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ABSTRACT

The global warming debate forces the vehicle industry to come up with new environmentally friendly solutions. In 10 years time, or even faster depending on the pressure from different governments in particular in Europe, vehicles will not only use gasoline, diesel and LPG, but also CNG, Hydrogen, ethanol, DME and other bio-fuels, as well as batteries and fuel cells.

This quick development and the diversity of new energy carriers can jeopardize the safety in underground infrastructures such as tunnels or car parks. This can cause a major drawback in the adoption of new energy carriers as regulators or operators may prohibit use of these vehicles in underground systems if no new relevant measures will be taken. Unclear situation will also affect the implementation of international policies aiming at reducing the environmental footprint and especially CO_2 emission in road traffic.

The problem became clear after a workshop with the vehicle industry, tunnel operators, authorities, and safety experts organised in November 2008 by L-surF Services with the support of ITA-COSUF, ECTP and HYSAFE. This workshop demonstrated that the construction sector lacks appropriate design data and tools as well as knowledge to build safe underground infrastructure compatible with a diversity of new and alternative energy carriers. Vehicle industry, infrastructure operators and regulators have not yet addressed this problem.

In a first part, an overview of the regulatory situation regarding safety and security of the admission of new energy carriers for vehicles in underground infrastructures is presented. Then, a detailed review of previous relevant research projects performed makes it possible to formulate recommendations in terms of a strategic research & development agenda. The overview shows that it is necessary to develop an integrated risk assessment and management method specific for underground transport systems, metros and hubs in confined spaces taking into account the "emerging risk" aspects.

Keywords: safety; security; new energy; underground; integrated risk management

1. INTRODUCTION

Improving safety and security in urban underground infrastructures is multi-disciplinary by nature because it deals at the same time with:

- New energy carriers for transport,
- Design and construction of the transport infrastructures,
- Safety and security of the whole systems.

Several recent or on-going international, European and national projects have been identified as a starting point. The paper presents a review of the main results gained in the following fields:

- Risk assessment and management in tunnels, underground, metros and confined spaces,
- Security management in transport systems,
- Integrated risk management of new and emerging risks,
- Innovative energy carriers for vehicles and their safety.

The review of the state-of-the-art in these field shows that often safety and security are analysed separately. Therefore, a combined risk analysis can contribute to find more cost-effective solutions.
In addition, an integrated approach considering the whole components of the transport stations and terminals and their interactions help to find the optimum to improve the safety and security by design, to include also emerging risks connected to new energy carriers.

2. OVERVIEW OF THE REGULATORY SITUATION

The regulations related to the use of new energy carriers in vehicles and the adaptation of the underground infrastructures has not yet been developed.

Informal discussions with several authorities from France, Germany, The Netherlands, Italy and Spain have lead to the following statements:

- The topic of the compatibility of the existing underground transport infrastructures with the diversity of energy carriers in the green vehicles of the future is not yet on the agenda.

- An approach combining technical requirements with political targets needs appropriate investment in R&D.

- Being pro-active, anticipating the problems at an early stage to develop a scientific based regulation, seems to be difficult (several authorities found that the question comes too early).

3. RISK ASSESSMENT AND MANAGEMENT IN TUNNELS, UNDERGROUND, METROS AND CONFINED SPACES

3.1. UPTUN, http://www.uptun.net/

Summary of the project
UPTUN dealt with issues and technology to improve existing tunnels in terms of fire safety in a holistic manner. The project consortium comprised 41 partners from 18 European countries.
The UPTUN project main objectives were:

- Development of innovative technologies for the assessment of existing technologies in tunnel applications. Focus was on technologies in the areas of detection and monitoring, mitigating measures, influencing human response, and protection against structural damage. The main output was a set of innovative cost-effective technologies.
- Development, demonstration and promotion of procedures for rational safety level evaluation, including decision support models; and knowledge transfer. The main output was a risk based evaluating and upgrading model.

