**SITI (Safety In Tunnel Intelligence).**
An Italian research project on tunnels safety

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Abstract
A concise description of actual evolution state of the TRAIN research meta-project SITI (Safety In Tunnel Intelligence) built up by a work package of 35 interconnected sub-projects will be given. This meta-project submitted for partial funds, to the Italian Research Ministry, by TRAIN Consortium* started six months ago.
The overall cost of research streams will be about 15 million Euros, assigned through the three next years.
This very wide meta-project includes both interconnected theoretical research and applicable prototypes.
The SITI-project is founded on a comparative time dependent risk analysis of railway, highway, and underground tunnels and will be developed by the application of innovative technologies, it is inspired by the experience gained in ITS and Nuclear Power Safety fields, rightly integrated and modified for the new goal: the applicability of the “Effective Safety” concept to all kind of Tunnels.

* TRAIN Consortium for transport researches was promoted by ENEA (Italian Agency on New Technologies, Energy and Environment ), and it also includes at present as partner TRENITALIA SPA, and Italian Railways Co, UNIONTRASPORTI S.c.a.r.l. ( Society promoted by Italian Chamber of Commerce for sustaining the development of transport, logistics and infrastructures), Ansaldo Trasporti Railways System Spa and AnsaldoBreda (Engineering companies operating in land transport and technologies), D’Appolonia Spa (Engineering company operating in information and safety technologies) Reggiane Cranes and Plant Spa (Industry operating in maritime transport technologies) Bertolotti Spa ( Industry operating in land, maritime and railways transport technologies) Salerno University and Lecce University.

The TRAIN -SITI philosophical background.

1. **Static versus Dynamic consideration.**
In the general overview performed by SITI on the status of the overall safety of tunnel, the first different and meaningful approach was the complete parallel approach among highway, railroad and underground tunnels.
This comparative view showed clearly that the classical safety vision utilized so far must be improved in the light of new knowledge obtained by this comparative analysis.
This study enabled us to understand not only the well known differences regarding highway, roadway and underground tunnel safety, but also unknown similarities and methodological interconnections.
The aim of the project was the application of new technologies for prevention; intervention and restoration of severe accident in tunnels.
The comparative analysis and the study of the state of the art of tunnel safety allowed us to introduce and define the original concept of “Dynamic Tunnel”, a point of view very different from the generic unified safety vision, normally utilized by engineering groups or corporation.
In general we may argue that for some parameters one tunnel is never equal to itself, in other words, each tunnel has its own degree of risk, not constant in life, but variable during the daytime. [1].
This statement underlies the importance of the dynamic evolution of the system, or the time
dependence role of the kinetic parameters, and it underlies also the necessity of a systemic
vision for tunnel safety. These two important improvements are the basis of the safety
methodology named: “Effective Safety” that will be built with the SITI research project.

Till now the tunnels are described by “Static” parameters as length, width, height, historic
numbers of accidents and so on.

Now in the “Dynamic” vision, the tunnel description will be extended by new random parameters,
changeable in time, as: intensity of traffic flow, ageing of the system structures, etc. Of course, this
tunnel “dynamical” description is connected to the stochastic properties linking the risk state to a
straightforward time dependence, (i.e. in the “dynamic” roadway tunnels description, it is necessary to
bring in new parameters such as “dynamic probabilistic occupancy” [1], hazard rate functions, etc.
[2]). The most important parameter in term of “probabilistic occupancy”, for road tunnels, is the car
number point flow, while, for railway and underground tunnel, this parameter is the people number
flow.

In time-space, a Poisson discrete distributions describes road traffic phenomena, for which the average
probability of a passage is constant in time and independent of the number of previous events, [1] in
this situation, the order of events cannot be interchanged Baccelli, Hasenfuss and Schmidt [3] give
some probabilistic conditions based on coupling, for a Poisson point process; these authors connect
these conditions to the queuing theory in a homogeneous Markov process.

In fluid queues with several merging inputs, stochastic integrals are used for describing the total
number of cars arriving during a time interval of random length.

