Self-optimising and self-organising urban traffic control systems

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Abstract

Much study in urban traffic control is directed towards operation and optimisation of individual signal-controlled road junctions. The effectiveness of traffic control systems greatly depends on its ability of reacting upon traffic patterns and changes. Signal control systems that have the capability of optimising and adjusting the traffic light settings are able to improve the vehicular throughput and minimise delay through appropriate response to changes in demand patterns

We investigate the usability of an intelligent dynamic urban traffic management and control system that, theoretically, can adaptively respond to real-time traffic conditions. A model, and after verification and validation of the model a prototype / simulation program, of an autonomous urban traffic control system will be used to get insight into the technical- and functional-applicability of autonomous, self-adjusting and self-optimising systems in traffic control. The subject to be investigated in more detail is the applicability of these self-adjusting and self-optimising traffic control strategies in urban traffic control. In that system the control agents will be artificial intelligent, capable of calculating and optimising. In the meantime we get an autonomous system that is able to search for an optimum in the use of intersection(s). The control agents may directly influence the control strategy of the intersection(s).

In the end, we hope to demonstrate that an integrated dynamic urban traffic management and control system, partly based on agent technology can adapt and respond to traffic conditions in real-time and still maintain its integrity and stability within the overall transportation system.

1 Introduction

Current estimates are that 65 percent of peak-hour travel on highways and urban roads and 10 percent of all daily urban travelling is done under congested conditions (Bernstein, 1993). The inability of the existing road network to cope with increased demand has been identified as one of the most pressing infrastructure issues of the decade. In recent decades traffic problems became a social and economical embarrassment: congestion, deteriorating road safety, regression of mobility and environmental effects of traffic are widely considered important issues. Under pressure from these problems, traffic management professionals and policy makers turn to new, better traffic management systems.

The basis of this research forms a theoretical framework of an Integrated Dynamic Traffic Management and Information System (IDTMIS); a framework incorporating all traffic management and -control systems, thus creating one multi-user, multi-disciplinary traffic management and control system. The focus will be mainly on concepts and the extra opportunities of an IDTMIS; not on the technological (read implementation) sides.

The main objective of this study is to investigate the applicability of autonomous intelligent systems in traffic control. Aim of this part of the research is to develop insight into the abilities of autonomous agents (self-adjustability and self-optimisation) and distributed artificial intelligent systems applicable in the domain of Intelligent Transport Systems (ITS) and specifically in urban traffic control (UTC). Intelligent signal control systems have the capability of optimising and adjusting the traffic light settings and the idea is that we may achieve a better vehicular throughput on intersections by using self-regulating systems. We try to find out if there is a possibility for a system-wide optimisation by individual, self-optimising agents. In such a system the agents will be artificial intelligent and are capable of calculating and optimising, have adequate knowledge about the intersection(s) and may directly influence the control strategy of their intersection(s). These agents are able to get insight in oncoming traffic and are able to co-ordinate the traffic signalling operations in a way similar to traffic calming or public transport priority measurements. Using all available information the agent (re)calculates the next state and operates the traffic lights accordingly. In such a way we, hope to, get a real-time system that makes better use of the capacity of the intersection and still maintain its integrity and stability within the overall transportation system.

2 Dynamics of urban transportation systems

One of the difficulties of traffic control is that traffic is not fully predictable. In systems where humans are in control a total deterministic system is beyond reach. Even if we are able to handle the predictability of dynamic systems we still have to deal with the optimisation of the urban traffic control system.

2.1 Typology of an IDTMIS

Part of this research project deals with a preliminary investigation for an integrated and dynamic traffic management and information system IDTMIS, for a more elaborate description of IDTMIS see Roozemond (1995 & 1996-a). The economical, environmental and social impacts of such an integrated system can be significant: improved operational efficiency, improved safety, reducing energy and environmental impacts, improved comfort and more co-operation between system users (de Romph, 1994). The framework of a multi-user, multi-discipline Integrated Dynamic Traffic Management and Information System is not propounded as one single system. Instead it is based on a scalable, open, distributed and recursive architecture where several smaller systems interact on different levels. The individual and modular parts are designed to keep information local, working closely together, acting on the rules implemented in the system and on actual information gathered by the system. Sub-systems are designed to perform autonomously, co-ordinating their own actions, interacting with other sub-systems trough standardised interfaces when necessary. To put IDTMIS in perspective, integration of dynamic traffic management systems alone, is no cure for current traffic problems, although it may streamline, reduce the traffic load and give better information and advises.

