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

Influence of panic on human behaviour during emergency egress for tunnel fires

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INTRODUCTION

… dead, injuries, structural damages and economic losses…

Tunnel system complexity

Geometry
- 1 dimension longer than the other two
- Confined and closed environment
- Cross section type (n° of tubes)
- Longitudinal slope

Traffic conditions
- Daily traffic volume
- % HGV

Fire
- Fire load
- HRR
- Number of vehicles involved in the accident
- Type of fuel
- Position of the accident

Safety measures
- Detection system
- Alarm system
- Sprinklers
- SOS stations
- Emergency exits
- Lay – by
- Illumination system
- Vertical signage
- Horizontal signage

Occupant
- Number of users
- Composition (gender and age)
- Psycological characteristics
- Habitual users (familiarity)
- Human behaviour
- Disabled people

SCENARIO – BASED APPROACH

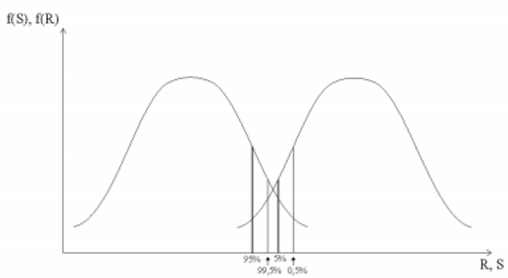
Scenario analysis is a process of analyzing possible future events by considering alternative possible outcomes, including the development paths leading to them.

Fixed data

Variables data

Classical Approach

• Structural and unstructural permanent load
• Antropic load
• Snow, wind, seismic action



Combination (ULS)

$$\gamma_{G1}G_1+\gamma_{G2}G_2+\gamma_P P+\gamma_{Q1}Q_{k1}+ +\gamma_{Q2}\psi_{02}Q_{k2}+\dots$$

Combination (SLS)

$$G_1+G_2+P+\psi_{11}Q_{k1}+\psi_{22}Q_{k2}+\dots$$

LPHC Actions

Low Probability High Consequences

A – Fire characteristics and safety measures

• Position of the accident
• Fire load (HRR)
• Ventilation conditions
• Presence and position of safety measures (by – passes, signage, illumination, sprinklers, detection systems, etc)

B – Traffic characteristics

• Traffic flow conditions
• Presence of HGV

C – People

• Number of people
• People composition (physics and psycological characteristics)
• Human behaviour
• Panic and familiarity with the structure
• Presence of disabled people

Normative

ANAS Circular 2009

(based on D.Lgs 264/2006 and Directive 2004/54/EC)


ANAS S.p.A.
Direzione Centrale Progettazione

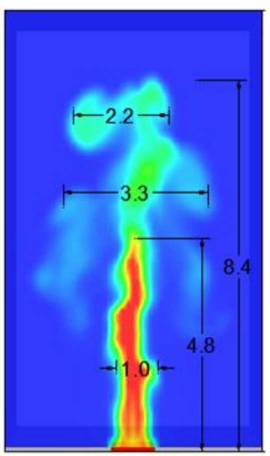
Linee Guida
per la progettazione
della sicurezza
nelle Gallerie Stradali

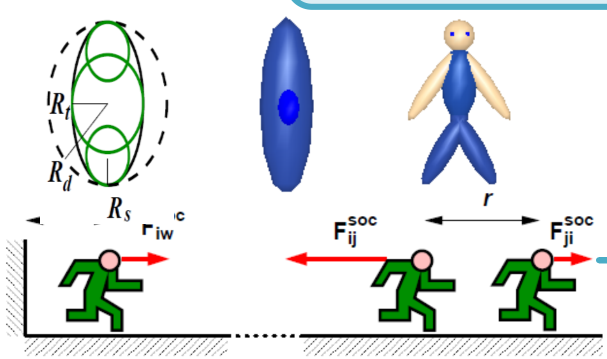
Novembre 2006

MODELING FIRE AND HUMAN BEHAVIOUR

PEOPLE INSIDE THE TUNNEL			
Situation	**Tunnel environment and its infrastructures**	**Psycological feelings**	**Behaviour**
IDEAL (Theoretical)	Complete knowledge	No fear	Perfectly rational
REAL	Partial knowledge	Panic	Imperfectly rational
	Failure in using the safety equipment	**Uncorrect exit door selection**	

FDS + Evac
NIST (USA) and VTT (Finland)





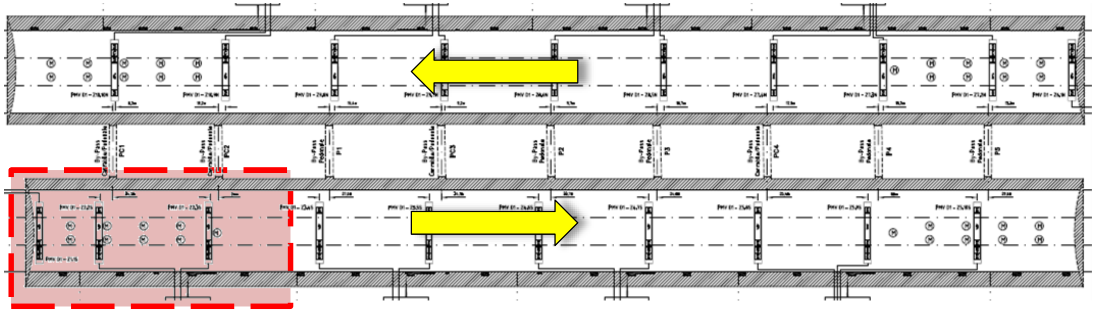
$$m_i \frac{d^2 \mathbf{x}_i(t)}{dt^2} = \mathbf{f}_i(t) + \boldsymbol{\xi}_i(t)$$

$$\mathbf{f}_i = \frac{m_i}{\tau_i}(\mathbf{v}_i^0 - \mathbf{v}_i) + \sum_{j\neq i}(\mathbf{f}_{ij}^{soc} + \mathbf{f}_{ij}^{c} + \mathbf{f}_{ij}^{att}) + \sum_{w}(\mathbf{f}_{iw}^{soc} + \mathbf{f}_{iw}^{c}) + \sum_{k}\mathbf{f}_{ik}^{at}$$

- Large Eddies Simulation (Low Mach equations)
- Movement algorithm
- Social force
- Panic model
- Reduced visibility for smoke and obstacles
- Reduced velocity for smoke, incapacitation and death
- Fractional Effective Dose concept
- Tendency to act independently or to form group
- 5 categories of humans with different physical characteristics
- 3 behavioural type (rational, conservative, herding)

Sicily, Catania – Syracuse Motorway E45

Cortesy of Eng. ***Luigi Carrarini****, ANAS*

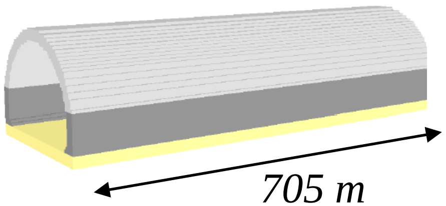


Syracuse – Catania tube, L = 2948 m

Catania – Syracuse tube, L = 2895 m

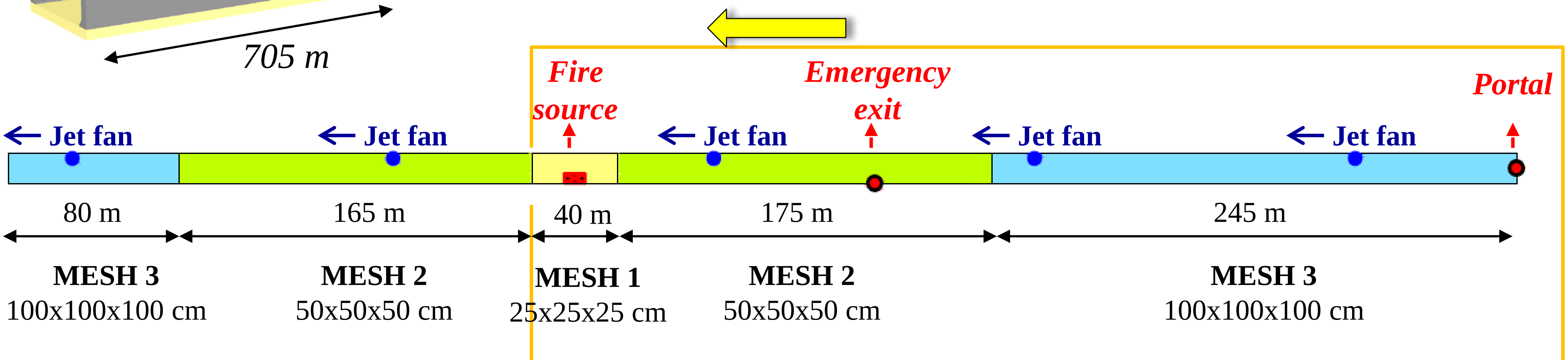
705 m

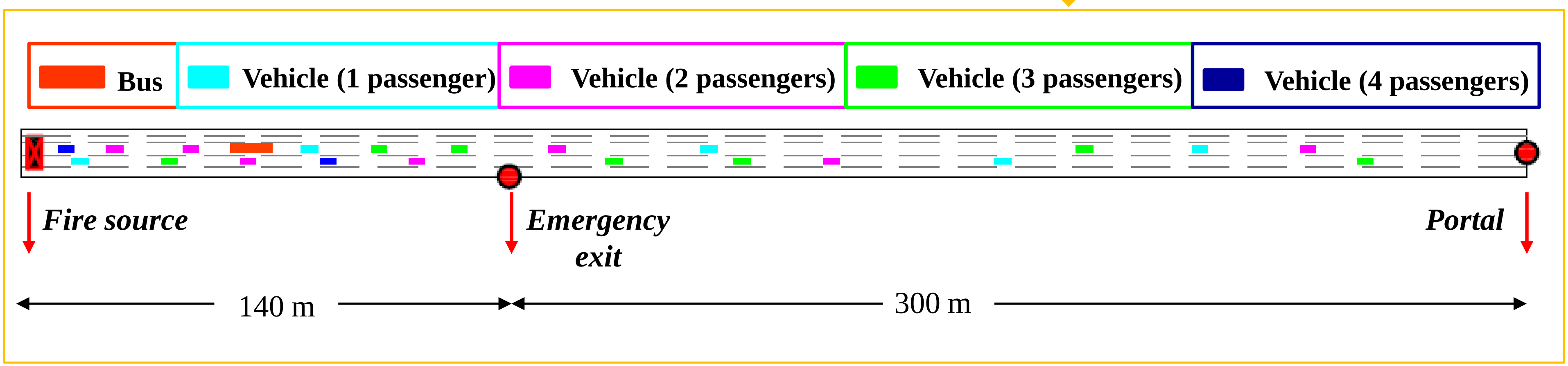
THE ST. DEMETRIO TUNNEL: *FDS+Evac* MODEL