If we pay attention to the probability of a traffic accident in a tunnel, the time dependent hazard
function rate could have the special form derived by the Weibull three parameters distribution.
This function could describe traffic phenomena for which the accident is a random occurrence. Thus
the related hazard rate function \( \lambda(t) \) would be decreasing for safety systems or increasing with a
snowballing effect for the rise of cars dynamic probabilistic occupancy in the tunnel.

\[
\lambda(t) = \alpha \left( \frac{t - \tau}{\beta} \right)^{\alpha-1}
\]

This last tragic occurrence will be verified if, regarding the Weibull parameters, the following
conditions are satisfied:

\[ \alpha > 1; \beta > 0; 0 \leq \tau \leq t \leq \infty. \]

The most general models of hazard rate functions are the Multivariate Conditional Hazard Rate
Functions. With these general functions it is possible to introduce a hazard rate ordering, among some
“dynamic” parameters, by introducing the notion of positive dependence for dependent random
lifetime parameters. This notion is useful for ordering kinetic parameters by special weights.

2. Effective Safety in Dynamical Tunnels

As it is shown by the time dependent risk analysis it is not possible to consider the tunnel as a simple
tube, for example in a mountain. In the new dynamic vision, it is vital for highway tunnel analysis to
pay attention to the connected route system before and after the tunnel.

The availability of access for enabling support to be available early and the capability of rapid
evacuation are fundamental components in train accident emergency planning.

However, it will be useful to consider these aspects also during the design phase of a tunnel project as
part of the system safety planning organization. The systemic vision underlies the same problems for
the underground. The system for the underground by the time dependent risk analysis is formed not
only by the upper road system (for intervention), but also by the complex incoming of the tunnel,
station and the out-coming of the tunnel. In addition, also in this case it is easy to understand that
project engineering must take account of these problems in the early phase of the new underground
project. Safety is driven by two principles:
a) Minimization of technical breakdowns;
b) Minimization of human error.
But it is worth to remember that it is not possible to improve a safe system like a Nuclear Power Plant over the value of less one accident per 10 million (in term of safety unity- like running time, passenger per km and so on). Achieving a total safety beyond this minimum quantity of accident is practically impossible. The solution of the overall problem depends on the global safety of the complete system. Then, when safety of one part of one old system is improved it means that you must implement this by an addition, rather than an optimisation. These actions make the system increasingly complex. Really this means that the old system tends to be ageing or over regulated, in one world “rigid”, and the accident very often results from a combination of factors none of which can alone cause an accident, especially a serious one. Therefore such combination of “marginal” situations is difficult to detect or to recover using traditional analysis, [4] (remember the burning role of butter in Mont Blanc Tunnel fire) fig.1.

Fig.1 Mont Blanc Tunnel after the destructive fire

3. The “Effective Safety” concept.
The SITI project has comprehensively revised the overall approach to tunnel safety. So in this new approach, there are no tracks of the unified categorization of tunnel risk, independent from his length or his traffic volume, nor of classic risk analysis result like a certain number of death every year and so on. In effect, the use of time dependent risk analysis added to ITS technologies [5] breeds the methodological concept of “Effective Safety” for each tunnel in his own System. For example it seems obvious that a short tunnel does not need the same safety equipments of a long one, but what about a long connected series of short ones? The concept of “Effective Safety” is a flexible methodology applicable to every tunnel in his system situation. It comes from different linked sources, like the concept of “Dynamic Tunnel”, derived by the time dependent risk analysis, the studies about the system ageing or the response capability against fire accident, the application of the proper technologies, the optimisation of emergency response, the integration of the very particular system conditions to the tunnel conditions, (for ex. If a serious accident happens in one short tunnel very near to other short tunnels connected by a roadway like Autostrada dei trafori in Italy, under particularly weather condition it is possible to have the maximum smoke concentration in the neighbouring tunnel, than in the accident tunnel), the consideration of different time scenarios, etc.

This flexible methodology is expressed by the following three time steps, considering for example the proper road tunnel system description:
A) Prevention –
   a) Interactive safety between tunnel and aware vehicle (see SITI overview);
   b) Active safety between intelligent tunnel or control robot (for short tunnels) and all vehicles;
B) Intervention –
   Fire detection and suppression systems;
C) Synergetic –
   Emergency optimization by interactive Virtual Reality, intelligent decision support systems and emergency operators

The division in three logical and connected time blocks of the safety measures, allows us to approach the risk in more flexible way for each kind of tunnel, and with the ITS technologies utilized it is
possible also to minimize the heavy time dependence of the problem, but it is important to remember that a chain is no stronger than its weakest link.

The main seven technological categories for the ITS, that will grow in the next future are connected with the increasing complexity of traffic, coupled with advances in computational methods and computer architectures.

They are: Decision Aids, Computer Vision, Virtual Reality, System Evaluation, Vehicle Control, Traffic Control, and Commercial Operation.

