

On Multiagent Co-ordination Architectures: A Traffic Management Case Study

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Abstract

This paper reports our experiences with agent-based architectures for Intelligent Traffic Management. We describe and compare TRYSA and TRYSA₂, two multiagent systems that perform decision support for real time traffic management in the urban motorway network around Barcelona. Both systems draw upon similar traffic management knowledge, but the former is based on a centralised architecture, while in the latter co-ordination emerges upon the lateral interaction of autonomous traffic management agents. We conclude that the centralised approach applied by TRYSA promotes efficiency for real time operation, whereas the decentralised approach used in TRYSA₂ promotes scalability.

1. Introduction

The increasing popularity of road transport and the incessant rise of the number of vehicles have caused a tremendous growth of the magnitude of traffic flows on public roads. Especially in urban areas, where the road network is dense and the traffic volume in peak situations is enormous, significant economic losses are produced by enduring and recurrent congestion. So, the complexity of the task of traffic engineers has grown enormously, and it becomes harder and harder for them to take good control decisions in real time. This is particularly true for the case of Barcelona, as in the follow-up of the 1992 Olympic Games the traffic management infrastructure has become increasingly complex. The urban motorway network, consisting of one ring-road and seven adjacent motorways, is endowed with 52 Variable Message Signals (VMS), 3 traffic lights for junction control, ramp metering on 7 ring-road drives and over 300 telemetered sensors ("loop detectors"). These devices are connected to the Barcelona Traffic Control Centre (JPT) by means of high performance fibre optics communication links, which allow for fast transmission of sensor data. This general scenario is sketched in figure 1.

In this paper, we compare two multiagent traffic management systems aimed at providing decision support to JPT traffic operators: based on real-time traffic data, congestion situations that may simultaneously appear in different parts of the network are detected, and control plan proposals are automatically generated. These proposals, along with their justifications, are presented to the operators, so as to outline possible courses of action and to promote the operators' confidence in their final decision. In section 2, the basic characteristics of centralised and decentralised multiagent traffic management for the Barcelona case are outlined. In section 3 and 4, we describe the TRYSA and TRYSA₂ system, respectively, in further detail. Finally, in section 5, we draw conclusions from a critical comparison of both architectures.

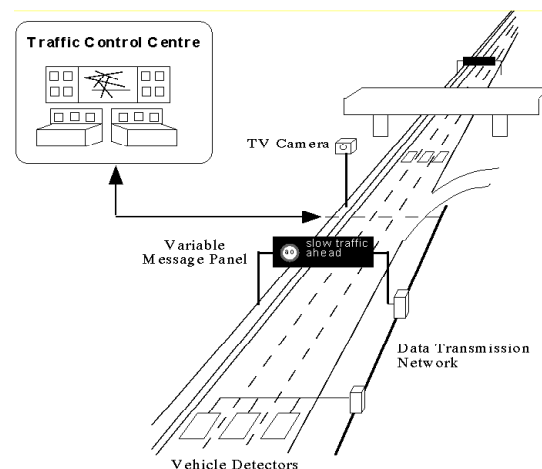


Figure 1. Traffic management scenario

2. Agent-based Intelligent Traffic Management: TRYSA and TRYSA₂

In the last decade much work has been devoted to incorporate an intelligent reasoning layer into conventional traffic management applications in order to allow for strategic management and intelligent

supervision of traffic behaviour, giving rise to *intelligent traffic management systems* (ITMS) [1,2,3,4]. At the same time, the multiagent paradigm has become increasingly popular, as there is growing evidence that agent-based architectures allow for an efficient construction of scalable software systems [10].

TRYS and TRYSA₂ (TRYS Autonomous Agents) are two agent-based ITMS for the Barcelona road network. They show significant similarities:

- (a) Both are knowledge-based applications for real-time traffic management in periurban networks.
- (b) The topological structuring approach is the same: the organisation of knowledge and reasoning matches the topological organisation of the traffic network and its spatial break down into a set of distinct but overlapping problem areas.
- (c) The knowledge and reasoning related to different problem areas are kept in distinct agents. These traffic agents receive traffic data, detect traffic problems in their problem area, diagnose their causes and generate signal plans to overcome them.

However, both systems differ significantly in the way that these traffic agents are *co-ordinated* (as shown in figure 2).