Catania – Syracuse tube

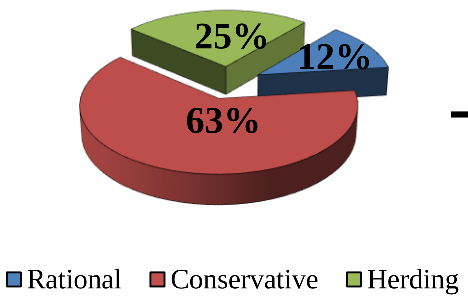
TRAFFIC FLOW DIRECTION





THE ST. DEMETRIO TUNNEL: *FDS+Evac* MODEL

Agents composition



N° tot = 100 AGENTS

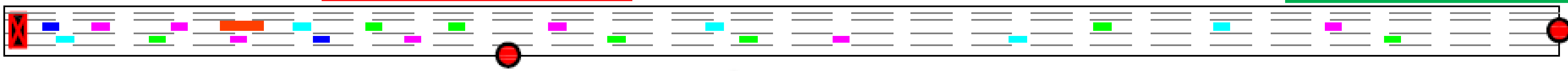
- **Rational : Adult**
- **Conservative : Male, Female**
- **Herding : Child, Elderly**

each category has a different exit selection preference order

FAMILIARITY CONCEPT

Emergency exit
Known door
probability = **0.5**

Portal
Known door
probability = **1**



Fire source

Emergency exit

TRAFFIC FLOW DIRECTION

Portal

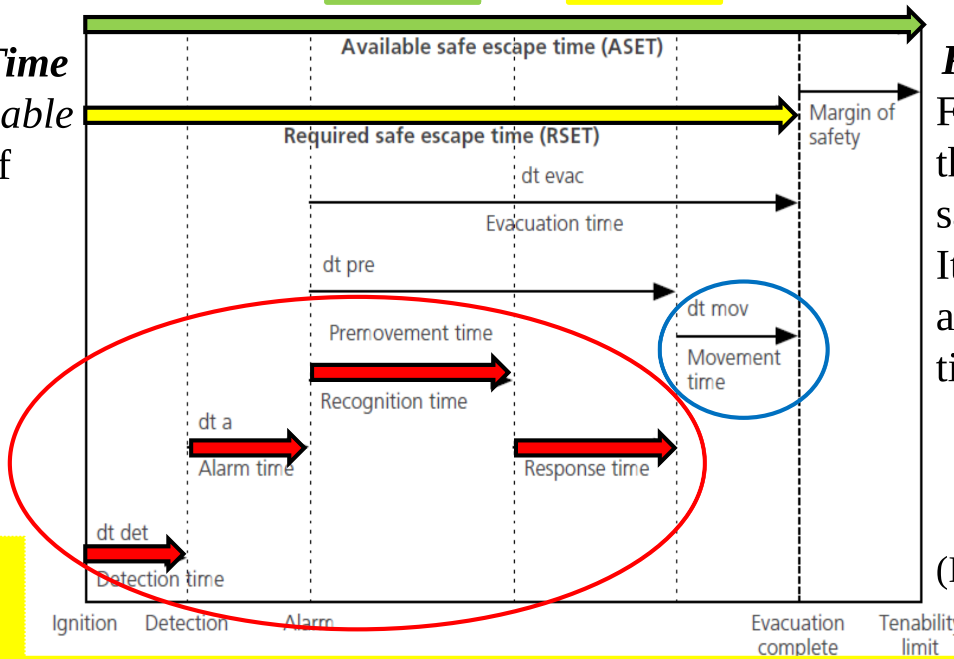
THE PERFORMANCE – BASED APPROACH FOR EGRESS

ASET >> **RSET**

Available Safety Egress Time

From ignition to *unsustainable* conditions for the egress of humans:

- Visibility < 10 m
- T > 60°C
- FED > 1



Required Safety Egress Time

From ignition until the time the last occupant reaches a safe place.

It depends on: detection time, alarm time, pre – movement time, travel time.

(ISO 13387-8)

HIGH LEVEL OF UNCERTAINTY

RSET

Pre – evacuation time = **Detection time** + **Reaction time**

+

Movement time

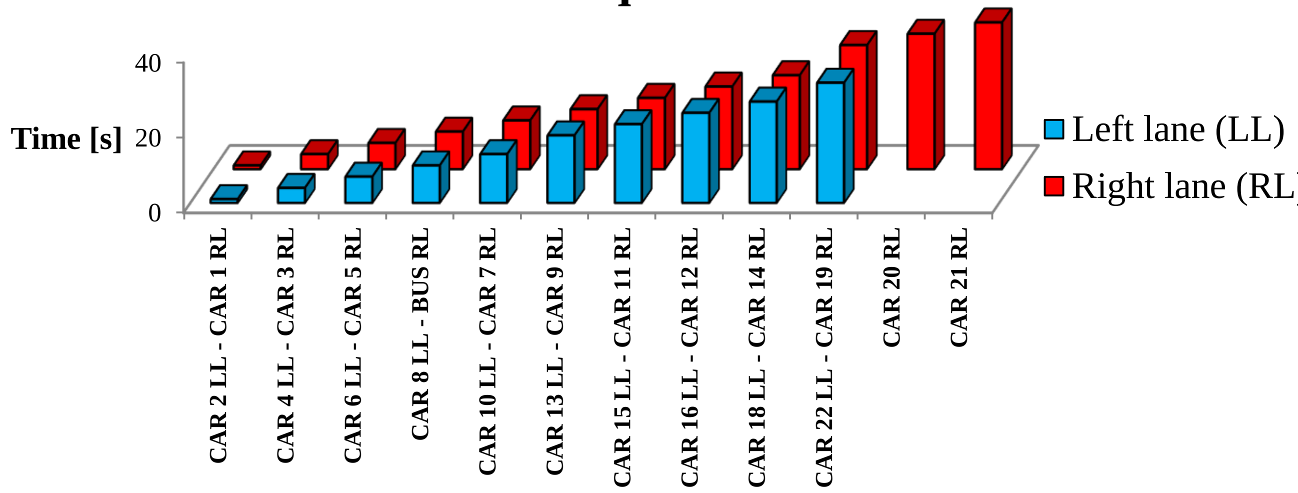
Reaction time → **Alarm time** | **Recognition time** | **Response time**

Decision – making process

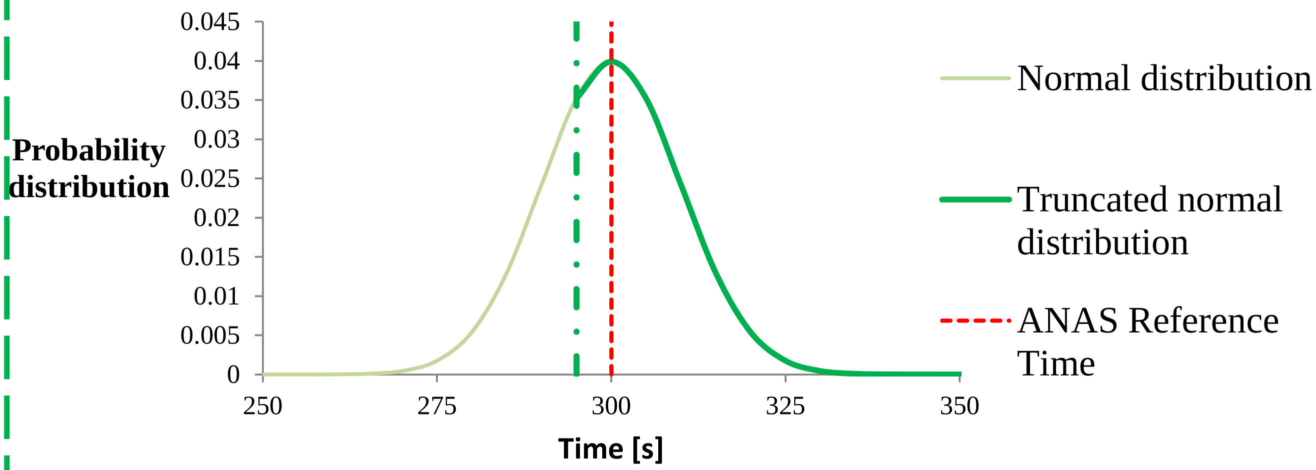
THE ST. DEMETRIO TUNNEL: *FDS+Evac* MODEL

