Towards Valuation-Aware Agent-Based Traffic Control

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ABSTRACT

Traffic authorities work hard to improve resource utilization in traffic. But these efforts do not consider that the valuations of waiting time can be different for each driver, e.g., a driver of a courier service delivering express mail typically has a higher valuation of reduced waiting time than other motorists. We propose that traffic-control mechanisms should be valuation-aware and propose and describe such a mechanism called *Time-Slot Exchange*. The idea of this mechanism is that vehicles are assigned time slots to cross the intersection, and vehicles, or, more specifically, agent-based driver-assistance systems of the vehicles can then trade these time slots. Simulations show that our mechanism increases overall satisfaction considerably, compared to a state-of-the-art traffic-control mechanism.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*Multiagent systems*

General Terms

Algorithms, Economics, Measurement

Keywords

Agents, Negotiations, Traffic management, Intersection control

1. INTRODUCTION

With the significant increase of traffic in inner cities [5], the design of traffic-control mechanisms gains importance. A key observation behind our current work is that different drivers value reduced waiting time differently. E.g., a driver of a courier service delivering express mail typically has a higher valuation of reduced waiting time than other motorists. Current mechanisms for traffic control do not take these valuations into account. An exception is [3] which prioritizes only emergency vehicles. But this approach, like the one in [4], only considers few distinguished vehicles. To alleviate this shortcoming, this paper proposes that traffic-control mechanisms should be *valuation-aware*, and it proposes and investigates a novel mechanism for traffic control at intersections with this characteristic. We call this mechanism *Time-Slot Exchange* because it allocates time slots to cross an intersection and allows vehicles to exchange these subsequently. To this end, it requires agent-based driver-assistance systems.

Designing such a mechanism and implementing and evaluating it has been difficult for many reasons. Traffic imposes several constraints which valuation-aware mechanisms must fulfill. Examples are the *high dynamics* of the environment, i.e., vehicles can arrive at the intersection at any time, and the *physical properties* of vehicles, like maximum speed, acceleration, or physical extent. Further, vehicles *cannot overtake* while approaching the intersection.

Extensive experiments show that our new mechanisms do indeed increase overall satisfaction. It reduces both average waiting time and average weighted waiting time.

2. DEFINITIONS

In this section we define measures to evaluate valuation-aware mechanisms for intersection control.

The *waiting time* T_w^j of a Vehicle j is the difference between the actual travel time and the minimal travel time. The *minimal travel time* is the travel time of a vehicle in the absence of any other vehicles, obeying speed limits but disregarding any other traffic regulations, e.g., red lights. The *average waiting time* $\overline{T_w}$ is the average of the waiting times of all vehicles crossing an intersection. Average waiting time does not take valuations into account. Thus, we will use the average waiting time weighted by the valuation of the drivers as our main measure of efficiency, as described next.

The *valuation* $v^j(t)$ of the driver of Vehicle j is the price the driver is willing to pay if he waits t seconds less. In the following, we only consider linear valuation functions. Thus, the valuation per second v^j is constant for the Vehicle j. Other valuation functions, e.g., specifying a deadline, are conceivable as well, especially when considering the whole trip where many intersections are crossed. But because we limit ourselves to single intersections in this work, a linear valuation function is adequate. The *weighted waiting time* vT_w^j of a Vehicle j is $v^j \cdot T_w^j$. The *average weighted waiting time* $\overline{vT_w}$ is the average of the weighted waiting times of all vehicles.

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Drivers with high valuations have a stronger influence on average weighted waiting time than drivers with low ones. The average weighted waiting time decreases if the waiting time of vehicle with a low valuation increases by the reduction of the waiting time of a vehicle with a high valuation.

Let b^j be the *budget* of the driver of Vehicle j. The *utility* u^j of the driver of Vehicle j is the difference between his budget and his weighted waiting time. The *total utility* U is the sum of the utilities of all drivers. This definition of utility assumes that every driver has the same valuation for money. We do not distinguish between 'rich' and 'poor' drivers with different willingness to spend money. Thus, the unit of both weighted waiting time and utility is the currency unit in use. Maximizing total utility is equivalent to minimizing average weighted waiting time, as long as money is paid among vehicle agents only. This is true for the mechanism described here, but not for any mechanism that is conceivable. Our goal is to minimize average weighted waiting time.

3. AGENT-BASED TRAFFIC CONTROL

Valuation-aware mechanisms need an infrastructure which allows to negotiate time slots. Because there should not be any distractions of the driver while driving, the negotiations have to be executed autonomously. To accomplish this, we use agent technology. Agents can interact autonomously with other agents to achieve their goals. This requires vehicles equipped with a platform providing a standardized interface. By offering communication features and access to vehicle sensor data, this interface allows to implement *vehicle agents*. A vehicle agent in turn may be part of or may communicate with a driver-assistance system.

There already exist platforms with communication features, e.g., the system described in [4] allows buses and trams to inform traffic lights about their arrival at an intersection. For some valuation-aware mechanisms, communication between vehicle agents is not sufficient. In particular, there should be a specific instance at an intersection administering the assignment of time slots to vehicles. Thus, there must be an agent corresponding to an intersection. We call this agent *intersection agent* in the following. It represents the interest of traffic planners. The vehicle agents, in contrast, are configured by their drivers and therefore share their goals.

Note that the vehicle agent does not have to do the driving of the vehicle autonomously, but this is an option. Our approach works both if the vehicle agent solely informs the driver, and if it takes control of the vehicle, as with adaptive cruise-control systems (ACC, [1]).

4. MECHANISMS

In the following we describe two mechanisms for traffic control at intersections, *FIFO* and *Time-Slot Exchange* (*TSE*). *FIFO* has been proposed in [2]. *TSE* in turn is our new valuation-aware mechanism. We describe *FIFO* here because it is the yardstick for our evaluations of *TSE*.

4.1 FIFO

With *FIFO*, agents of vehicles approaching the intersection request a time slot from the intersection agent. The intersection agent answers the requests in the order of arrival, hence the name *FIFO*. If the intersection is still free, the intersection agent confirms any time slot requested. Otherwise, it offers the vehicle agent the earliest possible time slot after the requested one. We prohibit vehicles approaching the intersection to overtake. Thus, the time slots of vehicles queuing from one direction are always in increasing order.

4.2 Time-Slot Exchange

The time slot received from the intersection agent, e.g., based on *FIFO*, might mean that the vehicle has to wait a relatively long time to cross the intersection (or, more specifically, that the driver of the vehicle deems this waiting time relatively long). To improve the situation, we propose *TSE*. *TSE* can complement *FIFO*.

Idea. A vehicle agent which is not satisfied with the time slot it currently holds can request an exchange of time slots. If successful, the requesting vehicle must pay and obtains an earlier time slot. The exchange partner in return receives the time slot of the vehicle of the requesting agent and the pay.

Exchange Agent. To ease the finding of exchange partners and to ensure the constraints defined in the following, we introduce the *exchange agent*. It is the component within our architecture that actually brokers requests for time-slot exchanges. Its goal is to accomplish as many exchanges as possible. The intersection agent in turn 'only' avoids overbooking, i.e., vehicles having time slots for intersecting lanes at the same time. When a vehicle initiates an exchange, it specifies the time slot currently held, the earliest time slot that is feasible, the price it is willing to pay for each second of reduced waiting time and the lane it will use to cross the intersection. 'Earliest time slot feasible' is the earliest time slot when the vehicle can cross the intersection without violating the speed limit.

Intersection Agent. As soon as the exchange agent receives an exchange request, it asks the intersection agent for a list of vehicles which are candidates for an exchange (*list of candidates*). A vehicle is a candidate if the following holds: First, the time slot of a candidate is between the earliest time slot feasible for the initiating vehicle agent and the time slot it currently holds. Second, after an exchange, time slots must not conflict with other reservations.

Contacting Vehicle Agents. The exchange agent goes through the *list of candidates* and notifies them about the offer – one after the other. The candidate in turn compares the price per second offered with its own valuation of waiting-time reduction. Only if the offer exceeds the valuation, the vehicle agent agrees to the exchange.

Conditions. The willingness of the candidate to exchange time slots is a necessary but not sufficient condition for the functioning of the mechanism. To preclude that vehicles not involved in an exchange are harmed we also require: (a) the time slot of the vehicle driving in front is earlier than the time slot a vehicle receives from an exchange, and (b) if the vehicle driving behind already holds a time slot, this time slot must be later than the time slot received from an exchange. The exchange agent is responsible to ensure these conditions for both vehicles participating in the exchange. If the exchange partner agrees, and both conditions are fulfilled for both vehicle agents, the exchange is executed.

Note that these conditions are a strong restriction. They limit the possible exchanges significantly. We adhere to these conditions anyhow because user acceptance is likely to be low if an exchange may harm vehicles not directly involved in it.

	mean	**0.95% CI**
$\overline{T_w^{FIFO}} - \overline{T_w^{FIFO+TSE}}$	0.567	[0.431,0.703]
$\frac{\overline{T_w^{FIFO}} - \overline{T_w^{FIFO+TSE}}}{\overline{T_w^{FIFO}}}$	0.040	[0.028,0.052]

Table 1: Differences of average waiting time $\overline{T_w}$

	mean	**0.95% CI**
$\overline{vT_w^{FIFO}} - \overline{vT_w^{FIFO+TSE}}$	0.010	[0.008,0.012]
$\frac{\overline{vT_w^{FIFO}} - \overline{vT_w^{FIFO+TSE}}}{\overline{vT_w^{FIFO}}}$	0.073	[0.056,0.091]

Table 2: Differences of average weighted waiting time $\overline{vT_w}$

5. EVALUATION

We evaluate the efficiency of *TSE* using a simulation framework of our own. We simulate the behavior of drivers, of vehicles and of vehicle, intersection and exchange agents. The simulation framework uses the Java Agent DEvelopment Framework (JADE, `http://jade.tilab.com/`) to build the agent-based components.

Our evaluation scenario is an intersection with four directions. Each direction consists of two incoming and two outgoing lanes. The left incoming lane allows to turn left, the right one to turn right. Both lanes also allow to go straight. From each lane 100 vehicles arrive per hour on average. So we have a total number of 800 vehicles per hour crossing the intersection. We allow only one vehicle to cross the intersection at a time. The crossing time of a vehicle is $4s$. Thus, the capacity is 900 vehicles per hour, which is above our number of vehicles. A driver has a random valuation per second with the average of 0.01 currency units per second.

We compare standalone *FIFO* to the combination of *FIFO* and *TSE*. For each of the mechanisms we execute 25 simulation runs. As preliminary experiments have shown, the performance of a simulation run heavily depends on its initialization. Thus, we only compare runs where every Vehicle j starts at the same time and goes in the same direction. We achieve this by using the same 25 randomly chosen numbers as seeds for the simulation runs. This lets us compare the ith run of *FIFO* to the ith run of *FIFO+TSE*.

For each simulation run we compute the average waiting time $\overline{T_w}$ and the average weighted waiting time $\overline{vT_w}$. We compute the difference of $\overline{T_w}$ and the difference of $\overline{vT_w}$ for each pair of equally initialized simulation runs. We use these differences to determine the mean and the 95% confidence interval.

Table 1 lists the the mean and the 95% confidence interval (CI) of absolute and relative differences of average waiting time $\overline{T_w}$. The results for the average weighted waiting time $\overline{vT_w}$ are given in Table 2. Using *FIFO+TSE* we can reduce the average weighted waiting time $\overline{vT_w}$ by 0.010 units, i.e., by 7.3%. This is a reliable result, as the 95% confidence interval shows. *FIFO+TSE* also has a positive influence on the average waiting time. The average waiting time is reduced by 0.567 seconds on average, i.e., 4.0%, compared to *FIFO*.

In these simulations only 7.4% of the vehicles initiate a successful exchange. These numbers are relatively small because of our rather strict conditions which avoid harming vehicles not involved in the exchange.

6. CONCLUSIONS

Most existing solutions for traffic control are not aware of the driver valuations of reduced waiting time. But valuation-aware mechanisms can increase overall satisfaction. Therefore, we have proposed the first valuation-aware mechanism for intersection control called *Time-Slot Exchange*. We combine it with the state-of-the-art mechanism *FIFO* for agent-based intersection control and lets driver-assistance systems exchange the right to cross an intersection. Compared to stand-alone *FIFO*, our mechanism increases overall satisfaction of motorists, as it reduces both average waiting time and average weighted waiting time.

As future work, we will investigate how to improve the results achieved so far. We assume that the number of successful exchanges will be much higher if some of the vehicles with high valuations arrive at the intersection on short notice. The same might be true if the rate of arriving vehicles is different for each direction. Another approach that we deem promising, rather than extending *FIFO*, is to replace *FIFO* with mechanisms which are already valuation-aware, e.g., with auction-based mechanisms.

7. ACKNOWLEDGMENTS

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