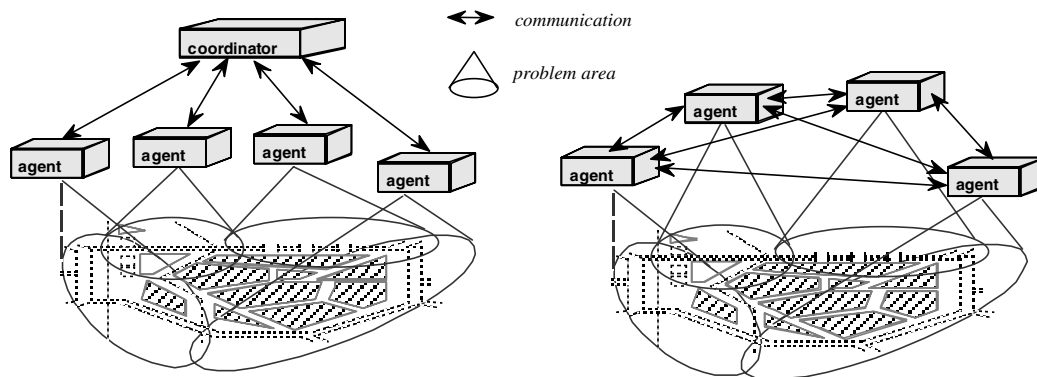


Figure 2. Centralised (TRYS) and decentralised co-ordination (TRYSA₂)

In TRYSA₂, 11 spatial problem areas are controlled by *autonomous* (self-interested) traffic agents that co-ordinate laterally, based on a mechanism called *structural co-operation* [6]. Control devices “belong” to certain agents, and the corresponding mutual dependence (agents may exchange favours respecting the use of “their” devices) provides a potential for co-operation. Normative prescriptions permit or forbid the use of some devices for certain agents, thus biasing agent interactions and influencing self-interested agent behaviour, so as to make it functional with respect to the desired traffic management functionality [7]. In the sequel, we will describe relevant details of both architectures.

3. A centralised approach: TRYS agents

In line with the traffic engineer’s logical subdivision of the road network into *problem areas*, the TRYS system [5] relies on a set of knowledge-based 18 traffic control *agents*, each responsible for traffic management in one such area. This number of agents was obtained considering both senses of traffic for every major adjacent road, and a partition of the Barcelona ring road in four parts. The traffic control infrastructure available included 52 VMS panels, ramp metering in 7 entrances to the ring road and more than 300 single and double loop detectors.

The network areas assigned to the agents are control dependent, as some agents have to share control devices. Therefore, a co-ordination mechanism that allows for the simultaneous enactment of the agents’ local control plans is required. The TRYS system faces this problem by means a special co-ordinator agent endowed with knowledge on how to integrate local control proposals into a coherent global signal plan for the whole traffic network [5]. It receives local control proposals from the traffic control agents, resolves conflicts between them, and sends the resulting globally consistent local signal plans back to the traffic agents.

In the TRYS system, agents are endowed with four main types of knowledge: possible traffic problem scenarios, potential traffic control proposals, and regarding traffic behaviour in the network, the network structure and historic traffic demand. This knowledge endowment has been organised in so-called Knowledge Units [5]. A knowledge unit identifies a knowledge block where both what the unit knows and what the unit does with this knowledge are put together. Then, a knowledge model is a hierarchically organised collection of knowledge units.

The *Behaviour* knowledge unit includes all the information related to traffic behaviour in the network. This information is organised in two other knowledge units: the *Physical Structure* unit and the *Demand Knowledge* unit. The *Physical Structure* unit perceives the

scenario data from loop detectors etc., records it, and analyses it to deduce signal information, basic traffic qualitative magnitudes (i.e. speed, occupancy, flows) and certain aggregated measures (i.e. traffic volume generated in an entrance node, spatial gradient of speed). This unit includes both static information about the topological structure of the problem area (components and their relationships) and the dynamic aspects of this structure. The physical structure is formulated using a declarative description of the network as a graph with nodes and links together with abstraction functions associated to components.