UPTUN has achieved a lot of innovations in the field of fire safety and related fields [1, 2]. They comprise detection and monitoring devices as well as mitigations systems. Tools assisting in evacuation and methods to protect structural elements have been developed as well. The risk based modelling activities lead to the establishment of a model capable of assessing the current fire safety level in a particular tunnel and also determining the improvements of the fire safety as well as the economic impact based on upgrading measures. The concept developed in UPTUN is of great value when doing future studies on new energy carriers as in many cases there is a need to upgrade the tunnels taking into consideration new energy carriers.

Further development needed
Reference scenarios were established to assess risks in existing tunnels, mainly road tunnels. The definition of reference scenarios has to be **generalised to other underground infrastructures** such as transport terminals and stations including the connections with metro tunnels, with the car parks and other underground depots to park the vehicles when they are not in use.
In addition, the scenarios considered were dealing with fires i.e. the impact of the fire load and of traditional toxic gas generated by the combustion (carbon monoxide, carbon dioxide). **In further initiatives, new scenarios including explosion and releases of various types of toxic gas have to be developed** to be representative of the real situations that can happen in transport terminals and stations, in case of accidents or attacks.

3.2. L-surF (Large Scale Underground Research Facility on Safety and Security), http://www.l-surf.org/

Summary of the project
Research on safety and security in enclosed underground spaces is of outstanding importance as current incidents (tunnel fires, terror attacks in metros etc.) have shown. However currently the EU competence related to safety and security is largely unstructured, fragmented and mostly national oriented. Especially missing is a large scale research facility and the coordination and synergy of existing facilities. The necessity for a European wide initiative in these respects also was identified and clearly expressed during the 1st International Symposium on safe and reliable tunnels, held in Prague in February 2004.
Within the Design Study for L-SURF all relevant aspects for such a facility were elaborated to a level that the facility could be established at least as a legal entity with the necessary structures and activities and that preliminary concepts and plans for the physical construction are laid out. The study describes the constructional lay-out of the facility, based on an entirely new concept for easily creating any contours, shapes and sizes of enclosed spaces needed, but also all other aspects like installations, environmental impacts etc.
The concept:

- will allow novel approaches to R&D work
- describes innovative measuring sensors, based on the latest technologies (e.g. nanotechnology) available
- evaluates the research needs and outlines the R&D - activities
- develops an integration process for the existing and projected national facilities with their competences and researchers, thus restructuring and improving the relevant EU competence while simultaneously showing ways for using R&D funds more economically
- shows ways and means to raise the necessary funds for the different stages in the setting up of the facility and networking of existing facilities
- includes a business plan (e.g. referring to models like CERN) for a new legal entity dedicated to the establishing of L-SURF.

The partners of the consortium have to set-up this legal entity based on the business plans developed within the frame of the Design Study [3].

Further development needed
From the project, the need for integration of expertise to find systemic solutions to global emerging risks was demonstrated.

3.3. EGSISTES: Global evaluation of intrinsic safety & security for underground transport systems
(French project funded by the National Research Agency (ANR))

Summary of the project

EGSISTES is a 3-year project dedicated to the evaluation of the global security in underground infrastructures (from January 2007 to January 2010).

Coordinated by INERIS, the consortium included E.S.E. (Egis tunnels), LME University of Valenciennes, RATP and CEA. This project was split into three phases described underneath.

The project is organized in 3 work packages:

1. Vulnerability analysis
    - Risk analysis
    - Accidental risk and threat
2. Knowledge improvement and model development for consequences evaluation
    - Experimental approach (fire, explosion, gas dispersion)
    - Numerical simulation (1D and 3D numerical tools)
3. Existing tools capability evaluation

The first part of the project was dedicated to the evaluation of the global risk in underground infrastructures. The risk analysis was performed considering both accidental risks and intentional threats in order to demonstrate the linked between the two in terms of physical phenomena. Fire, toxic gas dispersion and explosion are the three physical phenomena that can be encountered in underground infrastructures for both risk situations. The main difference relates to the hazardous substances to consider: in case of attack, the substance can be any substance while in case of accident, the substance involved is part of the system under consideration.

