CONTINUOUS NEGOTIATION FOR A VEHICLE-REGULATED INTERSECTION

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Abstract

Urban congestion is a major problem in our society for quality of life and for productivity. The increasing communication abilities of vehicles and recent advances in artificial intelligence allow new solutions to be considered for traffic regulation, based on real-time information and distributed cooperative decision-making models.

The paper presents a mechanism allowing a distributed regulation of the right-of-way of the vehicles at an intersection. The decision-making relies on an automatic negotiation between communication-equipped vehicles, taking into account the travel context and the constraints of each vehicle. During this negotiation, the vehicles exchange arguments, in order to take into account various types of information, on individual and network scales. Our mechanism deals with the continuous aspect of the traffic flow and performs a real-time regulation.

1. INTRODUCTION

During the 1990s and 2000s, artificial intelligence enabled to investigate new methods for traffic modeling and regulation, especially with multi-agent technologies that are able to solve various problems in a decentralized and/or distributed way [1]. Today's communication technology enables the design of regulation methods based on real-time communication of accurate information. In [3], K. Dresner and P. Stone propose a right-of-way awarding mechanism based on reservation for autonomous vehicles. It relies on a policy called FCFS (First Come First Served), granting the right-of-way to each vehicle asking for it, as soon as possible. This paper shows a possibility to take some steps towards new foundations of interactions. Based on this, we propose a new negotiation framework for an agent-based traffic regulation and tackle the continuous aspect of the traffic flow. In such negotiations, vehicles build various right-of-way awarding proposals that we call "configurations". These configurations are expounded to the other vehicles of their area, that can raise arguments about the benefits and drawbacks of each configuration. With the help of the intersection, that contributes to the coordination of the interactions, the vehicles decide on the configuration to adopt collectively. The problem we are concerned with in this paper is to allocate an admission date to each vehicle arriving at an intersection. An agent-based model is used where vehicles and intersections are the agents. The physical representation of the network consists in a cellular automaton model, as shown on Figure 1. The decision is distributed: each vehicle agent is able to reason and communicate with the intersection and the other vehicles. In our approach the vehicles build individually full configurations and then decide collectively in a negotiation process. Before addressing this negotiation step, the

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agents have to model the right-of-way allocation problem in order to build the configurations that will be negotiated.

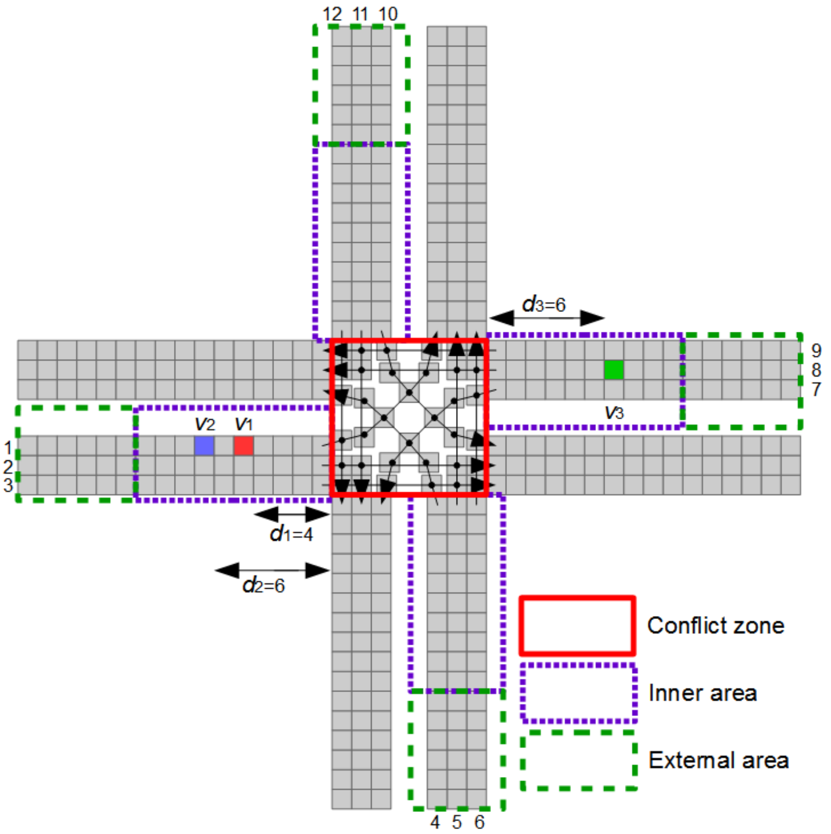

Figure 1: Intersection with 12 approaches and 12 outcoming lanes, divided into cells. The approaches are numbered from 1 to 12. The conflict zone is crossed by various trajectories, also divided in cells. The cells belonging to several trajectories (every cell of the conflict zone in this case) are conflict spots. Colored cells are vehicles, e.g. the rectangle noted v_1 on the approach 1 is a vehicle coming from the west, about to cross the intersection to the north.

2. MODELING THE RIGHT-OF-WAY ALLOCATION PROBLEM TO BUILD CONFIGURATIONS

The moving rules of the vehicles in the cellular automaton are the following:

- If a vehicle is on the front cell of an approach, this vehicle moves one cell forward and drives into the intersection (the first cell of its trajectory) if and only if it has the right-of-way.
- If a vehicle is on an approach, it moves forward if and only if the next cell of the approach is empty, or becomes empty during this time step.
- If a vehicle is in the conflict zone, it necessarily moves forward. Our method has to guarantee for each vehicle that it will not meet any other vehicle in the cells of its trajectory.

In order to build configurations, we model the right-of-way allocation problem as a Constraint Satisfaction Problem (CSP). The CSP fits our problem since it is easy to represent the structural rules of our problem (physical constraints and safety constraints) with 3 types of constraints.

- Distance constraint: a vehicle has to cross the distance separating it from the conflict zone before entering it.
- Anteriority constraint: a vehicle cannot enter the conflict zone before the vehicles preceding it on its lane (this rule could be removed with a more complex model that would take overtaking into account).
- Conflict constraint: two vehicles cannot be in the same cell at the same time. If the vehicles belong to the same lane or trajectory, the moving rules of the vehicles prevent this case. However, if a cell is a conflict point then we have to model this rule for the vehicles belonging to different trajectories.

This constraint must be reinforced for safety reasons. Indeed, adding a time lapse t_{safe} between the passage of a vehicle on a cell and the passage of a vehicle in a conflicting trajectory on this cell enhances the drivers' safety.

With this CSP model, an agent uses a solver to find compatible admission dates (i.e. respecting the above constraints) for a set of vehicles approaching an intersection.

3. RIGHT-OF-WAY NEGOTIATION MODEL

Each vehicle builds configurations allowing it to cross the intersection, however only one configuration will be applied at a given moment. A negotiation process takes place to select it. The mechanism we propose relies on an argumentation-based model [4]. Through the negotiation process, agents aim to reach a collective agreement by making concessions. To perform a negotiation, the vehicle agent relies on its own mental state, made of knowledge, goals and preferences. This mental state evolves during the negotiation. The agents use arguments to make the other agents change their mental states, in order to reach a better compromise for each one.

Each vehicle has a weight given by the intersections. Two kinds of arguments may be used by the agents, favorable and unfavorable arguments.
For safety reasons, the intersection has a current configuration at any time. The agents use this configuration as a starting point for negotiation. The goal of an agent through the negotiation is to change this current configuration by another that improves its individual utility. In a negotiation the agents rely on a communication language to interact. The set of possible negotiation speech acts is the following: Acts = {Offer, Argue, Accept, Refuse}.

- Offer(c_{new}, c_{cur}): with this move, an agent offers that a configuration c_{new} replaces the configuration c_{cur}. An agent can only make each offer move once.
- Argue(c, $arg(c)$): with this move, an agent gives an argument in favor of c or against c.
- Accept(c_{new}, c_{cur}), Refuse(c_{new}, c_{cur}): with this move, an agent accepts (resp. refuses) that a configuration c_{new} replaces the configuration c_{cur}.

c_{new} is accepted iff an acceptance threshold (> 0.5) is reached by the vehicles.

3.1 Role of the intersection agent

In order to perform a right-of-way allocation that maximizes the social welfare and encourages cooperative behaviors, the intersection agent takes part in the negotiation process. In a negotiation, each vehicle first defends its own interests, and also defends other interests that may guide the negotiation towards a favorable outcome for it. A vehicle can represent the interests of other vehicles outside the negotiation area (for example the vehicles that follow it) or network scale interests (for example clearing some lanes) if it can get

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advantage of it. However, it may happen that these arguments do not directly concern the vehicles of the negotiation area, that may ignore these arguments despite their positive contribution to global social welfare. To avoid this effect, the intersection agent is able to represent these external interests. Like the vehicle agents, the intersection agent has its own mental states and is able to produce arguments. However, it cannot accept or refuse proposals. The weight the intersection agent gives to each of its arguments depends on the importance of the external interests represented by these arguments. The weight w_i of a vehicle v_i is given by the intersection agents to encourage the vehicles to have cooperative behaviors. According to v_i 's cooperation level in its negotiation behavior, the intersection increases or decreases w_i for the remainder of v_i's journey. The behavior of a vehicle is cooperative if its acceptances and refusals do not conflict any arguments. A vehicle refusing a proposal having numerous strong arguments for it (or accepting a proposal having a numerous strong arguments against it) gets an important weight penalty. On the contrary, a vehicle accepting a proposal having numerous strong arguments for it (or refusing a proposal having numerous strong arguments against it) gets a weight reward.

For a vehicle, these rewards and penalties are significant in the middle and long term since it affects durably its capacity to influence the configurations of the next intersections. To perform this phenomenon, the intersection uses arguments to assign a reward (or penalty) value to each configuration proposal, so that the vehicles may evaluate the benefits and risks from each of their decisions about configurations before making these decisions.

The intersection uses reward or penalty according to the weight of the vehicles. A vehicle that already has a high weight gets a little advantage while getting a weight reward, but getting a weight penalty would be an important drawback. On the contrary, a vehicle having a low weight would get a little drawback from a weight penalty and an important advantage from a weight reward. Let $V_{min} \in V_{neg}$ be the set of the vehicles that emitted arguments contradictory to the intersection agent's preference. To have more influence on the vehicles, the intersection agent uses penalties when the average weight of the vehicles of V_{min} is greater than the average weight of the vehicles of V_{neg}, and uses rewards otherwise.

3.2 Continuous negotiation mechanism

The vehicles have the ability to communicate and to choose collectively a configuration for the intersection. However, since the flow of vehicles is continuous, the mechanism has to manage this dynamic aspect by defining the agents that take part in each negotiation step, the vehicles for which this configuration provides an admission date, and the conditions under which this configuration could be revised once chosen. In order to manage technical failures, the intersection has a current configuration c_{cur} at any time. According to the chosen continuity policy, the negotiation mechanism may allow the vehicles to collectively change this configuration. However, the mechanism has to consider safety measures before allowing this change. Changing the configuration at the last moment is risky because of the slowness of the reaction of the drivers. To avoid this, we define a safety time threshold th_{safe}. The admission date of a vehicle cannot be revised (removed or granted) in a too short term.

In this paper, we present two policies to manage the continuity problem. First, we distinguish two areas on the approaches of the intersection: the inner area, where all the vehicles are about to reach the conflict zone in a short term, and the external area, where the agents will reach the conflict zone in a slightly longer term. The size of each area depends on the intersection. At each time step t_i, the set V_i of the incoming vehicles is divided in two subsets: V_{inn} the vehicles of the inner area and V_{ext} the vehicles of the external area.

Iterated Policy (IP)

When this policy is applied, the vehicle agents join the negotiation by waves, and perform iterated decisions that cannot be revised. At a given instant t_{i-1}, V_{inn} is empty. At the next time step t_i, since the vehicles have moved, V_{inn} and V_{ext} change. The set of negotiating vehicles V_{neg} becomes equal to V_{inn}. Then the vehicles of V_{neg} perform a collective decision about the configuration, but only for the vehicles of V_{neg}. A negotiation process starts, with a limited duration d_{neg}. This limited duration leads the agents to quickly make reasonable proposals for every vehicle. At the end of this negotiation step, a configuration *ci* is chosen, awarding an admission date to each vehicle of V_{neg}. At t_{i+1}, a new iteration begins, and the vehicles in V_{neg} change again.

The vehicles of V_{neg} start a new negotiation, but the vehicles that already have taken part in a previous negotiation step do not take part in this one. The vehicles of V_{neg} are not allowed to revise c_i, the agents only extend c_i by negotiating the admission dates of the vehicles of V_{neg} since the other vehicles of V_{inn} were in the previous V_{neg} and already have an admission date defined in c_i or in previous configurations. A new configuration c_{i+1} is chosen, similar to c_i except it adds admission dates for the vehicles of V_{neg}. The policy continues to iterate and to produce new admission dates for the next vehicles in the inner area without revising those of the vehicles that already were in it.

Continuous Policy (CP)

When this policy is applied the vehicles dynamically join the current negotiation while entering the inner area, $V_{neg}=V_{inn}$ at any time. When a vehicle v_{new} joins V_{inn}, all the useful information about the current state of the negotiation (configurations and arguments) are communicated to v_{new} so that it can join the negotiation. The current configuration of the intersection can be totally revised by a collective decision, except for the vehicles that are concerned by the security threshold. Whenever new vehicles join V_{inn}, the current configuration of the intersection and the configurations under negotiation do not provide admission dates for these vehicles, since the configurations were emitted before these vehicles joined V_{inn}. However the intersection provides an ordering on these vehicles. With this ordering, it is possible for any vehicle in the negotiation to extend any of the vehicles' configuration proposal. Extending a configuration consists in adding an admission date for each new vehicle with the FCFS strategy, using the ordering on these vehicles. The agents consider that any proposal in the negotiation that do not provide an admission date to each vehicle of V_{inn} will be extended with FCFS. It guarantees that the intersection always have an admission date for each vehicle of V_{inn}.