The procedures applied with this kind of knowledge are data abstraction methods that compute qualitative values from basic traffic parameters provided by sensors, i.e. speed, occupancy, saturation. Figure 3 shows the functions used to abstract the speed, saturation and occupancy numerical values. These functions are fuzzy sets that although they are generally defined, it is possible to add particular versions of these functions for specific parts of the roads.

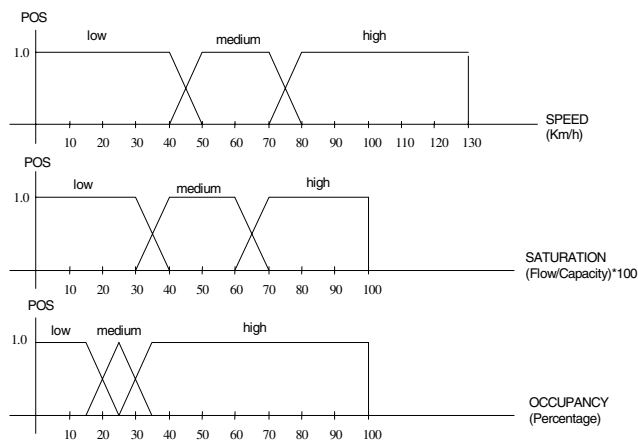


Figure 3. Fuzzy sets to abstract traffic values from numerical data.

The *Demand* knowledge unit contains historical information of traffic flow distribution among the different entry and exit points in the network. This information is represented through hierarchies of patterns of demand associated to temporal intervals. The use of this knowledge by an origin-destination flow assignment method generates an estimation of demand distribution scenarios that can be used both to support the diagnosis of traffic problems and the evaluation of control proposals.

Figure 4 shows a partial example of such a demand pattern. The first set of slots is used to define the temporal range where this demand is active, e.g. in this example, a working day from 6:30 am to 9:30 am. Then, slots representing origin-destination pairs with an approximate estimation of the traffic flow are included. For instance, from the origin Mataro to the destination Badalona Norte

there will be an approximate flow of 1000 veh/h. This type of frames are not general, i.e. they must be given for each particular traffic area.

FRAME morning peak TYPE weekday pattern	
type of day:	labour day,
temporal interval:	6:30 - 9:30,
....	
Mataro -> Badalona Norte:	1000 veh/h,
Mataro -> Badalona Centro Sur:	1000 veh/h,
Mataro -> Zona Urbana:	2000 veh/h,
Mataro -> Glories:	2000 veh/h,
NII -> Badalona Norte:	500 veh/h,
NII -> Badalona Centro Sur:	500 veh/h,
....	
Badalona Centro Sur -> Glories:	1000 veh/h.

Figure 4. Partial example of a pattern of traffic demand.

The *Traffic Problems* knowledge unit matches the situation described by the traffic data with a frame base of *problem scenarios* (see left box in figure 5), in order to identify whether the current situation is free flow, dense traffic, incident congestion or overflowing congestion. Within a problem frame representing these different situations three sections can be distinguished:

- The 'where' section includes a description of the problem in terms of basic traffic values.
- The 'why' section includes an interpretation of the causes and severity of the problem. The causes are distributed among the paths that cross the critical section carrying a significant traffic flow. The severity is established from the imbalance between the capacity and the demand in that critical section (excess) according to the demand structure expressed with the paths.
- The 'how' section defines the criteria to estimate the level of matching between the real data and the situation represented in the frame (it is not included in the example in figure 5).

If some problem frame becomes active (i.e. a conflictive situation has been detected) then the *Traffic Control* unit explores its knowledge base of *path use* frames (see right box in figure 5) to select control actions to improve the situation. Every path use frame contains three classes of information:

- A collection of VMS panel messages and signal plans for the traffic lights in entry ramps defining a control proposal.
- A characterisation of the estimated impact of the control proposal formulated as selection percentages of the available paths.
- A characterisation of the traffic state in the influence areas of the control proposal that determines its applicability.

The selection of signal proposals can be decomposed in two parts:

- (a) To look for proposals of VMS panel messages which may induce drivers to take paths that do not pass through congested areas.
- (b) To modify the phases in the traffic lights to (i) retain the upstream flows in those paths with the greatest influence on the state of the critical sections and (ii) to improve the capacity downstream the critical sections.