2.2 Handling dynamics

There has been a great deal of study on the subject of congestion using traffic flow theory. Prigogine & Herman (1971) show that flow- and kinetic theories are not appropriate ways of modelling traffic in urban areas; even current flow-theoretical traffic models do not sufficiently account for the specific problems in urban traffic. Traffic flow theory is only valid if there is a certain amount of freedom for participants. We know this is not the case in urban areas and in turbulent situations (congestion on highways, distortion due to accidents, etc.) From a mathematical point of view the stability and behaviour of participants in transportation systems are essential.

The dynamic aspects of complex road systems are too important parts of the transport system to be ignored in a modern traffic management and control system. To be able to handle the dynamics in traffic we need a theory that can provide a basis for traffic modelling that can cope with the many different modes of transport that traffic participants use, as well as handle the great flexibility in routing and uncertainties in urban and inter-urban environments. As traffic management and control systems must react to the different states of traffic, a fully pro-active dynamic control mechanism should be an integral part of that system. To be able to, fully automatic, operate transportation systems the dynamics of vehicles and their drivers should be minimised or taken into account. As with dynamic systems small changes may lead to large distortions, there should be limits to changes. Autonomous control systems however need to have some sort of adaptability to react and learn from experiences (Hogg & Huberman 1991). So there should be limits to the adaptability of the sub-systems.

2.3 Urban traffic control

Traffic management and traffic control in cities is the most problematic and complicated part of the whole transportation system as well as the most challenging and least researched. In urban areas the basic units of traffic participants are varied: cars, pedestrians, bicycles, etc. In urban areas the complexity exceeds that of the highway conditions due to the variety in means of transport, the difference in the speed of the participants and the greater probability of unanticipated events. In the domain of Urban Traffic Control (UTC) more research is directed towards operation and optimisation of individual and linked signal-controlled road junctions based on actual traffic (Kronborg & Davidson (1993), Saito et al. (1997), Bang (1976), Vincent (1993)).

Signal control systems have the capability of improving the traffic flow by adjusting the traffic lights and co-ordinate operations between each signal in order to maximise the person- and vehicular throughput and minimise delay through appropriate response to changes in demand. In a more detailed analysis, four basic forms of traffic signal control where distinguished: fixed-timed, semi-actuated, fully-actuated without volume-density control and fully-actuated with volume-density control (Bruno & Improta 1994). When carefully calibrated, traffic actuated signals can provide considerable advantages over fixed-time control, but both traffic-actuated and fixed-time systems have their own capabilities.

For optimisation throughout networks a fully-actuated and connected traffic control system is needed. The capability to adjust the traffic signal timing may include computer-generated timing plans with or without additional manual operation by a skilled and knowledgeable operator. This is also a world of problems, yet unsolved.

An inner-city traffic light system is, generally spoken, a computerised system. Handling unforeseen changes in traffic flow, such as accidents, is not provided in known systems. In most cases the control strategy is isolated with no interaction with other traffic management systems provided. Theoretically, the various jurisdictional control systems are capable of electronically sharing fully actuated traffic flow data with the signal systems of adjoining jurisdictions to provide metropolitan-wide signal co-ordination. In urban traffic control, responsive plan generation is a much discussed, but little implemented idea. The basic premise is that existing signal-plan generation tools (e.g., TRANSYT or SCOOT) make rational decisions about signal plans under varying conditions. True as this may be, these tools cannot be used in a real-time setting for more than traffic control as no meta-rules are incorporated into the system. Other systems capable of self-optimising is MOVA (UK) and LHOVRA (Sweden). Both are designed for optimising isolated intersections and no explicit integration takes place between intersections. Both are mainly used at intersections in high-speed environments. MOVA uses several detector types and some sort of optimisation algorithm based on stage control and mathematical optimisation as LHOVRA uses signal group control and heuristic traffic engineering functions. Research by Kronborg & Davidson (1993) showed that both optimisation algorithms are good, but signal group control can be of benefit for critical traffic movements even during congested situations. The study showed that the effectivity of the controller comes from minimum signal group times and maximum stage times. For isolated intersections they recommended the use of heuristic signal group control with mathematical optimisation.