Deterministic Approach ←

Formation of the queue inside the tunnel



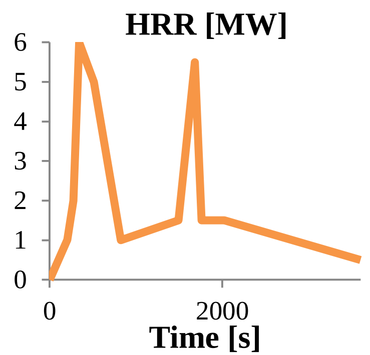
Pre - evacuation time distribution



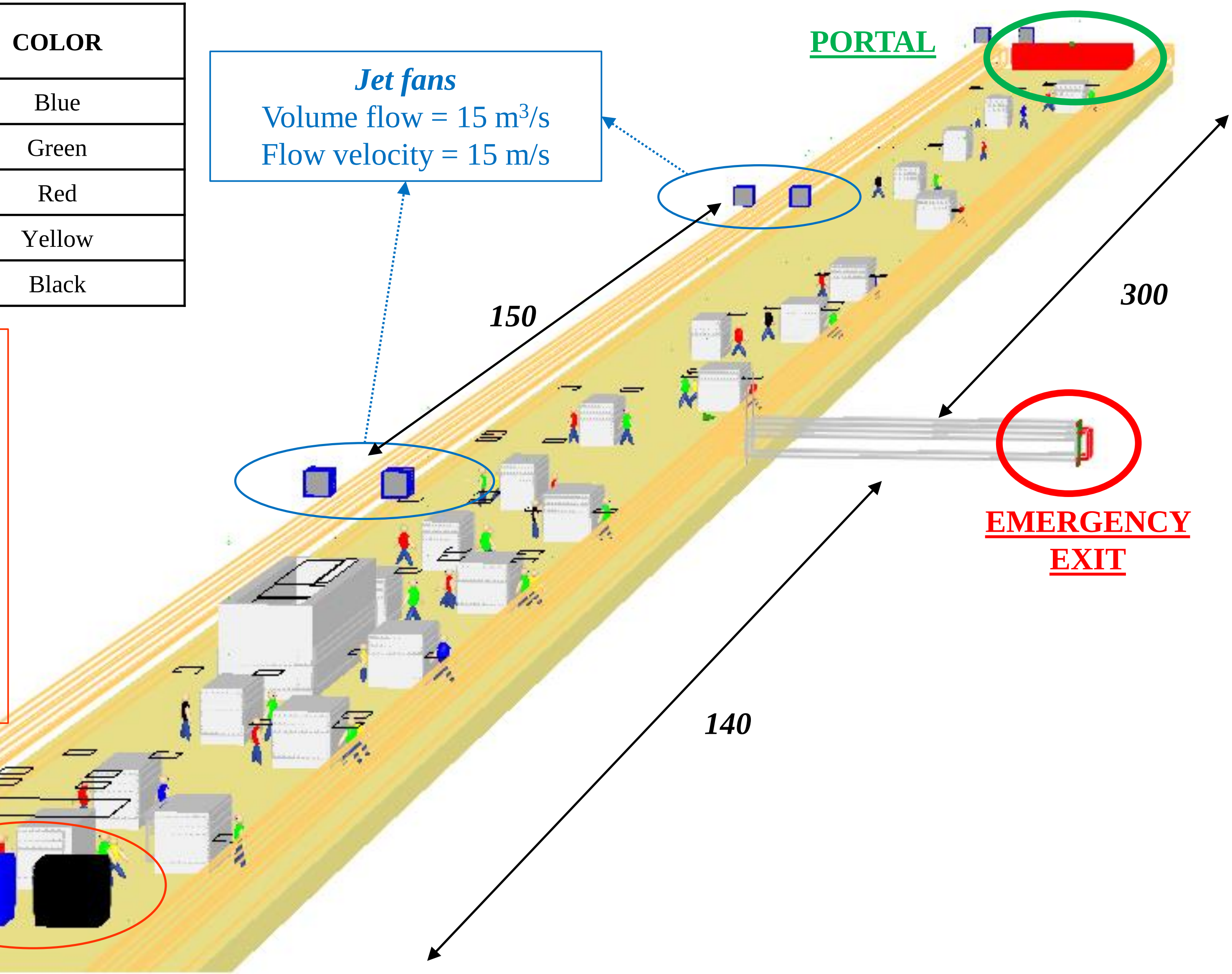
→ *Probabilistic Approach*

THE ST. DEMETRIO TUNNEL: RESULTING MODEL

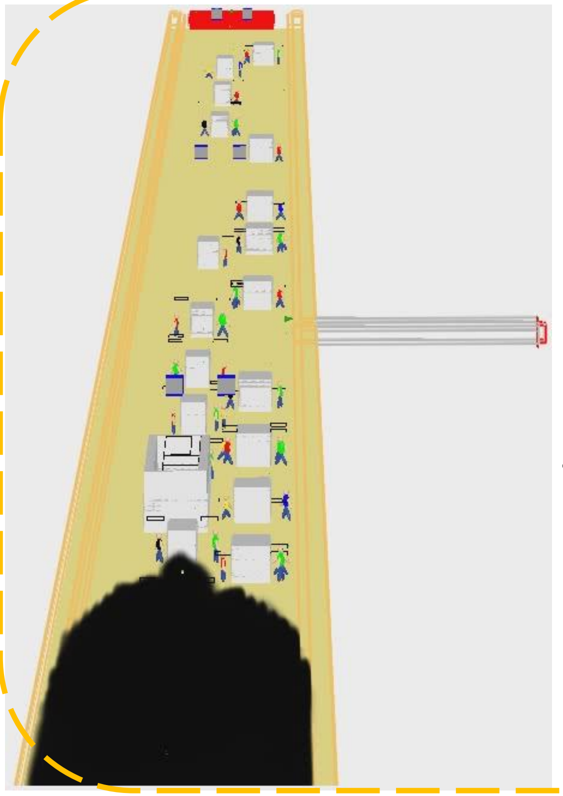
HUMAN CATEGORY	COLOR
Adult	Blue
Male	Green
Female	Red
Child	Yellow
Elderly	Black



Fire source
HRR = 6 MW

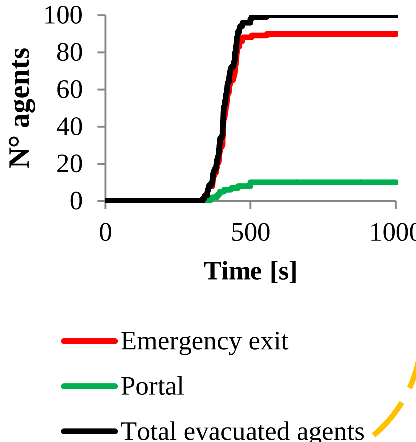


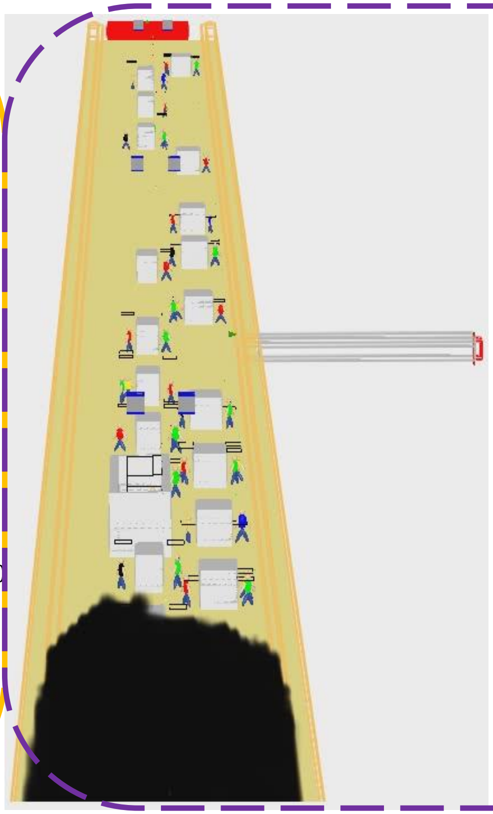
RESULTS



RATIONAL BEHAVIOUR

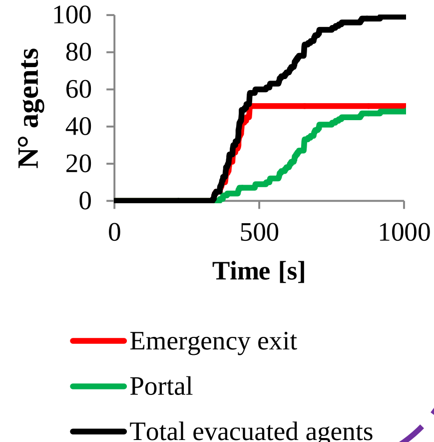
Ideal egress

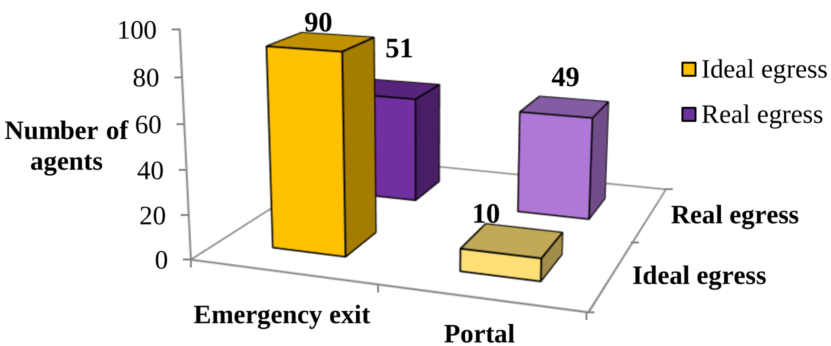


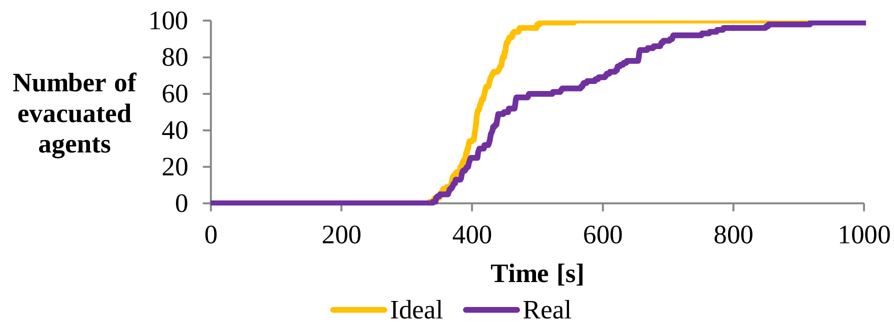


PANIC

Real Egress







CONSIDERATIONS

POSITIVE ASPECTS

• The possibility of using numerical simulations for egress scenarios is important for the Safety Engineering, because it is possible to verify the **efficiency of the escape routes** of many different types of building (civil building, stadium, tunnel, etc) by controlling the most problematic streaks next to the exits.

• The FDS+Evac code is a good tool for the assessment of the emergency egress for road tunnel fires: **fire and smoke influence human motion and their effects imply different choices of the escape route, intoxication (until the death) and reduction of the walking velocity**.

NEGATIVE ASPECTS

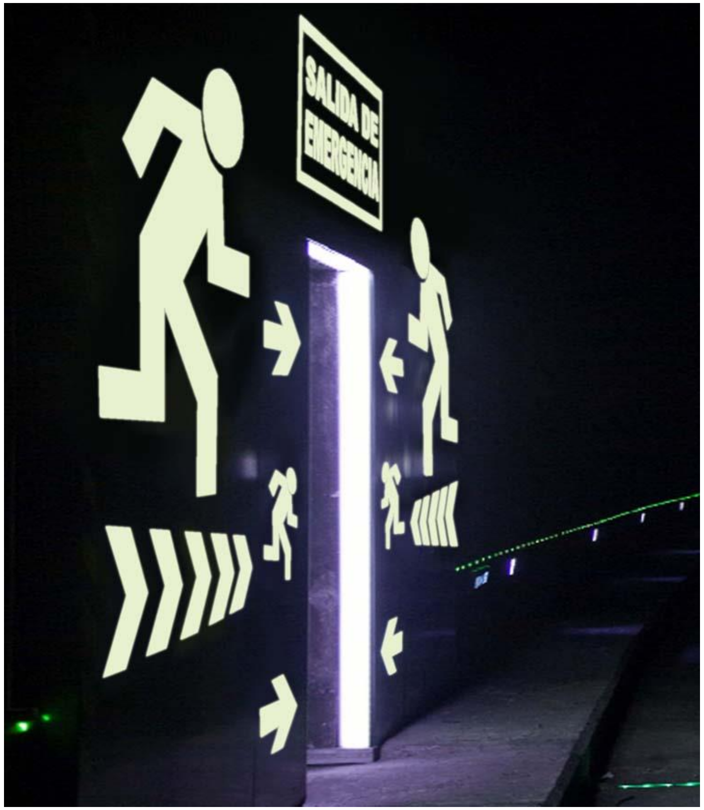
•This kind of numerical codes depend strongly on **input data**: a large number of different fire and egress scenarios should be analyzed to obtain a realistic assessment of what could happen during a fire accident.

• FDS+Evac should be run using **Monte Carlo method** (repeated sampling to determine the properties of the phenomenon). The same simulation should be run at least 12 times in order to average the results.