4. EXPERIMENTATION AND DISCUSSION

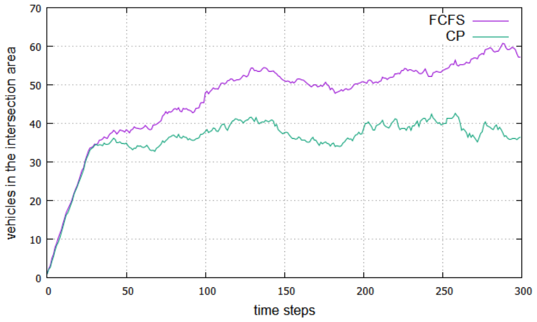

Figure 2: Number of vehicles in the area

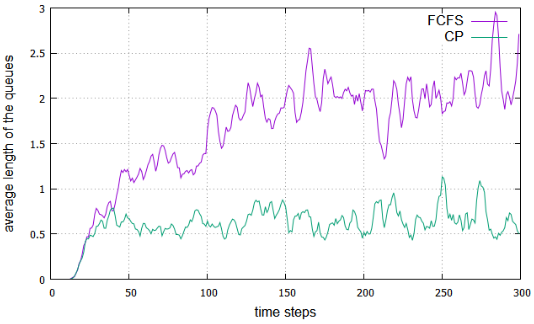

Figure 3: Average length of the queues

This work has been implemented in Java with the Choco library for CSP [2], on an intersection with 12 approaches (cf. Figure 1). The length of the inner area is 6 cells on each

approach. Agents are implemented as threads: each agent has its own solver and its own negotiation strategy. The agents communicate with other agents with direct messages.
On a personal computer (RAM 2Gb, 1.9 GHz mono-core processor), 1 second is enough to run the solver and compute several good configurations for about 30 vehicles, and the negotiation time is low enough to enable to run the mechanism in real time.
In this section, we present the results of the comparison between FCFS and the CP policy.
We simulated a continuous incoming flow of vehicles (1.2 vehicle/step in average). These simulations were performed on a more computer with RAM 32Gb, 64-core processor. Results are shown on Figures 2 and 3. These figures respectively represent the number of vehicles in the intersection area and the average number of vehicles waiting for the right of way on each approach, relatively to the time. For example in simulations of the CP policy, after 100 time steps the average number of vehicles in the area were 37.9 (cf. Figure 2) and 0.64 vehicles were waiting for the right of way on each approach of the intersection (cf. Figure 3). The main improvements of our negotiation-based mechanism are expected to appear on the network scale, and so far we only experimented it on a single intersection. The main goal of these early experiments, and our main result, is to show the feasibility of this mechanism. The slight performance improvements shown on Figures 2 and 3 may also be explained by the use of the solver to optimise the right-of-way of the vehicles. Moreover, this improvement is accentuated with the use of the safety time lapse t_{safe} defined in the conflict constraint that gives more importance to the ordering of the vehicles.

5. CONCLUSION

In this paper, we have proposed a coordination mechanism which represents a large step towards easing traffic, minimizing time losses while respecting safety constraints. This paper has made three significant contributions. Firstly, it defined the problem of intelligent agent-based intersection management. Secondly, it presented a negotiation mechanism that deals with continuous negotiations and applies a set of policies, and behavior rules that show how to exploit this framework over intersection control methods. This paper has taken one step forward to show how a system can take action to manage the decision of the vehicles cooperatively. This paper suggested that it is both algorithmically feasible and reasonable in terms of delay and computational cost to enable such sophisticated reasoning.
However, substantial work must still be done. For example, a possible direction concerns the intersection agent that can switch among several policies, for instance by learning from the reservation history to find the best policy suited to particular traffic conditions. In current work we are adapting the behavior of the intersection to handle vehicle priorities.

ACKNOWLEDGEMENTS

Funding for this project was provided by a grant from la Région Rhône-Alpes. The authors would like to acknowledge the students Guillaume Collombet, Paul Talvat, Anita Barry, Bruno Dumas, Loubna El Manany, Jérémy Ferrer, Damien Mornieux and Antoine Richard for their support in the implementation of the mechanism.

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