All current traffic signal control methods are based on traffic demand data in the past. The time span between data collection, data transmission, calculation of parameter settings may vary from years to a minimum of 5 minutes. These methods are good in circumstances where traffic demand does not change rapidly within the time interval of 5 to 10 minutes. Then a delay in data-collection - signal control will not give rise to the worsening of a traffic. However, such delay will become a problem in the case where traffic demand changes rapidly within a time interval of 1 - 10 minutes as in the morning or evening rush hours. When we want to improve traffic signal control systems we need a fully pro-active, real-time traffic control system; anticipating what will happen within the next couple of minutes (urban traffic control). A possible disadvantage of such a short term signal timing setting is that it may introduce cycle to cycle fluctuations. Possible advantage is that such a system could cope with major traffic disruptions. A mix of both systems seems the right direction: being able to change the signal settings, but not that large a differentiation each time (for stability reasons). The agents will take action, based on rules implemented in the system and actual information gathered by the system

The aforementioned considerations suggest a need to complement existing systems for traffic control with strategic knowledge applied to understand the situation, traffic behaviour, the specific processes of congestion development, and then corresponding actions could be taken. An UTC exhibiting intelligent behaviour must, minimally, have the following capabilities: handle operations in real time and, given the vast amount of knowledge, show some adaptive and goal-oriented behaviour. The system should also be able to handle unexpected or wrong input and learn from experiences. One of the possible IT tools to achieve these goals is the use of Intelligent agents. Intelligent agents should be able to solve problems; understand information; have intentions; draw distinctions between situations; plans and predict consequences of actions; evaluate alternatives; generalise and synthesise new concepts / ideas. Meta-rules need to be included for traffic control situations when operational goals are contradictory. The agents can communicate; so they are able to get insight in oncoming traffic and are able to co-ordinate the traffic signalling operations in a way similar to traffic calming or public transport priority measurements. Using all available information (historic knowledge in the rule base and actual information from detectors or other agents) the control agent (re)calculates the next, most optimal, state and operates the traffic lights accordingly. Here we should ad that the most optimal often isn't an optimisation problem, but more often a problem of finding a feasible solution.

3 Intelligent Agents

Intelligent agents can be described as computational systems that inhabit dynamic, not necessarily fully predictable environments. They interpret sensor data that reflect events in the environment and execute commands that produce effects in the environment. An agent is "autonomous" to the degree that it decides for itself how to relate data to commands in its efforts to achieve goals, satisfy motivations, etc. Autonomy is the ability to function as an independent unit or element over an extended period of time, performing a variety of actions necessary to achieve pre-designated objectives while responding to stimuli produced by integrally contained sensors (Zeigler 1990). Besides the necessities of AI, intelligent agents should have some additional attributes. Intelligent agents, as an entity, should be able to solve problems by itself in real-time; understand information; have intentions; draw distinctions between situations; generalise; synthesise new concepts/ideas; model the world they operate in and plan and predict consequences of actions and evaluate alternatives. Distributed artificial intelligence (DAI) can be characterised by the interaction of many agents trying to solve a variety of problems in a co-operative fashion (Hogg & Huberman 1990). The problem solving component of an intelligent agent can be a simple rule based system but can also be a neural network, an expert system or just some fuzzy rules.