The comparative safety evaluation among different tunnels, considering the Jack Linch Tunnel in Ireland; the Oslo Tunnel, in Norway opened in the January 1990 with three hierarchical orders of control, and the Ted Williams Tunnel in US monitored and controlled by the Integrated Project Control System (IPCS) formed by a central unit and nine workstations with operators; force us to observe that “Effective Safety” for roadway claims that road tunnel needs to become “intelligent”, with first target car safety, and indirect primary target people safety. Instead “Effective Safety” shows us that for rail and underground tunnel, such kind of approach is unsafe, it is more effective in this case, that train becomes “intelligent” and not tunnel. With target train safety and indirect primary target people safety.

4. The SITI overview.

We show the complete expansion of the connected organization of the SITI Cluster Project for the 35 research activities projects:

Underground diagnostic system
Intelligent roadway Tunnel system
On site follow me system
Human Factors pre and post accident.
“Aware Trunk”, intelligent on board control system both for engine status and dangerous goods
Training organization systems
Classical risk analysis
Classical Risk monitoring
Source term from different materials
3D smoke propagation study
Thermal qualifications of tunnel materials
Thermo structural superstructure models
Underground coaches project principles
Emergency simulation systems
Queues management simulation systems
Emergency lighting systems
Optimization of drop diameter

Optimization of water droplet heat exchange between air-water and concrete
Intelligent training systems
Control and / or emergency robot
Interactive Virtual Reality Tunnel system model
Intelligent decision support system
Instrumentation for infrastructure
Time dependent risk analysis
Application to individual and collective risk
Cost benefit analysis
Validation risk analysis
Validation RAMS
Reliability of electronic safety system
Fractal flame interaction model
In-field operation with advanced on fire suppression system.
In-field operation with advanced on fire suppression system.

5. The research organization.

The SITI project is organized in 15 major work packages; the most important systems are in the work package N°1. In this work package there is the roadway tunnel intelligent control systems that will be applied to an Italian case study and the rail/underground control systems also applied to an underground station, both ones under patent pending. [6]

Road tunnel intelligent control, it works for an open tunnel system like freeway or highway tunnels, and it is focused on traffic flow [7, 8, 9] control by television outside the tunnel. This system is able to detect also driver behaviour and to forecast the accident possibility in such way: the traffic flow outside the tunnel is under a control unit system which assesses an optimal car speed and separation distance, depending by the traffic conditions, by an integrated system of variable messages; in the tunnel the car flow is controlled by a connected “follow me system” with a changeable light (green,
yellow and red) based on the best distance and optimal speed allowed in the tunnel in the specific time and flow situation among the cars.

**Underground intelligent system**, it is related to rail and underground operations. The system is connected with different kinds of sensory signals which come from the train; such signals discharged, on board, in a special mass memory are connected by wireless with a receiver in each station. Each receiver is connected to a central unit in which a special genetic algorithm gives forecasting information on possible system failure.

**Advanced integration in mathematical models**, this group of important studies belongs to different work packages but the aim is to characterize unitary mass of different source term materials (like butter, plastic and so on) by heat and smoke production, these data are the input in one original software program of ‘fire flame’ which calculates the interaction among fractal front flame, concrete and the geological structure of the tunnel system. The outputs of the program are connected to a CFD smoke program that provides the concentration of smoke in the scenario; all these programs are connected to a Virtual Reality model of the specific tunnel system, for example in the underground (tunnel, station, tunnel) to produce a number of web based bi-dimensional maps (at ground and eye-level), with the time evolution of smoke concentration and heat field, that are ready to be sent to the fire brigade for the emergency strategy optimization.

In off line approach the same results can be utilized for architectural optimization of smoke control strategy or evacuation of the underground station.

For the roadway tunnels, smoke influence on the jet fan ventilation system at first on the basis of Memorial Tunnel data are analyzed and then applied to an Italian case study.[7,8,9]Fig.2, shows the jet fan arrangement and a map of the experimental situation in the Memorial Tunnel.
Materials special studies, other packages are connected to the experimental study of the thermo structural behaviour of materials in the Tunnels (concrete, rail, coaches and trunks materials, etc.).

New suppression systems, experimental studies are performed on the optimization of water drop diameter fig.3 and on the optimization of heat-exchange between tunnel concrete and water drops for cooling the tunnel wall, Fig 4

These researches are the means to test a new suppression fire system that will be studied under real fire condition in a specific Italian tunnel (8 km long) in order to have real data from an unknown experimental situation till now never proved. Fire accidents under tunnel longer of 20 Km are never studied in controlled way; we hope from this experience to get data useful to parameterize our knowledge.