The second part of the project was focused on the improvement of the physical phenomena understanding using both the experimental and numerical approaches. Experiments were carried out for fire, heavy gas dispersion and explosion. The first two phenomena were studied in the 1/3rd scale INERIS fire gallery in order to study the interaction between the stratification and the ventilation. The impacts of disturbances on the smoke layer were studied using scaled vehicles and fan, photography's from experiments are reproduced on Figure 1. Explosion was experimentally studied in the INERIS explosion gallery. Two series of experiments were achieved for studying both solid explosion and flame propagation in an explosive cloud. For those different situations, the 3D simulation tools were used to enlarge the experimental results.

Figure 1: Photography's of the EGSISTES experiments. Left: Backlayering reference case, i.e. without disturbances. Right: Impact of vehicles.

Finally, the third part of the project consists in validating existing simulation tools and achieving real cases to show the capability of existing tools to model the physical phenomena for both intentional threats and accidental risks. Several real configurations were simulated split into two main topics: the first is underground station for mass transport and the second is road tunnels.

The results from the EGSISTES project are directly linked to the splitting into three parts.
The first part has enlightened the physical link that exists between accidental events and threats for critical infrastructure.
The second part has enabled to improve the understanding about smoke behaviour in case of fire in tunnel for the congested tunnel configuration. The smoke stratification was evaluated for both backlayering and downstream smoke layer showing that if the backlayering layer remains quite stratified, the downstream smoke layer stratification is weak, with and without vehicles. The second main result of the experimental campaign is the description of the toxic gas behaviour in case of leak in tunnel. The experiment has shown that the behaviour is not only governed by the ventilation system but by different external parameter such as atmospheric parameters, leak direction, etc. Consequently, it is quite impossible to have a precise prediction of the gas behaviour in tunnel because of the impossibility to have a great description of the source term.
Finally, in the third part addressing the simulations tools, it has been shown in the project that CFD codes are able to give an acceptable description of the physical phenomena. The comparison for the fire experiments were achieved with the FDS and Phoenics CFD codes while the toxic gas dispersion was modelled using only FDS. On top of that, a specific explosion model was developed to predict the pressure wave propagation specifically for tunnel geometry.

Further development needed
As described above, the EGSISTES project provides results concerning the physics of generic dangerous phenomena and a first overview of the numerical tools capability to predict the consequences. This first approach has to be used as input data for new projects considering that new energy carriers will not generate fundamentally different phenomena but will induce an important modification of it. Considering for example the case of batteries, they will produce highly toxic gases (HCN, NO_2, HCl…). The smoke composition has to be characterized in order to predict consequences in case of fire in confined spaces. Furthermore, the physic composition of batteries generally induces a rapid heat release rate rise that can modify substantially the fire curve.
To put it in a nutshell, EGSISTES offers a global risk study that use experimental and numerical approach for current risks in underground infrastructures. It is important to provide an extension of this approach to the future risks in these infrastructures in relation with the evolution of the energy sources for transport.

3.4. TUNCONSTRUCT, http://www.tunconstruct.org/

Summary of the project
TUNCONSTRUCT was a multi-disciplinary research project that promoted the development and implementation of European technological innovation in underground construction under participation of some of Europe´s best recognized names in the underground engineering industry.
The 41 project partners, from 11 European countries, integrated not only the on-the-field engineering experience and technical know-how of the industry, but also the research capabilities and conceptual innovation of the academic sector.
TUNCONSTRUCT was fully committed to contributing to an increased quality of life for Europeans by reducing construction time and cost of planned and future underground infrastructures [4].
The project was co-financed by the European Commission, under its 6th framework program, which provides 54% of its 26 million Euro quadrennial budget. Coordination rested on the Graz University of Technology, Austria. An innovation developed within the project – the Integrated Optimization Platform (IOPT) – resulted in a breakthrough in the design optimization, reducing cost, time and risk in underground construction.

Further development needed
The philosophy behind this is perfectly suitable to work on the improvement of safety and security in urban underground infrastructures using innovative energy carriers. All information about the life cycle of an underground facility is put together in a data base management system. All kinds of risks are included in

this life cycle analysis. This makes the approach suitable for design optimization for safety and security. As the focus is on confined spaces, the risk assessment tool from TUNCONSTRUCT can be used as a blueprint for further development.

