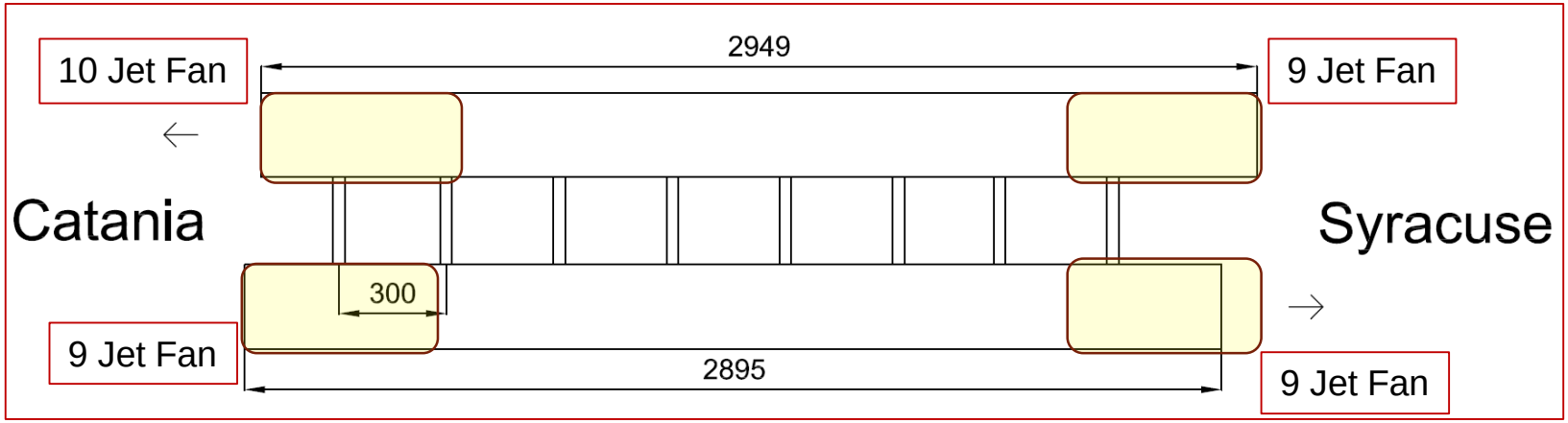
TUNNEL ST. DEMETRIO: EQUIPMENT & TRAFFIC DATA



Equipment

- Pedestrian Bypass every 300m
- Bypass Carriageable every 900m
- Control Centre → Catania
- CCTV cameras placed every 282m
- CO sensors
- Smoke Meters (Opacimeters)
- Linear Thermal Sensors (heat sensing cable)
- Variable Message Panels every 300m
- SOS stations every 200m

Emergency Ventilation System

Longitudinal Ventilation
average speed (on the cross section) of **3 m/s** in the direction of traffic

time of fire detection (via thermo sensitive cable) of **3 minutes** from the ignition

a time of **5 minutes** for the emergency ventilation establishment

TUNNEL ST. DEMETRIO: EQUIPMENT & TRAFFIC DATA

Traffic — AADT = 21190 veh/day (1 direction)

	QUIET	NORMAL	PEAK
22÷07	325 veh/h HGV-ratio = 2% v_{car} = 126.4 km/h v_{HGV} = 90.5 km/h	1050 veh/h HGV-ratio = 10% v_{car} = 126.4 km/h v_{HGV} = 90.5 km/h	1553 veh/h HGV-ratio = 11.7% v_{car} = 114.5 km/h v_{HGV} = 82 km/h

63% Flammable Liquids (motor spirit, diesel oil, etc.)

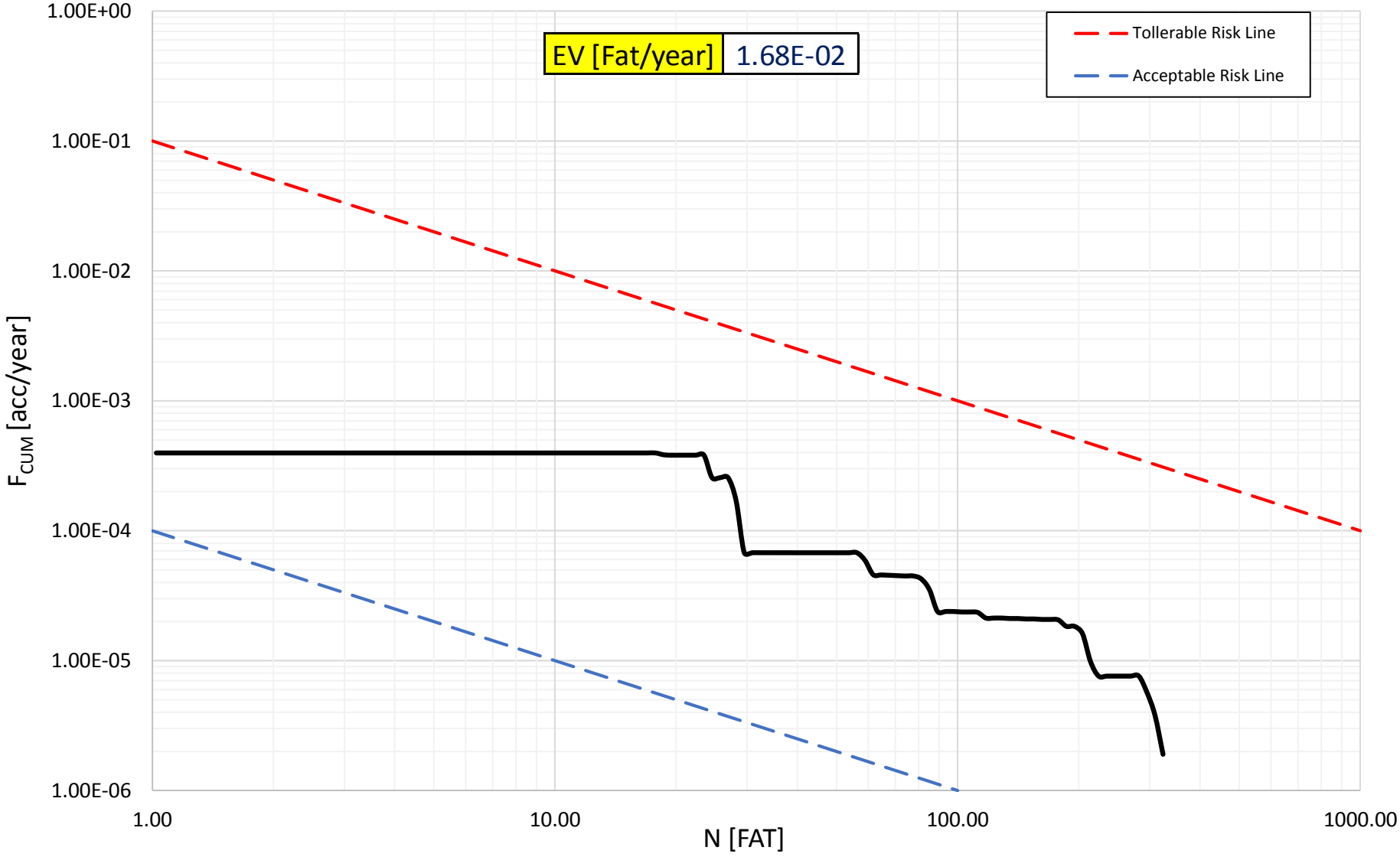
31% LPG

6% Others

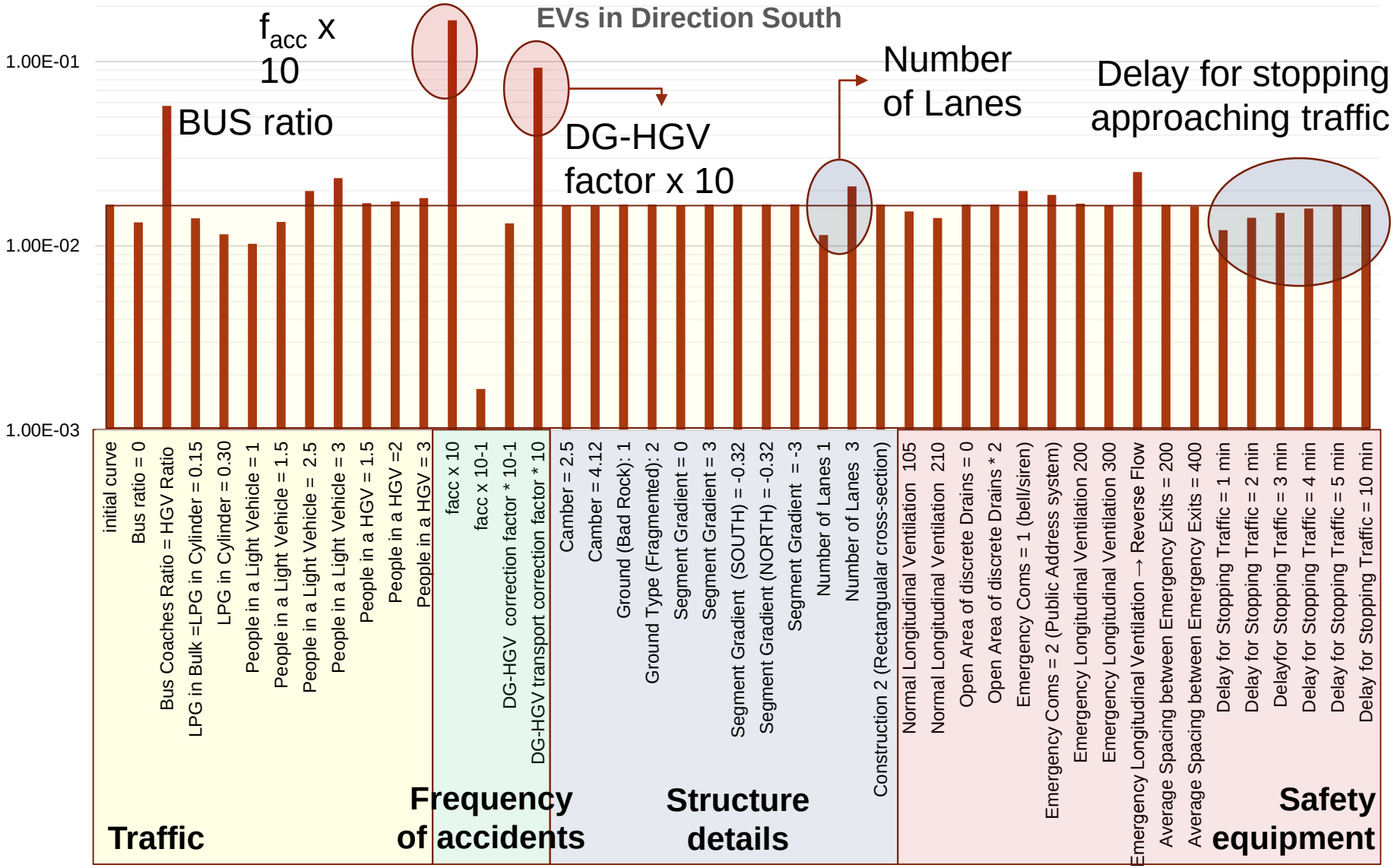
	DG-HGV / h	
	SOUTH	NORTH
QUIET	1	1
NORMAL	7	3
PEAK	12	5