Normally CFD [10, 11] simulations are utilized to study both the evolution of:

- The fire process and
- The movement of buoyant smoke stratified under forced ventilation action.

This strategy to create a safe route upstream clear of smoke for evacuation and fire fighting, utilized in all tunnel emergency plans, is normally known as prevention of back-layering.

The first assessment is very sensitive to several different parameters, for example, heat input rate, combustion model, fuel type, quantity and type of combustible material, and last but not least, a good turbulence model description.

The second significant parameter is the presence and the dimension of the upstream turbulent layer, and the downstream stratified layer, these parameters is sensitive for example to the slope of the tunnel to the inclination, to the roughness of the wall, to the convective and radiative heat transfer.
The problem is to know the so-called “critical velocity”, that is, the minimum air velocity to prevent the smoke spreading. There are a few uncertainties in the current methods of prediction of the critical ventilation velocity. Certainly the first is the influence of the firepower; the second is the influence of the tunnel geometry. Experimental data show the influence of the cross sectional geometry of the tunnel on the “critical velocity”, it was also clearly shown that the “critical velocity” has two regime of variation, at a low rate of heat release and at a high rate. In the first, the “critical velocity” varies as one-third power of the heat release rate; in the second, it is independent of it. With reference to two critical problems, fire temperature and downstream stratified layer dimension, good model approximations are affected by an error difference with experimental measurements that can range from 20 to 30%. However, if we consider the quantitative evaluation of the physical part of the model as natural convective and radiative heat transfer, or wall roughness and turbulence models the overall uncertainties would be around the 40-50%.

That is the best situation, in my knowledge, that physics could promote, until now, in computational fluid dynamics programs.

Short tunnel control systems, other research projects are focused on a very cheap wire-guided control robot, for short roadway tunnel able to control and give also indication on accident scenarios like heat field intensity, dangerous smoke component and so on, under patent pending (Italy have the 97% of the European short road tunnels).

Risk analysis and evaluation, further studies are connected to the global risk evaluation as Classical risk analysis, Classical Risk monitoring, Application to individual and collective risk, Validation risk analysis and the new Time dependent risk analysis of the tunnel, in connection there is also the global Cost benefit analysis to evaluate the price impact of these innovation on the Italian Tunnel system. [12, 13, 14, 15, 16, 17]

The mathematical theory has been applied to “Dynamic Tunnels” flows, in a general way, through the concept of tunnel Availability and Reliability. [18, 19, 20, 21, 23]

The Tunnel availability A (t) is defined as the probability that the tunnel is operating in his system at time t.

If the cars, in Tunnel system, are independent variables, it is well known that the tunnel availability as function of time can be calculated by using the Boolean theory.

Let \( A_j(t), j = 1(1)n \) \( j = 1, n \), be the availability of the cars in tunnel system and \( n \) representing the number of cars in this tunnel system. Then the tunnel availability could be evaluated by (\( \Psi(\beta) = \))

\[
A_j(t) = \Psi(A_1(t),...,A_n(t))
\]

For Tunnel systems the system transport theory (Dubi et al.) could be applied in a favourable way.

Now, for simplicity, we present the basics of the theory for a single parameter.

For the tunnel availability calculation, for non exponential distributions, as suggested by Dubi & Gurvitz, a general state equation can be used. [22]

In contrast to the Markov model, we are interested to the entering into a state \( i \) at time \( t \) as main focus instead of to being in a state \( i \) at time \( t \), this approach based on time evolution clarifies that we speak about non Markov models.

Dubi & Gurvitz define the number density of entries into a state \( i \) at time \( t \), per time unit, denoted by \( \Psi_i(t) \).

Let \( \Delta t \) be a time interval and \( N_i(t, t+\Delta t) \) denote the average number of entries into state \( i \) in the interval \( (t, t+\Delta t) \), the event density can be defined as:

\[
\Psi_i(t) = \lim_{\Delta t \to 0} \frac{N_i(t, t+\Delta t)}{\Delta t} = \frac{dN_i(t)}{dt}
\]
Another important quantity is the ‘state reliability’ \( R_i(t - t') \), as the probability that the tunnel will remain in state \( i \) without accident up to time \( t \), given that it will be happen an accident and the tunnel entered the state at time \( t' \).

The mathematical description is based on the (car or people) probability density function \( f(t) \), and the conditional density distribution \( F(t) \) with \( f(t) = dF(t)/dt \),

In this approach the tunnel reliability will be described by \( R(t) = 1 - F(t) \) and the tunnel failure rate or tunnel hazard function by \( \lambda(t) = f(t)/R(t) \).