The reasoning performed by this knowledge unit is based on a *generate & test* method [9]: First, all the path use frames defined to overcome conflictive situations in

the areas where problems have been detected are selected. Then, the associated signal plan of these frames is evaluated through a macrosimulation of its effects on the current traffic situation. This simulation is supported by the expected redistribution of traffic included in the frame definition and by the demand knowledge. If this simulated scenario shows an adequate decrease in the excess flow associated to the congestion then the signal plan is delivered to the co-ordinator. Otherwise it is rejected..

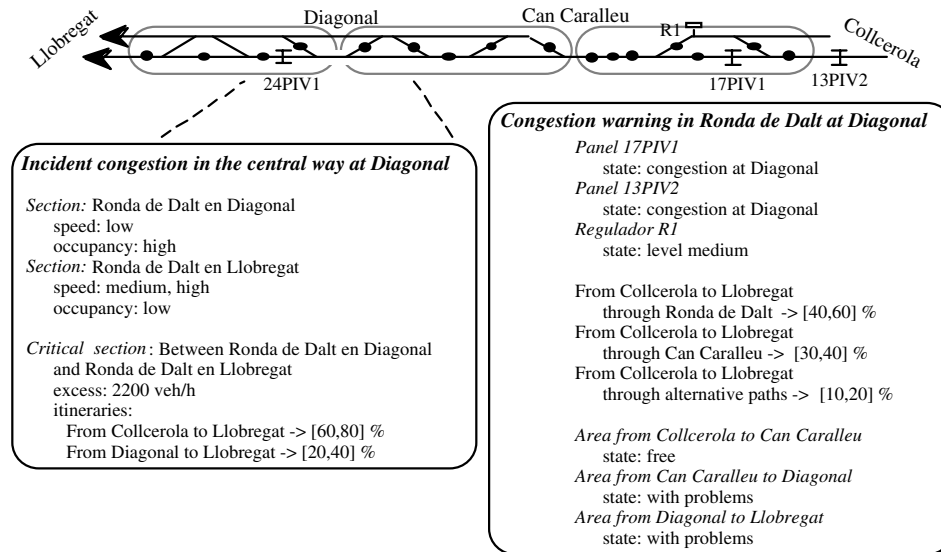


Figure 5. Problem-scenario and path-use frames in the model for Barcelona

The result of the individual reasoning performed by the local agents is a set of control plan proposals for the corresponding problem areas. All these proposals are sent to the co-ordinator agent, which analyses them with the aim of building global proposals by coherently synthesising the local proposals into signal recommendations for the whole network. This functionality is performed through a *propose & revise* method [9] supported by three knowledge units (see Figure 6):

- Knowledge to evaluate the compatibility of the different proposals delivered by the local agents included in the *Proposals Compatibility* unit.
- Knowledge to solve co-ordination conflicts within the *Agent Priorities* unit.
- Knowledge to deduce complementary signals that improve the global impact of the previous proposals included in the *Proposals Completion* unit.

The knowledge used by the *Proposals Compatibility* knowledge unit is a set of characterisations of no-good

situations of two types: (i) physical conflicts caused by different actions on the same signal device and, (ii) semantic incoherence between proposals which provoke undesirable effects on the traffic behaviour. These no-good situations are formulated with rules whose left hand side is a description of the conditions that make two control actions incompatible. When some of these incompatibilities are detected, the *Agent Priorities* unit makes use of different control criteria (the importance of the area, the value of the state variables, etc) to decide which local agent must change its proposal. This knowledge is specified as a set of priority tables, organized in different levels of request. The inference procedure tries to satisfy the first level for the maximum number of local agents. If this is not possible, because there are incompatible control actions, then the procedure tries to satisfy the next level and so on reducing the set of agents to be satisfied. It finishes when a level where no incompatibilities are detected is reached.