		[acc /(MVkm*year)]	[acc /(veh*km*year)]
f_{acc}	SOUTH	0.161	0.000000161
	NORTH	0.160	0.000000160

TUNNEL ST. DEMETRIO: F-N CURVE IN THE SOUTH DIRECTION



TUNNEL ST. DEMETRIO: SENSITIVITY ANALYSIS RESULTS



"Risk Analysis for severe traffic accidents in road tunnels"

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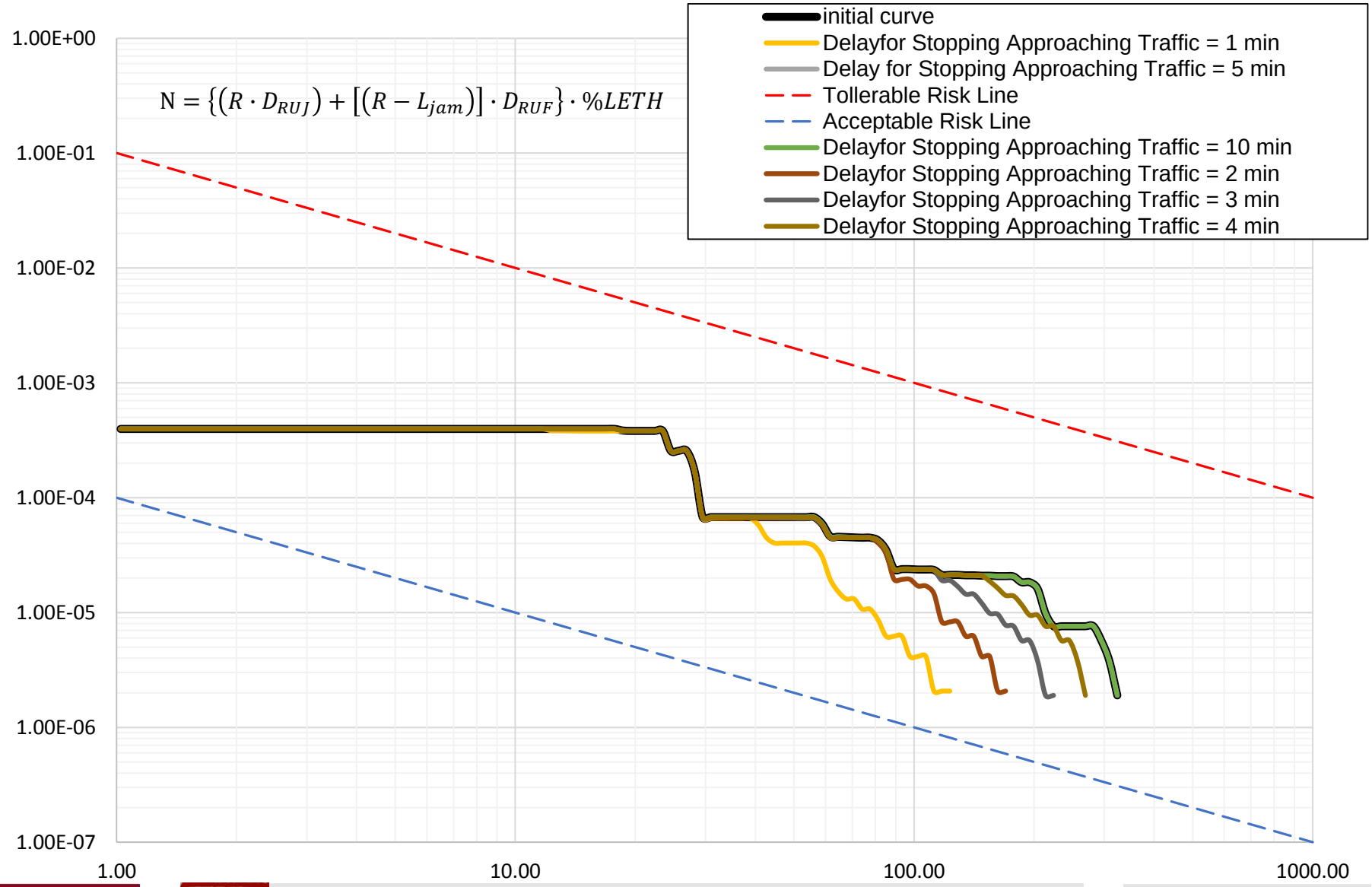
TUNNEL ST. DEMETRIO



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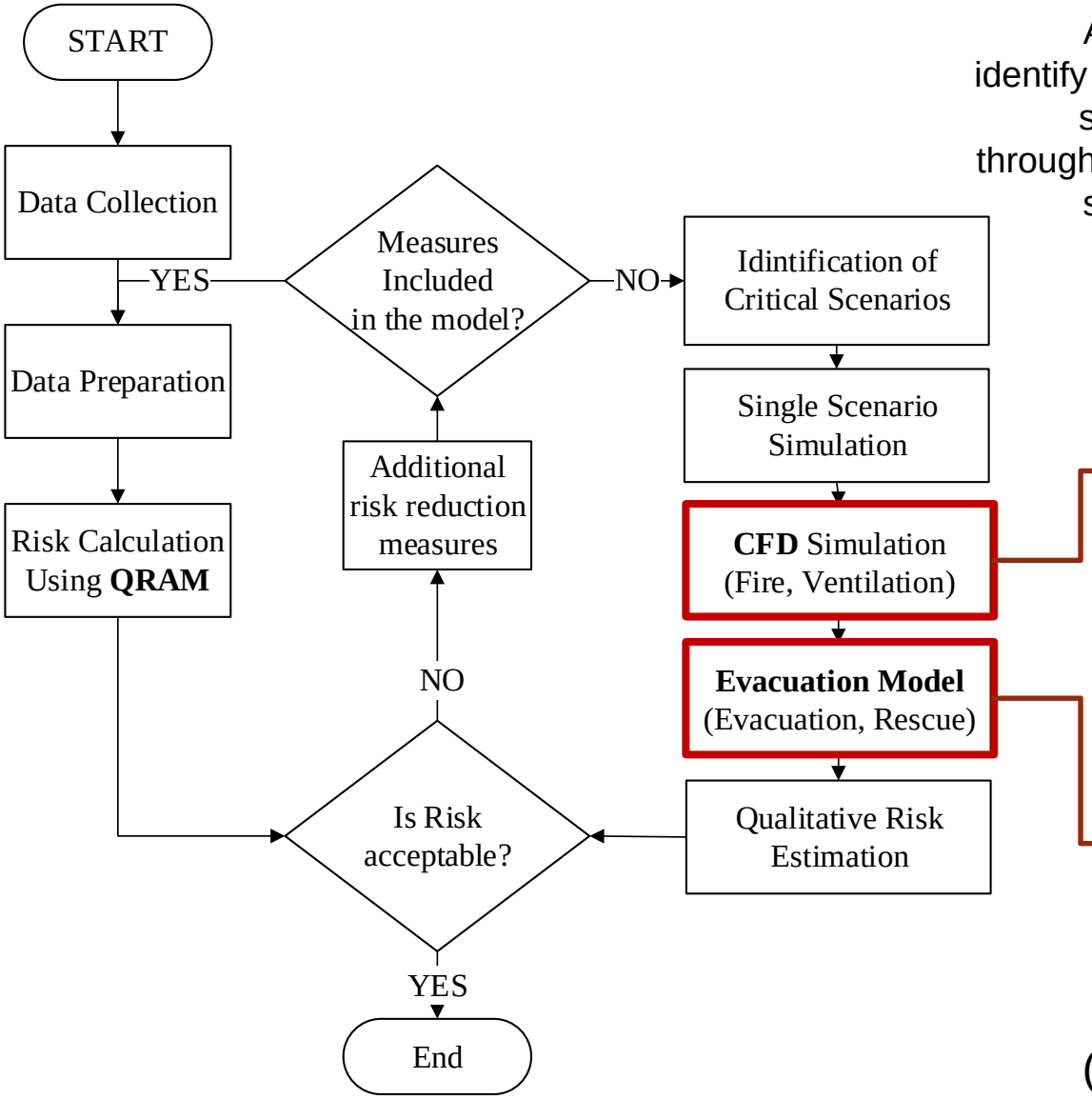
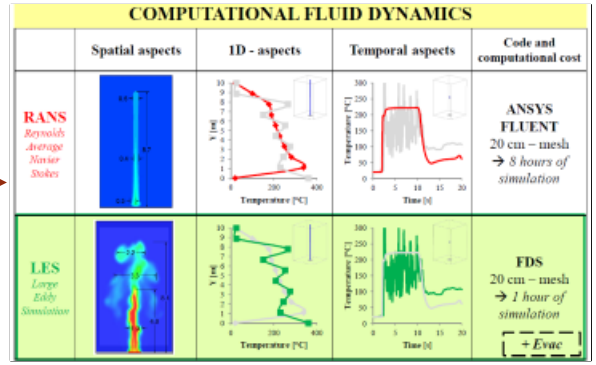
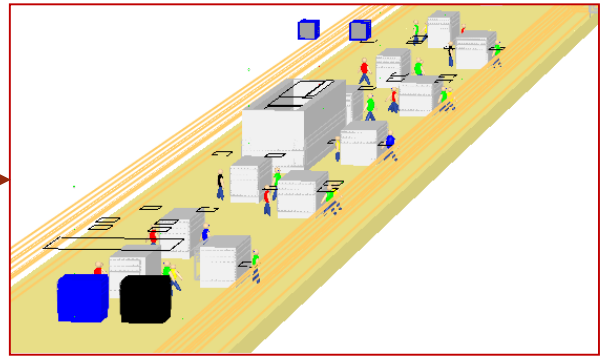
CONCLUSIONS: QRAM AND FLUID DYNAMICS/EVACUATION MODELS



An operating method to follow can be to identify the critical scenarios that give the most significant contribution to the overall risk through the QRAM, and then to simulate those scenarios in detail in order to define risk reduction measures (Petelin S. 2009)





(Gai et al., Proceedings IF CRASC' 15)