While considerable effort is being devoted to understanding the detailed interactions among a few agents and designing operational DAI systems that can deal with simple problems, relatively little is known about the global behaviour of these systems as they are scaled up to deal with more realistic problems. A notion of events and processes is essential for reasoning about problem domains involving one or more agents situated in dynamic environments. Important facets are processes that perform an action and may cause an event. Co-ordination is an important issue for several reasons, for instance to promote beneficial interactions, to avoid harmful interactions and because individual decisions may have global impacts. Large systems offer a wide range of choices and strategies for addressing different aspects of the overall problem. Thus a major question is how agents should choose among their problem-solving strategies and, in particular, with which other agents they should collaborate. Since the appropriateness of these choices can change as agents receive new information and update their state, the system acquires global dynamic characteristics. In general, more responsive co-ordination mechanism- those which enable quicker reaction to changing circumstances- rely more heavily on detailed information exchange because they require greater precision. In figure 1 the interaction and communication links of an agent system based on several agents and agent groups is shown. In figure 2 (chapter 4.2) an example of a specific traffic control agent is given.

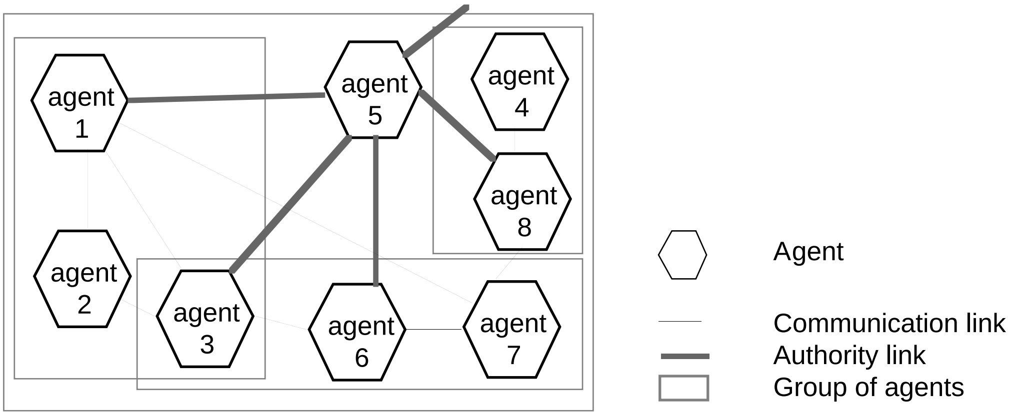

Figure 1: Groups of agents and their connections.

There are a number of shortcomings and problems that are related to the distribution of autonomous agents and tasks. One of the difficulties in both the design and the understanding of distributed artificial intelligence systems comes from the lack of central controls, and the ensuing conflicting, uncertain, incomplete and delayed knowledge on the part of the agents. In this respect, concurrency is important issue, because several processes can be performed simultaneously. Messages arrive with delays and in arbitrary order. Therefore plans and actions of agents should be designed to handle those situations. It is not possible to reconstruct, during run-time, the correct picture of the succession of events. When computational agents in such systems make choices in the presence of delayed and incomplete knowledge about the state of their system; their dynamics can become extremely complex. Part of the complexity in behaviour is due to the nature of the system, i.e. the value of an agent's decision depends on the choices made by the all the others. We may come across local minima in traffic control solvers. Some neural networks have the ability to avoid local minima. It may be obvious that a provision to find a more global optimum or finding a feasible solution is a necessity for an agent. This complicated dynamics can result in many agents making poor decisions when seen from a global perspective (even though they appear locally reasonable). This may lead to significantly lowered performance and great difficulty in programming the individual agents. Thus, it is important to devise effective decentralised control methods that can simplify the global dynamics. It may be necessary to get a hierarchy of agents. Such higher-level agent investigates the performance of a group and has the ability to change the goals or actions of other agents in that group. The design of the control laws governing the behaviour of individual agents is crucial for the design of co-operative agent teams. These laws utilise a combination of local and/or global knowledge to achieve the desired emergent group behaviour.