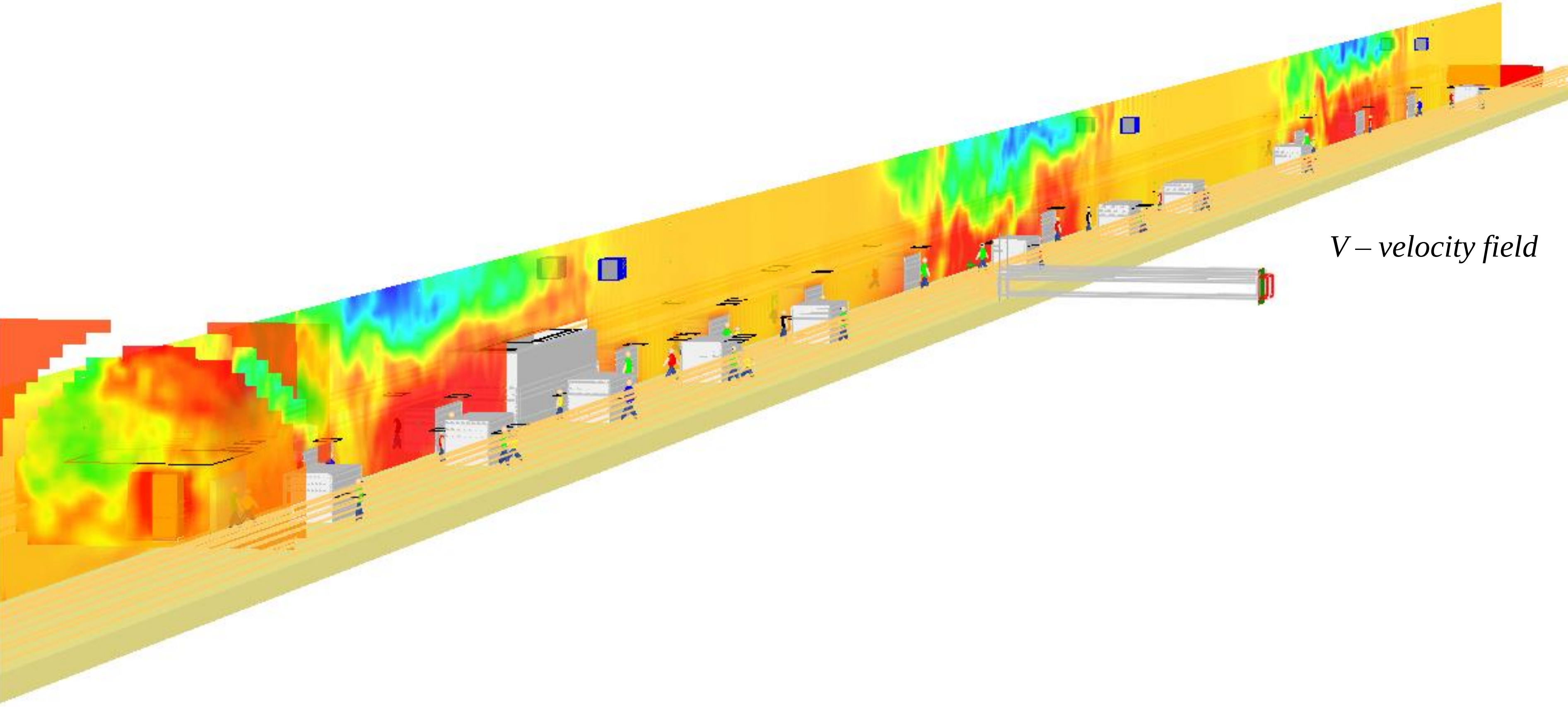
CONCLUSIONS

"An adequate knowledge of human factors in the context of road tunnels optimizes safety by acting in the direction of the user, the tunnel design and more generally, the organization (tunnel operating body and emergency services)."

(PIARC Road tunnels manual, 2011)



THE END

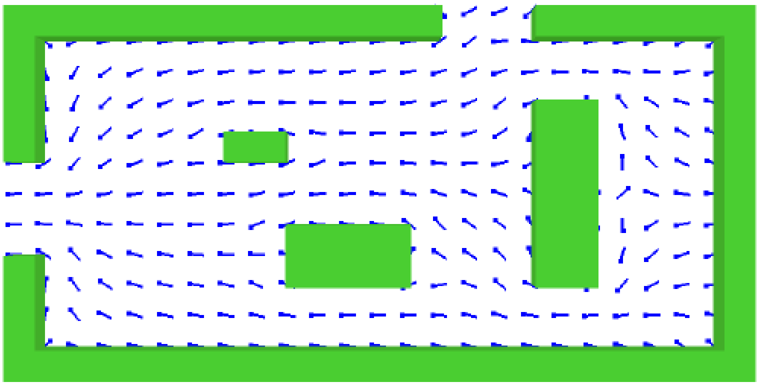


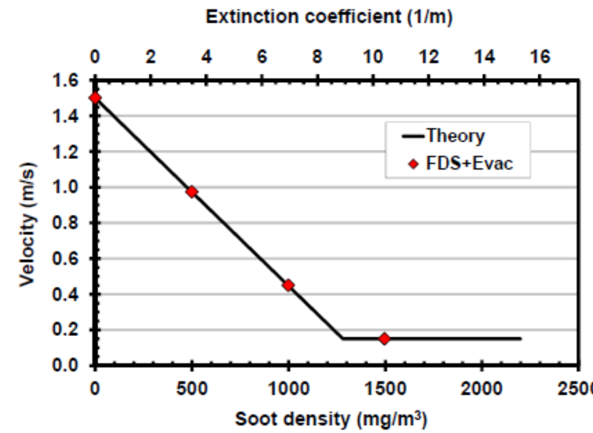
V – velocity field

CONCLUSIONS

FDS+Evac

• Solving *a potential flow problem of a incompressible 2 – D fluid* (where walls are inert and exits act as fan extracting air) → **driven flow field used by humans** to go towards the exits





• Then, the **choice** of the exit is driven by
- *familiarity* (i.e. known door probability)
- *visibility* (presence of smoke or obstacles)
- *distance* and *queue*

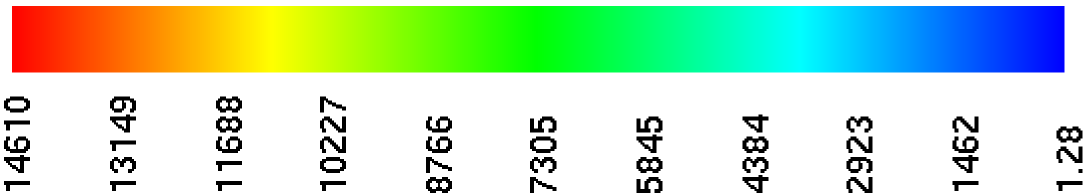
→ An exit can be used until **Visibility > 0.5 distance** (agent – exit) where visibility is 3/K and K is the extinction coefficient

Note that the **preference order** depends on **human behaviour** assigned to the agents (*rational*, *conservative*, *herding*)

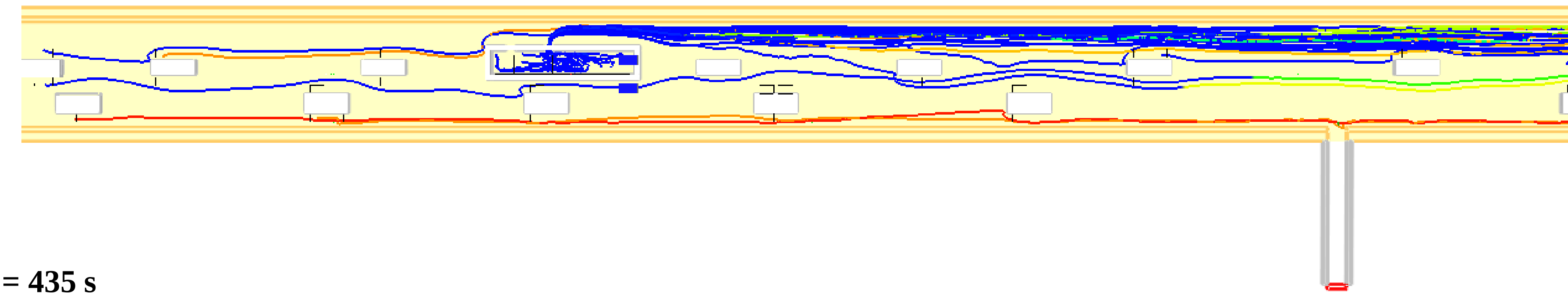
visibility | familiarity | follow what other agents do