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PIARC/OECD QRAM

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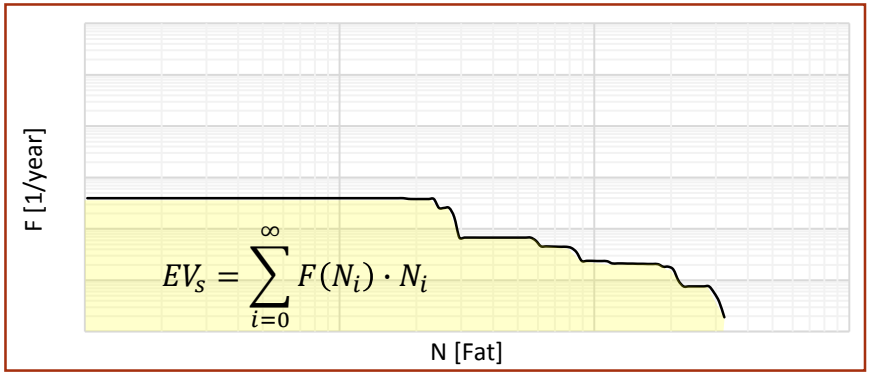
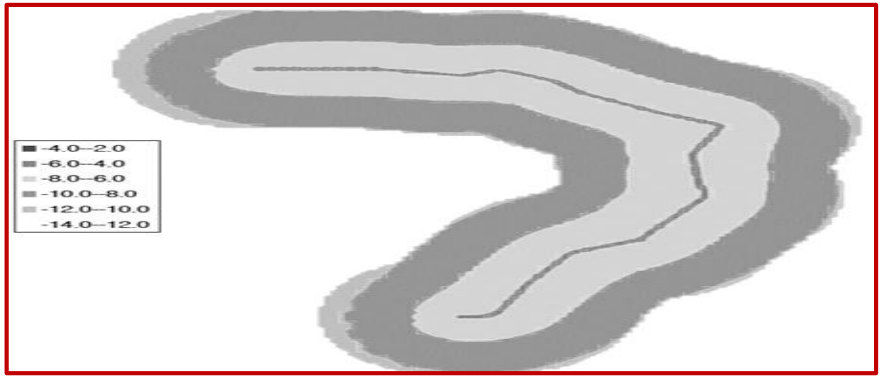
The risk to which a group of people is subjected in case a scenario s occurs.



Individual Risk

Prob. that a person (among local population and within a certain distance from the road) dies due to the scenario s.

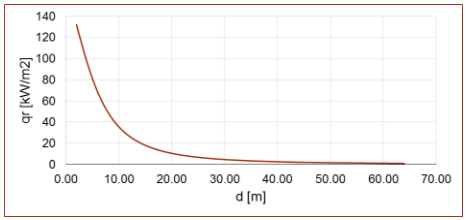


F-N CURVE CONSTRUCTION PROCESS FLOW

1 – Dangerous Goods and **Accident Scenarios** selection

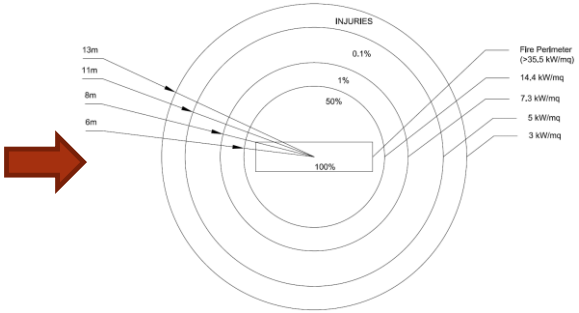
2 – **Effect j** (due to the scenario "s") and its **Range** from the epicentre

$E_j=f(d) \leftrightarrow R_j$



3 – **Mortality Rate** within the range R_j

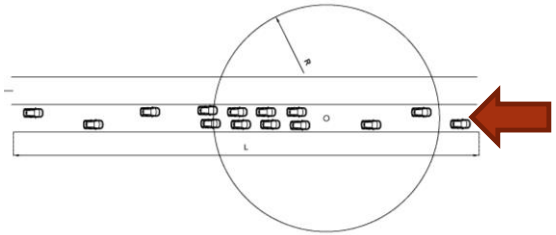
$\%LETH_j$



4 – Mortality Rate corrected considering the **possibility of escape**

$\%LETH_j=f(t_{evac})$

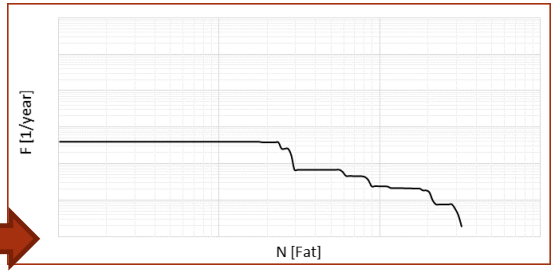
5 – Scenario s **Probability of occurrence** $\rightarrow f_s$



6 – **Number of victims due to the scenario s**

$N=\sum_j N_j=f(R_j, D_{ru}, L_{jam}, \%LETH_j)$

7 – **F-N curve** for the scenario "s" and its relative **Expected Value**



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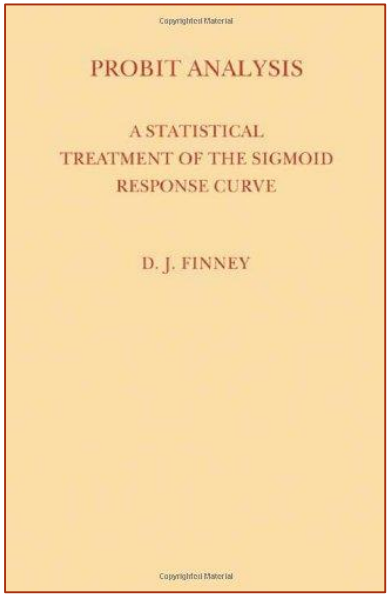
DANGEROUS GOODS AND ACCIDENTS SCENARIOS

Dangerous Good	Mode of Containment	Diameter release hole	Mass Flow Rate	Scenario	n°
No DG	-	-	-	20 MW HGV Fire	1
	-	-	-	100 MW HGV Fire	2
Liquefied Petroleum Gas (LPG)	Cylinder (50 kg)	-	-	BLEVE	3
	Bulk (18 t)	-	-	BLEVE	7
		50 mm	36 kg/s	VCE	8
				Torch Fire	9
Motor Spirit	Bulk (18 t)	100 mm	20.6 kg/s	Pool Fire (≥400MW Fire)	4
				VCE	5
Acrolein (toxic liquid)	Bulk (30000 liters)	50 mm	24.8 kg/s	Toxic Liquid Release	11
	Cylinder (100 liters)	4 mm	0.02 kg/s	Toxic Liquid Release	12
Chlorine (toxic gas)	Bulk (20 t)	50 mm	45 kg/s	Toxic Gas Release	6
Ammonia (toxic gas)	Bulk (20 t)	50 mm	36 kg/s	Toxic Gas Release	10
Liquified CO_2	Bulk (20 t)	-	-	BLEVE	13

PROBIT ANALYSIS

Is a type of regression used to analysing the relationsheep between a stimulus (dose) and “all or nothing” (such as death) response



FINNEY 1971

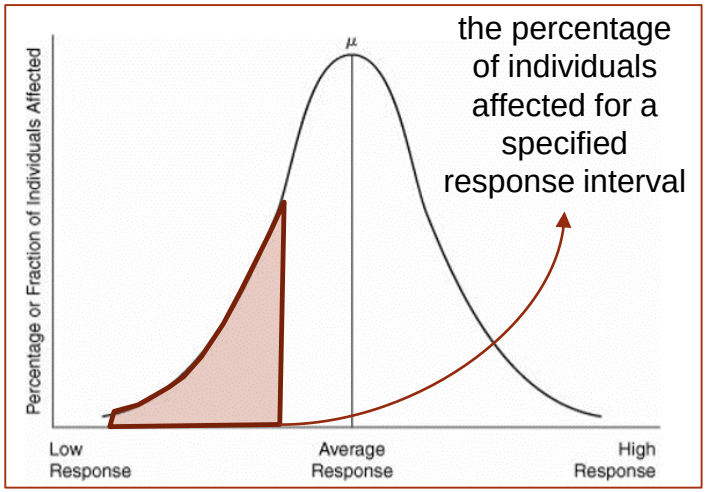
The following items must be identified:

- The toxicant
- The target
- The effect or response to be monitored
- The dose range
- The period of the test

Biological organisms respond differently to the same dose of a toxicant.

Each individual is exposed to the same dose and the response is recorded.

Curves are frequently represented by a normal or Gaussian distribution



A Gaussian or normal distribution representing the biological response to exposure to a toxicant.

- The toxicological experiment is repeated for a number of different doses, and normal curves are drawn.
- The standard deviation and mean response are determined from the data for each dose.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

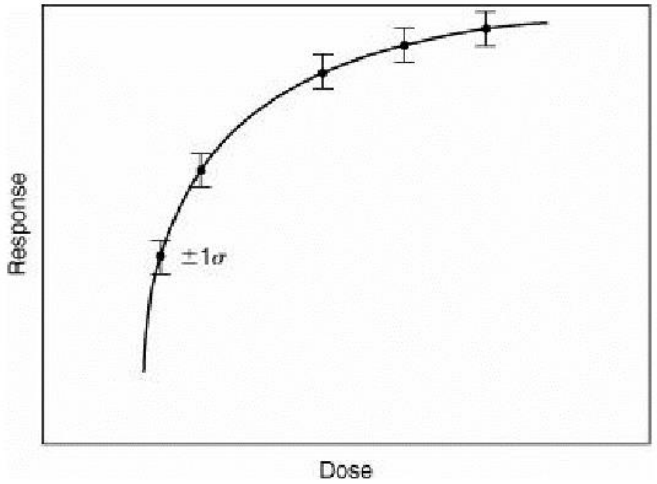
probability (or fraction) of individuals experiencing a specific response

x is the response, σ is the standard deviation, and μ is the mean.

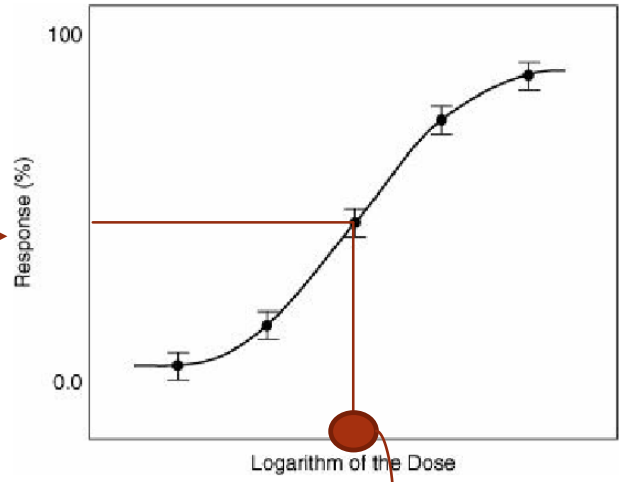
σ determines the shape and μ characterize the location of the curve with respect to the x axis

PROBIT ANALYSIS

A complete dose-response curve is produced by plotting the **cumulative mean response** at each dose.



