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FrejusVR

On the Use of Virtual Reality for Studying Human Behaviors
During Emergencies

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Abstract

Virtual Reality (VR), since its appearance, played a big part in the development of more and more effective training tools in comparison with the past. Training simulators could provide the inexperienced user a realistic, immersive and safe Virtual Environment (VE) designed to accurately reproduce a given scenario with the purposes of information, training and evaluation. This work aims at providing a beneficial VR tool with the purpose of the communicating to the general user the emergency procedures concerning a particular scenario, a fire developing from an heavy vehicle inside the Fréjus road tunnel.
Taking advantage of the collaboration with the tunnel Authority and undergoing a tailored testing plan, the work also provides an in-depth data analysis with the purpose of assessing the developed platform.

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Chapter 1

Introduction

1.1 Safety in road tunnels

The safety in road tunnels is one of the most critical aspects regarding the management of road infrastructures; tunnels are an essential features for countries where road networks have to deal with great oro-geographic obstacles such mountain ranges or water separation. Considering the peculiar tunnel characteristics such presence of confined spaces, lack of non-artificial light sources and difficulties with both intervention and evacuation, the logical consequence is a significant and continuous investment in order to improve security devices, emergency procedures and communication methods for both users and staff.

At European level, the European Directive 2004/54/EC[3] on minimum safety requirements for tunnels in the Trans-European Road Network establishes the mandatory requirements for all the galleries included in the Trans-European Road Network.

Then at national level there are countries, like Italy, with an higher percentage of road tunnels due to morphology of territory; this encourages the administrations of those countries to provide for additional projects or initiatives by their own and, in case of cross-border infrastructures, in conjunction with the neighbouring countries in order to enhance the community measures.

1.2 Motivation

This thesis is the result of the collaboration between Politecnico di Torino and SiTI[1], within the broad context of the PRODIGE[2] project.
The above-mentioned project is a partnership between Italian and French Authorities about the emergency management, realized with the contribution of the European Union and with active partners such the city of Turin, SiTI, the city of Cuneo and the French fire department (SDIS04[3]).

The PRODIGE acronym stands for to protect citizens, to defend the infrastructures, to manage major events; it's an hard task, and the Authorities in charge of the emergency management, such as Civil Defense, Fire Department and rescue teams, have to face it everyday, in a challenging environment created by climatic changes and the growing anthropic pressure over territory and infrastructures.
In order to guarantee the efficacy of the previously-mentioned Authorities, it's mandatory to assure an effective management of the operators, also ensuring the coordination of field teams at both national and cross-border level.
Within this project many Virtual Reality (VR)-based innovative tools have been developed, and now these solutions are available for facilitating the transition to a new approach based upon a mix of technology, management and training.

Four main pilot scenarios were initially developed, each of them characterized by different technical specifications, in order to show the various characteristics of excellence can be put together in VR:

- flooding among the river park Gesso e Stura in the province of Cuneo;
- flash flood and traffic accident near Saint-Paul-Sur-L'ubave;
- spill of chemicals in the area of the Maddalena Pass;
- accident inside an airport with toxic cloud formation running over a crowded area.

FrejusVR is not formally part of the list, but has been though as a possible extension of the above scenarios in the frame of a collabotion between SiTI and the GRAphics and INtelligent Systems (GRAINS) group at the Department of Control and Computer Engineering of Politecnico di Torino.

[1]Istituto Superiore sui Sistemi Territoriali per l'Innovazione, a no-profit founded in 2002 by Politecnico di Torino and Compagnia di San Paolo
[2]PROteggere i cittadini, Difendere le Infrastrutture, Gestire i grandi Eventi
[3]Service Départemental d'Incendie et de Secours

1.2.1 SiTI - Istituto Superiore sui Sistemi Territoriali per l'Innovazione

As said, SiTI is a no-profit, founded in 2002 by Politecnico di Torino and Compagnia di San Paolo, which carries out research and training activities geared towards innovation and socio-economic well-being.
Its activities are directed towards logistic and transport, environmental heritage, urban re-qualification and safety of the territory.

1.3 Objectives

The work done was focused on the realization of a serious game in a VR scenario representing an emergency inside the Fréjus tunnel (Figure 1.1); the hazardous situation in object is a massive fire, caused by a single-truck accident and spread along the tunnel by the truck.
Differently from the four main scenarios developed for PRODIGE, FrejusVR is not operator-oriented; in fact the target audience was moved to the civilians, as non-habitual users of the tunnel. The main goal of the interactive simulation is the communication of the prescribed procedures, in order to safeguard user's security in case of emergency by making them experience the emergency situation and the consequences of their actions.