FDS+Evac

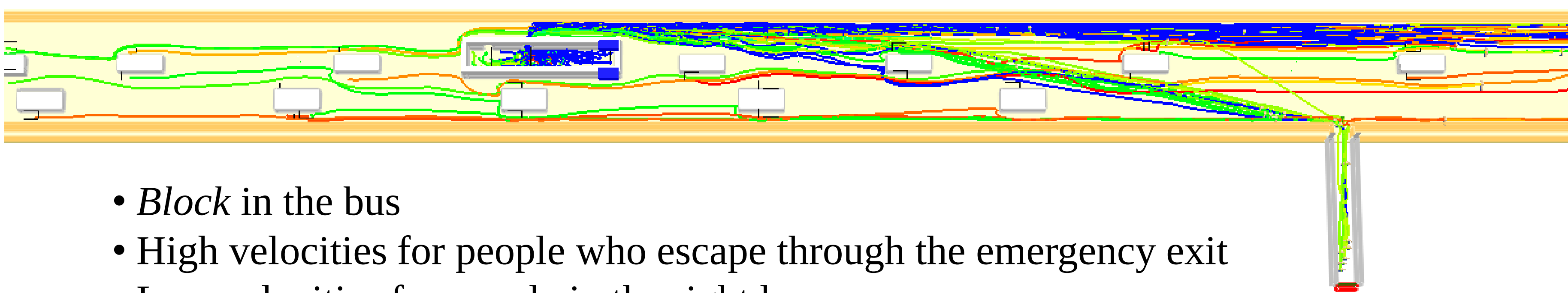
Human _ speed
[m/s]*10^{-4}
STREAKS



t = 621 s

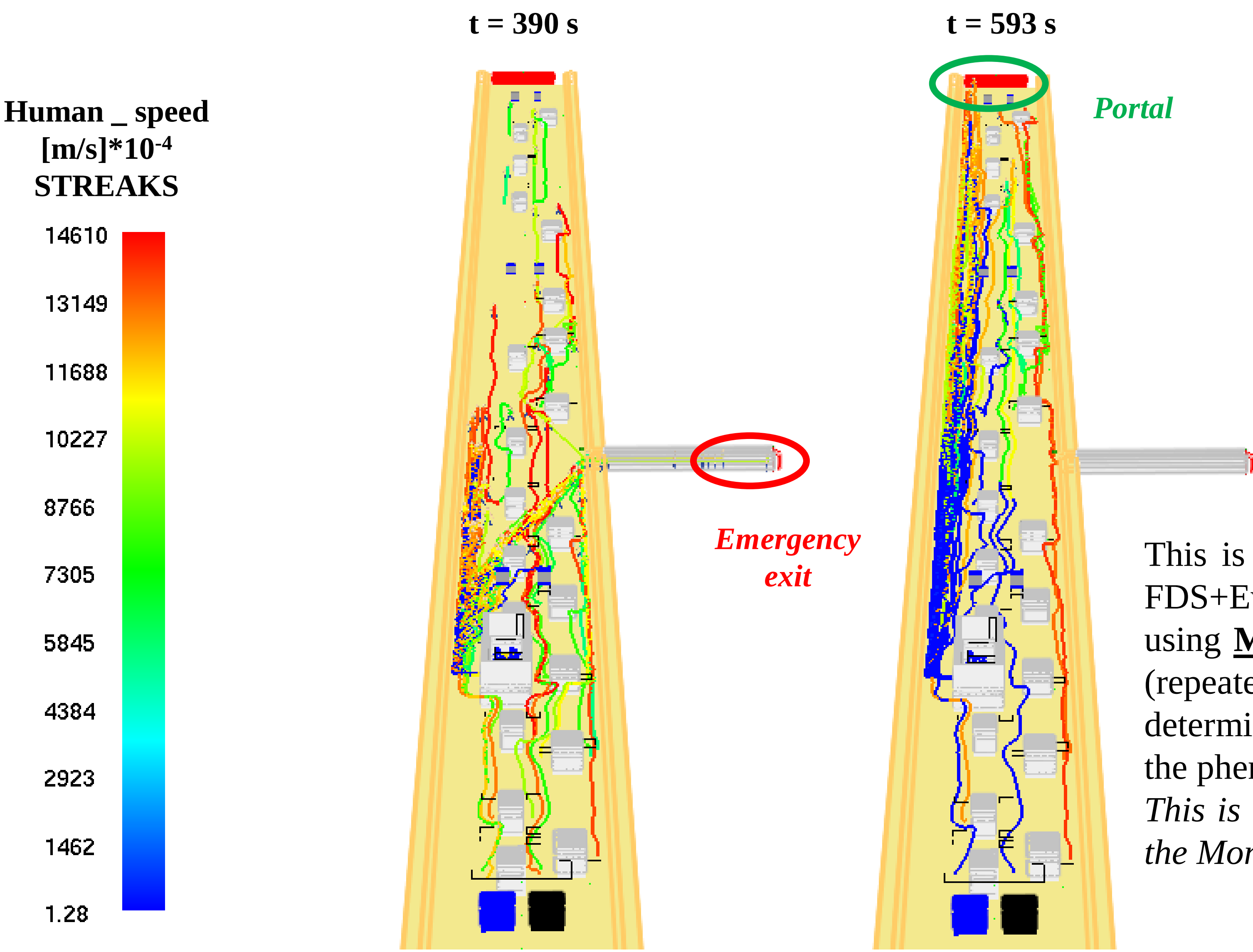


t = 435 s



- *Block* in the bus
- High velocities for people who escape through the emergency exit
- Low velocities for people in the right lane

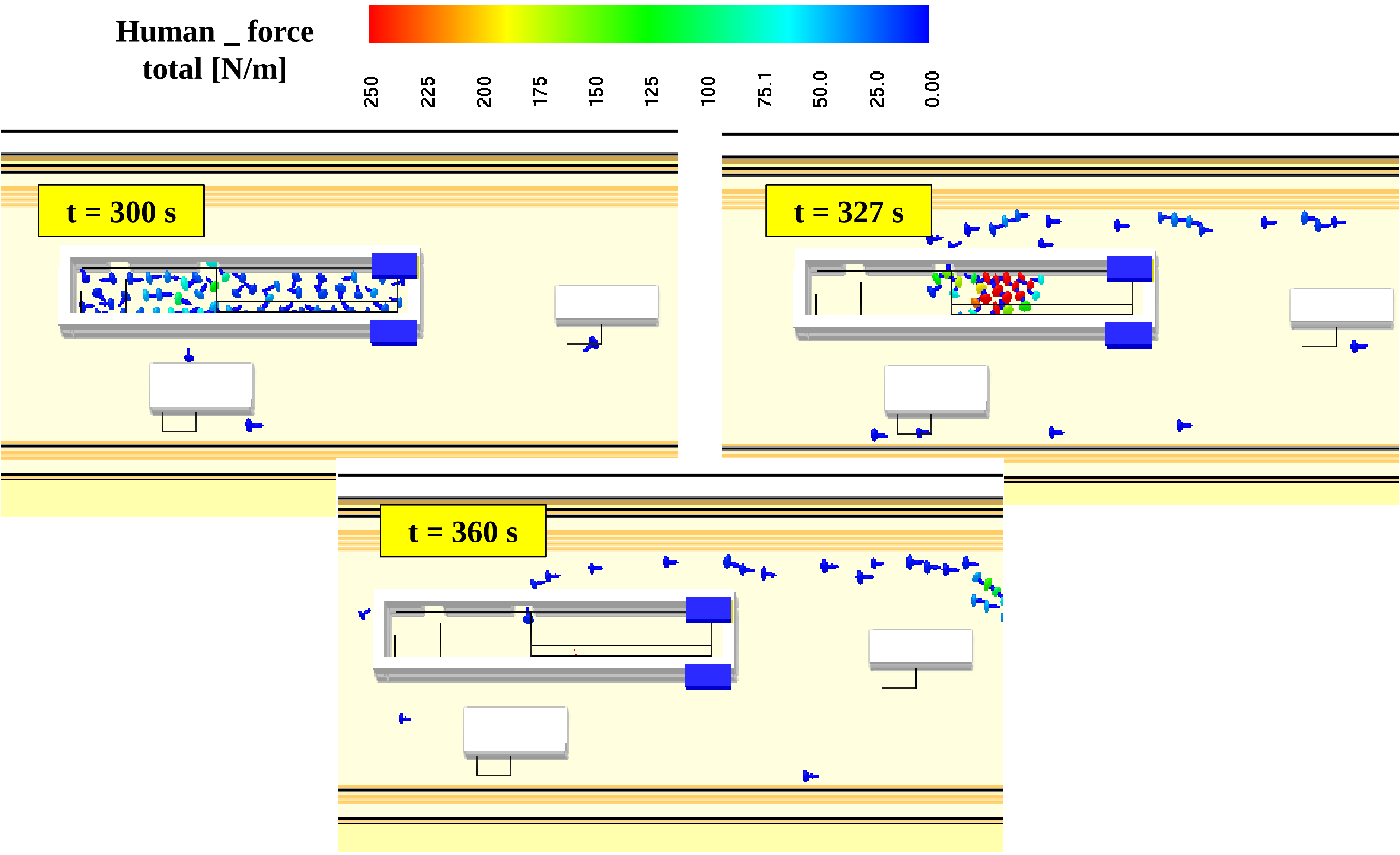
RESULTS (6 MW fire)



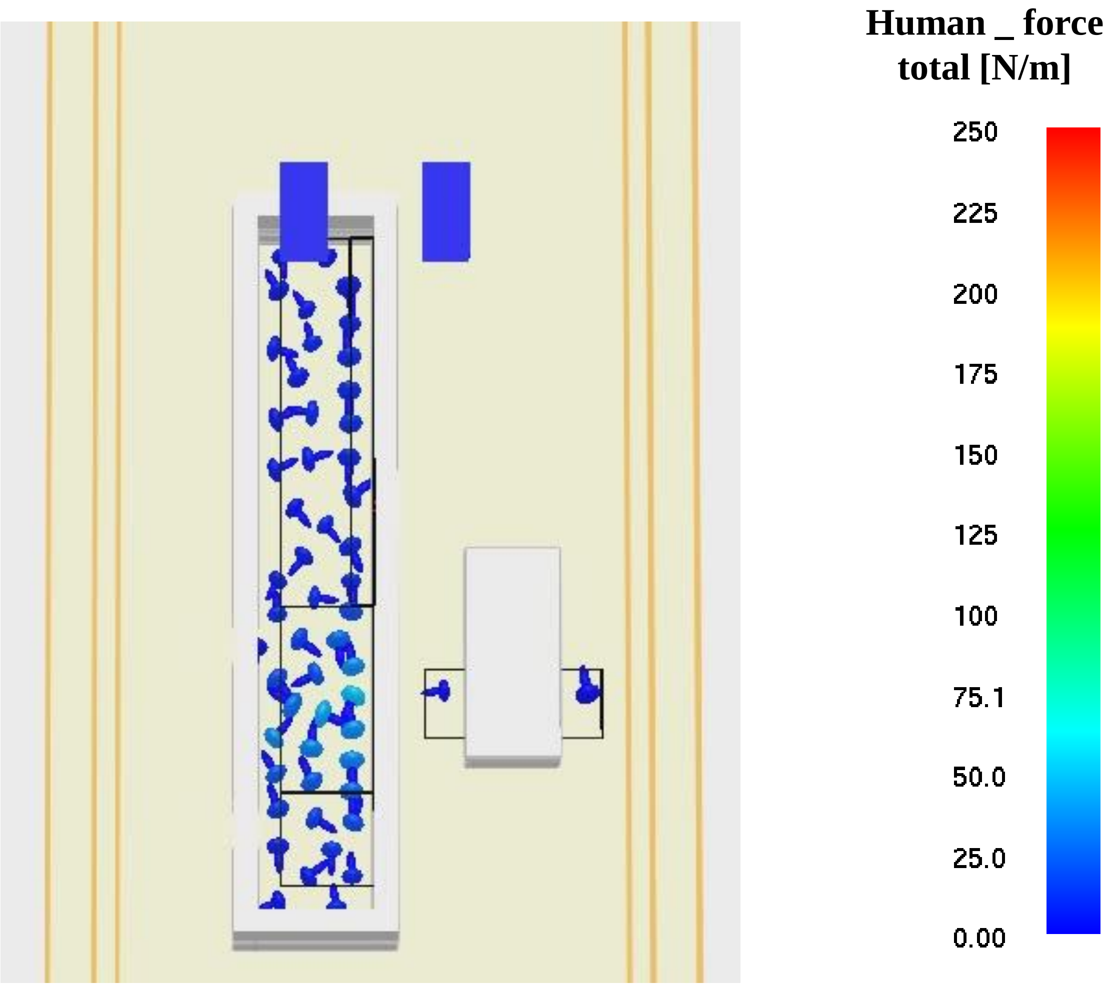
This is not a general result: FDS+Evac should be run using **Monte Carlo method** (repeated sampling to determine the properties of the phenomenon).

This is only one sampling of the Monte Carlo simulation.