4. SECURITY MANAGEMENT IN TRANSPORT SYSTEMS

Progress on security management can benefit from a recent project performed in the USA by the FTA and two European projects.

4.1. FTA Transit Security Design Considerations (US project, 2004)

Summary of the project

The most interesting reference dealing with security management in transport terminal and stations and summarizing the state of the art is the report from the US Department of Transportation [5].
The report provides security design guidance on three major transit system components – bus vehicles, rail vehicles, and transit infrastructure. It provides a resource for transit agency decision makers, members of design, construction and operations departments, security and law enforcement personnel and consultants and contractors, in developing an effective and affordable security strategy following the completion of a threat and vulnerability assessment and development of a comprehensive plan.
Developed by the Federal Transit Administration in collaboration with transit industry public and private sector stakeholders, these design considerations provide actionable steps that transit agency staff can select from to create a security strategy.
However, the report focuses exclusively on security assessment, and does not address risks related to innovative energy carriers.
The approach recommended in the FTA report is similar to the method classically used in Europe, i.e. scenario and consequence analyses.

Further development needed

Concerning the behavior of mitigation devices, the report does not mention specific tests to better understand the dangerous phenomena that can take place in underground terminal and stations. It does not mention any simulation tools for the accidental situations or attacks. It is therefore necessary to further develop models and simulation tools that will help refining the design of the infrastructure under consideration.

At European level, the two projects of significant importance are COUNTERACT and RAILPROTECT.

4.2. COUNTERACT http://www.counteract.eu/

COUNTERACT means Cluster Of User Networks In Transport and Energy Relating to Anti-terrorist ACTivities.

Summary of the project

COUNTERACT is a European research project funded under the Sixth Framework Programme by the Directorate-General for Transport and Energy of the European Commission.
The main objective is to improve security against terrorist attacks aimed at public passenger transport, intermodal freight transport and energy production and transmission infrastructure.
When the security of people and the integrity of critical infrastructures are involved, reducing the risk of terrorist attack and its consequences is paramount.
The project will review existing security policies, procedures, methodologies and technologies to identify the best practices which in turn will be promoted throughout the relevant security community in the EU.
The project is divided in three industry clusters covering public passenger transport, intermodal freight transport and energy. In addition to their sector specific aims, the clusters will also exchange experiences and views between them.

4.3. RAILPROTECT, http://elsa.jrc.ec.europa.eu/showproject.php?id=13
Innovative Technologies for Safer and more Secure Land Mass-Transport Infrastructure under Terrorist Attacks

Summary of the project

The project aims at reducing the vulnerability of rail station infrastructures and rolling stock to explosion loads. The assessment of this vulnerability is achieved via numerical simulations of the blast effects. Thus, engineering design simulation tools are being developed based on structural and fluid mechanics and appropriate geometry mapping techniques for large structures. Case studies of typical stations and coaches are also elaborated for assessing the efficiency of these tools in predicting the performance of structures and the injury risk levels of the occupants.

The project has been motivated by the need to mitigate shortcomings identified subsequent to the most recent terrorist attacks that have targeted the urban transport systems of two major European capitals. The need to take initiatives in this area is reinforced by the current climate, which indicates that such attacks will not abate in the foreseeable future.

The nature of land mass passenger transport, with its open security architecture and widely dispersed assets, would suggest that measures comparable to those applicable to civil aviation cannot, and will not, be put into place in the near future. Nevertheless, a number of security measures have been introduced following conventional lines and centering on increased surveillance and patrols.

If it is not possible to completely eliminate the hazard, and it is not possible to secure all the assets that make up the land mass passenger transport system, then the best option available is to reduce the overall risk by securing specific vulnerable system elements. One such area is the resilience of moveable and unmovable parts of the land mass passenger transport infrastructure.

Further development needed

COUNTERACT and RAILPROTECT provide valuable inputs for the risk assessment and **the choice of security scenarios**, for the modeling of the hazardous phenomena (RAILPROTECT provides important inputs on explosion modeling) and the **most recent technologies to reduce risks**.