The response is plotted versus the **logarithm of the dose**, to provide a much **straighter line in the middle** of the response curve



For comparison purposes the dose that results in 50% lethality of the subjects is frequently reported. This is called the LD50 dose (lethal dose for 50% of the subjects).

For computational purposes the **response versus dose curve is not convenient.**

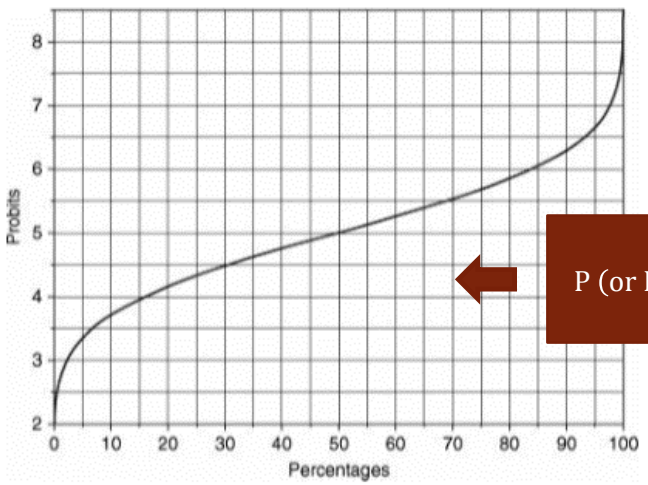
Many methods exist for representing the response-dose curve.

For single exposures the **probit** method is particularly suited, providing a straight-line equivalent to the response-dose curve.

$$\mathrm{P\ (or\ RATIO)} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{Pr}-5} e^{-\frac{1}{2}u^2}\, du$$

provides a relationship between the probability P and the probit variable Pr.

PROBIT ANALYSIS

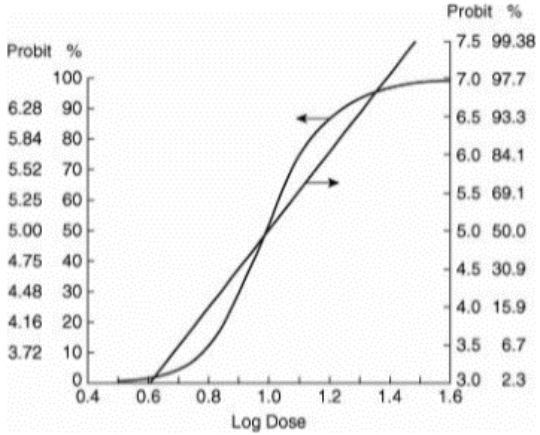


$$P\ (\text{or RATIO}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Pr-5} e^{-\frac{1}{2}u^2}\, du$$

Transformation from Percentages to Probits

%	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
%	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

The probit relationship transforms the sigmoid shape of the normal response versus dose curve into a <u>straight line</u> when plotted using a linear probit scale



The probit variable **Pr** is computed from

$$Pr = a + b\ln(D)$$

4) POSSIBILITY OF ESCAPE OR OF FINDING SHELTER

Dose of physical effect j that affects a man crossing the segment i

$$D_{ij} = \int_{t_{in}}^{t_{out}} D_j(t)dt$$

Total dose received during the escape

$$D_{j,TOT} = \sum_i D_{ij}$$

$$Pr_j = a + b \cdot \ln(E_j \cdot t_{exp,j})$$

$D_{j,TOT}$

t_{evac}

Pre-movement time

t_{pre}

$t_{rec} + t_{res}$

t_{mov}

Movement time

$$\frac{v}{d_{safety}}$$

$$t_{pre} = t_{pre-bps} \cdot w_{eff}$$

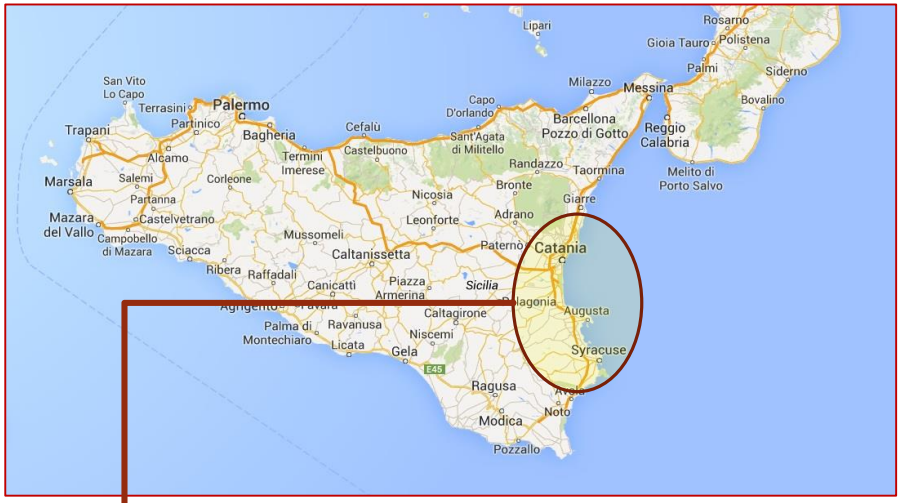
$$w_{eff} = \frac{5}{average\ rating\ of\ parameters}$$

warning system	Pre-movement time (t_{pre}) best scenario (bps) (seconds)	average scenario (seconds)	worst scenario (seconds)
W0	< 300	420	> 720
W1	< 180	360	> 540
W2	< 120	240	> 360
W3	< 60	120	> 180

- Alertness (4)
- Mobility (4)
- Social Affiliation (3)
- Commitment (3)
- Familiarity (2)
- Distance from the accident (by calc)
- Perceived severity (4)

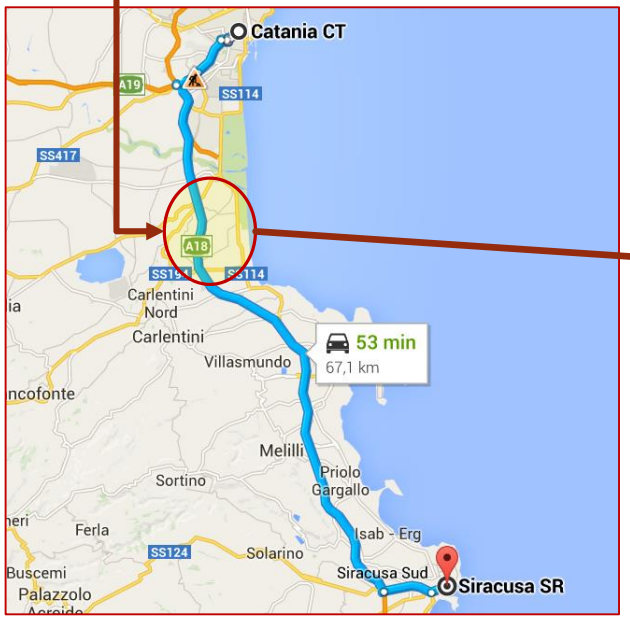
Occupant Response Model

THE ST. DEMETRIO TUNNEL



Motorway Catania – Syracuse
(European route E45)
ANAS s.p.a.

Construction:
2007-2009
Pizzarotti & C. S.p.A. Parma

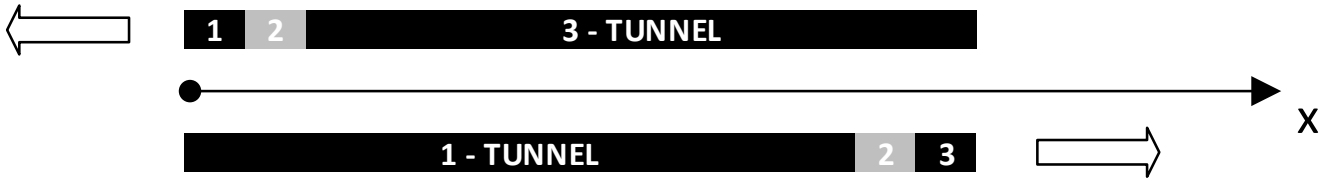


Courtesy of Dr. Luigi Carrarini
(ANAS S.p.A.)

Courtesy of Ing. Alessandra Lo Cane
(M.I.T.)

TUNNEL ST. DEMETRIO: QRAM INPUT DATA

NORTH (Catania)



SOUTH (Syracuse)

Tunnel QRAM Model

Accident Scenarios

Yes / No — Non-DG HGV considered ? <----(

Select the scenarios you intend to study:

- [x] Scenario 1: 20MW fire
- [x] Scenario 2: 100MW fire
- [x] Scenario 3: BLEVE of a 50kg propane cylinder
- [x] Scenario 4: Motor spirit pool fire
- [x] Scenario 5: VCE of motor spirit
- [ ] Scenario 6: Chlorine release
- [x] Scenario 7: BLEVE of a 18 tonne propane tank
- [x] Scenario 8: VCE of propane
- [x] Scenario 9: Propane torch fire
- [ ] Scenario 10: Ammonia release
- [ ] Scenario 11: Acrolein in bulk release
- [ ] Scenario 12: Acrolein in cylinder release
- [ ] Scenario 13: BLEVE of a 20 tonne CO2 tank
- [ ] Scenario 14:
- [ ] Scenario 15:
- [ ] Scenario 16:
- [ ] Scenario 17:
- [ ] Scenario 18:
- [ ] Scenario 19:
- [ ] Scenario 20:

Traffic & Population Data

Average number of people in a light vehicle	[-]	2
Average number of people in a HGV	[-]	1.1
Average number of people in a Bus/Coach	[-]	40
Bus/Coaches ratio	[-]	0.01
Delay for stopping approaching traffic	[s]	9000
Area (Urban/Rural)	[-]	urban
Average density of population	[hab/km^2]	0.01
DG transport correction factor	[-]	1.00E+00