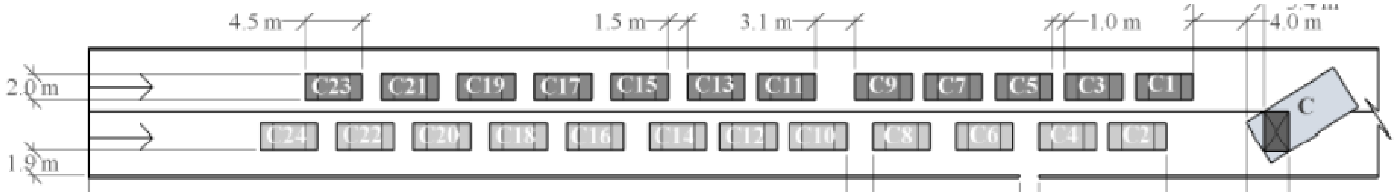
FDS+Evac

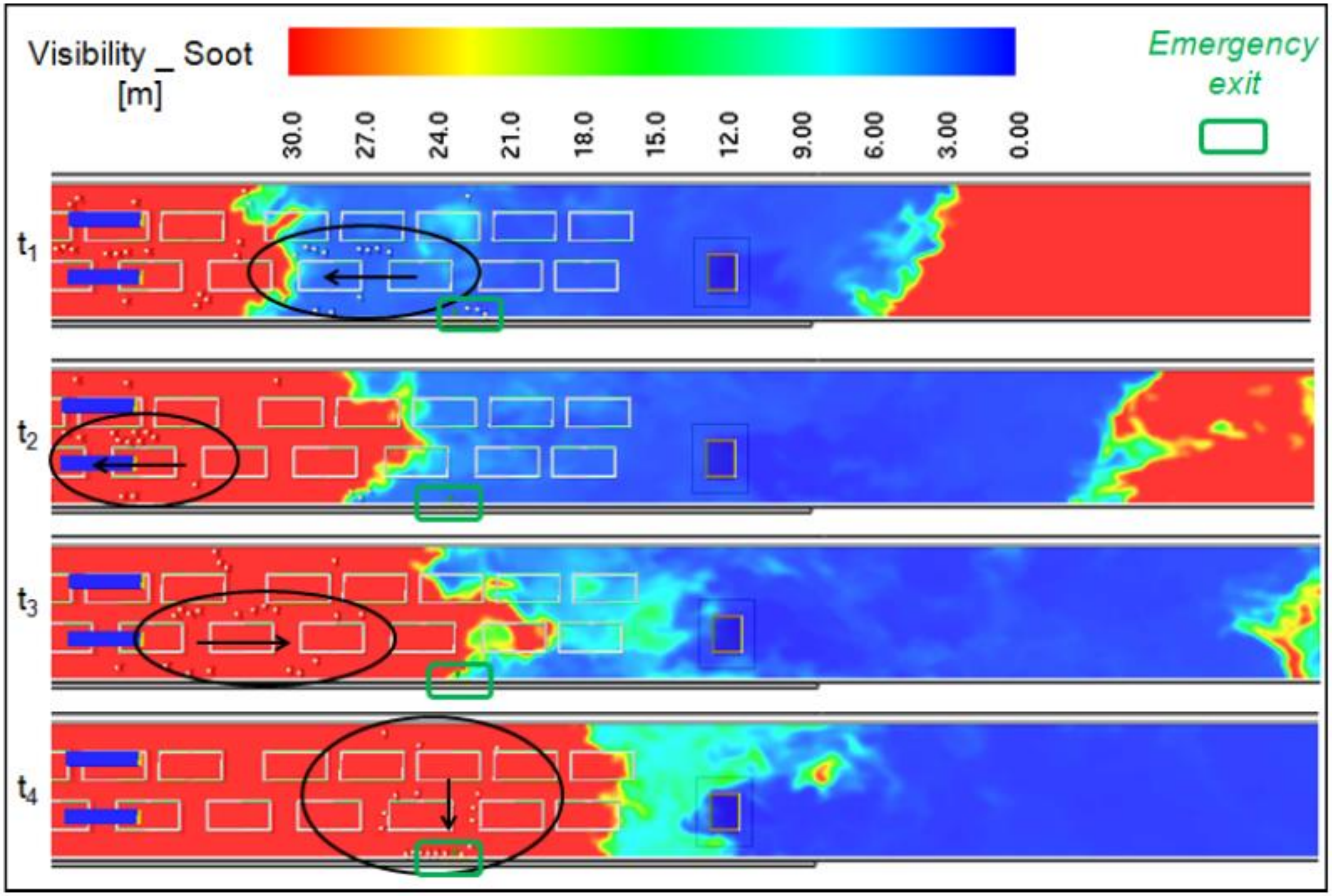

Human _ force
total [N/m]
250
225
200
175
150
125
100
75.1
50.0
25.0
0.00
t = 300 s
t = 327 s
t = 360 s

Block in the bus



FDS+Evac - Benchmark





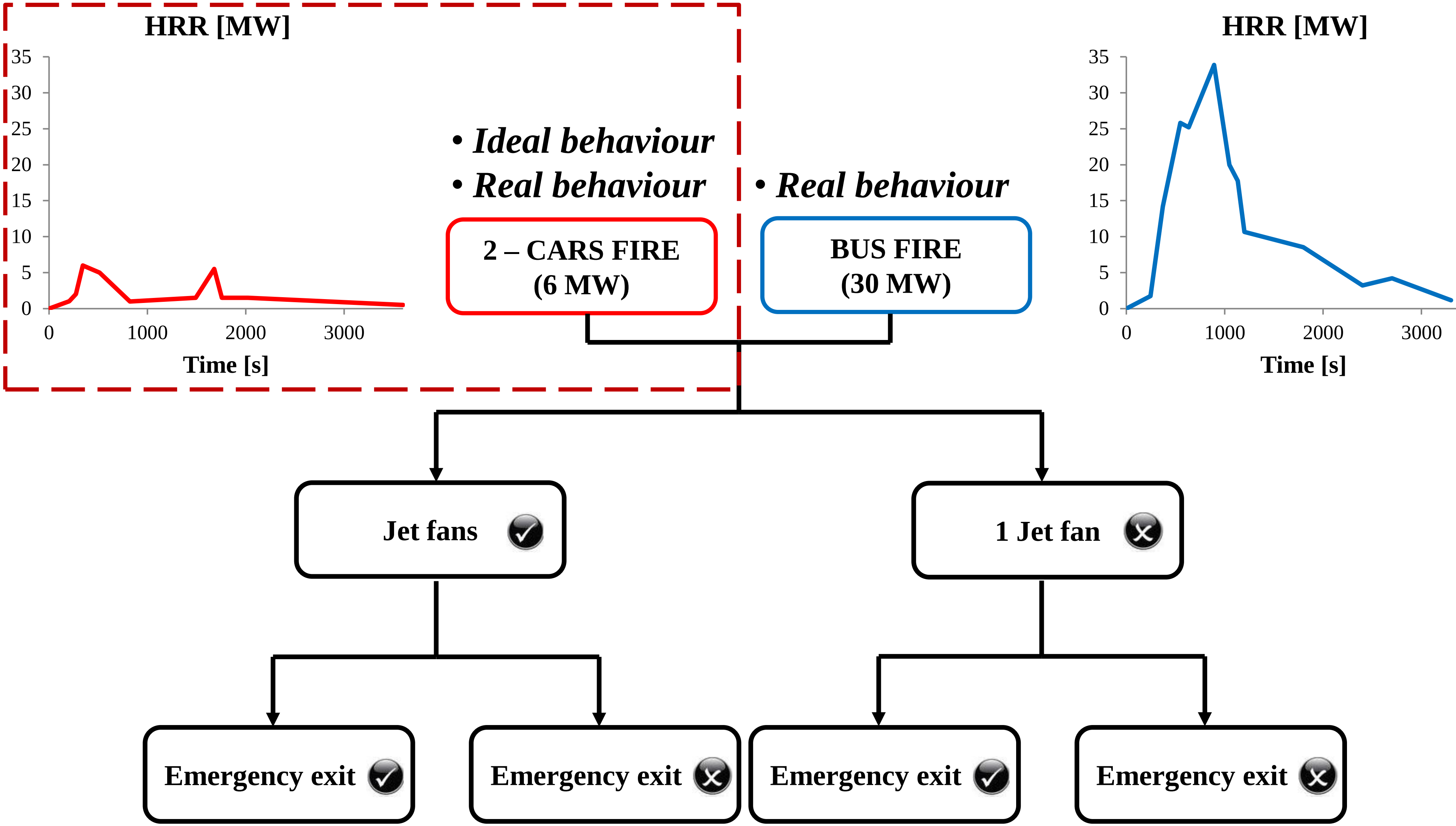
"Influence of panic on human behaviour during emergency egress for tunnel fires"

ANAS – Linee Guida Gallerie

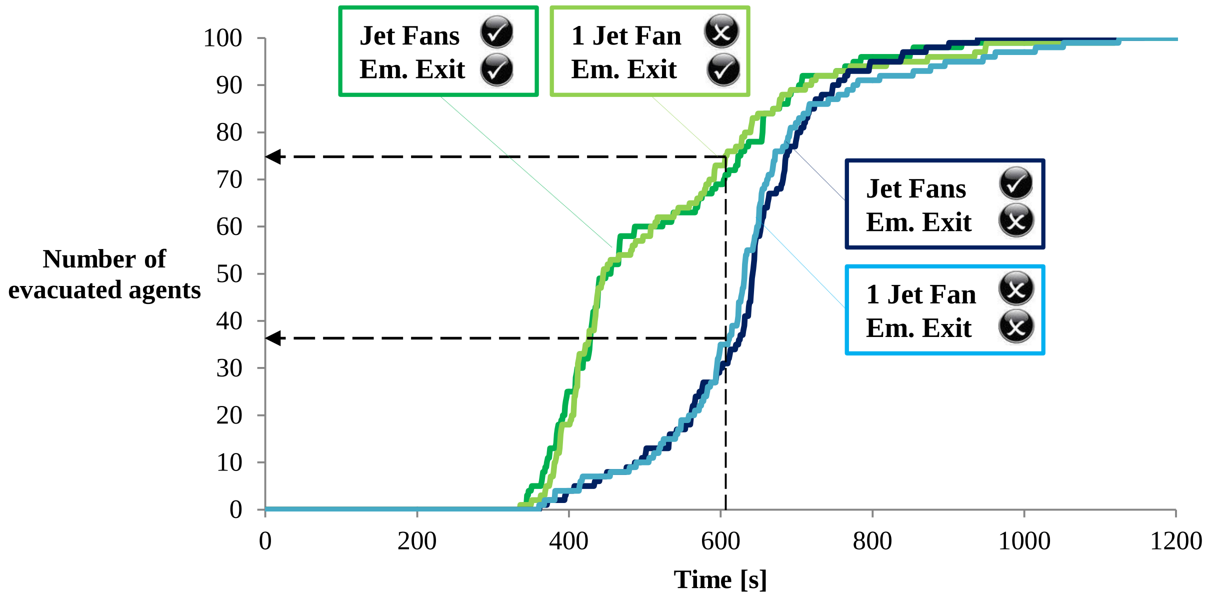
Tempi medi impiegati dagli utenti ad abbondare il proprio veicolo	
Veicoli leggeri	300 s
Veicoli pesanti	90 s