4 Autonomous intelligent agents for UTC

From the previous chapters it may become clear that the basic functions of an automated Urban Traffic Control system are reasonably well known. The particular techniques proposed are experimental and not mainstream, especially when proposed for such a large, on-line, application. Therefore we have to start with a study of what is necessary to build. After that there we need to determine how we are going to build such a system therefor we need prototyping to test the given claims and feasibility.

4.1 Concept and requirements

The most useful agent in UTC would be a traffic signal control device. As stated before, the time-span from data collection to signal control parameter settings can be shortened to improve the control strategy. In a study of Saito et al. (1997) is found that the use of quick response demand prediction models in saturated situations (degree of saturation > 0.5) could improve delay's per vehicle on a single approach intersection by 5% to 15 %. In saturated situations such an improvement is huge and is achievable by intelligent signal control.

An agent based system is essentially discrete as all agents have a finite number of states. The agents' state evolution is driven by occurrence of events. Events (output) are generated by agents due to events triggering an agent (input) or as a passage of time. It may be clear that the time-step of every agent may not necessarily be the same. The whole process of operating a global clock and dealing with the message passing system is a network affair. As is the data transfer, which is not the main issue in this project. Therefor we only give some basic details on the requirements of dynamic urban signal control systems. These systems need regular, fast and reliable transmission between the different agents and sub-systems of small but frequent messages, with a high integrity. The communication type should be multi-cast (to a designated group of agents) or point to point (to one single agent).

Intelligent transport Systems (ITS) requires intelligent agents of many types. In this paper we only address the specific ones dealing with urban traffic control. The traffic signalling agent (TSA) makes a decision based on goals, capability, knowledge, perception and data. The decision is followed by action, where doing nothing is also an action. When necessary an agent can request for additional information or receive other goals or orders from its authority agent. This may prove a necessity to get a less local optimum, e.g. not one optimised intersection but several, and so adapting the goals of a higher level. For a specific TSA, implemented to serve as an urban traffic control agent, the following aspects are taken into account (Roozemond, 1996-b):

- The TSA has some goals or tasks to accomplish, for instance maximising the traffic flow, given the underlying rules.
- The TSA has rules and roles to perform. The rules are based on the normal traffic regulation rules and the rules used for designing traffic control centres. The roles an agent can perform are comparable to roles a policeman can perform by controlling the traffic lights.
- The TSA is helped to decide what actions to take by its problem solving component (making diagnosis of traffic problems), the view and knowledge it has of its environment, its abilities and its state. Different situations can lead to better understanding of a situation for an agent by gaining additional knowledge.
- The TSA has skills and tasks that it can perform depending on situations. In seemingly similar situations an agent can act differently. The agent solves a problem as independently as possible, acting on its own "feeling' and its knowledge.

4.2 UTC agents

The UTC should be a demand responsive, pro-active, system based on actual information and adapting to situations. The IDTMIS-UTC consists of several intersection control TSA's and some authority agents. The design of a multi-agent system requires flexible autonomy. Meaning that agents will sometimes be required to work autonomously, but will often be commanded or influenced by others. Often an TSA should sacrifice some performance for the purpose of co-operative behaviour caused by appointment of an authority agent or self-control of TSA's. The authority agents are not discussed here, but their tasks are controlling and leading the TSA's towards a more global optimum.