Tunnel Data

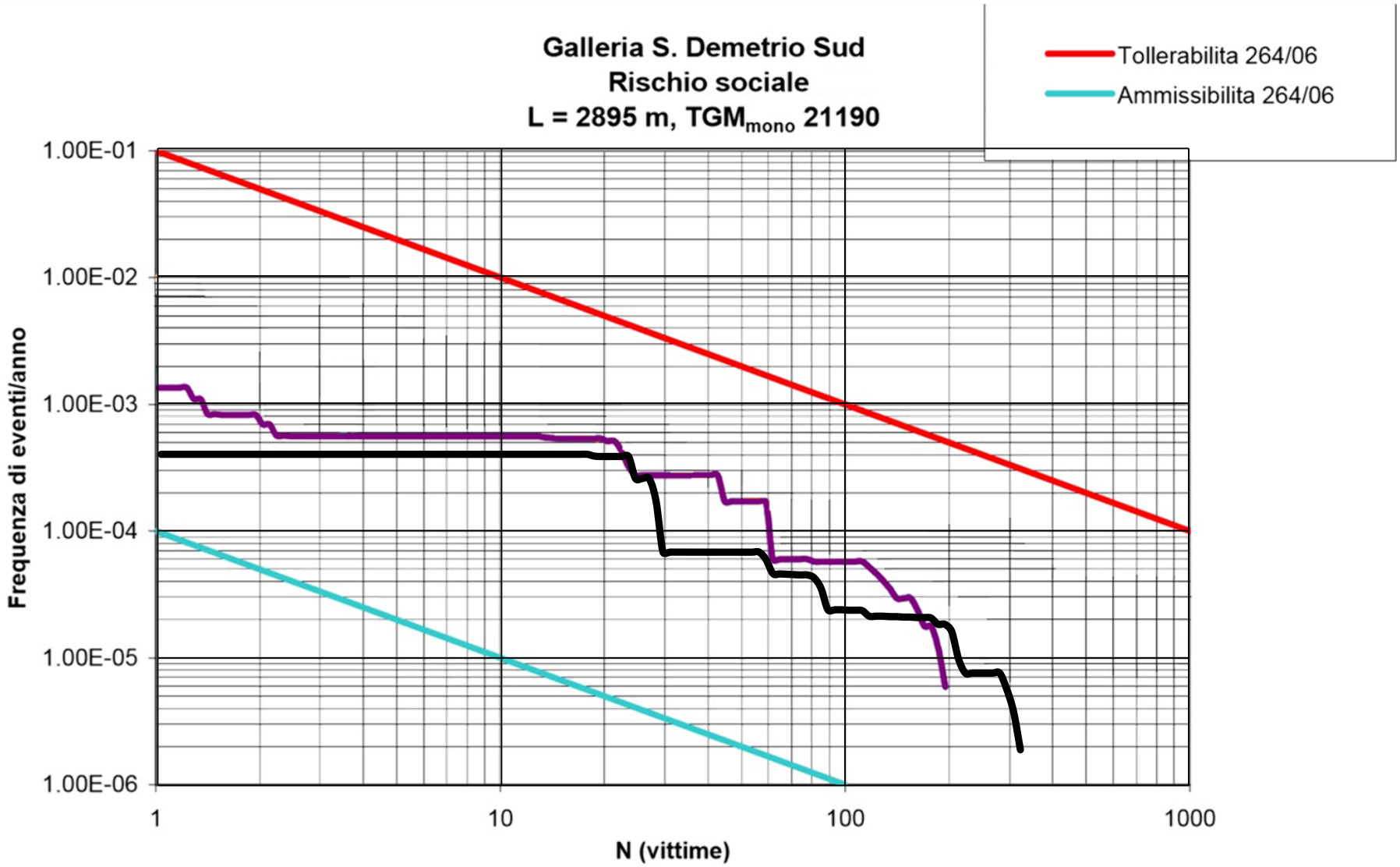
W (effective width)	[m]	**11**
H (effective height)	[m]	**7.9**
A (open cross sectional area)	[m^2]	**86.9**
Cam (camber)	[%]	**0**
G_s (Segment gradient)	[%]	**0.32**
V_nN (volume flow rate along tunnel at nodes)	[m^3/s]	**0**
V_nE (volume flow rate along tunnel at nodes)	[m^3/s]	**261**
A_d (open area of discrete drains)	[m^2]	**0.075**
Xd (interval between drains)	[m]	**20**
Xe (average spacing between emergency exits)	[m]	**300**
E_{com} (emergency coms) → 1, 2 o 3	[-]	**3**

TUNNEL ST. DEMETRIO: QRAM SENSITIVITY ANALYSIS

		Societal Risk			A - SOUTH Syr		B - NORTH Cat	
		input parameter	*Variation*		*Initial Value*	*Final Value*	*Initial Value*	*Final Value*
TRAFFIC	I	Bus Coaches Ratio (for each period: QUIET, NORMAL, PEAK)	0	[-]	0.01	0.00	0.01	0.00
			equal to HGV ratio		0.01	0.02; 0.1; 0.117	0.01	0.02; 0.1; 0.117
	II	Propane in Bulk ratio - Propane in Cylinder ratio	0.15 - 0.15	[-]	0.30 ; 0.00	0.15 ; 0.15	0.30 ; 0.00	0.15 ; 0.15
			0 - 0.30		0.30 ; 0.00	0.00 ; 0.30	0.30 ; 0.00	0.00 ; 0.30
	III	Average Number of People in a Light Vehicle	1	[pass]	2	1	2	1
			1.5		2	1.5	2	1.5
			2.5		2	2.5	2	2.5
			3		2	3	2	3
	IV	Average Number of People in a HGV	1.5	[pass]	1.1	1.5	1.1	1.5
			2		1.1	2	1.1	2
			3		1.1	3	1.1	3
Frequency of Accidents	V	Accidents Frequency (f_{acc})	x 10	[acc/(veh* km*year)]	1.61E-07	1.61E-06	1.60E-07	1.60E-06
			x 10^{-1}		1.61E-07	1.61E-08	1.60E-07	1.60E-08
	VI	DG-HGV transport correction factor	x 10^{-1}	[-]	1.00	0.10	1.00	0.10
			x 10		1.00	10.00	1.00	10.00
Changes to the structure	VII	Camber (transversal slope)	2.5	[%]	0.00	2.50	0.00	2.50
			4.12		0.00	4.12	0.00	4.12
	VIII	Ground Type: 1 (Bedrock), 2 (Fragmented), 3 (Fragmented and Under Water	1	[-]	3	1	3	1
			2		3	2	3	2
	IX	Segments Gradient	A,B: 0	[%]	0.32	0.00	0.32	0.00
			A,B: 3		0.32	3.00	0.32	3.00
			A: -0.32		0.32	-0.32	-	-
			B: -0.32		-	-	0.32	-0.32
			A,B: -3		0.32	-3.00	0.32	-3.00
	X	Number of Lanes	1	[-]	2	1	2	1
			3		2	3	2	3
	XI	Type of Construction (1 Circular, 2 Rectangualar cross-section)	2	[-]	1	2	1	2
Safety equipment	XII	Normal Longitudinal Ventilation, Volume Flow Rate along tunnel (at each node)	105	[m3/s]	0.00	105.00	0.00	-105.00
			210		0.00	210.00	0.00	-210.00
	XIII	Emergency Longitudinal Ventilation, Volume Flow Rate along tunnel (at each node)	200	[m^3/s]	261.00	200.00	-261.00	-200.00
			300		261.00	300.00	-261.00	-300.00
			REVERSE		261.00	-261.00	-261.00	261.00
	XIV	Open Area of discrete Drains	0	[m^2]	0.075	0.00	0.075	0.00
			0.15		0.075	0.15	0.075	0.15
	XV	Emergency Coms: 1 (bell/siren), 2 (Public Address system)	1	[-]	3	1	3	1
			2		3	2	3	2
	XVI	Average Spacing between Emergency Exits	200	[-]	300.00	200.00	300.00	200.00
			400		300.00	400.00	300.00	400.00
	XVII	Delay for Stopping Approaching Traffic	1	[min]	150	1	150	1
			2		150	2	150	2
			3		150	3	150	3
			4		150	4	150	4
			5		150	5	150	5
			10		150	10	150	10

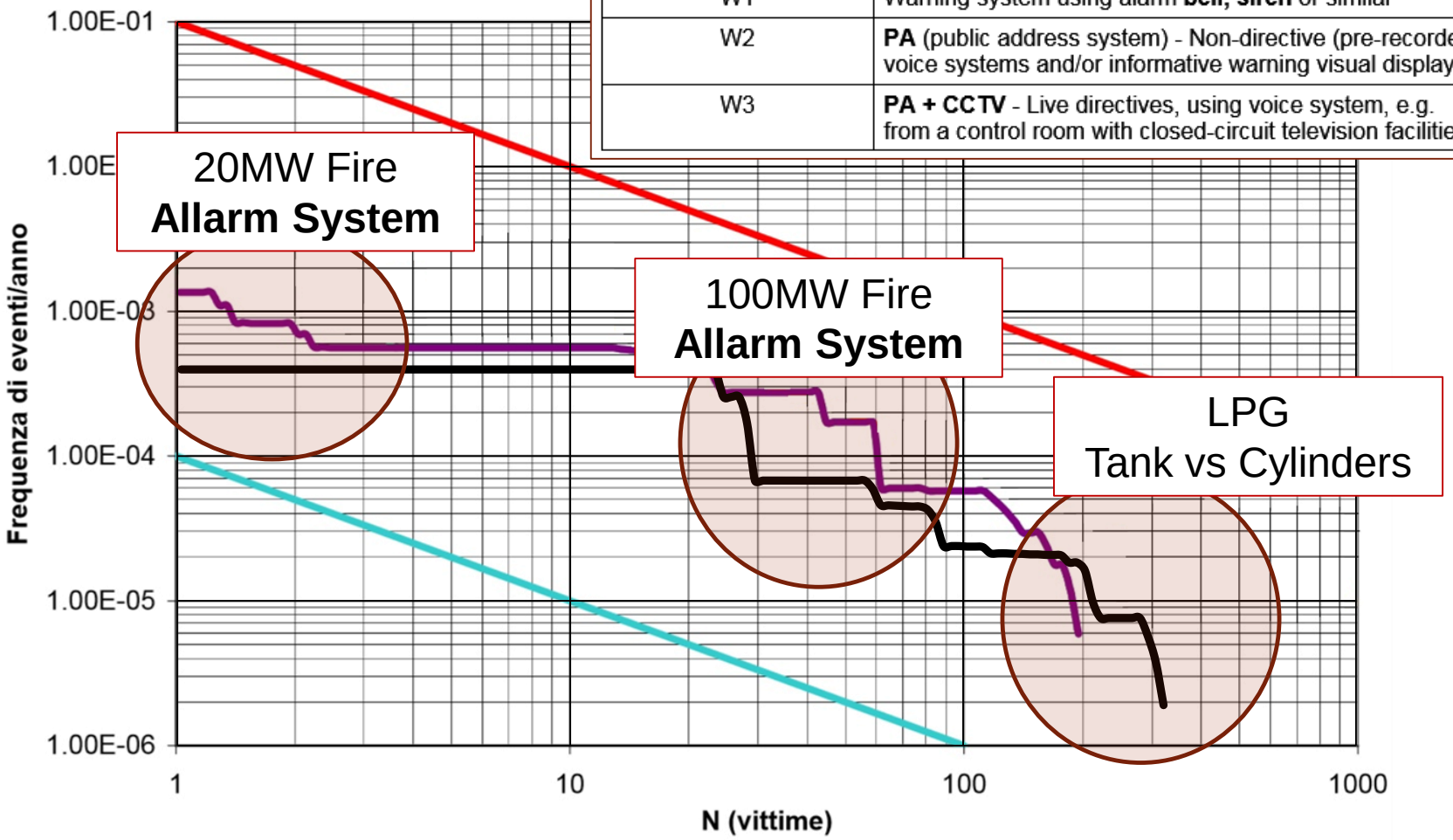
C. Di Santo
F. Bontempi
K. Gkoumas

TUNNEL ST. DEMETRIO: F-N CURVE IN THE SOUTH DIRECTION



TUNNEL ST. DEMETRIO: F-N CURVE IN DIRECTION SOUTH

Warning system reference	Description
W0	**No** warning system
W1	Warning system using alarm **bell, siren** or similar
W2	**PA** (public address system) - Non-directive (pre-recorded) voice systems and/or informative warning visual display
W3	**PA + CCTV** - Live directives, using voice system, e.g. from a control room with closed-circuit television facilities