5. INTEGRATED RISK MANAGEMENT OF NEW AND EMERGING RISKS

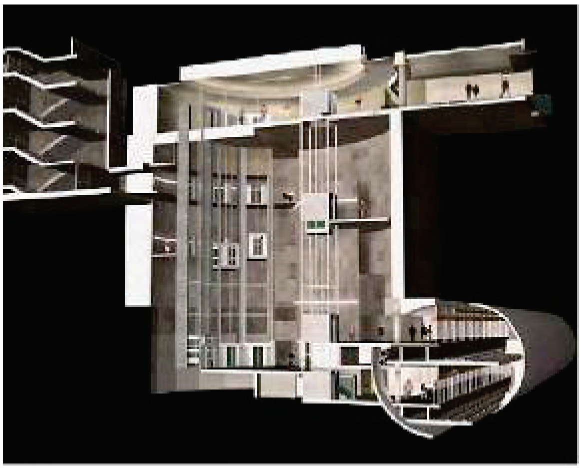
iNTeg-Risk
Early Recognition, Monitoring and Integrated Management of Emerging, New Technology Related, Risks
Grant agreement number: CP-IP 213345-2

http://www.integrisk.eu-vri.eu/

Summary of the project

iNTeg-Risk is a large-scale integrating project aimed at improving the management of emerging risks in the innovative industry. This will be achieved by building a new risk management paradigm for emerging risks, which is a set of principles supported by a common language, commonly agreed tools & methods and Key Performance Indicators integrated into a single framework. As main impact, it will reduce time-to-market for the lead market EU technologies and promote safety, security, environmental friendliness and social responsibility as a trade-mark of the advanced EU technologies. The project has started in December 2008.

Within the project, there is a specific case study called "**Safety and Security of Underground hubs with interconnected transportation services and shopping centers**" involving INERIS, SP, STUVA and VSH.



The project has identified so far the problem framing which is summarized hereunder.
Urban public mass transportation systems rely to a large extend on efficient and effective underground transportation system which are well connected to all other transport means of public traffic. The result of these developments in the use of the underground is twofold: On one side new metro tubes must be built deeper and deeper and on the other side they are interconnected with the other transport media in large underground constructions (hubs), including stations, parking lots and shopping areas on different underground levels. This results in longer access and escape routes, complex and hard to overlook structures split in several levels which are used by ten to hundred thousands of people every day, implicating new risks for constructors, operators, passengers and users.
In case of emergency there are entirely new boundary conditions for the evacuation of passengers, for example: Longer distances to reach the surface or safety structures underground, more demanding ventilation systems which must be adapted to the geometrical conditions as well as to the bigger amounts of air to be managed, higher interaction between different transport means (cut of traffic, emergency stops, evacuation of people etc).
Therefore, underground hubs require innovative concepts for ventilation and evacuation.

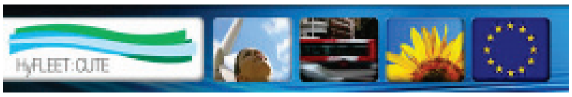
Further development needed
This project will neither develop detailed technical solutions such as new simulations tools for accidents or attacks, nor recommendation on the design of infrastructures. This is a work to be done in future specific project.

6. INNOVATIVE ENERGY CARRIERS FOR VEHICLES AND THEIR SAFETY

Several projects especially co-financed by the European Commission in the transport activities address development of innovative energy carriers for vehicles. In this paragraph a brief review is made to show the diversity of energy which are under consideration and the quick development which is expected in the public transport system mainly concerned by safety and security in transport stations and terminals.

6.1. HyFLEET:CUTE

One of the most impressive project is the HyFLEET:CUTE project.
http://www.global-hydrogen-bus-platform.com



In the last few years a series of demonstration projects have taken place that have demonstrated the potential of a transport energy system based on hydrogen. These have shown the development and demonstration of:

- Different hydrogen infrastructures;
- Fuel cell powered buses and cars; and
- Buses and cars powered by hydrogen internal combustion engines.