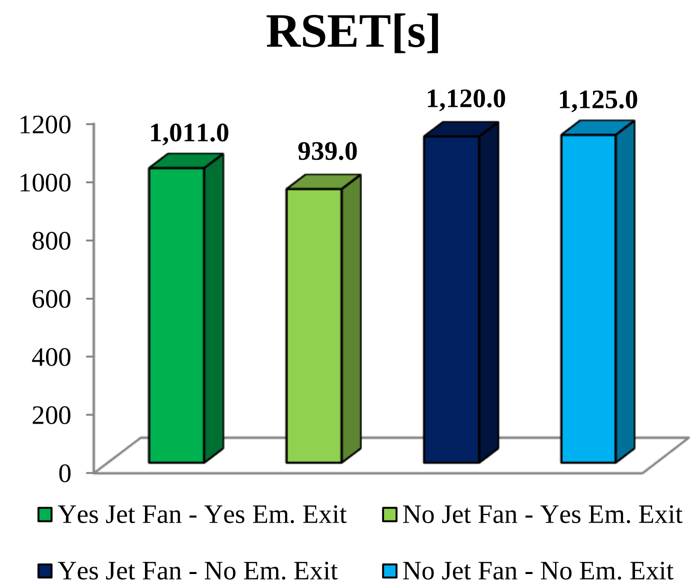
Visibiita'	Velocità [m/s]
Buona	1
Ridotta	0.5
Nulla	0

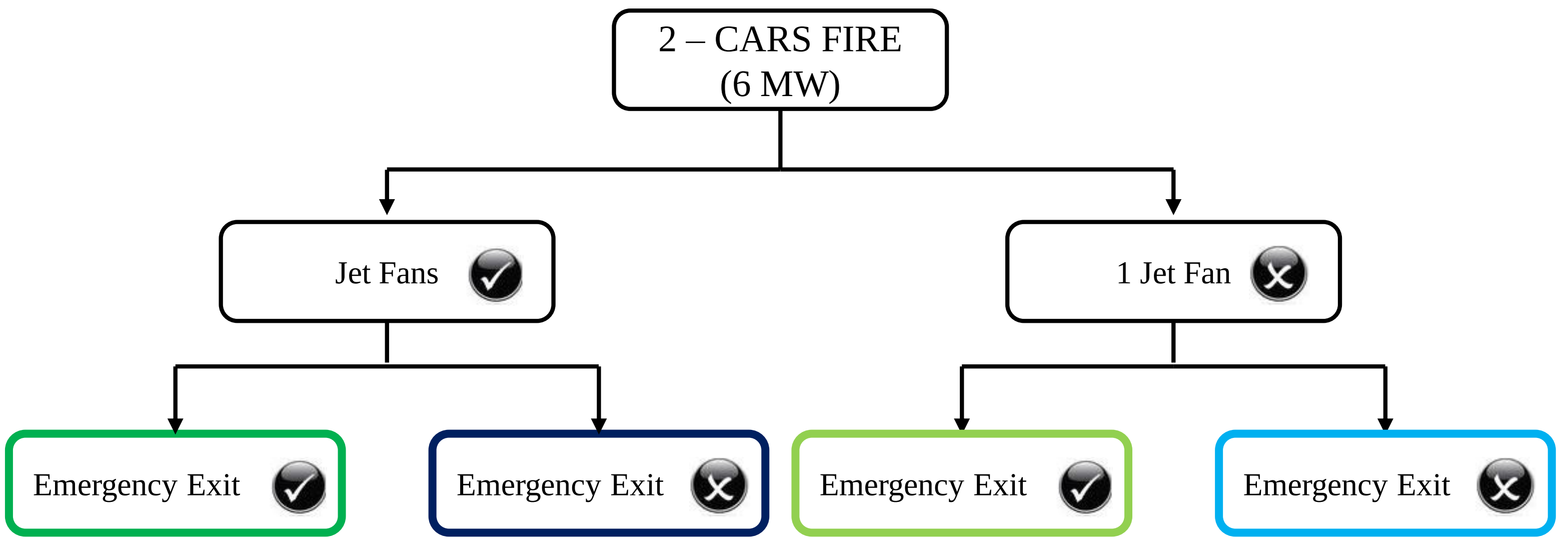
SCENARIOS


HRR [MW]
35
30
25
20
15
10
5
0
0
1000
2000
3000
Time [s]
• Ideal behaviour
• Real behaviour
2 – CARS FIRE
(6 MW)
• Real behaviour
BUS FIRE
(30 MW)
HRR [MW]
35
30
25
20
15
10
5
0
0
1000
2000
3000
Time [s]
Jet fans
1 Jet fan
Emergency exit
Emergency exit
Emergency exit
Emergency exit

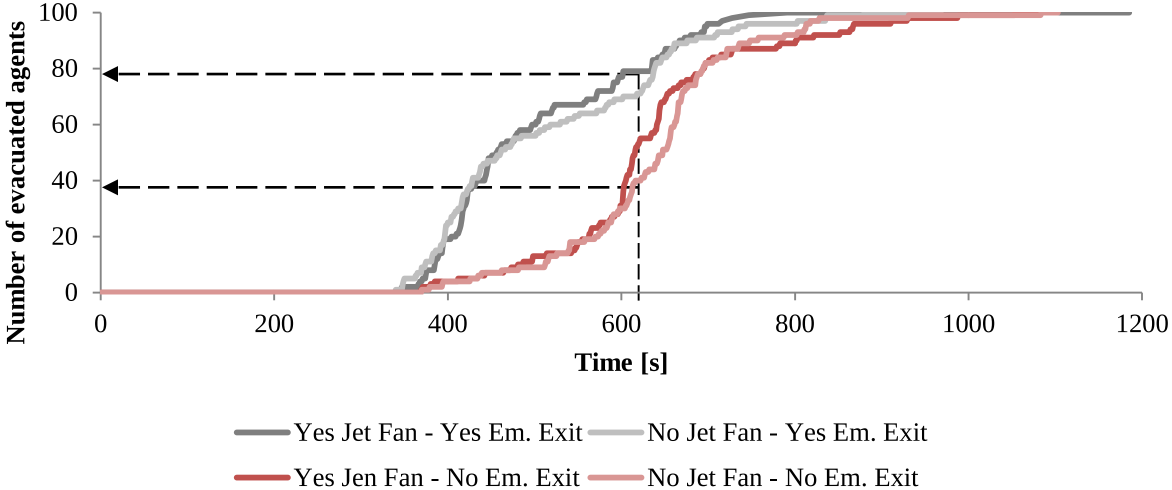
RESULTS (6 MW fire)

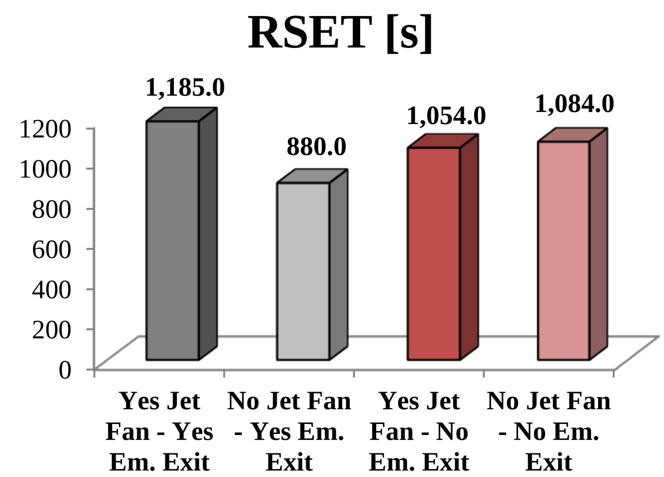


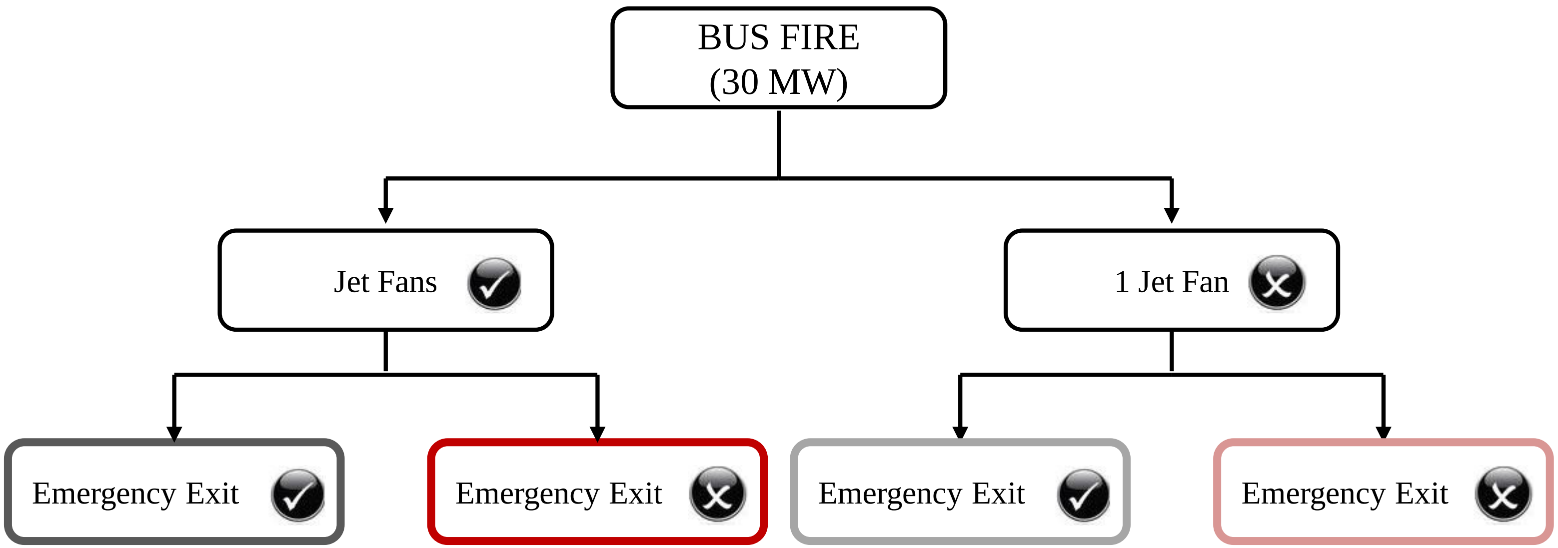




RESULTS (30 MW fire)







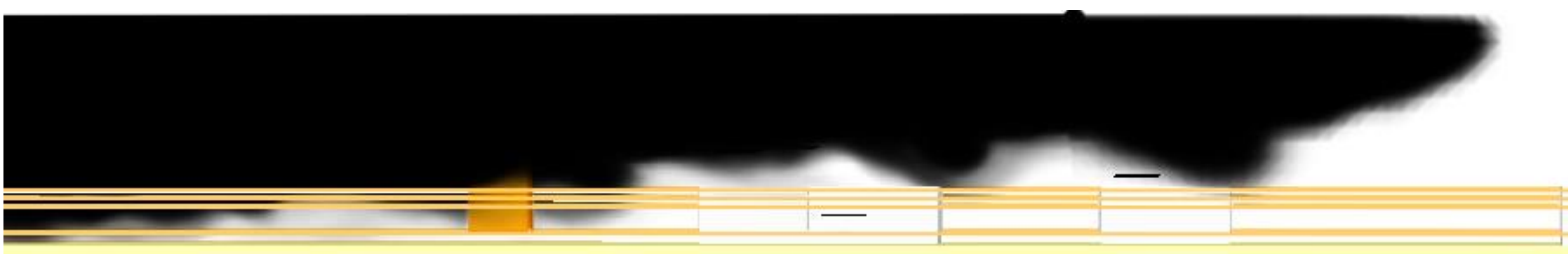
RESULTS (30 MW fire)