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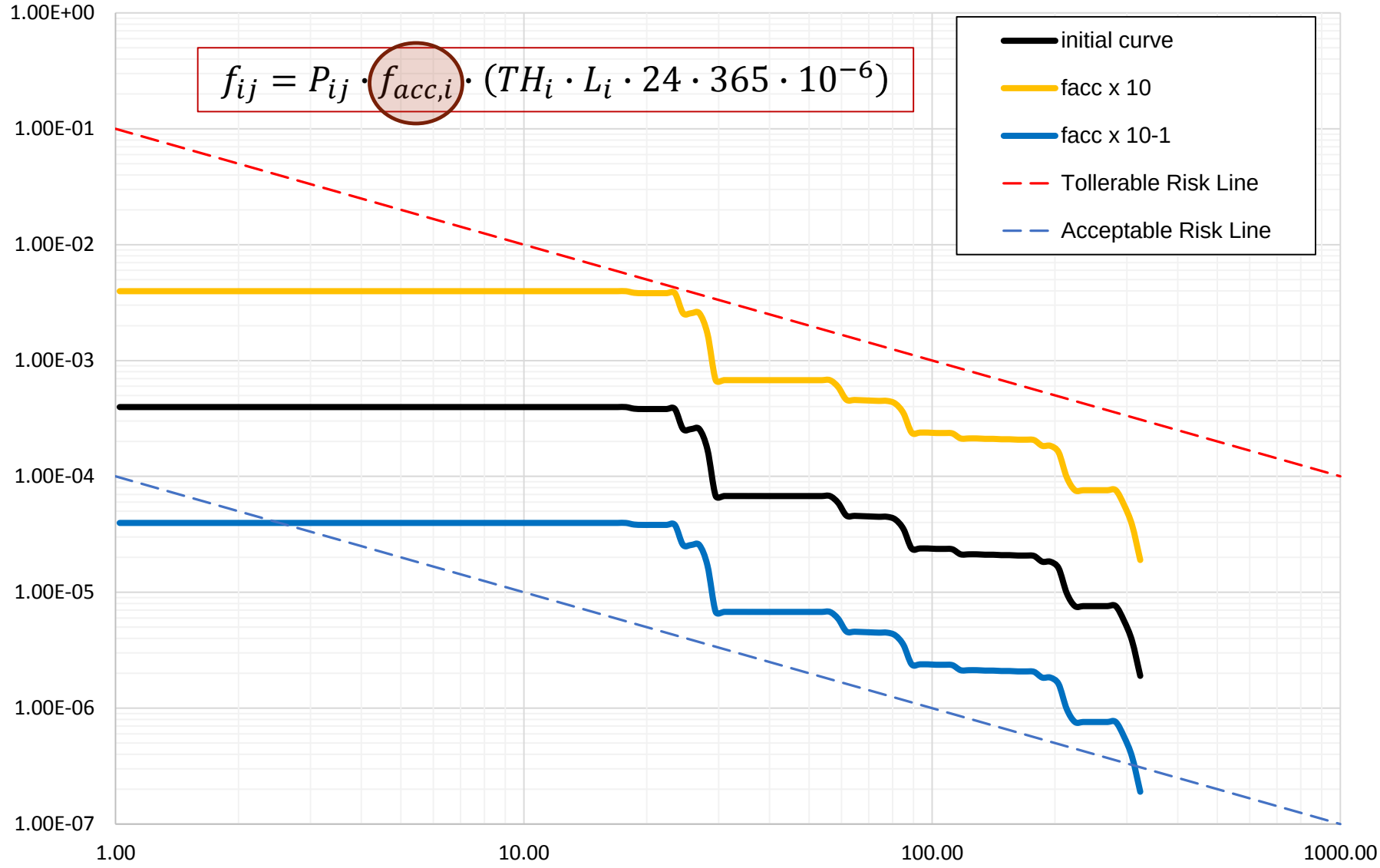
TUNNEL ST. DEMETRIO



CONCLUSIONS

San Demetrio Tunnel Risk Analysis

- Further risk mitigation measures (adopted only after a cost benefit analysis)
- The safety margin is high

General Conclusions on the PIARC/OECD QRA model

The parameters that most affect the risk curve:

- Density of people on the road
  - Traffic (veh/h)
  - Bus ratio (%)
  - Number of lanes
  - Delay for stopping approaching traffic
  - Average vehicle occupancy

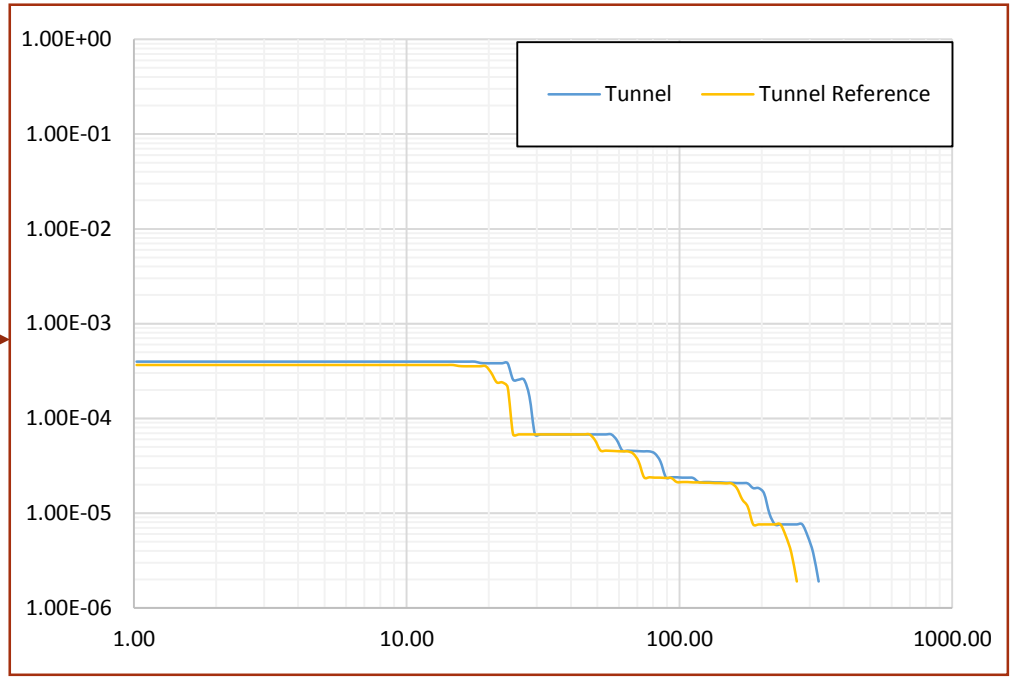
$$N = \{(R \cdot D_{RUJ}) + [(R - L_{jam}) \cdot D_{RUF}\} \cdot \%LETH$$

- Accident scenarios frequency [scen/year]
  - f_{acc}
  - DG-HGV traffic
  - HGV traffic
  - Proportion of each DG

$$f_{ijk} = P_{ijk} \cdot f_{acc\_DG,i} \cdot (TD_{ik} \cdot L_i \cdot 24 \cdot 365 \cdot 10^{-6})$$

SOCIETAL RISK ACCEPTABILITY CRITERIA

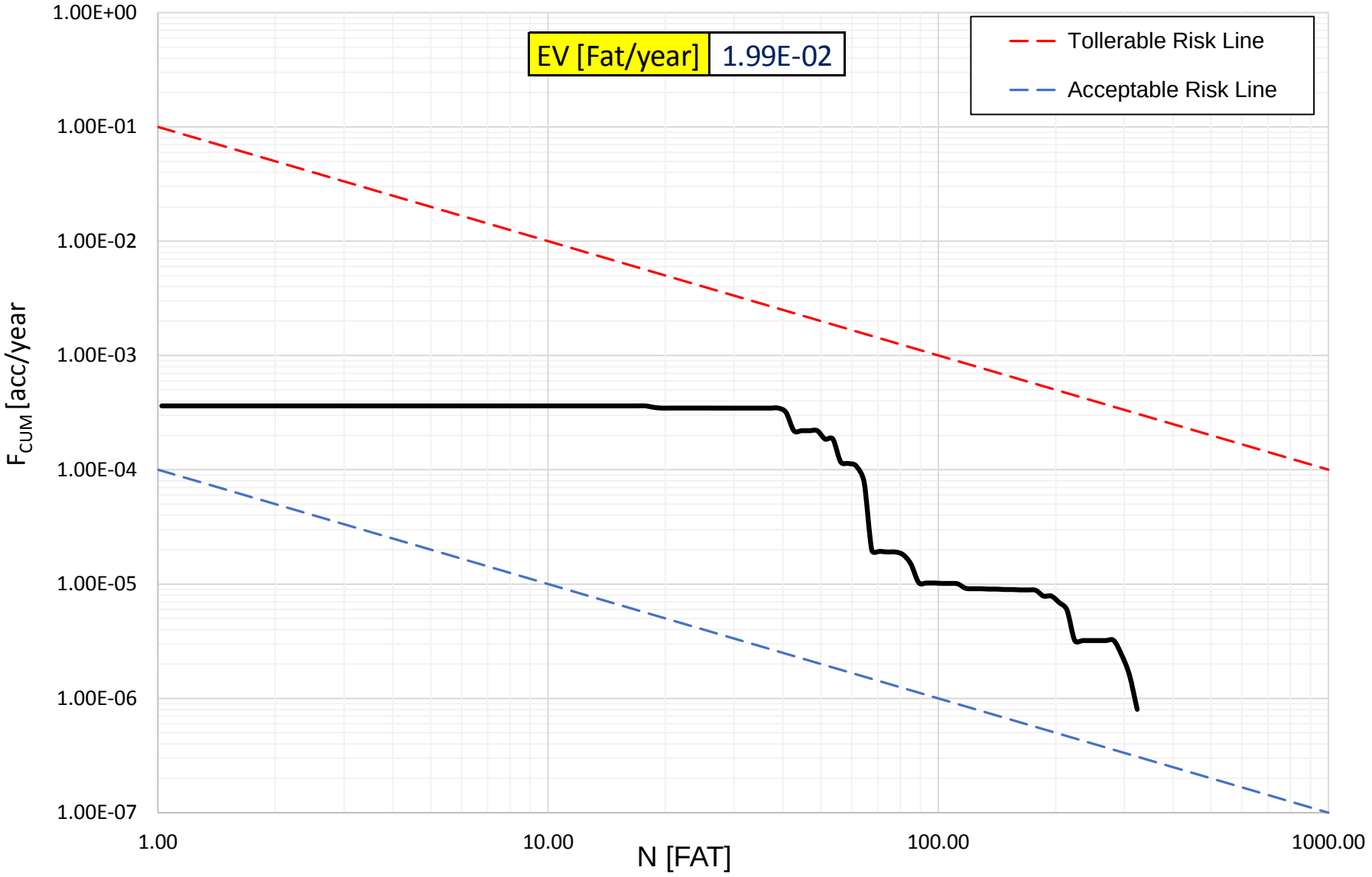
Relative Criteria → $EV_s \leq EV_{s,ref}$