As a result, there are some 100 FC (fuel cell) and ICE (internal combustion engine) cars, a few FC delivery vans, and between 40 and 45 FC and ICE buses in operation around the world. Most of the buses are in regular public transport and airport trolley service.
The bus projects in particular have provided the developers and the operators with excellent data and experience because the vehicles are generally operated by professional drivers and often under especially

hard conditions, such as uninterrupted operation for more than 12 hours under some very harsh, extremes of climatic conditions.
The HyFLEET:CUTE project sees the operation of the world's largest fleet of hydrogen powered buses. It builds on the learning and developments from many of these previous projects.
The HyFLEET:CUTE bus fleet is supported by a hydrogen infrastructure which will produce, refine, distribute and dispense hydrogen in many different ways.
New advanced prototypes of hydrogen Fuel Cell and Internal Combustion Engine buses will also be developed and trialled.
An advanced hydrogen infrastructure is being established in Berlin which is capable of refuelling a fleet of up to 20 buses. This is aimed to achieve reliability and availability performance as good as current CNG (Compressed Natural Gas) infrastructure, and to be highly energy efficient.
A very active and extensive dissemination and information programme – the Global Hydrogen Bus Platform – combined with the inclusion of Beijing, China, aims to extend the impact of this technology world-wide.

One of 14 hydrogen ICE Buses at the refueling station in Berlin

See more at: http://www.greencarcongress.com/hsub2sub/index.html

HyFLEET:CUTE project provides information on the typical technology for hydrogen buses:

- Typical specification:
    - Fuel cell or ICE (internal combustion engine) propulsion
    - 350bar CGH2 storage
    - Up to 50kg hydrogen
- Typical configuration:
    - Roof mounted storage
    - Roof or rear mounted FC stacks
    - Good ventilation (in case of outdoor leakage)
    - Use buoyancy to advantage (in case of outdoor leakage)

There are other interesting examples of new energy carriers for public transport. In 2005, the Fraunhofer Institute for Transport and Infrastructure Systems (IVI) in Germany has developed a fuel cell-flywheel hybrid trolley (tram). The fuel cell-based system is a derivative of an earlier diesel-powered hybrid version. (April 23, 2005)
Source: http://www.greencarcongress.com/

6.2. STEEM

More recently, RATP and Alstom have tested ultracapacitor power supply for trams[1].

RATP and Alstom have developed a series of tests that will last a whole year 2009 to test the technology based on ultracapacitors. The research and development project called STEEM will be launched following the equipment certification granted by the railway authority in France, Certifer. The equipments will be installed to the supply system of 21 Citadis trams and regularly tested on Line 3.

Picture of the tramway T3 in Paris. Source: http://www.techno-science.net/

The STEEM programme, Maximised Energy Efficiency Tramway System, is an initiative developed by RATP, Alstom and INRETS with Predit funds, the French programme for transport research and Ademe, the body in charge of environment and energy management. A total of 48 ultracapacitors installed on the tram roofs can ensure a catenary-free operation, the supply taking only 20 seconds between stops. For this purpose, a fast supply station was installed at Lucotte depot (near Paris).

6.3. Biogas train

In Sweden, an Y1 Diesel train has been rebuilt to instead run on biogas. It has been in regular traffic since 2006 with good experience. This might be a possible solution also for other non-electrified train routes, where Diesel trains are most often used today.

6.4. HySafe Network and other related projects

A lot of other examples can be found on the development of the technology; however, regarding the safety aspects, the research is less prolific.

One the most important project at European level is the HySafe network of excellence (http://www.hysafe.org) and the internal projects such as HyTunnel (http://www.hysafe.org/HyTunnel) and InsHyde (http://www.hysafe.org/InsHyde) which were directly addressing safety of hydrogen vehicles in confined spaces.

In addition, the HyApproval (http://www.hyapproval.org/) project aimed to make a "handbook for approval of Hydrogen refuelling stations" which will be used to certify public hydrogen filling stations in Europe.

Among the project mentioned, HyTunnel and InsHyde are the one producing preliminary results useful for further development on the topic.