Bus fire – 1 jet fan off

t = 418 s

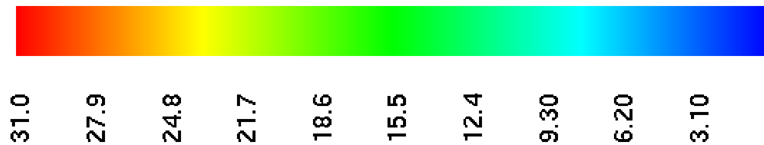
t = 594 s

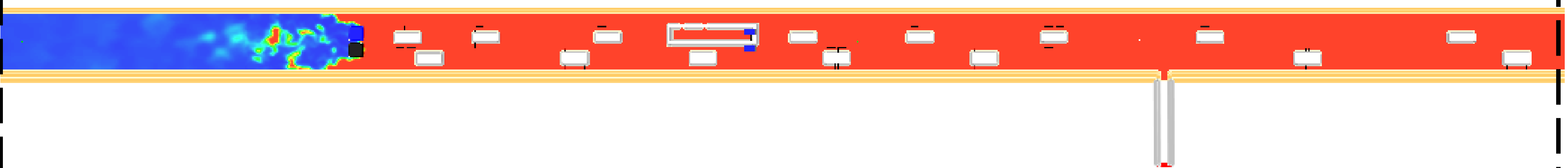
t = 720 s



RESULTS (6 MW fire)

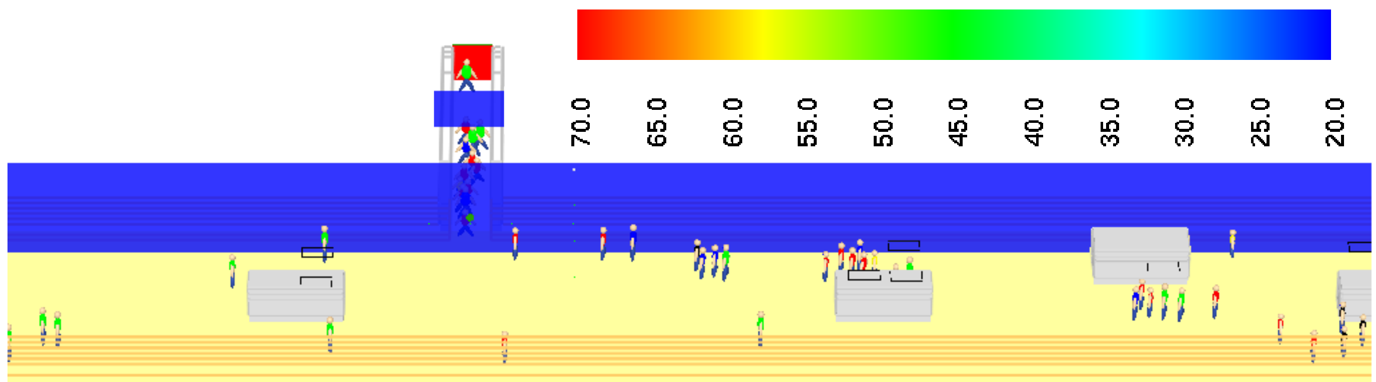
- **Visibility _ soot [m] at z = 1.6 m**
high visibility upstream the fire source during the egress time





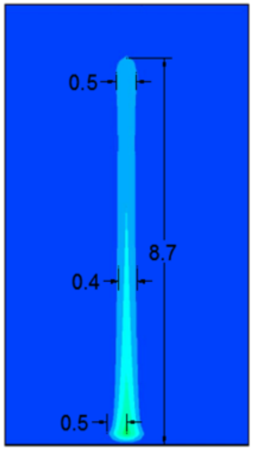
- **Humans FED ~ 10^{-5}**
very low value, even for those scenarios with 1 jet fan off (emergency ventilation is so strong that there are no problems of intoxication)

- **Temperature slice [°C]**
low value (< 60°C) next to the emergency exit



ASET >> RSET ∀*considered scenario*

COMPARISON BETWEEN NUMERICAL CODES

<table>
<tr><th></th><th>Spatial aspects</th><th>1D - aspects</th><th>Temporal aspects</th><th>Code and computational cost</th></tr>
<tr>
<td>RANS
Reynolds Average Navier Stokes</td>
<td>
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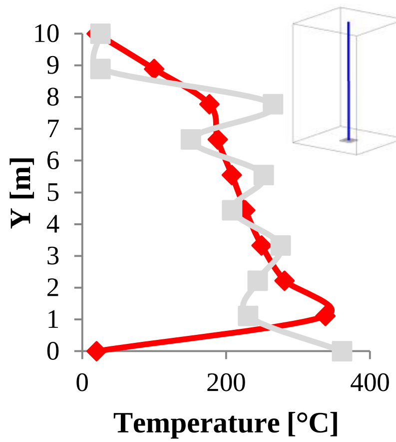
<td>
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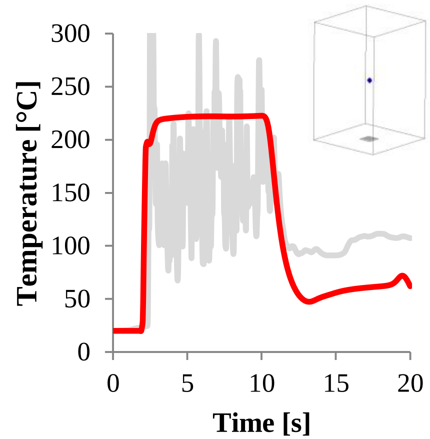
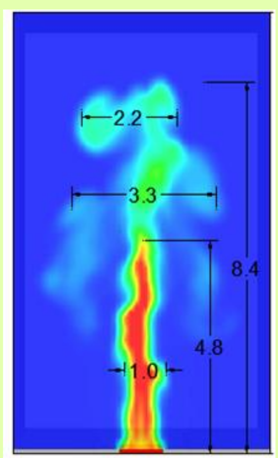
<td>
</td>
<td>ANSYS FLUENT
20 cm – mesh
→ 8 hours of simulation</td>
</tr>
<tr>
<td>LES
Large Eddy Simulation</td>
<td>
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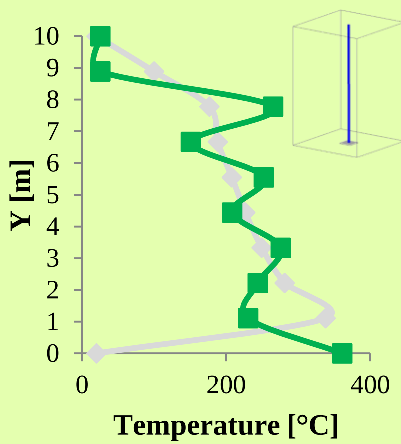
<td>
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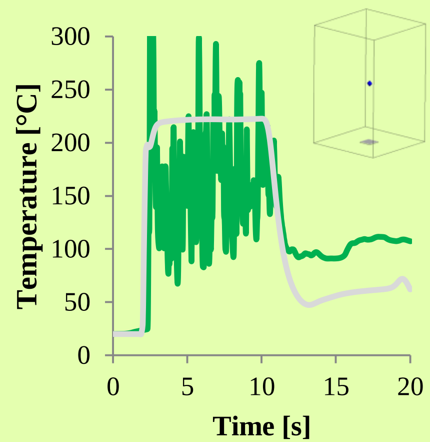
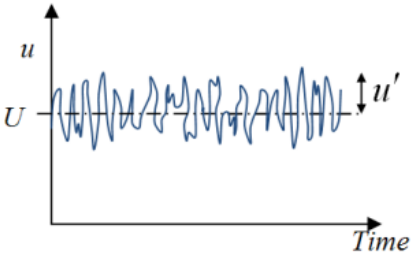
<td>
</td>
<td>FDS
20 cm – mesh
→ 1 hour of simulation
+ Evac</td>
</tr>
</table>

COMPARISON BETWEEN NUMERICAL CODES

	FLUENT *(developed to study problems typical of mechanical engineering)*	**FDS** *(developed to study problems typical of civil engineering)*
ADVANTAGES	• GUI (Graphical User Interface) that permits modeling of complex geometries • available different types of 3D – cells (tetrahedron, hexahedron, pyramid, prism, polyhedron) • structured and unstructured mesh	• non – iterative algorithm (based on CFL) • it solves Low Mach equations • less computational cost • LES simulation • a coarse grid gives good results • simple to use for civil engineering (it uses radiation and chemistry models, calibrated on experimental data) • it is FREE!!
DISADVANTAGES	• iterative – algorithm • high computational cost • RANS simulation (because of the computational cost, that grows quickly) • a fine grid is necessary to obtain good results • difficult to use for civil engineering (it requires the definition of chemistry, radiation and turbulence models)	• it does not have a GUI (it requires to write an input text file..) • it does not permit modeling of curved geometries because it allows only rectangular grid and prismatic finite volumes

RANS

It is the oldest approach to turbulence modeling. An ensemble version of the governing equations is solved, which introduces new *apparent stresses* known as Reynolds stresses. This adds a second order unknown tensor for which various models can provide different levels of closure.



It is based on the decomposition of a quantity in "averaged part" and "fluctuant part" → u = U + u'

The average of the fluctuant part is zero: by applying the Reynolds average to NS Equations (where u is expressed as U+u') it is obtained a new system of equations.

Reynolds stresses tensor depends on u': it is unknown and has to be modeled → Boussinesq hypothesis : the tensor has the same structure of molecular stresses tensor (a term depending on ν_T appears) → k – ε model : it assumes that $\nu_T = c_\mu k^2/\varepsilon$ and it expresses k and ε by writing two transport equations (*the model has 5 constants of calibration*)

LES

It is a technique in which the smallest scales of the flow are removed through a filtering operation, and their effects are modeled using *subgrid scale models*. This allows the largest and most important scales of the turbulence to be resolved, while greatly reducing the computational cost incurred by the smallest scales.

-Define the filter function (Box or Gauss) that cuts the fluctuations of velocity

→ u = u (filtered) + u (residual, of sub-grid)

- Apply the filter to NS Equations → Filtered equations
- Model the unknown terms of the filtered equations (Sub Grid Models)
  - Smagorinsky *Eddy – Viscosity* model (it models the effects of residual scale *by increasing the viscosity*)

    It treats the residual stresses tensor such as molecular tensor and it models the term of residual kinematic viscosity by using *a constant of calibration* C_s
- Solve

This method requires greater computational resources than RANS methods, but is far cheaper than DNS.