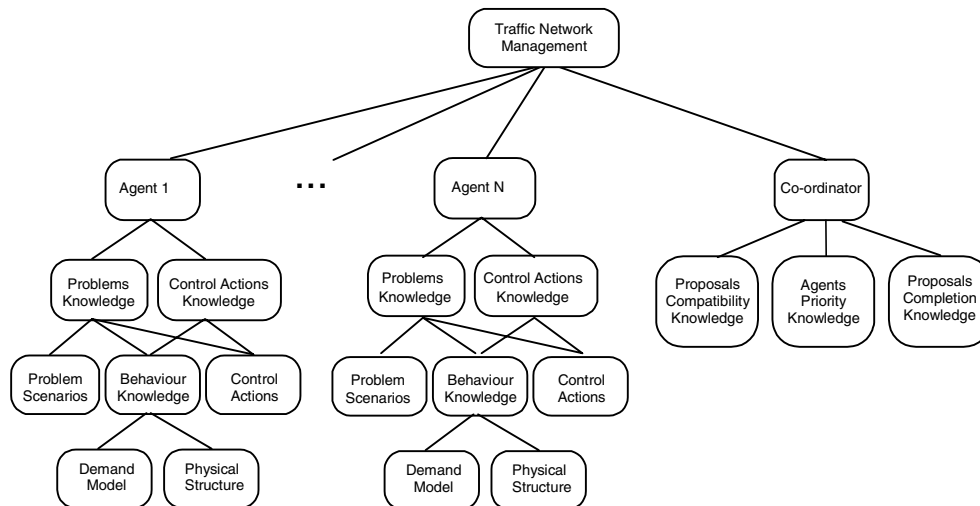


Figure 6. General structure of a TRYS model

Sometimes, the control proposals generated in the previous steps can be completed with additional messages chosen from a global, strategical view. This knowledge is organised in a collection of prototype situations contained in the *Proposals Completion* knowledge unit. Once the

co-ordinator has integrated the control proposals for individual problem areas into a consistent global signal plan, the adapted local plans are sent back to the corresponding traffic operator.

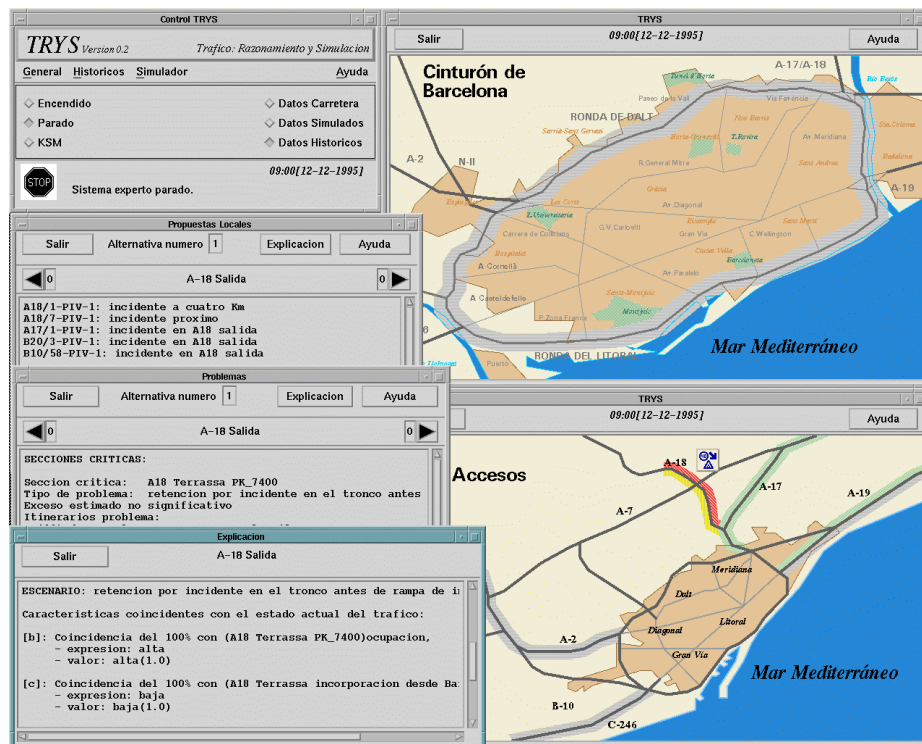


Figure 7. The TRYS system for Barcelona

The TRYS system for Barcelona was developed during one year (four persons) which meant a significant decrease in the required effort compared to the development of previous TRYS-based applications, and in

particular to the TRYS model for Madrid. This was possible thanks to the possibility of reusing most part of the generic traffic management model previously applied to Madrid and the operational support based on software

components. The main activities to develop this system for Barcelona were focused on knowledge elicitation following the knowledge units approach established for the generic model, together with activities related to software development in order to integrate the knowledge-model in the control centre. As a result, this experience showed that the use of knowledge models at generic level based on high level structuring concepts (tasks, problem-solving methods, knowledge units, etc.) was extremely useful in order to increase the productivity and the quality of the final system in the development of complex and large knowledge systems as it is the case of decision-support applications for traffic management. Figure 7 shows several windows of this system.

4. A decentralised approach: TRYSA₂ agents

A key idea in the design of the TRYSA₂ system was to augment local traffic problem-solving, similar to the one outlined above, by a model of self-interested pursuit of (local) goals, thus converting the original “benevolent” TRYS agents into autonomous agents. So, although the particular decomposition of the road network into problem areas is slightly different, the basic tasks of problem detection, diagnosis and selection of control plans are realised as described in the previous section. As the result of local reasoning, each TRYSA₂ traffic agent is endowed with a set of alternative local control plans. In addition, it has obtained an expectation of the reduction of local traffic excess associated to each local plan, which we call the plan’s local *utility*.

TRYSA₂ agents co-ordinate in a decentralised fashion by means of structural co-operation [6], a generic co-ordination mechanism developed for societies of autonomous problem-solving agents. As local control plans are interdependent, agents can mutually influence the effectivity (or: local utility) of their acquaintances’ control plans. By consequence, agents are interested in co-ordination, but there is a conflict of interest respecting the *way* in which local signal plans are adapted. The essential idea is that the more autonomous an agent is (i.e. the less its local utility can be influenced by others), the more weight will have its opinion respecting which local plans to modify and how to adapt them. Still, sometimes the resulting basic co-ordination does not lead to globally optimal control plans, so the system designer can issue rights or prohibitions for some agents to use control devices in certain ways. By this, he modifies the degree of autonomy of some agents, *biasing* the outcome of co-ordination (i.e. the resulting global signal plan) in a desired direction.

An *operational* model of structural co-operation is achieved by mapping this specific problem of distributed rational decision making to a *bargaining scenario* [8]. Axiomatic bargaining theory provides us with a

reasonable solution to the dispute of the TRYSA₂ autonomous traffic control agents [7].

In practice, co-ordination based on structural co-operation is achieved by means of a distributed multi-stage constraint optimisation algorithm that directly calculates the solution to the aforementioned bargaining scenario. This algorithm draws upon ideas of asynchronous weak commitment search [11]. In the sequel, we shortly sketch its structure (see figure 8). In stage 1, setting out from the local sets of alternative signal plans, agents repeatedly exchange messages, so as to determine the set of undominated consistent local signal plans. This is done in an asynchronous distributed fashion, which allows for local and temporarily incompatible views of the overall state. The agent that detects the termination of stage 1, takes the initiative in stage 2. On the basis of the outcome of stage 1, it computes an (approximate) probability with which each of the sets of consistent local signal plans shall be enacted, so as to maximise the product of local agent utilities (which constitutes a solution to the bargaining scenario [7]). Finally, in stage 3 a set of local signal plans is selected by means of a lottery (in accordance with the result of stage 2), and the agents are informed about the corresponding outcome.

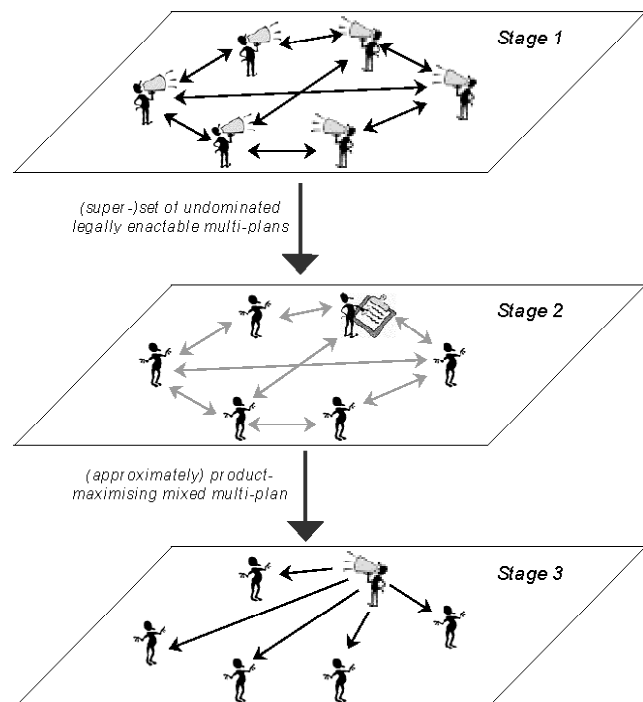


Figure 8. Sketch of the TRYSA₂ co-ordination algorithm

This algorithm requires a traffic agent to be endowed with Knowledge Units respecting both, domain

knowledge and social knowledge (see figure 9). The *Plan Interrelation* unit expresses physical relationships between plans and the possible ways of dealing with them in terms of states of control devices. This knowledge is represented by rules, that obey to the following format:

$$\begin{aligned} [cdev_1, \dots, cdev_n] &\Rightarrow [cdev_m, \dots, cdev_j] \\ [cdev_1, \dots, cdev_n] &\Rightarrow [nogood] \end{aligned}$$

The operational semantics of such a rule determines that the control device states of the antecedent can be substituted by those of consequent without any important changes in the effect of the signal plans (e.g. by merging different messages “congestion at A” and “congestion at B” to be displayed on the same VMS into one “congestion at A and B” message). If control devices are merely incompatible, the consequent is the constant *no-good*.

The above knowledge defines *physical* relations between plans. The *Agent Dependence* knowledge unit models *social* relations between agents in the shape of rules of the form:

$$[cdev_1, \dots, cdev_n] \Rightarrow [\alpha_1, \dots, \alpha_m]$$

If all control devices $cdev_1$ to $cdev_n$ switch to new states, then this concerns the agents α_1 to α_m . For instance, if agent α_i may set a message M_i on VMS P , and α_j possibly displays a message M_j on the same panel, while both messages are incompatible, then the knowledge base of α_i 's dependence unit will contain a rule stating that setting M_i on VMS P concerns agent α_j . This knowledge serves two purposes: when used with forward inference, it allows an agent to deduce which agents are to be informed about its change of local signal plans; using backward inference, it enables an agent to determine its degree of autonomy, by deducing which agents can affect the executability or the outcome of a local signal plans.

It remains to be shown how normative biasing is achieved. In TRYSA₂, the *Norms* knowledge unit deduces prohibition for some agents to use certain control device or to set certain control device states. Although the set of these normative prescriptions is quite stable over time, they must vary along with important changes in the traffic demand structure. So, the *Norms* knowledge unit contains temporally qualified sets of normative prescriptions, which are represented by frames containing two parts:

- *Temporal classification*

The current date and time is classified in terms of two categories: type of day and type of season. Values for the former are either Working day, Sunday, Saturday or Holiday. Rules specify how the value holiday is derived. The category season may be instantiated to Xmas, Easter, Summer, or Normal. Again, the values

are related to the current date and time by means of rules;

- *Normative structure*

As a function of the type of day and the type of season, a normative structure is defined by two categories: prohibitions and permissions. Each of these categories may be instantiated by a set of control devices.

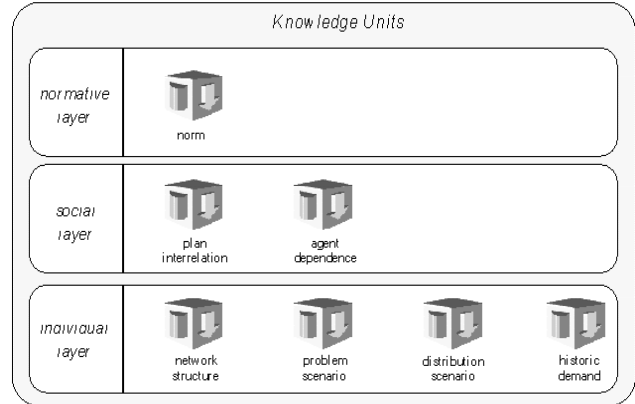


Figure 9. Knowledge endowment of TRYSA₂ Agents

In TRYSA₂, the agents' norm knowledge bases are globally consistent: if one agent is allowed to use a control device, all others that might access it are prohibited to use it. The associated reasoning method first classifies the current date and time, in order to match the resulting temporal categories against the normative patterns. By means of this information, the outcome of the distributed algorithm that computes the outcome of structural co-operation is biased.

5. Conclusions

In this paper we have described two ITMS for providing intelligent decision support for the Barcelona motorway network. TRYS is a centralised multiagent system, consisting of several local traffic agents that act on behalf of a co-ordinator. It was installed in the Traffic Control Center in Barcelona and on-line connected with the telematics infrastructure for several months. The advanced services provided and progressive assimilation of this technology by the traffic operators made possible the current presence of a later version in the TCC.

TRYSA₂ is based on a decentralised multiagent architecture, substituting the authority of the co-ordinator by the socially bounded autonomy that agents enjoy within structural co-operation. It was developed up to a prototype level and validated with the same data as the TRYS system.

An important issue in our evaluation of both approaches has been the *complexity* of the co-ordination

task. In this respect, TRYS approach defeats the decentralised solution of TRYSA₂. This is due to the fact that both methods implicitly apply different “search paradigms”. TRYS combines the locally most preferred signal plan from the set of each traffic agents control proposals. The possibility of solving conflicts within this

plan by merging control devices is exploited exhaustively. If some conflict persists, the global plan is rejected and a new one is constructed. Otherwise the signal plan constitutes the co-ordination outcomes. By contrast, the TRYSA₂ strategy may imply an exhaustive search for plans to be selected by the involved agents.

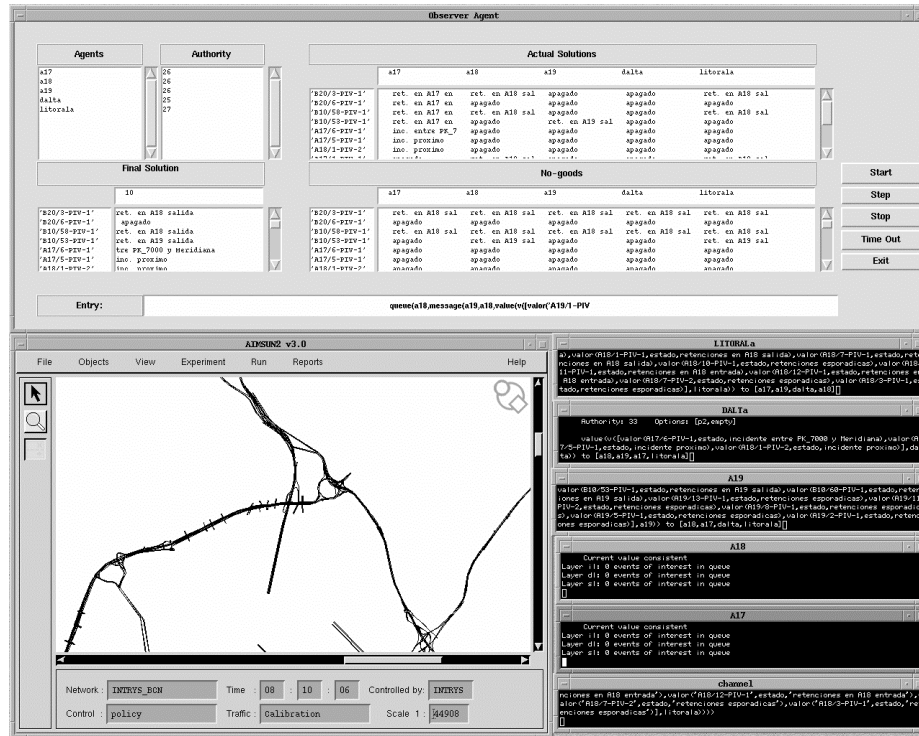


Figure 10. TRYS₂ interface

Still, our claim is also that the TRYSA₂ approach promotes *scalability*. When a new agent is introduced into the system, agents still need to be informed about its capabilities and, if the newcomer may enact previously unknown signal plans, the interrelation of these plans with existing control actions is to be added to the agents' knowledge bases. Still, the introduction of the new agents produces a shift in the social equilibrium, leading to a new base-line co-ordination without any further modifications to the agent knowledge. In the centralised approach, however, this effect can only be achieved by completely reconsidering priority relations that a distinguished co-ordinator agent is endowed with.

6. References

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