The objectives of the HyTunnel project were to:

- review tunnel regulations, standards and practice in respect to the management of hazards and emergencies, e.g. EC directive
- identify appropriate accident scenarios for further investigation
- review previously published experimental and modelling work of relevance
- extend the understanding of hydrogen hazards inside tunnels by physical experiments and numerical modelling.
- suggest guidelines for the safe introduction of hydrogen powered vehicles into tunnels

During the project, 10 experiments were performed with hydrogen and compressed natural gas, as well as a benchmark exercise for the numerical simulation. The tests, small and large scales, have shown the various

1 Source: http://rinsider.club-feroviar.ro/en/afiseaza_stire.php?id=4437, and press release RATP & ALSTHOM dated July 1st, 2009

combustion regimes according to the size of the cloud (air-hydrogen) and the concentration of hydrogen in the mixture.

In addition to the results gained, HyTunnel project has pointed out needs for further research in particular on the following topics:

- Realistic scenarios in tunnels (release downwards under the car) with delayed ignition of non-uniform mixtures
- Scientifically grounded requirements to location and parameters of PRD
- Impinging jet fires and conjugate heat transfer in conditions of blow down
- Releases into congested space with DDT
- Develop hydrogen safety engineering methodology and apply it to a tunnel scenario (long term).

Another internal project from the HySafe NOE is the InsHyde project aiming at investigating realistic small-medium indoor leaks, based on experimentation and CFD modelling and providing recommendations for the safe use/storage of indoor hydrogen systems. The performed experimental and modelling activities covered hydrogen/helium dispersion, hydrogen combustion and hydrogen sensors evaluation. The project in general enabled to improve the modeling of small releases and to better understand the hydrogen dispersion and combustion phenomena.
The project delivered a 90 pages document entitled "Initial guidance for using hydrogen in confined spaces - Results from InsHyde", which can currently be publicly accessed from the InsHyde webpage (www.hysafe.org/Inshyde) [6].
At the end of the project, the project team suggested further work in particular pre-normative activities in order to formulate the requirements (at EC and global level) for permitting the use of hydrogen vehicles (cars and commercial vehicles) in confined spaces. This pre-normative work should extensively be based on experimentations and simulations.

Further development needed
These two projects described the preliminary research work performed to understand hazardous phenomena related to the use of hydrogen in tunnels and confined spaces, and have clearly shown the need for further work to improve safety and have it capitalised in normative documents.

7. RESEARCH PERSPECTIVES

Improving safety and security by design in transport infrastructures using innovative energy carriers is a key issue for sustainable surface transport and mobility, especially in urban environment.

The review of the recent projects presented in this paper demonstrates that addressing this challenge requires a multi-disciplinary approach.
Therefore, based on the state-of-the art, it appear necessary to develop an integrated risk assessment and management method specific for underground transport systems, metros and hubs in confined spaces taking into account the “emerging risk” aspects (lack of knowledge on the socio-technical system using innovative energy carriers, different believes in the public, lack of regulations).

8. CONCLUSIONS

The progress beyond the state-of-the art which is expected in future research should address the following aspects:

- **Develop a scenario-based methodology to analyse and assess risks in transport infrastructures using innovative energy carriers**
  The innovation of the approach should come from the combination of safety and security by implementing the “bow-tie” model and therefore optimise the choice of risk reducing measures for

both aspects (safety and security), in particular for phenomena not yet well covered in the technical literature for designers, i.e. the explosion and the release of toxic gases.
The risk assessment should be quantitative regarding the prediction of the consequences of accidents or attacks and also regarding the probabilities of failure of the active mitigation devices and the human behaviour. Therefore, test campaigns should be performed to improve advanced simulation models.

- **Build an integrated approach to improve safety and security by design addressing with a holistic approach the whole system composed by:**
  a) the vehicles (using innovative energy carrier),
  b) the infrastructure including the lay-out and the mitigation devices, and
  c) the human behaviours
  This objective requires a multi-disciplinary and well coordinated research investment in several disciplines such as civil engineering, modelling and fluid dynamics, safety and security technologies as well as in human factors. The advanced modelling of the effects of accidents or of an attack will consider all aspects of the system.

All the development expected to make the existing infrastructures compatible with the innovative energy carriers of the vehicles of the future will have to be applied very quickly and in a homogenous way in Europe. Therefore, the development will need to pay attention to **the usefulness and practicality of the results and the large dissemination among the end-users**.

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