The usual description of the failure behaviour of highway dynamic tunnel systems or rail dynamic tunnel system could be provided by the three-parametric *Weibull* distribution, with the following probability density function:

\[
f(t) = \frac{b}{(T - t_0)} \left( \frac{t - t_0}{T - t_0} \right)^{b-1} e^{-\left(\frac{t - t_0}{T - t_0}\right)^b}, \quad t \geq t_0 \geq 0
\]

Where \( b = \) shape parameter; \( T = \) characteristic lifetime (scale parameter); and \( t_0 = \) failure-free time.

It is obvious that the failure rate of a *Weibull* distribution is a function of time which could depict all three sections of the well-known *bath-tub* curve depending only on the shape parameter.

Considering the tunnel probability to have a serious accident or not, as a stochastic point process with two possible states; let one state be numbered as 1 and called ‘operational’, and the other numbered as 0 and called ‘failed’.

With these definitions it is possible to introduce the state indicator function

\[
S(t) = \begin{cases}
1 & \text{if the tunnel is operating at time } t \\
0 & \text{if the tunnel has a serious accident at time } t
\end{cases}
\]

Let the probability density function \( f(t) \) describe the transition from 1 to 0 (failure) and the probability density function \( g(t) \) the transition from 0 to 1 (repair).

Remembering that, the event density before defined is:

\[
\Psi_i(t') = \lim_{\Delta t \to 0} \frac{N_i(t, \Delta t)}{\Delta t} = \frac{dN(t)}{dt}
\]

Due to this definition, it is clear that \( \Psi_i(t')d\tau \) is the probability that the system will enter state \( i \) at an infinitesimal interval \( d\tau \).

Therefore \( \Psi_i(t')R_i(t - t')d\tau \) is the probability that the tunnel is in state \( i \) at time \( t \) conditioned upon entering at time \( t' \) into the state.

Integrating over \( t' \) yields to the probability of being in the state \( i \) at time \( t \).

\[
P_i(t) = \int_0^t \Psi_i(t')R_i(t - t')dt'
\]

Consider the two time \( t \) and \( t'(t' < t) \) and let \( i \) and \( j \) be two different tunnel states.

Using the ‘state reliability’ in combination with the transition rate \( \alpha_{ji}(t - t') \), the expected number density of entries into state \( i \) at time \( t \) resulting from former entry into state \( j \) at \( t' \) is given by:

\[
dP* = \Psi_i(t')R_i(t - t')\alpha_{ji}(t - t')dt'.
\]

This equation describes the following sequence of events: The tunnel enters state \( j \) at \( t' \), remains in that state up to time \( t \) and then transfers into state \( i \).

The total event density is obtained by integration of this equation over \( t' \) and summing over all states \( j \neq i \). This leads to the general state equation fulfilled by the event densities:

\[
\Psi_i(t) = P_{i0}\delta(t) + \sum_{j \neq i} \int_{t=0}^t \Psi_i(t')R_j(t - t')\alpha_{ji}(t - t')dt'
\]

Where \( P_{i0} \) is the probability that the tunnel starts at \( t = 0 \) in state \( i \) and \( \delta(t) \) is the Dirac delta function.
The general state equation, however, is extremely complicated and provides an analytic solution to just a few simple cases. Even numerical solutions are rather difficult. But the mathematical framework is sufficient to be useful in the application of dynamic tunnel concept.

6 Conclusions

The 35 projects of the SITI cluster are now in progress, their natural end, will be in the October 2007. The main theoretical goals of the SITI cluster project are: by the time dependent risk analysis, to find tunnels’ potential “weak points” during their life time; by the finite elements analysis, CFD models, Virtual Reality models and the in field experiences to increase our interconnected knowledge on serious fire accidents in tunnels.

From the practical point of view, getting ready many prototypes and intelligent systems, we try to introduce really practicable solutions, not very expensive, (if it is possible) to minimize the fire accident probability and to improve the emergency response.

In term of dissemination it is planned also a book on the SITI project and its main results.

We hope with this global effort to go further in the real ambitious plans of the overall project: to rationalise the matter in comparative way, and simultaneously to rescue people from the fire, trying to minimize the severe structural tunnel damages derived by a serious fire accidents.
References

[23] Jeffrey A. Bergamini; Preliminary Research Survey for a Decentralized Multi-Agent ITS for Highway Congestion Avoidance; California Polytechnic State University- 3/ 2004