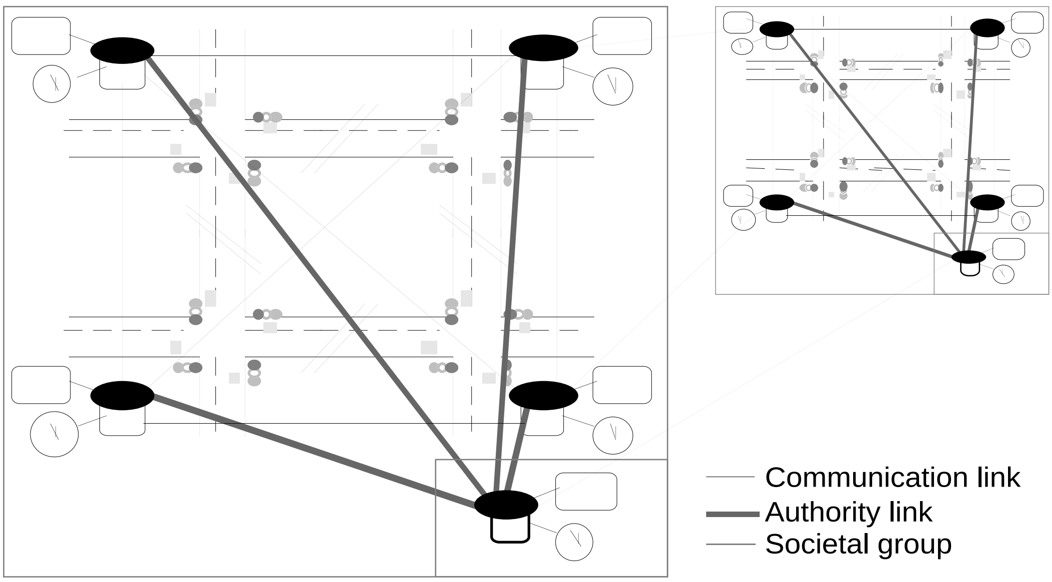

Figure 2: Simple UTC system.

In figure 2 a more specific example of a simple UTC system is given. There we have one authority agent controlling several intersection agents, which in their turn manage the intersection controls. An other possible solution is that the intersection agent controls several signal group agents. In this paper we have chosen to elaborate primarily on the first example.

An intelligent TSA, capable of controlling or advising in real-time, should be designed with the following data handling and knowledge driven actions (Roozemond, 1996-b):

- The agent receives at (given) time intervals the information on the current state of traffic (data collection).
- The agent knows the recent trends (analysis/interpretation of data).
- The agent receives information on other adjoining signalised intersections from other TSA's (data collection).
- The agent has a accurate model of the controlled intersection and knows the traffic rules (analysis).
- The agent should be able to calculate the next cycle mathematically correct (analysis/decision).
- The agent should be able to actuate the next cycle and operate the signals accordingly (control).
- The agent should be able to detect and handle current traffic problems by itself (analysis/decision and control/action) and should inform other agents of the nature, severity and possible cause of the problem, if necessary (data distribution).
- The agent passes information on to other adjoining agents (data distribution).

In the intersection system TSA, several sub-systems are united in one agent. The expert system, a central part of the agent, acts as a controller. This device is fed by several inputs. Firstly there is the vehicle detection system, nowadays implemented as detectors. There are control strategies, such as anti-blocking, public transport priority and other adaptive strategies. Finally there is communication with several other agents of nearby intersections, the urban traffic control centre, other control centres (bus / route guidance, etc.) and the operator. The controller estimates the states in the near future, calculates signal plans to pro-act on these, checks with other agents and if approved it plans signal operation.

To be able to forecast the traffic load on the intersection properly we use both historic data and current data from monitoring devices as input for our dynamic control model which in its turn is the basis for the control strategy calculation process. Thus we should be able to forecast travel times in the near future based largely on actuated data as well as travel times for some time ahead based on actuated and historic data. In general we can see that the need for actuated data becomes more obsolete as the needed forecast lies further away. Accuracy and variability of data are important as they are the key element when these models will be incorporated in traffic management schema's.

The needed data itself needs to be extracted from the system; only specified data is given to (or asked for by) each TSA forecasting system:

- the relevant road conditions: expected traffic (historic/current), measured (upstream) traffic;
- additional data on important aspects of traffic conditions: kind of day, part of the day, weather conditions, etc.;
- additional data on important aspects of this specific intersection.

The forecasting system gets its data specified and related to intersection and road segments; as an object that ‘knows’ the forecasting equations, actual traffic conditions and constraints and, in combination with the above given data, future traffic situations can be calculated by way of an inference engine and it’s knowledge- and data-base. The knowledge is presented as production rules as: IF <condition 1><condition 23>...<condition n> then <action 1>...<action m>. (Roozemond, 1997)

Single junction controllers often make use of mathematical programming methodologies based on constraints for evaluation and optimisation of the cycle. In arterial and network systems this subject becomes more complex due to co-ordination and synchronisation (Bruno & Improta 1994). A voting system may be helpful for agents to co-ordinate and choose between contradicting actions and synchronise actions between agents. Moreover, since the decisions are not centrally controlled, the agents independently and asynchronously select from the available choices the one with the highest efficiency. As written earlier, relatively little is known about the global behaviour of these agent systems as they are scaled up to deal with more realistic problems situated in dynamic environments. Co-ordination is an important issue and is implemented in the ability of agents to co-ordinate themselves by means of voting and the ability of the authority agent to co-ordinate several agents. Some sort of negotiation is necessary in case of incompatibilities among traffic co-ordination. Negotiation then becomes a process of relaxing some of the constraints so a satisfying situation can occur; even priority alteration is possible. Also advice sought by the authority agent can be a solution for conflicts as conflicts need to be solved quick.

5 Further research

From the previous chapters it becomes clear that the study on automated UTC is in a preliminary stage. First we need to consider the state of art technically and politically. Next, a study in how to implement this in the best way is a necessity. Furthermore, several ‘details’ have to be researched. The most important research questions, regarding agent based urban traffic control, will be mentioned.

• We have to start with a study of what is necessary to build. We need to get a very clear view on the subject of intelligent UTC and into the possibilities to change towards new systems. Therefor we need to get a clear view into available solutions and available systems. It may be possible that such an agent based system can be implemented in current UTC systems like SCOOT, LHOVRA or MOVA .

• After defining what we need and what we ‘ve got, we need to determine how we are going to build such a system. It looks that we need prototyping to test the given claims and feasibility. Dynamic systems require accurate and up-to-date traffic data – data that must be provided by agencies through some type of infrastructure based monitoring device to user communication scheme. We also need to de some research towards understanding the detailed interactions among a few agents and designing operational DAI systems that can deal with simple problems. Relatively little is known about the global behaviour of these systems as they are scaled up to deal with more realistic problems.

• One other aspect to be researched further is the way how to develop traffic control algorithms that can handle dynamic cycle-recalculation in real-time. To be able to do this pro-actively we need some forecasting properties incorporated in the system.

• To forecast properly we should use both historic data and actuated data from monitoring devices as input for our dynamic control model which in its turn is the basis for the control strategy calculation process. We should be able to forecast travel times in the near future based largely on actuated data as well as travel times for some time ahead based on actuated and historic data. In general we can see that the need for actuated data becomes more obsolete as the needed forecast lies further away. The kind of calculus used is effectively a state prediction model: predicting the states on time t_j, given the state on time t_{j-dt}. (where dt is not fixed). The abovementioned data, combined with the requested downstream traffic forms the basis for the calculation process.

• Minimising objectives is, in theory, quite simple:

$$Min \sum_{i=0} objective_i * weight_i$$

The minimisation process in this system is far more complex due to several different, continuously changing, weights and different goals of the different TSA's. For this problems we need to find some sort of solution in the form of an algorithm, other then directly giving the decisions to authority agents. For optimising signal timings the minimised sum of the total delay is often used for this purpose, but also number of stops, fuel efficiency, etc. may be incorporated in such an optimisation. For isolated traffic signals such an optimisation is already been made (Bang 1976). For arterial and connected junctions several of-line and heuristic methods are becoming available and are still been made.

•Feasibility is the last detail that has our attention. The agent based system should not only give the best solution, but in the process there should be an emphasis towards getting a feasible solution. The optimisation of a junction could introduce severe problems for others, so a global optimisation process / optimisation control via authority agents should be researched. Relatively little is known on this, most important subject.

6 Conclusions

• An IDTMIS is no cure for the traffic problems; it may streamline and reduce the traffic load, have more direct routes available, give good information and advise and still there would be a traffic problem. So research on changing attitudes, other ways of transport, etc. is equally important. As may be clear from the previous chapters, the whole urban traffic control part of IDTMIS is far from operational.