Among the expected results of the work, there is the evidence of the benefits that VR technology can bring to the emergency management processes regarding the enforcement of security procedures to the civilians, with the goal to minimize the risk for people involved and to maximize the effectiveness of the operations carried out by the Authorities responsible for the intervention.

Figure 1.1: Main Menu of FrejusVR

Chapter 2

Analysis of the Case Study

2.1 Fire in tunnels

When it comes to firefighting, fires in confined spaces are not particularly hard to manage in comparison with other kind of events such large forest fires; however, this assertion loses meaning when it comes to fires inside tunnels.
This kind of events can have different causes, and they can become very hard to manage in case of lacking security measures or users' serious misbehavior.

2.1.1 Causes

The causes of fires inside tunnels, especially road tunnels, are various; in most cases heavy vehicles such trucks are involved, and this amplifies the risk due to their flammable loads. The fire can origin from a malfunctioning of the engine, from a collision between vehicles, from a fuel loss and from external factors too (e.g., a cigarette thrown out of the window).
Once started, the fire temperature starts growing as long as it has fuel and oxygen available; being the tunnel a obstacle for heat dispersion, the temperature can hits peaks of 1000° , melting the asphalt and collapsing the structure of the tunnel itself. For this reason, a tunnel fire can burn for hours and days before becoming reachable for the firefight teams.

2.1.2 Spread

As previously mentioned, the fire can quickly grow till becoming uncontrollable. Firstly, the fire spreads from the point of ignition to the whole vehicle by burning the flammable components.
Then, the high temperature of the produced gasses makes the nearest object burn through the radiation phenomenon; this is how the tunnel fire can subsequently catch one by one every other vehicles, spreading through the tunnel along the wind direction.

2.1.3 Combustion products and effects on the human body

For the whole duration of the fire, many combustion products are continuously produced by the combustion, and those products have a huge impact on the survival of the people involved. There are four main types of combustion products: heat, flames, gas and smoke.

- The heat is the major obstacle when it comes to go through the tunnel in case of fire; the human body cannot resist for more than five minutes with a temperature of 150°, and firefighting protections too cannot guarantee a complete or durable isolation[6]. This, along with the extreme temperatures reached by fires in confined spaces, can isolate whole sections of the tunnel, rendering useless every effort to rescue people inside.

- Flames are heat and light emission sources originated by burning combustible material, they can propagate the fire by contact with other fuel and they're characterized by a color useful to estimate the relative temperature. Most of firefighting protections have a very limited resistance to direct contact with flames (usually seconds).

- The gasses produced by combustion are numerous, and they depend on the kind of fuel involved in the combustion; they can also be extremely toxic and they can contribute to spreading by moving huge amount of heat through the tunnel.

- Smoke, instead, is composed by small unburnt solid particles, which nullify the visibility inside the tunnel and cause severe symptoms to whoever is exposed, such difficulty in breathing and burns of face, skin and respiratory system. Although operators cannot do anything for the visibility, the other effects of the smoke can be prevented by wearing special tools like masks or breathing apparatuses.

2.1.4 User behaviour

In case of emergency, the user if forced to make unusual decisions in condition of time pressure, panic and stress. This could led to wrong decisions, in the for of an incorrect behaviour which can endangering himself and other people.

Among the not recommended behaviours, the user should not.

- neglect the safety brochure provided at the entrance;
- travel through the tunnel with the radio off;
- waste time inside the own vehicle when asked to leave it;
- surpass a road obstacle by invading the opposite lane, especially in case of low visibility;
- surpass a vehicle on fire laying on the opposite lane, creating an airflow directed towards the fire hence providing comburent to the combustion;
- ignore the SOS devices, such buttons or telephones (this was more critical in the past when automatic detection systems were not available);
- get out from a safe area, unless requested by the rescue teams;
- stop the own car too close to other vehicles or too far from the right side;
- stop the vehicle when not specifically requested;
- forget to turn on the emergency lights or leaving the engine on before leaving the own vehicle.

Some of these wrong behaviours played a big part on some of the serious events described in the following section.

2.2 Severe accidents happened in tunnels

As previously mentioned, large fires are the most hazardous situations from the point of view of both users and rescue teams. For this reason, tunnel fire events have always been diffusely studied and analyzed in order to find the factors involved with the origin, the evolution and the exhaustion of the phenomenon.
This kind of events are very numerous, so the research has been focused on a limited set of representative cases of the near past.

2.2.1 Mont Blanc Tunnel (1999)

This event was probably the most severe in recent history in therms of loss of human life. On March 24, 1999 an heavy truck caught fire inside the Mont Blanc tunnel, and the large fire originated from the vehicle caused the death of 39 people.
The truck, loaded with flour and margarine, was travelling from France to Italy.

The driver, after noticing the flames coming from the vehicle, stopped the truck and unprofitably tried to extinguish the initial fire.
The fire, fueled by the truck load and amplified by the tunnel itself, reached an extreme temperature of 1000° which melted down the asphalt and caused the collapse of the ceiling.
Human behaviour also contributed to the worsening of the situation[9]. The operator in charge for controlling the ventilation system started pumping in fresh air in order to help people inside one half of the tunnel; by doing this, he also directed the hot smoke towards the people stuck inside the other half, while at the same time fueled the massive fire with oxygen.
Furthermore, vehicles were allowed to enter the tunnel even after the ignition of the truck, and emergency shelters didn't resist to the high temperatures reached inside the tunnel. It took three years and hundreds of millions of euros to make the road tunnel again operational, and the renovation brought a huge improvement to the security measures.

2.2.2 Saint Gotthard Tunnel (2001)

October 24, 2001, another serious event extended the list of road tunnel fires.
At 9:30 AM a tragic collision between two trucks took place inside the Saint Gotthard tunnel[5], in Switzerland. The heavy vehicles were loaded with hundreds of tires, and one of the fuel tank got damaged by the collision, spreading its content on the road around the crash. Then, a spark caused by a short circuit ignited the flammable liquid, causing a huge explosion followed by a violent fire.
In this case the entrance of further vehicles was prevented and rescue teams were promptly alerted; despite this, ten people died due to intoxication and one due to burning.

2.2.3 Fréjus Tunnel (2005, 2010)

Since Fréjus tunnel has been the main focus of the scenario in question, the last fire events happened inside this tunnel have been considerably analyzed during the development of the work.

The most severe one, in terms of human lives lost, took place on June 4, 2005[4]: at 6:00 PM, a truck loaded with tires suffered from a fuel loss, which generated a fire at contact with the truck engine. Four more vehicles caught fire due to radiation, since temperatures overtook 1000°, and it took four hours for the rescue teams to reach the fire from the French side. Several hours later, two human bodies were found close to the A6 shelter, probably killed by smoke inhalation because they did not promptly leave the cabin[2].

The last fire event, which inspired most the design of the work, occurred on November 23, 2010[8], and it didn't provoke any casualty. At 8:25 AM, an heavy vehicle entered the tunnel, and six minutes later the engine started producing smoke without being noticed by the driver. At the same time, the automatic detection system notifies the starting of a fire to the control center, automatically tune in to the nearest camera.

The driver stopped the truck next to the niche number 44, and the vehicles of the opposite lane kept passing by, creating air-flows and fanning the flames. At the same time, the control room enabled the smoke extraction system and alerted the rescue teams in charge, following the bi-national emergency plan.
The driver, once got out of the truck, didn't press any SOS button, and he was rescued by another driver who got through the fire by overtaking the truck, exposing himself to a huge risk of collision. Later, every civilian involved reached or was brought inside the security shelters and later evacuated, while the firefighting worked on the extinguishing till about 8:50 AM.

2.3 The Fréjus tunnel

The Fréjus tunnel is a road tunnel which links the French city of Modane with the Italian city of Bardonecchia; it's 12,895 Km long (6,8 of them in Italy), and entered into service in 1980. It's managed by two companies, the Italian SITAF[1] and the French SFTRF[2], each with a section of competence.

2.3.1 Original structure (1980)

Initially, the tunnel was composed by a single barrel with the following characteristics[7].

- Length: 12.895 m.
- Quota at Italian entrance: 1.297 m.
- Quota at French entrance: 1.228 m.
- Slope (descent from Italy to France): 0.54%.
- Average length between sidewalks: 10.10 m.
- Traffic lanes: 2.
- Usable length for traffic: 9 m.
- Maximum height allowed: 4.30 m.
- Maximum height up to false ceiling: 4.48 m.
- Lay-bys: 5 (every 2.100 m circa).
- Lay-by length: 40,5 m.
- Lay-by width: 2 m.
- U-turns: 5 (every 2.100 m circa).

[1]Società Italiana per il Traforo Autostradale del Fréjus per Azioni
[2]Société Française du Tunnel Routier du Fréjus

- U-turn length: from 3 m to 8,5 m.
- U-turn usable length: from 6 m to 7,5 m.
- French-side outside service area: 32.000 mq.
- Italian-side outside service area: 35.000 mq.

After the Mont Blanc accident (1999), the tunnel security has been greatly improved in order to avoid similar events. In particular, the user can find the following tools.

- Yellow tracking lights on piers every 20 m.
- Blue lights on piers every 150 m indicating the safe distance.
- Semaphores every 530 m.
- SOS niches every 265 m, equipped with 2 extinguishers, 1 220 V 16 A wall socket and 1 telephone.
- SOS buttons every 20 m, corresponding to lights on piers.
- Hydrants every 130 m, connected to water pipes.
- 11 ventilated security shelters, protected by a fire-wall door and equipped with 1 medical kit, 2 5-tank racks of oxygen, 1 communication module, 1 extinguisher, 6 bottles of water, 1 bench and 1 information and localization sign (being gradually replaced by the new bypass shelters linked to the second barrel).

The traffic is continuously monitored by 241 security cameras:

- 204 fixed cameras inside the tunnel;
- 11 security cameras inside the shelters;
- 5 for the garage areas;
- 12 cameras in the Italian service area;
- 9 cameras in the French service area.

In case of alarm, the footage is streamed to the control room on various monitors depending on the type of alarm (road or DAI[3]).

- Road alarms are triggered by opening the door of a niche, by pressing an SOS button, by opening a shelter door, by opening a door to the ventilation duct or by activating of the communication module inside a shelter.

[3] *Détection Automatique d'Incidents*, a type of alarm which is automatically triggered in case of incidents

- DAI alarm are automatically enabled when a vehicle stops or slows down below the minimum mandatory speed, in case of traffic jam, or when a vehicle is emitting smoke in an unusual manner. Those kind of alarms are transmitted to the control room in form of one minute video-clip over a touch console, allowing the operator to inspect the cause.

As previously mentioned, the tunnel Authority also transmit on two frequencies (103.3 FM and 107.7 FM) various recorded radio messages to guide the user in every kind of situation (Table 2.1).

Table 2.1: List of the reproduced radio messages

Message type	**Message content**
Standard	Welcome to the Fréjus tunnel. For your safety, the tunnel is equipped with a video-surveillance system. The compulsory distance between vehicles is 150 m, two blue lights every 150 m must separate your vehicle from the one travelling in front of you please observe speed limits, minimum 50 km/h, maximum 70. In case of emergency, move to the right side and stop your vehicle and follow the safety instructions you were given at the toll booth, always listen to the radio and have a nice trip.
Emergency	Attention please, attention please, stop at the red light, turn off the engine of your vehicle, quickly reach a safe green area indicated by flashing lights, help anyone who finds himself in difficulty.
Inside shelter	Welcome to the safe area, this area is ventilated with fresh air and you will be able to wait until a rescue team arrives. Make sure the access doors are tightly closed. Carefully follow our instructions and read the information cards. The control room operators are informed of your presence in this safe area. In case of emergency, you can directly contact an operator by pressing the SOS button. Do not go back into the tunnel, stay in the safe area, here you are safe. Try to keep the people in your group calm, a rescue team is on the way to take you out in safe conditions.

In addition, a large number of operative radio frequencies are re-transmitted, in order to guarantee the communication for the rescue teams in case of emergency.

2.3.2 Security tunnel (2009)

The doubling of the tunnel was planned in 2009, in principle as security tunnel only; the work started in 2011, and the excavation was completed in 2014. Since then, both Italian and French Authorities started the creation of a newly designed by-pass shelters, providing a connection between the traffic tunnel and the new security tunnel; the French half already divested the old shelters in favour of the new by-passes, while the Italian half is still working on the conversion.
The presence of a second tunnel greatly improves the freedom of movement of the rescue teams, giving them a way to get close to the fire and to rescue people without having to deal with smoke, heat and abandoned vehicles.

2.3.3 Conversion of the security tunnel to transit tunnel (2012-2019)

The current long term plan for the security tunnel (formalized in 2012 and provided for 2019) is a conversion of the security tunnel to road tunnel[1]. The main goal of this decision is to reduce the probability of head-on crashes to zero by splitting the two directions of travel between the two barrels, and at the same time to increase the volume of traffic bearable by the tunnel.

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