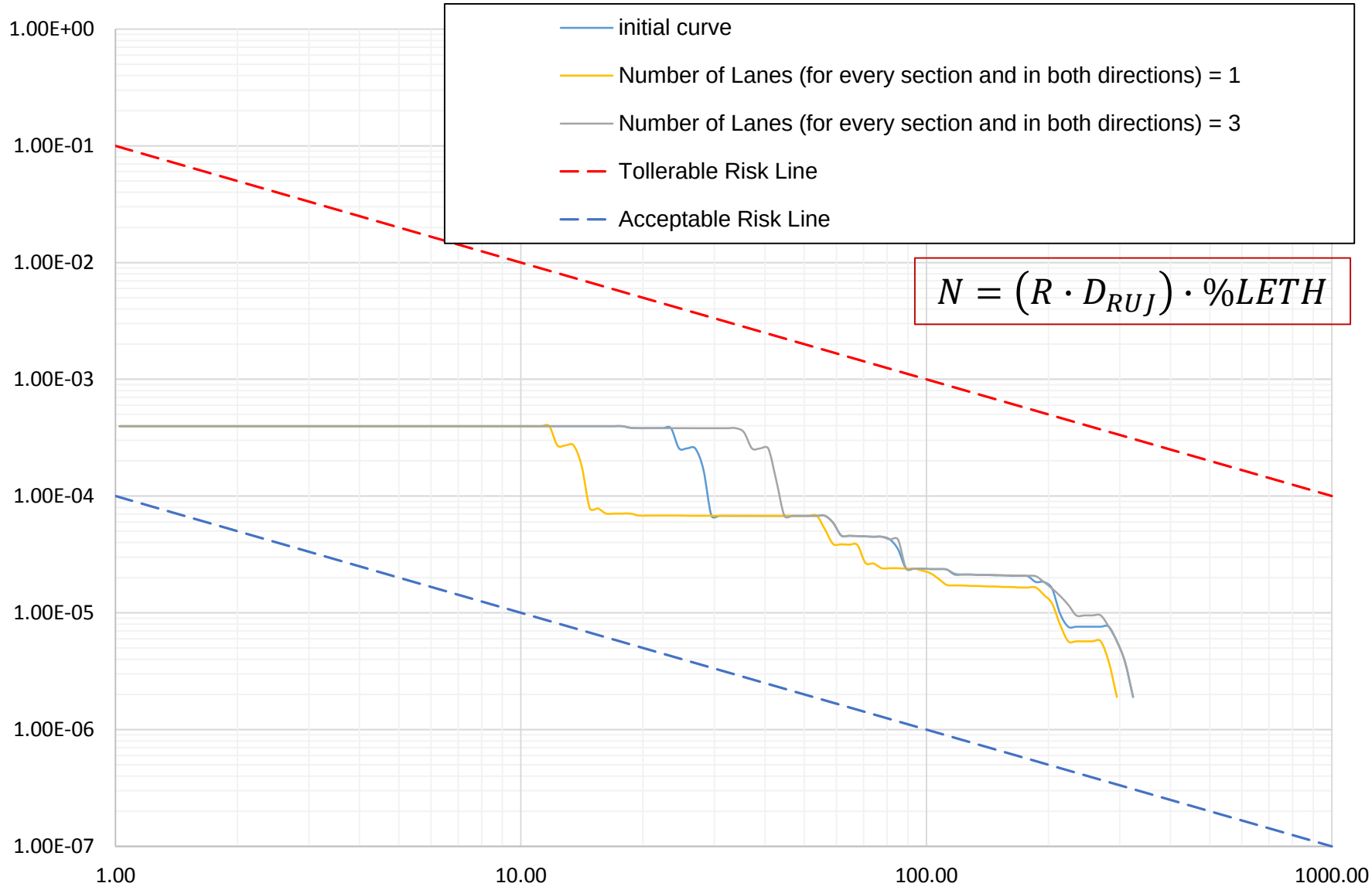
Applying the same calculation method, compare the examined risk with:

- the risk of an **alternative route**
- that calculated for a **reference tunnel**, which must have characteristics similar to the one examined, but with all the safety requirements required by the relevant regulations

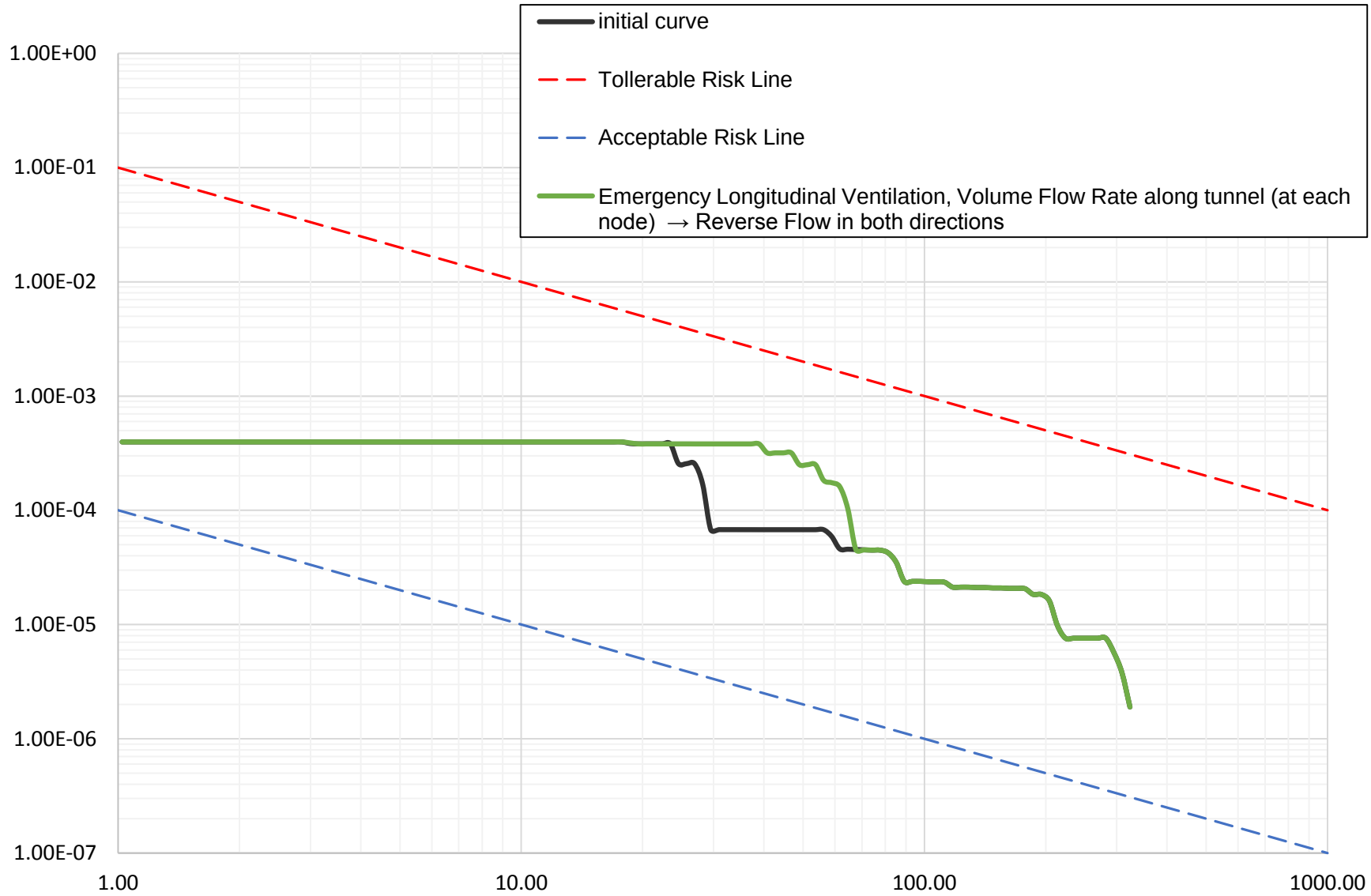
TUNNEL ST. DEMETRIO: F-N CURVE IN DIRECTION NORTH