• For urban traffic control the research agenda comprises to adjusting the control schemes to ones that can deal with dynamic and actuated data. Further research on a control strategy, based on intelligent autonomous agents, is necessary to provide appropriate evidence on the usability of AI / agent based control systems. Such a control strategy may improve inner-city traffic control by reducing traffic delays and improve safety.

• The pro-active and re-active nature of agents is a helpful paradigm in intelligent traffic management and control. Several loosely coupled systems might be able to cope with the dynamic actions of traffic. A fully automated controlled UTC-agent based system is not reachable due to the large amount of different kinds of individual traffic participants in urban areas, but for the current intersection control systems an agent based UTC could be an alternative.

• In normal system engineering, testing (verification, validation and evaluation) is an integral part of the design process. Testing a dynamic, complex system is far more difficult to perform. Intelligent distributed sub systems, as used in IDTMIS, should be extensively (field) tested before being widely used in the real world.

• Preliminary results indicate that, given an automated control strategy implemented in the traffic signalling devices, we can get a system that makes better use of the capacity of the intersection. In case of unsaturated intersections the strategy proves to be better then intersections with detectors, the question remains if these strategies prove to be better in saturated situations or if they can improve current actuated control systems.

References

Bang, K. (1976), Optimal control of isolated traffic signals, in: *traffic engineering + control, july 1976*

Bernstein, D. (1993), Congestion pricing with tolls and subsidies, in: *proc. Pacific Rim TransTech Conference, vol 11,* ASCE, New York

Bruno, G., Improta, G. (1994), Urban traffic control,: current methodologies in *artificial intelligence applications to traffic engineering, Bielli, M., Ambrosino, G., Boero, M.(eds.)*, VSP, Utrecht

Hogg, T, Huberman, B.A. (1991), Controlling Chaos in Distributed Systems; in *IEEE Transactions on Systems, Man & Cybernetics. v 21 n 6 Nov-Dec 1991*

Kronberg, P., Davidson, F. (1993), MOVA and LHOVRA: traffic signal control for isolated intersections, in: *traffic engineering + control, april 1993*

Prigogine, I., Herman, R. (1971), Kinetic theory of vehicular traffic, Elsevier, New York

Romph, E. de (1994), *A dynamic traffic assignment model: theory and applications*, DUT-press, Delft

Roozemond, D.A. (1995), An Integrated Multi-Discipline Dynamic Traffic Management System, Based on Information, Objects and Inter-Object Communication; in: *Urban transport and the environment in the 21st century,* Sucharov, L.J.(ed.), CMP, Southampton

Roozemond, D.A. (1996-a), Analyzing and managing traffic, a model based on intelligent objects and self organization; in: *Analyzing complex societal problems, DeTombe, D.J., Dijkum, C. van (eds.)* Rainer Hampp verlag, München

Roozemond, D.A. (1996-b), Intelligent traffic management and urban traffic control based on autonomous objects, in : *Sixth annual conference on: AIS'96, Artificial intelligence, simulation, and planning in high autonomy systems*; San Diego, March 23-37, 1996

Roozemond, D.A. (1997), Intelligent Transport Systems: autonomous urban traffic control, *4th world congress on Intelligent transport Systems*, 21-24 Oct 1997, Berlin, ITS America, Ertico and Vertis

Saito, T, Yasui, K, Ukyo, T, Nakano, J (1997), Study on traffic demand prediction methods for intelligent traffic signal control, *4th world congress on Intelligent Transport Systems*, 21-24 Oct 1997, Berlin.

Vincent, R., (1993), Safer signalized junction design and self-optimizing control, in *journal of advanced transportation*, vol 28, no 3

Zeigler, B.P. (1990), High autonomy systems: concepts and models; in *proceedings AI, simulation, and planning in high autonomy systems*, Zeigler, B., Rozenblit, J (eds.), IEEE, Los Alamos