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# Computational Intelligence and Agent Paradigm for Intelligent Tunnels Design

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### Abstract

Tunnel safety is a problem of great interest. Recent tragic events have led community and politicians to start a process of legislation harmonization planning investments toward new technologies designed to improve tunnel safety. The purpose of this paper is to present an innovative system aiming at monitoring and steering vehicular flows nearby tunnels with high accidents risk rate. Based on the integration of IC, video, agent and soft computing technologies, the system mission is to reduce the risk of accidents which occur inside tunnel through the adaptive generation of speed limits and information to the users approximating tunnels. Hard real-time requirements of the applicative context impose our goal being achieved through a parallel Hierarchical Fuzzy Controller (HFC) implemented by means of a Fuzzy Control Agents Network (FCAN) allowing the system to gain higher performances. The fuzzy controller is divided into several sub controllers conceived separately. Some of these, adopt in turn a hierarchical prioritized structure.

**Keywords:** intelligent agents, ambient intelligence environments, priorization, distributed hierarchical fuzzy control

## 1 Introduction

Mobility is essential for growth in competitiveness of the countries and for free movement of citizens. Nevertheless, the growing need for people and goods transportation leads to a constant increase of road traffic and represents a huge safety challenge. In the European Union (EU), for instance, where the transit by road represents 44% of transport of goods and 79% of transport of passengers of the entire Union, road accidents in 2001 led to nearly 40000 deaths and 1.7 million injured with a direct and indirect cost estimated at 160 billion euros [1]. In Italy, where about 60% of goods and 85% of passengers use transit by road, the cost is estimated at 10 millions of Euro each 100 km of road [2].

These facts have highlighted in turn road safety as a priority in the EU. Many actions to improve road safety have been taken by each country and by the European Commission (EC) itself with the target to halving the number of road deaths by 2010. Main measures concern both the carriage of hazardous goods and the critical parts of the road infrastructure, as well as tunnels. Tunnels, in fact, are among the most critical elements of the road infrastructure, especially when very long or characterized by high traffic density (highway tunnels or fast roads): accidents in tunnels, particularly when involving fires, can have dramatic consequences and prove extremely costly in terms of human lives, increased congestion, pollution and repair costs [3], [4].This risk is increasing either because of tunnels getting more and more older (most of them having been built in the 60s' and 70s').

In such a context, the Italian situation appears to be quite complex due to both traffic growth and peculiarity of its territorial orography, making Italy the European Nation with the highest number of road tunnels with a length over 500 meters (246 tunnels compared to the 34 that represent the European average).

In order to improve safety in the existing and new tunnels, a new directive [5] has been issued by the EC favoring a more uniform, constant and higher protection level for all European citizens of the Trans-European

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road Network (TEN). Moreover, this law will require a significant investments plan ranging, only for TEN tunnels, from 2.6 and 6.3 millions Euro, depending on low or high expected engagements.

Since it is financially and (very often) technically impossible to provide emergency lanes or escape roads within such tunnels [6], in this context, a meaningful aid can be offered by the introduction of new information and communication technologies (ICT) to control both the infrastructures and vehicular flows [7], [1], [3]. The use of advanced transport telematic systems can bring significant benefits as regards environment, efficiency, productivity and, mainly, transport safety [1], [7].

This paper presents an innovative system aiming at monitoring and steering vehicular flows nearby tunnels with high accidents risk rate. The primary goal of the system is to reduce the risk of accidents significantly in tunnels through an adaptive generation of both road speed limits and infomobility services to drivers getting closer to tunnels. These services are meant to be provided by using Variable Message Signs (VMS) distributed along the road nearby the targeted infrastructure.

The system (financed by the Italian Ministry of the University and of the Research), is based on the integration of standard IC and video technologies with agents paradigm and soft computing. Vehicles approaching tunnels are identified by four telematic portals equipped with CCTV cameras for traffic flow monitoring that watch each lane of the roadway. The information is first locally treated by a microprocessor obtaining instantaneous vehicle speed, vehicle classification, traffic jam detection and wrong way vehicle detection. Afterward, a pro-active agents based hierarchical fuzzy controller architecture identifies potentially dangerous behaviours and infers corrective actions to be suggested at vehicle drivers by means of VMS.