TUNNEL ST. DEMETRIO



TUNNEL ST. DEMETRIO



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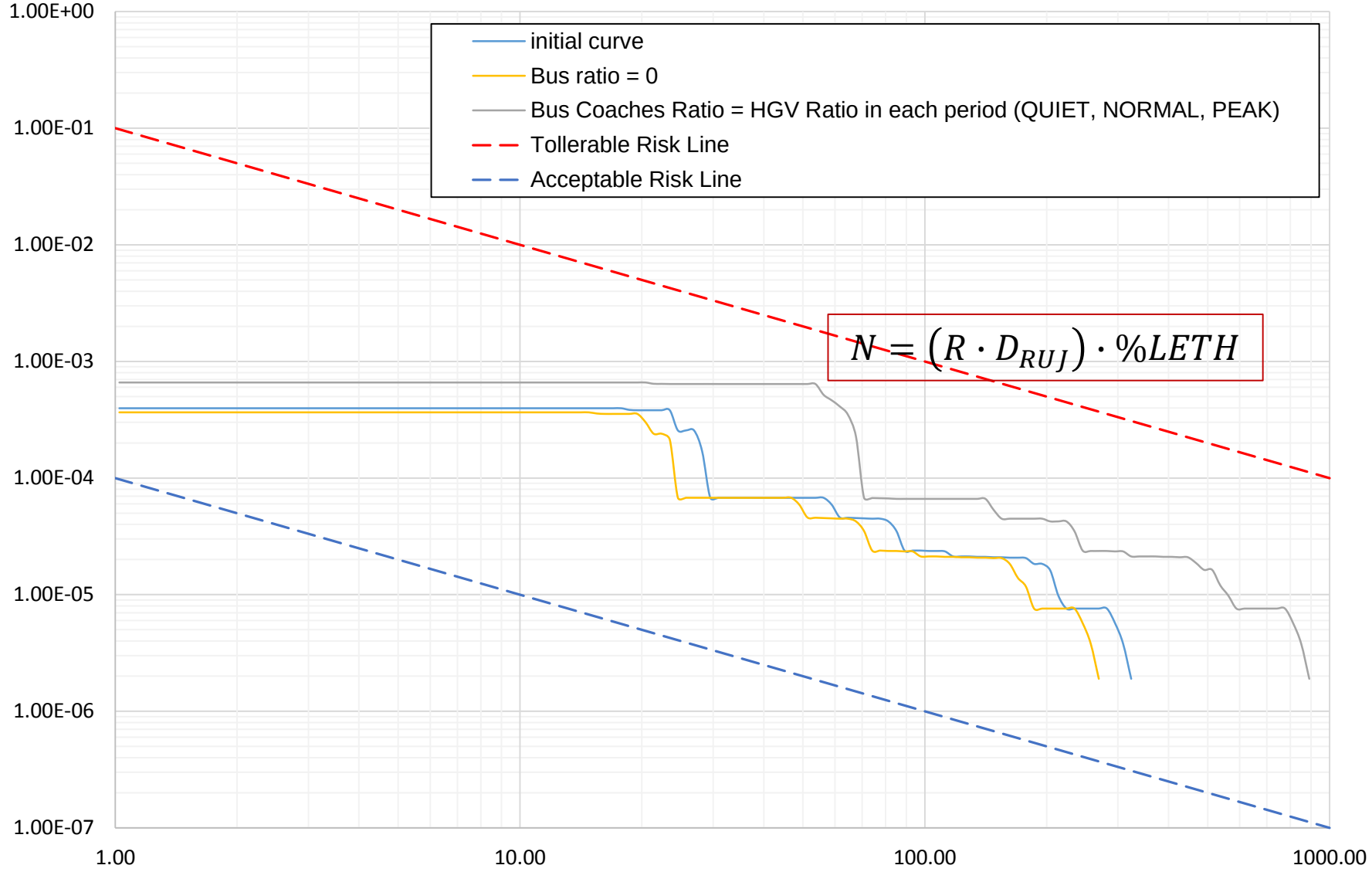

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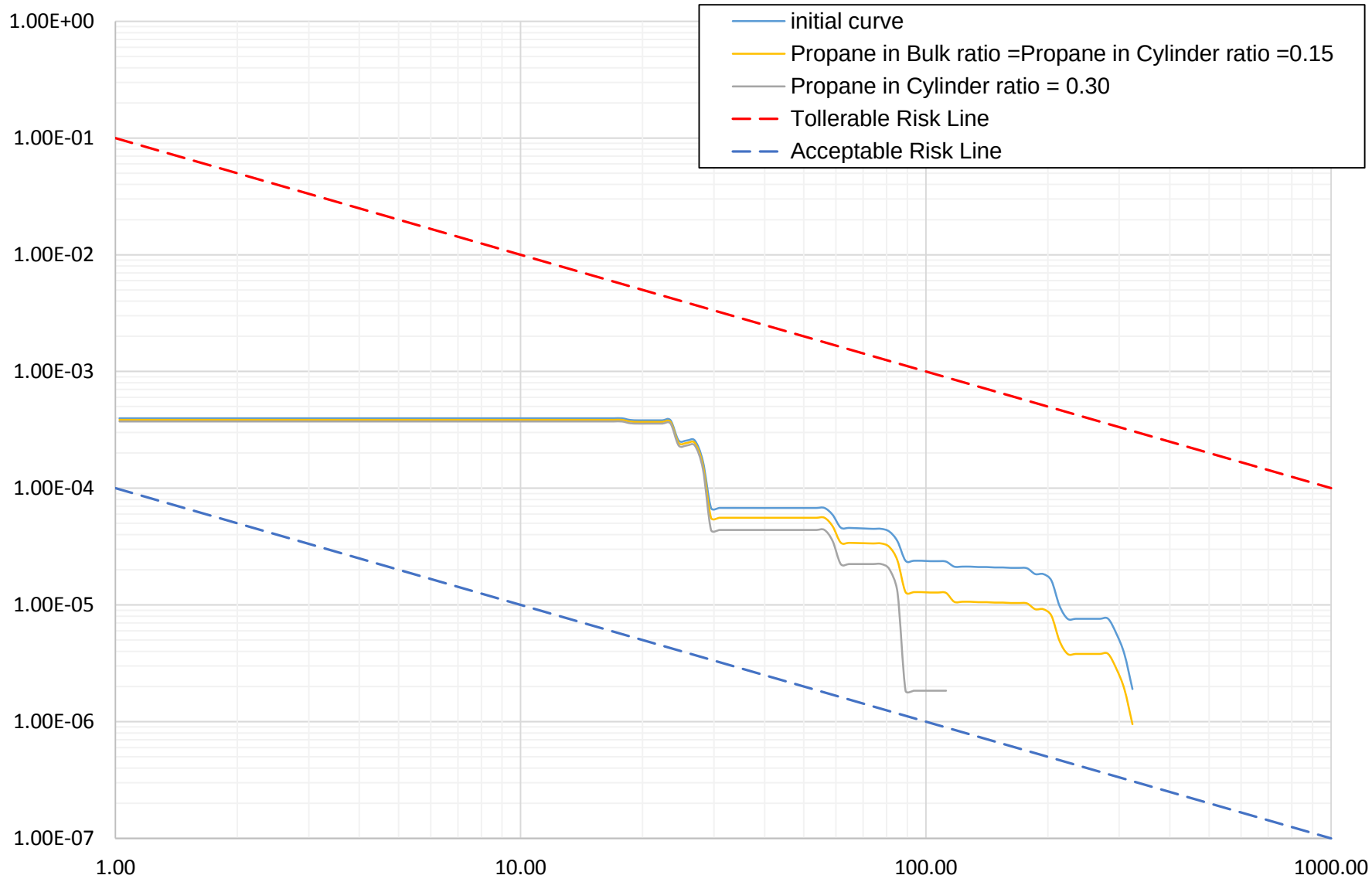
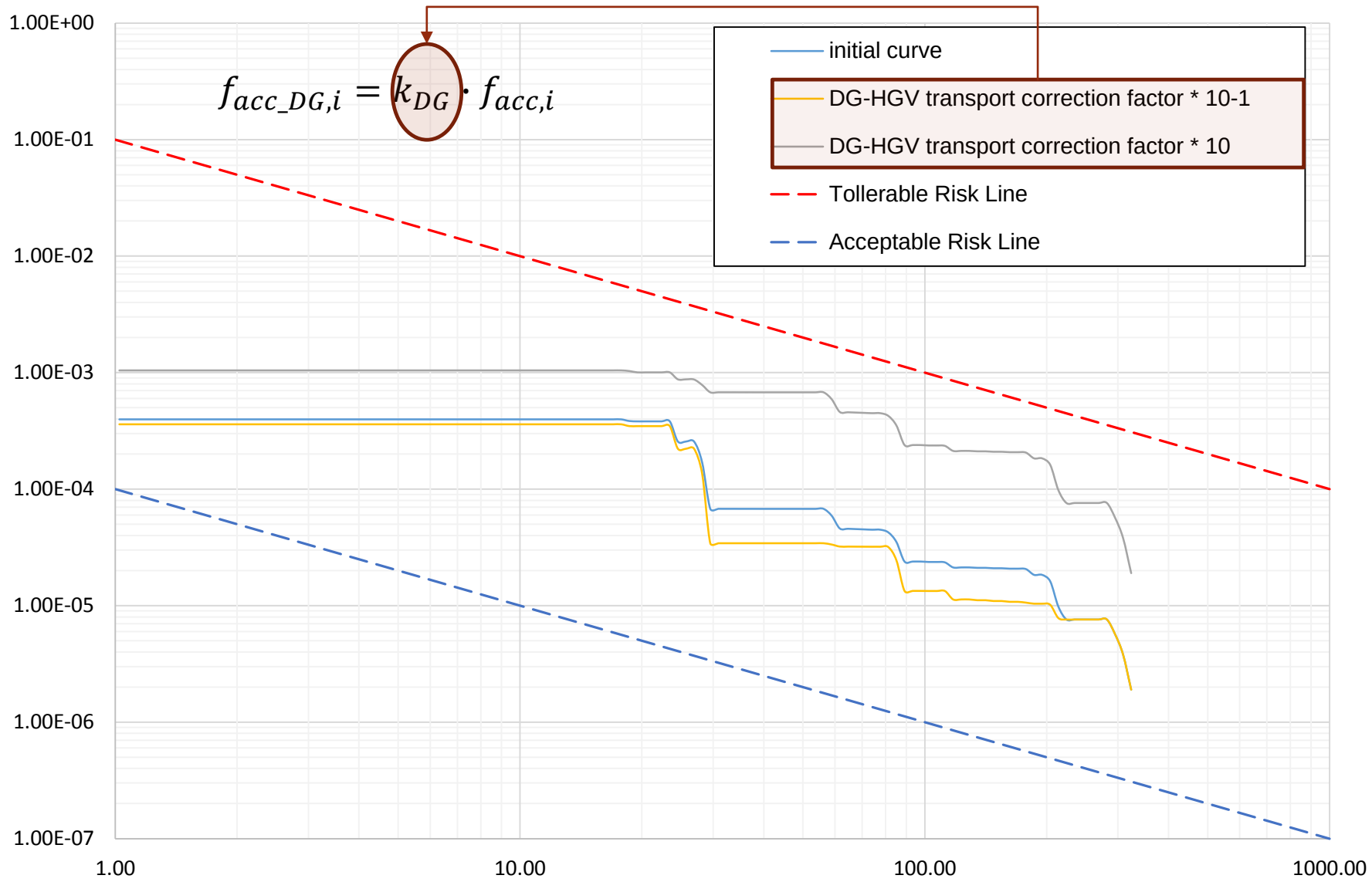


TUNNEL ST. DEMETRIO



TUNNEL ST. DEMETRIO: