Evaluation of Inter-Jurisdictional Cooperation Strategies for ATMS/ATIS Deployment

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SUMMARY
This paper describes the validation of a new methodology for the deployment of inter-jurisdictional Advanced Transportation Management and Information Systems (ATMIS) strategies, for responding to non-recurrent degradations in traffic system performance. The methodology employs a multi-agent, real-time knowledge-based system developed under the Caltrans (California Department of Transportation) ATMS Research Program. A simulation-based evaluation analysis is described, that provides quantitative and qualitative measures for the effectiveness of real-time traffic management on combined freeway/arterial networks. The analysis demonstrates the effectiveness of the approach in producing real-time, integrated control solutions that reduce the adverse impact of incidents on circulation, network-wide.

ADDRESSING INTER-JURISDICTIONAL COOPERATION
The spatial and administrative organization of transportation management agencies in metropolitan networks requires a coordinated solution effort that preserves the different levels of authority, guarantees privileged data control, and in general reflects the inherent distribution of the decision-making power. A coordinated response to congestion avoids the implementation of operations that may otherwise conflict, and therefore be counter-productive.

To address such issues, a multi-agent real time system called CARTESIUS (Coordinated Adaptive Real-Time Expert System for Incident management on Urban Systems (1)) was designed, developed and evaluated. The distributed architecture in CARTESIUS is composed of two interacting, real-time problem-solving agents that communicate with each other through a fast TCP/IP-based real-time protocol. The agents are able to perform cooperative reasoning and resolve potential conflicts for the analysis of non-recurring congestion and the formulation of system-wide ATMS/ATIS response strategies (2). As shown in Figure 1, the two agents are decision-support systems for a Transportation Management Centre (TMC)

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operator: one agent supports incident management operations for a freeway subnetwork and interacts with a human operator at the TMC of a freeway management agency. The other supports operations for the adjacent arterial network, and interacts with an operator at the local city TMC. Each module continuously receives real-time measurements from traffic detectors and a description of the current status of the control devices (signals, ramp meters, and changeable message signs (CMS)) under the jurisdiction of the corresponding agency. The modules provide the operators with traffic control and traveller information recommendations in response to the occurrence of incidents. These recommendations consist of a set of alternative, network-wide strategies, composed of suitable settings for signals, ramp meters and CMS. The agents provide an explanation of the reasons why each strategy is proposed and an estimation of the benefit it is expected to provide.

Figure 1: The distributed architecture in CARTESIUS

The uniqueness of the CARTESIUS approach lies in the efficient integration of existing techniques for real-time generation and assessment of appropriate control strategies, with emphasis on the coordination between multiple decision makers in a multi-criteria environment. The analysis of the network state and the search for suitable control plans is based on a structured combination of heuristic approaches and well-established traffic control algorithms (3,4) in a general distributed framework that provides the means for cooperation and conflict resolution.

The interaction mechanism between the agents is based on the Functionally Accurate, Cooperative (FA/C) paradigm (5). FA/C is a distributed problem solving approach that is particularly suited to applications where there is a natural spatial distribution of information but where each agent has insufficient knowledge to completely and accurately solve the global problem. In the context of traffic management in metropolitan networks it is often impossible or too expensive to decompose the problem in such a way to ensure a perfect match between the location of information and data processing expertise, and the
computational requirements for problem solving. On one hand, the impracticability of sharing expertise and decision-making power in a real-time context often limits the flexibility of transportation management systems, by requiring the adoption of predefined, previously established cooperation plans. On the other hand, the maintenance of accurate, complete, and up-to-date information requires too heavy and frequent communication of intermediate processing results, thus burdening the agents with high communication and synchronization delays that are not practical in real-time applications.

The FA/C problem-solving approach allows agents to cooperatively solve tasks, using only limited and uncertain knowledge of the processing performed and the results obtained by other agents. According to the FA/C approach, CARTESIUS agents cooperate by generating and exchanging partial results at various levels of abstraction, obtained during the problem-solving process. These results, which may be incomplete or inconsistent, are based on the agents' limited local view of the problem and of the solution domain. The ability to determine a local solution even in the absence of completely specified and up-to-date information and to use remotely processed data for the selection of a consistent global solution, allows the agents to reduce their communication synchronization delays.

**EVALUATION OF SYSTEM PERFORMANCE**

The evaluation of the ATMS/ATIS strategies proposed by CARTESIUS involved the analysis of network performance under different traffic conditions, determined by the occurrence of several types of incidents, and a comparison between network-wide measures of effectiveness (MOE), with and without the implementation of those strategies. Three real-time ATMS/ATIS response strategies were concurrently applied:

- Adaptive system-wide ramp metering,
- Adaptive arterial traffic signal control, and
- Traffic diversion based on traveller response to CMS information.

The MOEs considered include:

- An assessment of the network travel time reduction obtained by the implementation of incident response plans suggested by optimal deployment of the three ATMS/ATIS response strategies.
- The system's response time.
- The impact of the integration between the various control components, by comparing the effect of fully integrated control plans (freeway traffic diversion and arterial signal control) to incomplete control plans that use exclusively traffic diversion schemes.

The remainder of this paper first describes the site for which the analysis was developed, with details on how real-world data was incorporated, whenever possible, within the simulated environment. Then it reports on the quantitative and qualitative results of the evaluation process.

**The Test Site**

The test site selected for this analysis is a highly congested corridor network in the city of Irvine, Orange County, California, shown in Figure 2, that includes 4-mile sections of the Interstate 5 and 405 Freeways, the SR-133 Freeway, and the adjacent subnetwork of surface streets. The City of Irvine Traffic Management Centre (ITRAC) is responsible for traffic operations on the arterial network, with a computer-aided traffic system that controls over 240 signalised intersections, 32 of which are within the test network, and 5 arterial CMS. Signal control is fully actuated, and signal control parameters (minimum and maximum green, phase
recall, etc.) are set according to a time-of-day basis. ITRAC also has control over 30 CCTV cameras located at major intersections and connected to the TMC through a fibre-optic network. Caltrans District 12’s ATMS (Orange County) uses state-of-the-art computer, software, and communication systems to manage the flow of traffic on the county freeway network. Vital elements at the core of the system’s operations include 30 CCTV cameras, 34 CMS, the Highway Advisory Radio, 278 metered on-ramps, 1,098 incident call boxes and 258 directional miles of loop detectors. Within the subnetwork for which this evaluation was conducted, Caltrans controls 3 CMS. Meter control is performed on all 18 freeway on-ramps within the network.

![Figure 2: The test site](image)

The two agents within CARTESIUS are able to receive real-time traffic and control data from the Caltrans District 12 ATMS, through a wide-area communications network that links the Cities of Anaheim and Irvine TMCs to the Caltrans' District 12 TMC and to the University of California, Irvine, where the tests were performed. The communication with Caltrans District 12 ATMS provides the freeway agent with loop detector data (volume and occupancy), with CMS and ramp metering data, and with the ability to transmit, subject to Caltrans' approval, ramp metering rate control. A real-time connection between the arterial agent and ITRAC is currently under development and could not be used in this research. It will allow the arterial agent to receive traffic and control status data from the arterial system, and to transmit, subject to ITRAC approval, alternative signal timing and CMS setting plans.

**The Simulated Environment**

An enhanced version of the traffic simulator DYNASMART (6) was used for simulation. For communicating with the agents, DYNASMART was provided with an interface that simulates the functions of the Caltrans and City of Irvine traffic data servers. Traffic and control device data (detector, CMS, signal, and ramp metering data) are exchanged between the agents and the server using exactly the same interface on the client side. A time-varying OD matrix was estimated for input to the simulation, based on data from the Irvine Transportation Analysis Model (7), using standard commercial software packages.
EVALUATION RESULTS

At the core of the evaluation process was the assessment of the system's ability to provide traffic control plans in real-time response to the occurrence of incidents. Total and average travel time and travelled distance, were considered suitable MOEs, both because they provide an indication of the network level of service and because they are easily measurable using a simulator.

Network Performance

A set of 18 test scenarios was created, by running simulations of 90-minute peak periods and artificially injecting incidents (temporary reductions in the capacity of a link), by varying such characteristics as the incident location, the associated loss of capacity and the duration of the capacity reduction. In scenario 0, no incident was included, in order to obtain estimates of the basic network average and total travel time and distance. Such estimates were used to assess the relative performance deterioration caused by the occurrence of incidents, across the different scenarios. Thus, for each case, the average travel time increase with respect to scenario 0 was measured. Two scenarios were also included that describe cases for which two incidents were injected simultaneously. In both scenarios, the first incident was simulated on the freeway, while the second was injected along one of the major paths that had been chosen by the system as a bypass for the first incident. The purpose of the latter tests was to analyse the system's response to multiple incidents with interacting effect on each other.

For each scenario, the MOEs provided by the simulator were collected. For each test case, two simulations were executed: one, the before case, using the default control (no CMS message and the default, time-of-day signal and ramp meter timing plan), and one, the after case, implementing the integrated ATMS/ATIS control suggested by the agents, in response to the notification of the occurrence of congestion. The comparison of the network performance, through the implementation of the two forms of control (non ATMS/ATIS vs. ATMS/ATIS), provided a measure of the performance increase that can be expected when the default control is substituted with the control plans based on the responses suggested by CARTESIUS.

The analysis shows that the implementation of the control plans proposed by CARTESIUS results, in general, in a reduction in the average and total network-wide travel time. The average and total travelled distance is not significantly affected by the alternative control, even though the control plans, in all test scenarios, included the use of CMS messages. This result should be perhaps attributed to the limited size of the network.

The quality of the improvement, in general, varies according to the availability of alternative routes, the amount of spare capacity on those routes, and the demand/capacity ratio on routes affected by congestion. Thus, the scenarios, described in Table 1, are partitioned according to the location of the incident. For each incident, its characteristics are: the location, the associated capacity reduction (number of lanes closed versus total number or lanes), and the duration of the capacity reduction. Table 1 shows the total and average (per vehicle) travel time resulting from the simulated scenarios. The percentage travel time difference between the before and the after case is shown (in bold). Furthermore, in order to obtain a normalized measure of the travel time reduction across the scenarios, the last two columns of the table show, for each case, the average travel time increase with respect to scenario 0, which corresponds to a no incident situation, and thus represents a common base case. For each case, the percent difference in per-vehicle travel time corresponding to the two forms of control (non ATMS/ATIS vs. ATMS/ATIS) is reported.
Table 1: Total and average travel time for the simulated scenarios.

<table>
<thead>
<tr>
<th>Incident Characteristics</th>
<th>Total Travel Time (x10^4 veh-hrs)</th>
<th>Average Travel Time (min./veh)</th>
<th>% Change from Scenario 0&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Change (%)</td>
</tr>
<tr>
<td>0</td>
<td>no incident</td>
<td>0.380</td>
<td>0.380</td>
</tr>
<tr>
<td>1</td>
<td>405 N</td>
<td>1(4)</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>2(4)</td>
<td>20</td>
<td>0.496</td>
</tr>
<tr>
<td>3</td>
<td>2(4)</td>
<td>25</td>
<td>0.528</td>
</tr>
<tr>
<td>4</td>
<td>405 S</td>
<td>1(4)</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>1(3)</td>
<td>20</td>
<td>0.502</td>
</tr>
<tr>
<td>6</td>
<td>2(4)</td>
<td>20</td>
<td>0.584</td>
</tr>
<tr>
<td>7</td>
<td>5 N</td>
<td>2(5)</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>3(5)</td>
<td>15</td>
<td>0.400</td>
</tr>
<tr>
<td>9</td>
<td>3(5)</td>
<td>20</td>
<td>0.426</td>
</tr>
<tr>
<td>10</td>
<td>5 S</td>
<td>1(5)</td>
<td>15</td>
</tr>
<tr>
<td>11</td>
<td>2(5)</td>
<td>20</td>
<td>0.510</td>
</tr>
<tr>
<td>12</td>
<td>3(5)</td>
<td>30</td>
<td>0.634</td>
</tr>
<tr>
<td>13</td>
<td>Alton E</td>
<td>2(3)</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>Alton W</td>
<td>2(3)</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>on-ramp</td>
<td>1(2)</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>405 N</td>
<td>2(4)</td>
<td>20</td>
</tr>
<tr>
<td>17</td>
<td>Alton W</td>
<td>1(2)</td>
<td>15</td>
</tr>
<tr>
<td>18</td>
<td>on-ramp</td>
<td>1(2)</td>
<td>10</td>
</tr>
</tbody>
</table>

Average: -7.4 | 32.6 | 20.3

It is not a simple task to draw general and absolute conclusions beyond the simple observation that in almost all tested scenarios the implementation of the ATMS/ATIS control plans suggested by CARTESIUS results in an improvement of network-wide traffic conditions. In scenarios 1, 7, 10, and 14, the small capacity reduction did not have noticeable effects on traffic flow, thus no incident notification was received by CARTESIUS. Scenario 13 is the only one, among those for which CARTESIUS was used, in which no travel time reduction is observed; this is due to the fact that no alternative solution to the default control was found. It must be noted, however, that in this case, the occurrence of an incident results in a very low deterioration of average travel time, with respect to scenario 0 (0.4%). The mean percentage reduction of average (per vehicle) travel time across the 13 scenarios for which CARTESIUS received an incident notification is 7.4%. Compared to scenario 0 (the no incident case), the mean percentage increase of average travel time, caused by the occurrence of incidents, is reduced from 32.6% to 20.3%.

<sup>1</sup> These two columns describe the percentage difference in average travel time when each scenario is compared to scenario 0, corresponding to the no incident case.

<sup>2</sup> No incident notification to CARTESIUS.
The reduction in average travel time ranges between 0.0% and 15.3%. The variation is due both to the different duration and capacity reduction of the incident and, perhaps more importantly, to the characteristics of its location, such as the flow to capacity ratio and the availability of alternative routes.

On average, higher performance improvements are experienced in the scenarios related to incidents occurring on freeway sections (the first 12 scenarios), in particular on the I-405 freeway southbound (scenarios 4-6). The lowest improvements are observed for incidents occurring on surface streets (scenarios 13-15). In those cases, the effect of incidents is marginal (0.4% travel time increase), thus the improvement of traffic conditions is also very small. The network performance is improved by CARTESIUS also for the cases of multiple incidents, which seems to demonstrate the effectiveness of the approach in dealing with multiple, concurrent sources of congestion.

Response Time
Given the real-time nature of the problem that the system is intended to address, it was important to provide a measure of the system response time. The response time is the time required by the agents to determine a list of control plans, once they have been provided by the operator with all the necessary input. In all tested scenarios, the system response time is below 22 seconds, with an average of 15.3 seconds. This indicates, in practical terms, that combined system-optimal ATMS/ATIS strategies can indeed be implemented in something close to a real-time response. These measures were obtained using a SUN Ultra 30 Workstation, with an Ultra SPARC2 processor.

Effect of Signal Plans
As part of the analysis of system performance, a quantitative assessment of the synergistic effect of coordination between signal control and traffic diversion was performed within the integrated ATMS/ATIS strategies proposed by CARTESIUS. For three of the scenarios for which diversion through the arterial system was recommended due to freeway incidents (scenarios 2, 5,9), an additional simulation was performed (scenarios 2', 5', 9'), in which the adjustment to plans for signals and ramp meters suggested by CARTESIUS were not transmitted to the traffic simulator.

<table>
<thead>
<tr>
<th>Signal coord.</th>
<th>Scenario #</th>
<th>Incident Characteristics</th>
<th>Average Travel Time (min./veh)</th>
<th>Comparison with Scenario 0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>0</td>
<td>no incident</td>
<td>5.24</td>
<td>5.24</td>
<td>0.0</td>
</tr>
<tr>
<td>yes</td>
<td>2</td>
<td>6.76</td>
<td>6.32</td>
<td>-6.5</td>
</tr>
<tr>
<td>no</td>
<td>2'</td>
<td>1.31</td>
<td>1.46</td>
<td>-5.8</td>
</tr>
<tr>
<td>yes</td>
<td>5</td>
<td>6.86</td>
<td>5.85</td>
<td>-14.7</td>
</tr>
<tr>
<td>no</td>
<td>5'</td>
<td>5.33</td>
<td>5.35</td>
<td>-8.3</td>
</tr>
</tbody>
</table>

In each case, the network performance for the modified simulations was compared to that of the corresponding scenarios, in which the complete control directives were transmitted to the simulator. These tests were aimed at estimating the synergistic effect of integrated response
control plans, by computing the reduction in the network performance caused by the lack of integration between traffic diversion control and signal and meter control.

Table-2 shows the result of these tests. The two scenarios that involve incidents on the I-405 freeway (scenarios 2 and 5) are characterized by a clear superiority of the integrated control compared to the partial one. Scenario 9, which involves diversion from the I-5 freeway, does not show such a noticeable performance gain. This difference can be explained perhaps by considering the characteristics of the major alternative routes available for the freeway traffic in the three scenarios. In the first two cases, a portion of the freeway flow is diverted through arterial routes that cross several signalized intersections, thus the lack of coordination between diversion and signal control would deteriorate the network performance. Also, in both cases, as a consequence of congestion, arterial traffic directed to the freeway is advised to use the on-ramp downstream of congestion, thanks to the availability of arterial CMS, thus further adjustments to signal and ramp control plans are required. In the last case (scenario 9), the alternative route for freeway traffic crosses a smaller number of signalized intersections. Also, the travel time increase due to the incident in this case is lower (10.9% higher than scenario 0) than in the other cases, thus not as much diversion through the arterial streets is required.

CONCLUSION

This paper reports on the simulation-based validation of the performance of CARTESIUS, a multi-agent decision-support system for incident management. The approach used by CARTESIUS, which is described in more detail elsewhere (1,2) employs coordination mechanisms that support cooperation and conflict resolution between two distinct automatic problem solving agents. The agents have access to separate databases and data sources, and may use different control algorithms, thus reflecting the inherent administrative distribution of data and expertise among separate management agencies. The cornerstone of this cooperative approach is the assumption that effective integrated traffic control solutions can be obtained in real-time by relaxing the requirement that agents have shared access to all globally available information. The validation of the system performance confirmed the need for a seamless coordination between signal control and traffic diversion, and demonstrated the effectiveness of CARTESIUS in producing real-time, integrated control solutions that reduce the adverse impact of incidents on traffic circulation, network-wide.

REFERENCES