The system has been conceived by researchers from the University of Salerno in the context of SITI (Safety In Tunnel Intelligence) project conducted by TRAIN consortium (Consorzio per la Ricerca e lo Sviluppo di Tecnologie per il TRAsporto INnovativo), with the University of Salerno among its associated members [8]. The project expects the implementation of a testing site on the S.S.145 Dir. Sorrentina, a dual carriageway main track road with high traffic density, joining the highway Napoli-Pompei-Salerno with the municipalities of Sorrento Peninsula in the region of Campania.

The paper is organized as follows: the whole architecture and its main modules are described in Section 2. Sections 3 and 4 focus on the modeling details of the system explaining the mechanism of a hierarchical fuzzy controller upon which BF activities are based. Then, a hierarchical prioritization schema is presented in Section 5 as a way to improve system responsiveness. Finally, some brief remarks and future works recommendations will follow in Section 6, where a short report on the state of art of existing works related to tunnels and roads safety is therefore proposed in order to point out the benefits arising from the adoption of the system under discussion.

## 2 Architecture Overview

SITI system is made up by several different sub-systems that, once integrated, build up a complex architecture designed and implemented according to the agent paradigm, i.e. as a multi-agent system whose distribution model is a *central index peer-to-peer model* where communications rely on *asynchronous message passing.* The whole system is designed as an n-tier web-centric application according to the logical schema depicted in Figure 1.

- *Data Tier* provides data storage and retrieval services.
- *Data Access Tier* holds generic patterns and methods to support data usage.
- *Business Tier* embodies objects and rules needed to process and manipulate data.
- *Presentation Tier* provides the interface between the application ('business') and users.

Due to its peer-to-peer distribution model, based upon the agent paradigm, the system architecture has been analyzed and designed through a set of architectural views according to the *GAIA Agent Oriented Software Engineering technique.* Each view uses specialized notations depending from the system aspect on which it is focused. In particular, during the analysis of the behavioural forecaster and control system, we took mainly care of roles and interactions models, while, on a design level, agent, acquaintances and services models have been adopted. The diagram depicted in Figure 2 presents the general architecture of the vehicles

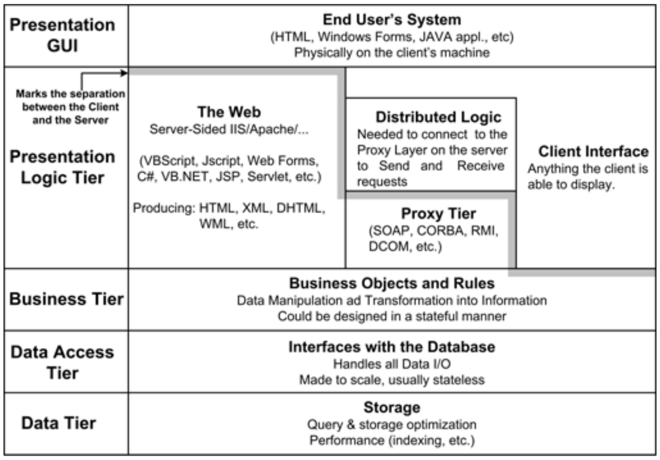

Figure 1: N-Tier applications logical schema

behavioural forecaster under development, showing all its fundamental components. As can be seen, the system is composed by three main interconnected sub-systems.

- *Behavioural Forecaster - BF* system, realized as a FIPA (Foundation for Intelligent, Physical Agents)-compliant multi-agent system, along with a web services based interface allowing interactions from external systems.
- *Behavioural Forecaster Interface - BFI* in the form of a web-centric multi-tier application, using BF as data and services source.
- *Support systems* providing generalized services, such as an UDDI server where BF services are published and a Media Server where infrastructure monitoring video streams are retrieved.

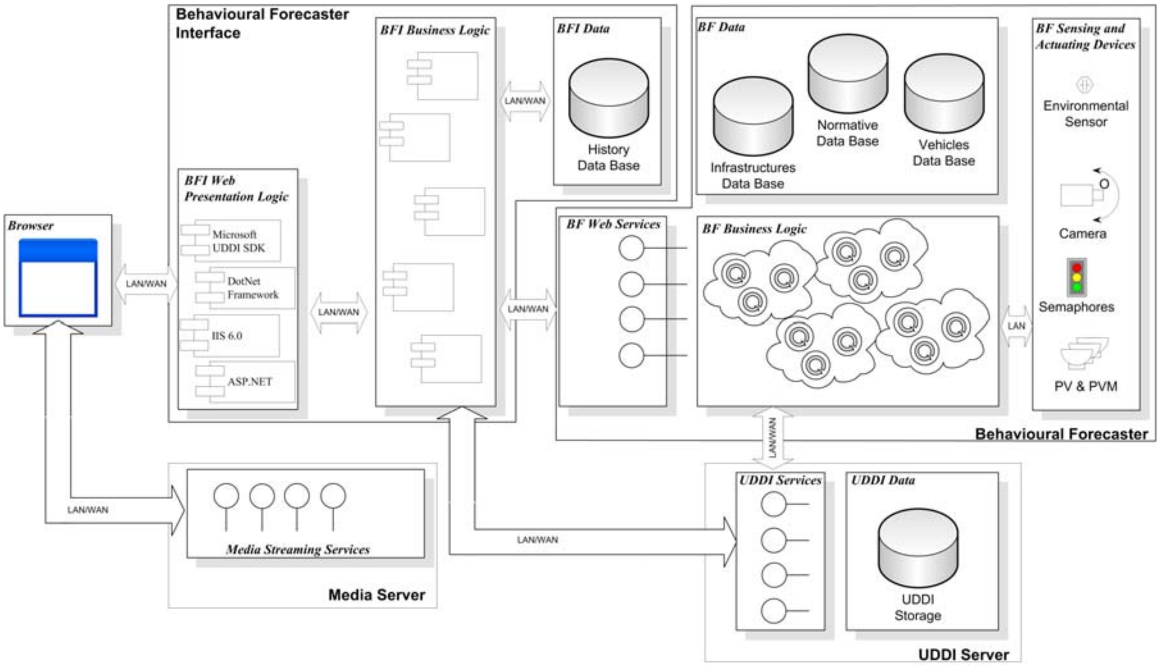

Figure 2: General architecture of the Behavioural Forecaster

Sub-systems are integrated in order to compose a multi-tiered stack where

- BFI works as Presentation Logic Tier on behalf of the whole system.
- BF plays a twofold role, it acts both as system's Business Tier and BFI Data Tier.
- Support systems, fundamentally, operating as system's data tier.

It is worth noticing that, as depicted in the diagram, in turn each sub-system is designed to be a multi-tiered application itself, in order to provide and ensure the whole system scalability. Furthermore, the adopted technologies are intentionally different. This is due to the need to enhance the driving principle relying on a design approach based on the maximum interoperability with technologically different systems. Thus, BF has been implemented using Java$^{TM}$ Enterprise Edition technology while BFI has been implemented using Microsoft$^{TM}$ .NET technology.

## 3 Modeling View

The system defined to tune road tunnels vehicular flow proposes itself as a short-medium term solution to the tunnel safety problem. According to the European Commission's programmatic guidelines in terms of tunnels safety, the goal of the project is to help the prevention of critical events by operating on tunnel management and users' behaviour, i.e. two out of the four categories, besides infrastructure and vehicles, which are able to affect road tunnel safety level. In particular the system gives behavioural directives to users driving toward road tunnels in respect of the infrastructure condition, to prevent or mitigate human failures consequences.

From a technological point of view, the project is characterized by a high architectural, modelling and methodological innovation level. The designed system is based on a set of telematic portals appropriately spaced, to identify/detect and subsequently monitor vehicles driving towards/fromwards tunnels. Measurements at each check point will enable the system to infer potentially dangerous behaviours which will increase the risk of tunnel accidents if not properly regulated.

The system will autonomously produce appropriate messages to alert vehicle drivers about the potential danger of their behaviour to make them more sensitive to safety issues; while at the same time tuning and uniforming the vehicular flow to help decrease the risk of accident. These messages will be shown on variable message signs (VMS) distributed along the road.

In the same way, the knowledge of number, class and speed of each vehicle as well as road status and environmental conditions allow the system to evaluate dynamically and adaptively suggested maximum speed limits both inside and outside the road tunnel. In the last case, speed limits will be evaluated and customized for each inter-portal segment and shown by means of VMS. Whereas, inside the road tunnel this information will be presented by instructing a light guide in the form of a follow-me wave moving at the suggested speed and indicating the safety distance to keep from preceding vehicles.

Among the others architectural components, *Behavioural Forecaster* constitutes the real heart of the monitoring and traffic flow steering system. Based on soft-computing and agents technologies [14], it works on a virtual projection (cyber-space) of the controlled infrastructure (as depicted in Figure 3). The big picture expects this projection to associate a software agent to each vehicle driving on the road towards the tunnel. Each agent is in charge of monitoring and classifying the driving behaviour of a buddy vehicle, taking into account observations and measurements performed by sensor devices w.r.t. the general conditions of road infrastructure, traffic and environment.

The evaluation of this set of conditions is one out of several activities under the care of *Portal Agents*. Indeed, a further responsibility in charge of the *Portal Agent* requires it to act as a bridge with the video surveillance system, packing measurements and identification data to be forwarded to the corresponding agent. An instance of this kind of agent is associated to each telematic portal and controls the segment between the buddy portal and the subsequent one.

## 4 Hierarchical Fuzzy Control

Due to strict real-time requirements provided by the applicative context, evaluation and control activities are really achieved through several parallel Hierarchical Fuzzy Controllers (HFCs) implemented by interconnected Fuzzy Control Agents Networks (FCANs). Namely, each node of an HFC has been implemented by an intelligent agent playing fuzzy sensor, fuzzy consumer or fuzzy inference engine role. This way, the big

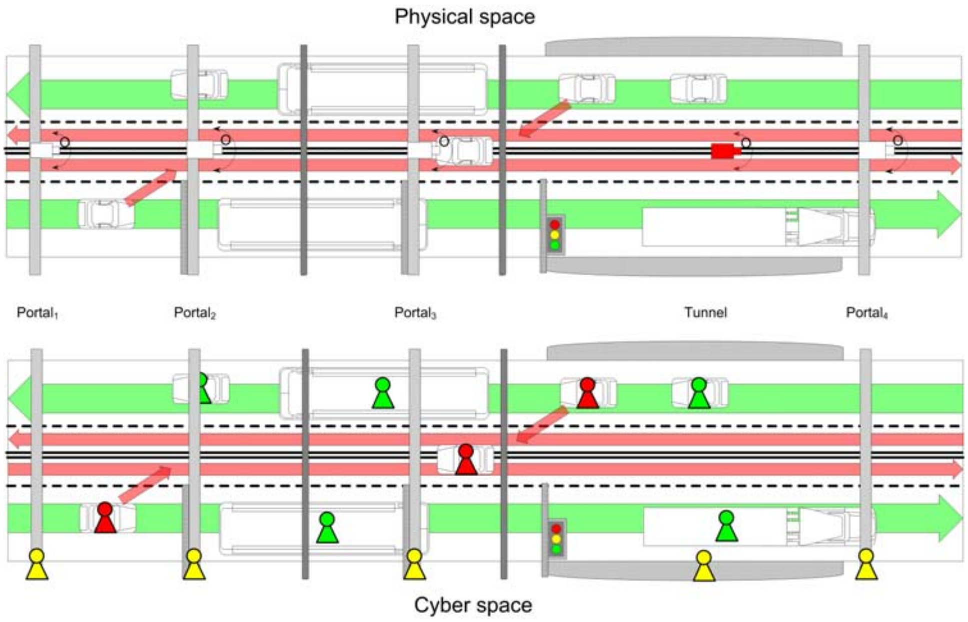

Figure 3: Cyberspace projection of the controlled infrastructure

picture's agents have been implemented by given sets of agent nodes, namely *agencies*, acting in the whole as a single entity.

The chosen schema provides many benefits to the Behavioural Forecaster. First, allowing each controller's node to work parallelously the system gains higher performances. Furthermore, the chosen implementation allows to exploit agent paradigm's specific proactive coordination and social features in order to:

- Decide how to trigger control activities;
- Implement prioritized rule base evaluation schema while preserving the computational parallelism;
- Reconfigure dynamically the control network at run-time.

Finally, choosing an agent-based implementation the system is able to scale up easily by modifying, replacing or adding new agent-wrapped sensors or actuators, thus enhancing the whole system scalability and flexibility.

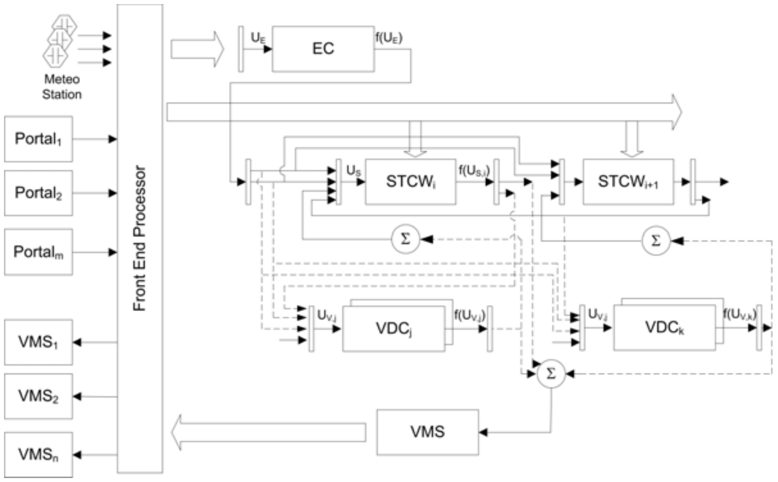

Figure 4: Hierarchical Fuzzy Controller architecture

As shown in Figure 4, the global hierarchical fuzzy controller (from now on we will call it as *BFHFC - Behavioural Forecaster Hierarchical Fuzzy Controller*) has been split into several components each designed separately. In the depicted diagram all arrows represent a data flow path. Solid arrows represent unconditioned continuous data transmitted with a producer-consumer approach. Whereas, dashed arrows indicate social coordination depending data transfers, i.e. data explicitly queried through ad hoc interaction protocols.

BFHFC can be described by the following hierarchical fuzzy control components:

- *Environmental Condition - EC* inference engine, which evaluates the road status due to environmental conditions;

- *Segment Traversing Conditions Warning - STCW* inference engine, which evaluates a specific inter-portal road segment running-through warning level;

- *Vehicle Driving Conditions Warning - VDC* inference engine, which evaluates the driving behaviour of a given vehicle running through the road towards the tunnel.

All of these HFCs are implemented adopting a hierarchical prioritized structure [16] exploiting agents' proactive coordination and social features.

Figure 5 depicts the structure of EC inference engine. Reading inputs from a meteorological station and a light sensor, EC produces two fuzzy measurements, *Slipperiness* and *Visibility* respectively indicating road adherence status and visibility conditions, both of them w.r.t. environmental or climatic conditions. These values are referred to as relevant information affecting road running-through warning level while enhancing vehicles' dangerous driving behaviours.

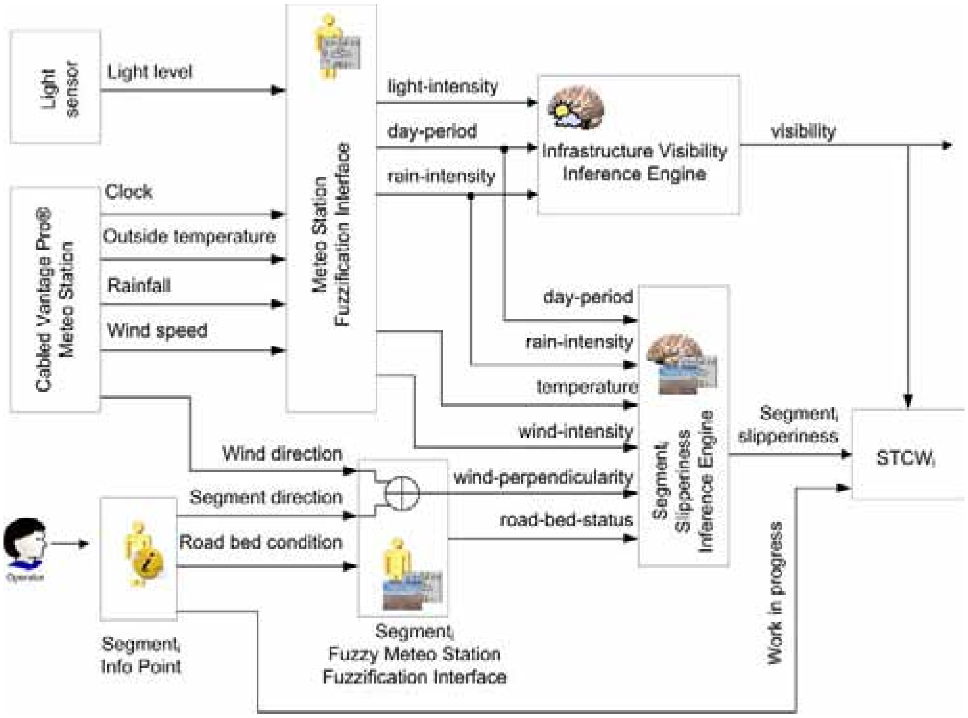

Figure 5: Environmental Condition Inference Engine

The EC has been actually split into two kinds of components:

- a *global* visibility inference engine, in charge of evaluating the whole infrastructure visibility conditions given light intensity, hour of day and rain intensity; and

- a set of *localized* slipperines inference engines, each of them in charge of inferring a specific road segment slipperiness. As a manner of fact, this latter depends on a more specific and localized set of features such as the road-bed status (whether it's new or worn-out), the road segment direction w.r.t. the wind intensity and direction, and so on. Thus, a localized slipperiness inference engine has been defined for each controller's STCW.

A STCW inference engine represents the virtualization of a telematic portal and monitors the road segment between buddy physical portal and its subsequent one. Given that, BFHFC has as many STCWs as telematic portals each of them dedicated to monitoring and steering a fixed road segment. STCW (Figure 6) produces both a fuzzy measure and a crisp value. The first value states the *warning level* a vehicle have to take care of when running through the STWC's monitored segment. The latter element provides a *suggested speed limit* to comply with in order to preserve driving safety. This speed limit will be shown to users through the aforementioned modalities (i.e. by VMS, VSS or sliding lights). Vice versa, the *warning level* is used to feed other BFHFC components needing it as input. This is particularly true when looking at the STCW itself. Here the *warning level* evaluated at a STCW is used as input to the former one on the road to the tunnel (if present). Adhering to this feed-forwarding schema allows each STCW to take care of eventually occurred accidents along the road to the tunnel. The *warning level* is still fed as input to VDC, the last considered HFC component. A VDC inference engine is implemented by a fuzzy control agency. It corresponds to an identified physical vehicle driving on the road towards/fromwards the tunnel. As to STCW, BFHFC has as many VDC's instances as vehicles currently on the road. Each VDC is in charge of evaluating the driving behaviour of the buddy vehicle w.r.t the running through warning level of the road segment on which it is currently located together with road-bed general status and visibility conditions. Besides the latter set, VDC has crisp control inputs including vehicle's class and speed, engaged lane and driving direction. These inputs are fuzzified first through suitable membership functions, then the fuzzified values are fed into a HFC to be processed. The inferred output is the *vehicle's driving warning level.* All fuzzy results obtained by VDCs running through the same STCW are aggregated and used to produce an indicator fed as input to the STCW itself in order to update its driving through warning level.

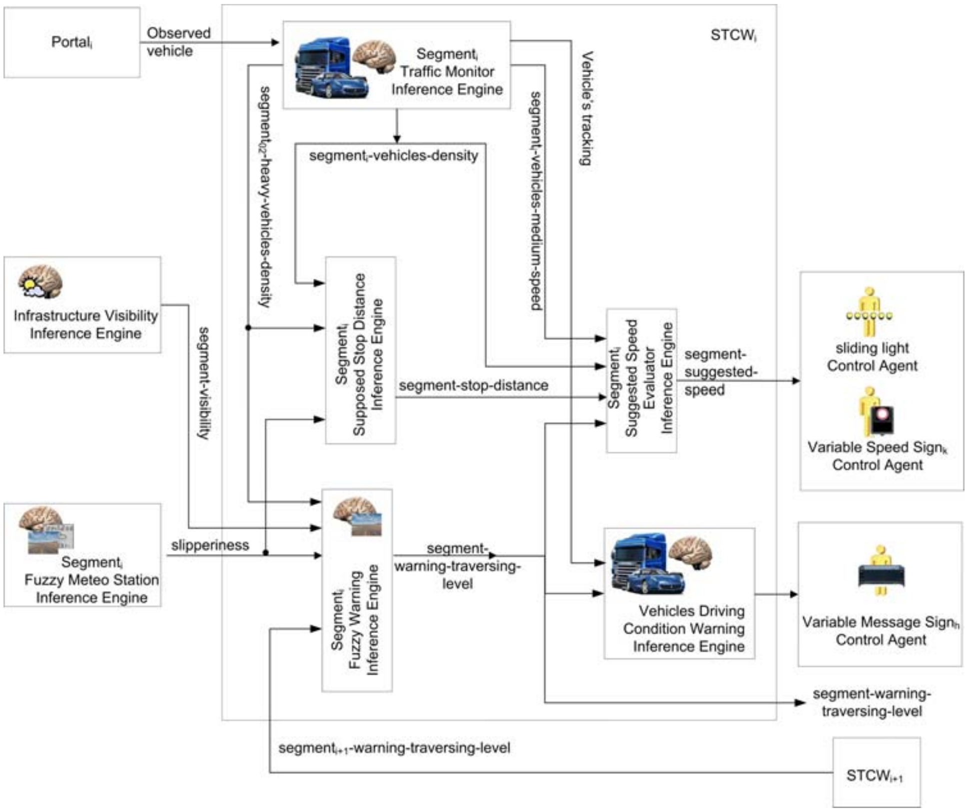

Figure 6: Segment Traversing Condition Warning Inference Engine

Dealing with VDC let us use the occasion to talk about the dynamic structure of BFHFC. Indeed, the one presented in Figure a particular instant. At any time triggered by new physical portal vehicle's identification or tracking, each STCW has a given number of VDC registered at and depending on it which are feed forwarding in turn aggregated behavioural information. Each such triggered event allows:

- New VDC to be introduced into the system;
- Existing VDCs migrated from a STCW to the next/previous one;
- By exiting the monitored infrastructure useless VDCs to be removed;

letting the BFHFC architecture provided by fuzzy control agents (FCAs) to be reconfigured on intentional basis.

Moreover, BFHFC components' activities are triggered by different event types and timing, i.e. they generally use different triggering and data transfer strategies.

As already aforementioned, VDCs' activities are triggered by physical portals vehicle's identification or tracking which provide crisp control inputs. All the other hierarchically produced fuzzy control inputs are explicitly obtained by means of ad hoc interaction protocols with intentionally specified peers. On the contrary, STCW activities are continuous in that it applies fuzzy inference mechanism as soon as new control inputs are provided, resulting in a continuous evaluation and updating of control outputs.

## 5 Hierarchical Prioritized Structure of HFCs

As already stated in previous sections, due to strict real-time requirements provided by the applicative context, all HFC components have been designed with a hierarchical prioritized structure (HPS) according to [16]. The general implemented structure is depicted in Figure 7. Here the overall fuzzy control function relating the input $\bar{U}$=$\langle u_1, ...u_m \rangle$ to the output $V$ is composed of a whole collections of sub boxes. Each sub box, denoted $f_i$, is a collection of rules relating a part of the system input $\bar{U}$ and the current iteration of the output, $V_{i-1}$, to a new iteration of the output. The output of the $n^t h$ subsystem becomes the overall output of the control system. As stated in [16], "*for i<j we say that $f_i$ has a higher priority than $f_j$*". It is worths noticing here that in our prioritized envision, the highest priority box has commonest rules with antecedents stating conditions whose truth supersedes any other possible reasoning. Out of that, the prioritized boxes have been designed in order to specify at higher priority levels less general information (by set of rules with more specific antecedents) than those of lower priority. This allows both avoiding the most specific information to be swamped by the less specific one and gaining better performances when dealing with commonest (higher firing level) rules. Refer to [16] for a deep and formal analysis of HPS definition and functioning.

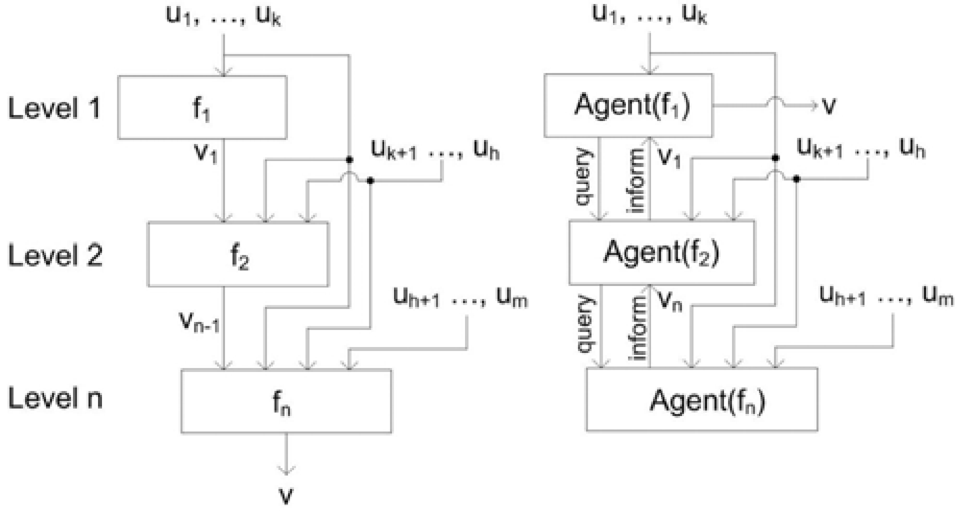

Figure 7: Hierarchical prioritized controllers' general structure

Due to the chosen agent based model (Figure 7) the outputs aggregation has been performed on intentional basis and reversed order. Namely, at each hierarchy level corresponds an agent in charge of evaluating the associated rule base and acting as a standard Mamdani type controller. All hierarchy levels are evaluated independently an concurrently. When the rule base held by Agent($f_i$) matches low the input data, the agent requires the inferred control value to the immediately lower priority agent, Agent($f_{i+1}$). Once received, this value is used to produce

$$V_j = V_{j+1} \bigcup \tilde{B}_j$$

where $\tilde{B}_j$ is a value of $V_j$ obtained by the aggregation of the output of the collection of rules of $f_j$.
This schema allows faster performances both parallelizing rules blocks evaluations and avoiding the introduction of artifact antecedents when evaluating prioritized rule bases.

# 6 Conclusions

There are many ongoing financed projects taking place in the European context which connect telematic applications to road tunnel's safety [10, 11, 8]. These applications are based on the tight integration of sensing systems, (often redundant) communication infrastructures and elaboration systems proposed both with multiprocessor architectures and traditional ones.

Among the others, a prominent position is held by two systems. The first is the traffic monitoring and control system applied to the Jack Lynch Tunnel at Cork in Ireland, which integrates detectors, cameras and variable message signs in order to identify critical safety conditions, as well as traffic jams or accidents, by an automatic observer of critical situations which are being signaled to tunnel operators in real-time. The second is the surveillance and traffic monitoring system of the Oslo Tunnel, inaugurated on January 1990, which is able to point out accidents and anomalous conditions as well as traffic data.

Latest realizations rather than specific solutions for particular tunnel needs, propose modular platforms integrating standard solutions while offering added value services to operators in charge of monitoring and controlling road tunnels [9]. Among the commonest services there are functionalities designed to control either normal or emergency lighting, air flows, pollution, VMS, and emergency signaling systems.

Referring to used sensor devices most applications propose tunnel management oriented solutions and require supervision and control human checkpoints. They are generally very expensive and not spreadable on the territory so to be applied to medium sized road tunnels, which according to statistics present the highest accidents ratings.

The proposed system, on the contrary, has been thought of as a system able to reduce tunnel accidents by an unsupervised automatic tuning of vehicular flow in proximity to tunnels. Focus is the use of agent paradigm as a means to realize fast distributed hierarchical fuzzy controller with smooth control surfaces. Indeed, the described system reaches high levels of scalability due to the underlying adopted agents technology. In particular, the system exploits the runtime construction, maintenance and tailoring of hierarchical fuzzy control networks capabilities provided by the FuzzJADE[23] framework. These, in their turn, exploiting agent paradigm main characteristics enable the development of any desired schema allowing to take into accont simple serialized schemas as far as hierarchical prioritized ones.

The system readily offers information to users getting closer to tunnels and indicates the most convenient driving behaviour by evaluating the general status of road infrastructure, environmental and traffic conditions. In such a way the system may prevent human failures or reduce occurred road accidents consequences.

The adopted modular architecture and its scalability will allow to extend system's functionalities by easily integrating the monitoring system with preexisting control components. With regards to this, as future work, the integration with automatic tunnel fire-prevention and fighting systems as well as ventilation control systems will be inspected; thus overcoming latencies of other adaptive systems based on monitoring pollution gases (such as CO) and smokes concentration. This integration will allow both to adapt the ventilation system instantaneously as the tunnel traffic increases (thereby avoiding to reach critical CO levels with positive repercussions both on healthy and safety) and react quickly to fire events.

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