Agent-Based Traffic Control Using Auctions*

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Abstract. Traffic management nowadays is one of the key challenges for cities. One drawback of traditional approaches for traffic management is that they do not consider the different valuations of waiting-time reduction of the drivers. These valuations can differ from driver to driver, e.g., drivers who are late for their job interview have a higher valuation of reduced waiting time than individuals driving home from work routinely. This also applies to trucks with urgent load, e.g., as part of a just-in-time production chain. To overcome this problem, we propose a new mechanism for traffic control at intersections called *Initial Time-Slot Auction* that is valuation-aware. It relies on agent-based driver-assistance systems to allocate the right to cross an intersection. Our evaluation shows that it does yield a significantly higher overall satisfaction.

1 Introduction

Traffic control is a key problem cities currently have to deal with [1]. Drivers are dissatisfied with high waiting times at intersections. One characteristic of traditional approaches for traffic control at intersections is that they do not consider the valuations of waiting-time reduction of the drivers. These valuations are not at all equal among drivers. For instance, drivers who do not want to miss their flight or truck drivers who must stick to their time schedule have higher valuations of such reductions than individuals driving home from work routinely. Traditional traffic-control mechanisms do not take these valuations into account. Existing mechanisms do not even let drivers inform other vehicles or the traffic-control unit about their valuations.

To increase overall satisfaction of motorists, this article investigates new mechanisms for traffic control which take the valuations of waiting time of the drivers into account. We call such mechanisms "valuation-aware" in the following. Such mechanisms require interaction among vehicles and the infrastructure to exchange valuations. In this respect, they can benefit from ongoing advances in vehicle technology.

However, designing such valuation-aware mechanisms is challenging. This is because the traffic scenario imposes several constraints that are different from

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the ones in conventional settings. The situation at an intersection is *highly dynamic*. Vehicles can arrive at any time. With the arrival of a new vehicle, the optimal order of vehicles crossing the intersection may change. In contrast to scheduling in communication networks, vehicles are *physical objects* with physical characteristics, e.g., they need to accelerate/decelerate, and their speed is limited. Vehicles queuing from the same direction cannot change their order, i.e., *no overtaking*.

The mechanisms envisioned must be superior to existing mechanisms, i.e., yield a higher overall satisfaction (*effectiveness*). Next, mechanisms inducing drivers to reveal their valuations truthfully may be desirable (*incentive compatibility*). Further, there should be an upper bound of the waiting time, for all drivers (*avoidance of starvation*).

This paper proposes and evaluates an approach for valuation-aware traffic control at intersections. More specifically, we make the following contributions: We first identify desiderata any valuation-aware traffic-control mechanism should fulfill. We then propose our new mechanism called *Initial Time-Slot Auction* (*ITSA*). It auctions the right to cross the intersection for a certain period of time to arriving vehicles. We call this right *time slot* in the following. *ITSA* allocates a time slot to the vehicle with the highest bid. We describe the mechanism in detail, discuss design alternatives and possible extensions of the basic variant, and say to which extent they fulfill the desiderata. We have implemented two variants in full and compare them to a *FIFO* mechanism [2,3], a state-of-the-art agent-based traffic-control mechanism from the scientific literature, using simulations. A core result of our work is that *ITSA* yields a significant reduction of valuation-weighted waiting time.

This article is part of a long-term effort that strives to design valuation-aware traffic-control mechanisms that are applicable in the real world, and this article is a first stab at the problem. For instance, we currently limit ourselves to single intersections (the fact that a vehicle typically has to cross several intersections to reach its destination is future work), and we leave aside robustness and legacy issues, i.e., "old" vehicles that are not equipped to interact with valuation-aware traffic-control mechanisms. Nevertheless, this current work has yielded valuable insights into the general problem domain and has demonstrated the potential of our approach.

Paper outline: We discuss related work in Sect. 2. Section 3 describes fundamentals of valuation-aware traffic control. In Sect. 4, we propose our new valuation-aware mechanism for traffic control and its variants. Section 5 features an evaluation, Sect. 6 concludes.

2 Related Work

This section describes related work where agents have been used for traffic management at intersections and related valuation-aware approaches. Related work regarding other aspects, e.g., auctions, is cited elsewhere in the paper.

There already exist various approaches for agent-based traffic management. We only discuss a small subset that we deem most relevant for our work. [2,3] propose an agent-based reservation system for intersection-traffic control. It allows vehicles to reserve a time slot in advance for crossing an intersection. The system proposed is a reservation system, but not a platform where agents can trade time slots, and it is not valuation-aware. An extension of the reservation system [4] gives priority to emergency vehicles, e.g., ambulance or police cars. [5] describes an approach where trams or buses communicate their arrival to traffic lights. In both cases, only a small subset of vehicles is privileged, but the valuations of all other vehicles are ignored. [6] presents an agent-based system for urban traffic control. The authors introduce infrastructure agents that collect data and intersection agents which adapt their traffic-control policy to the data received. The model does not include agents that assist the drivers. They also do not take the different valuations of waiting-time reduction into account. *ITSA* is not the very first valuation-aware traffic control mechanism – [7,8] have recently proposed a mechanism called *Time-Slot Exchange* (*TSE*). However, *TSE* only allows vehicle agents already holding a time slot to negotiate time slots with other vehicle agents. *ITSA* in turn lets the intersection agent assign time slots to vehicle agents which do not have any time slot so far. Further, *TSE* imposes strong restrictions, and only few negotiations between vehicles are successful. This clearly limits the impact of *TSE*. This is not the case with *ITSA* – it yields a significant improvement, compared to *TSE*.

3 Fundamentals

In this section we describe our traffic scenario, measures to compare valuation-aware mechanisms for traffic control, desiderata for those mechanisms, and the components of agent-based traffic management.

Traffic Scenario. In this paper we focus on individual intersections of roads. An intersection consists of several intersection lanes. Depending on the intersection lane they have chosen, vehicles can only leave the intersection in one direction. An intersection lane can intersect other intersection lanes. The intersection points are potential spots of conflict. No two vehicles are allowed to pass such a spot at the same time. The considerations in this paper are not limited to the intersection area itself, but take the neighborhood of the intersection into account as well.

Definition 1. *The* neighborhood of an intersection *consists of the lanes of the intersection area, the incoming and the outgoing lanes.*

Measures. We use the following measures to evaluate valuation-aware mechanisms.

Definition 2. *The* travel time T_t^j of a Vehicle j *is the time from its first appearance in the neighborhood until it leaves the neighborhood. The* minimal travel time $minT_t^j$ of j *is the travel time if* j *was the only vehicle at the intersection, observed the speed limit and any constraints from the physical world, but ignored all rules concerning the right of way (i.e., crosses red lights, does not stop at stop signs etc.). The* waiting time T_w^j of j *is the difference of the travel time* T_t^j *and the minimal travel time* $minT_t^j$.

Because the minimal travel time is a lower bound of the travel time, the waiting time is always nonnegative.

Any new mechanism should be superior to existing ones. A useful measure to compare different intersection-control mechanisms is the average waiting time.

Definition 3. *The* average waiting time *is*
$\overline{T_w} = \frac{\sum_{j \in V} T_w^j}{|V|}$, *where* V *is the set of all vehicles.*

The average waiting time does not allow to evaluate valuation-aware mechanisms. Therefore, a more meaningful measure in our context is the waiting time weighted by the valuations of waiting-time reduction of the drivers.

Definition 4. *The* valuation $v^j(t)$ of Driver j *is the price* j *is willing to pay if he waits* t *seconds less.*

While other valuation functions might be realistic as well, we limit ourselves to linear valuation functions in this study. Thus, we denote the price per second with v^j. The valuation may be different for each vehicle, and we assume that it does not change over time.

Definition 5. *The weighted waiting time of Vehicle* j *is* $vT_w^j = v^j \cdot T_w^j$.

We use the weighted waiting times of all vehicles to compute the average weighted waiting time.

Definition 6. *The* average weighted waiting time *is*
$\overline{vT_w} = \frac{\sum_{j \in V} v^j \cdot T_w^j}{|V|}$, *where* V *is the set of all vehicles.*

Traffic planners have goals different from the ones of individual drivers. This is because they have to consider the common welfare while drivers only consider their own benefit. This conflict also occurs in our scenario. Drivers aim at maximizing their utility. In the following, we define the utility of a vehicle agent for our particular scenario.

Definition 7. *Let* b^j *denote the budget of the driver of Vehicle* j*. His* utility u^j *is* $u^j = b^j - v^j \cdot T_w^j$.

In other words, the utility of drivers is the difference between their budget and their waiting time weighted by their valuations of waiting-time reduction. Although the utility u^j of the driver of Vehicle j can be negative, e.g., if the budget is zero and the driver has to wait 10 seconds, he cannot exceed his budget b^j.

Example 1. Let l and h denote two vehicles. The driver of l is not in a hurry. His valuation is low, e.g., $v^l = 0.01$. If he had to wait 10 seconds longer, his weighted waiting time would increase only by $v^l \cdot 10 = 0.01 \cdot 10 = 0.1$. The driver of Vehicle h in contrast must meet a deadline. His valuation of waiting-time reduction is high, e.g., $v^h = 1.00$. If his waiting time was reduced by 10 seconds, his weighted waiting time would be reduced by $v^h \cdot 10 = 1.00 \cdot 10 = 10$. If the driver of Vehicle l was offered to wait 10 seconds longer for one currency unit he would accept the offer. This is because his utility would increase: $u^l_{new} = b^l_{old} + 1 - v^l \cdot (T^l_{w,old} + 10) = u^l_{old} + 1 - 0.01 \cdot 10 = u^l_{old} + 0.9 > u^l_{old}$. On the other hand, the driver of Vehicle h would readily offer one currency unit to wait 10 seconds less because this would increase his utility: $u^h_{new} = b^h_{old} - 1 - v^h \cdot (T^h_{w,old} - 10) = u^h_{old} - 1 + 1.00 \cdot 10 = u^h_{old} + 9 > u^h_{old}$. Of course, this is only possible if the budget b^h exceeds one currency unit.

In our context, it is not relevant if the budget of a driver is real money, or if it is any private currency issued and distributed by the traffic authority.

Definition 8. *The* total entry budget B_e *is the sum of the budgets of all drivers when they enter the neighborhood:* $B_e := \sum_{j \in V} b^j_e$*. V denotes the set of all vehicles. The* total leaving budget B_l *is the sum of the budgets of all drivers when they leave the neighborhood:* $B_l := \sum_{j \in V} b^j_l$.

Desiderata for Valuation-Aware Traffic-Control Mechanisms. Mechanisms for traffic control at intersections give the right to cross the intersection to arriving vehicles for a certain period of time. Sometimes this right is only given if the vehicles have fulfilled some preconditions, e.g., having stopped at a stop sign. Traditional mechanisms differ regarding the scheduling algorithm, depending on time, on the direction of arrival and on the direction of departure. The valuation-aware mechanisms envisioned should encourage drivers to reveal their valuations. If the best strategy of drivers is to reveal their valuations truthfully, provided that this holds for all other drivers as well, the mechanism is *incentive compatible* [9]. Incentive compatibility is desirable. It tends to provide more efficient solutions.

Next, the mechanisms should meet the objectives effectiveness, avoidance of starvation, and zero-sum. We say that an intersection-control mechanism is *effective* if the average weighted waiting time $\overline{vT_w}$ is lower than with *FIFO*. Clearly, effectiveness means higher overall satisfaction of the drivers. *Avoidance of starvation* means that a vehicle is guaranteed an upper bound of the waiting time. Such an upper bound should be traffic-dependent: If all roads are heavily congested, this upper bound should naturally be higher than in a situation with only few vehicles.

An intersection-control mechanism is *zero-sum* if the total budget of vehicles entering the neighborhood is equal to the total budget of vehicles leaving. We believe that users would not like to see an increase of mobility costs and therefore have a preference for zero-sum.

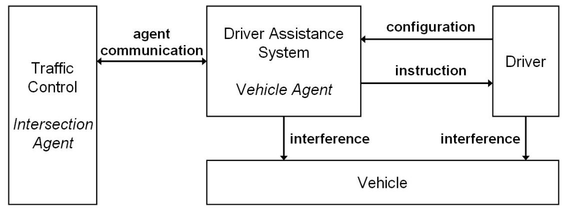

Fig. 1. Agent-based traffic control

Finally, there are two further conflicting requirements on traffic-control mechanisms at intersections, early allocation and late allocation. *Early allocation* means that the time slots should be allocated as early as possible. The reason is that a vehicle obtaining a time slot early does not have to stop and wait before entering the intersection. Instead, it can slow down and adapt its speed in advance so that it reaches the intersection exactly on time and can cross it without any stops. This makes driving more comfortable and is expected to reduce energy consumption. But time slots should also be allocated as late as possible (*late allocation*), to give vehicles with high valuations that arrive late a chance to acquire an early time slot. Clearly, these two requirements are in conflict. Choosing their weights depends on the preferences of the traffic planners and on the actual design of the mechanism.

Agent-Based Traffic Control. To take the different driver valuations of waiting-time reduction into account, vehicles and intersection control have to interact. But drivers should not interact with the intersection control while driving. Intelligent and autonomous driver-assistance systems make such distractions unnecessary. Agent technology is promising in this context: The autonomy property of agents [10] avoids unnecessary human interaction. We assume that every vehicle will be equipped with a platform with a standardized interface that allows for the installation of agent-based driver-assistance systems. Assuming the existence of such a generic platform within vehicles is in line with current developments in the real world. For instance, think of the so-called on-board units used by the German toll collect system for heavy trucks (http://www.toll-collect.de). To facilitate valuation-aware traffic control, intersections will have to be equipped with traffic-control units as well. These units implement the different mechanisms and use agent technology to interact with the driver-assistance systems of the vehicles.

An agent-based driver-assistance system hosts a *vehicle agent* (see Fig. 1). It can instruct the driver when to cross the intersection, and at which speed. The vehicle agent can communicate with other vehicle agents and with the *intersection agent* which represents the traffic-control unit of an intersection. The driver configures the driver-assistance system in advance to avoid distraction while driving.

Note that the traffic-control mechanisms proposed in this article are orthogonal to the extent of interference of the driver-assistance system with the driving behavior. The system could either merely instruct the driver, or, as it is the case with adaptive cruise-control systems (ACC, [11]), take control of the vehicle in certain situations. Our mechanisms would work with both alternatives.

4 Mechanisms

We first describe a generic procedure for agent-based traffic control at intersections. This will allow for a more structured presentation of our actual mechanisms. We then describe the *FIFO* mechanism. This mechanism, which has been proposed and evaluated in [2,3], will serve as a reference point for our new valuation-aware mechanism *ITSA* and its variants, which we describe subsequently. For all mechanisms we discuss to which extent they meet the desiderata incentive compatibility, avoidance of starvation, zero-sum and early and late allocation. We evaluate effectiveness in Sect. 5.

4.1 General Procedure

The following general procedure describes all agent-based mechanisms for traffic control at intersections which we currently have in mind:

(1) Vehicle and intersection agents *make contact*.
Vehicle agents have to obtain information which intersection is equipped with an intersection agent, and the intersection agent has to obtain information on vehicles that will arrive at the intersection.
(2) The vehicle agent acquires an initial time slot to cross the intersection (*initial time-slot acquisition*).
(3) If the vehicle agent is dissatisfied with the time slot acquired it can try to acquire a better one (*subsequent time-slot acquisition*) from other vehicle agents. It may try to do so repeatedly using different mechanisms.
(4) Finally, the vehicle crosses the intersection using its time slot.

The difference between Step 2 and 3 is that vehicles do not yet have a time slot before Step 2. They receive an initial time slot in this step. In Step 3 the vehicles already have received a time slot which they can now trade.

Some mechanisms do not need Step 3, e.g., those that do not allow vehicles to trade their time slots. But Step 3 is beneficial in general. Otherwise, Step 2 would have to reconcile the conflicting goals of early and late allocation. With Step 3 in turn, agents of vehicles arriving late can interact with vehicle agents which hold an earlier time slot.

While Step 3 is optional, Steps 1, 2 and 4 are part of all mechanisms described in the following.

4.2 FIFO

This subsection briefly reviews the agent-based reservation mechanism *FIFO* described in [2,3,4]. It allows vehicle agents to request time slots from an intersection agent (Step 2). It schedules the time slots in the order of request.

All vehicle agents entering the neighborhood of the intersection request a time slot from the intersection agent. If several vehicle agents ask for the same time slot, the one which requested the time slot first will obtain it.

To make a reservation, the intersection agent looks for free time slots. The intersection agent checks if the current request does not conflict with time slots reserved previously. A conflict occurs if the requested intersection lane or an intersection lane crossing the requested intersection lane is already reserved. If the desired time slot cannot be assigned, the intersection agent offers the earliest non-conflicting time slot after the desired one to the requesting vehicle agent.

Because *FIFO* is not valuation-aware, the notion of incentive compatibility does not apply. *FIFO* avoids starvation because it ensures an upper bound of waiting time. Vehicle agents do not pay any money, thus *FIFO* is zero-sum. Late allocation is not beneficial with *FIFO* since the order of arrival determines the assignment of time slots. Thus, *FIFO* should implement early allocation.

So far, we do not know any valuation-aware mechanism for intersection control, (except for [7,8] which are very recent). To evaluate the mechanisms to be described in the following, we compare them to a mechanism which is not valuation-aware. Since [2] has shown that *FIFO* outperforms traffic lights regarding average waiting time, it will be our reference point for the evaluation. We think that valuation-aware mechanisms from other domains, e.g., data routing, are not appropriate: They typically do not take physical constraints into account, like no overtaking.

Even though *FIFO* is not valuation-aware, it can be combined with other mechanisms for Step 3 of the general procedure, and such combinations could be valuation-aware. Some of these combinations are discussed in [7,8].

4.3 Initial Time-Slot Auction

In the following we propose a new mechanism which is valuation-aware. It auctions the time slots to the arriving vehicles. We call it *Initial Time-Slot Auction* (*ITSA*). This is because the auction is part of Step 2.

Basic Variant. Vehicle agents register at the intersection when entering its neighborhood. The intersection agent initiates a second-price sealed-bid auction [12] of the next available time slot. I.e., the bidder with the highest bid wins but pays only the second highest bid. Not all of the arriving vehicles can take part in the auction. Some of the vehicles already have acquired an earlier time slot. They may not take part. Further, vehicles can only take part if the vehicles driving in front already have acquired a time slot. Otherwise they cannot be sure that the vehicle in front will acquire an earlier time slot. Thus, only one vehicle per direction can bid for a time slot. We refer to them as *candidates*.

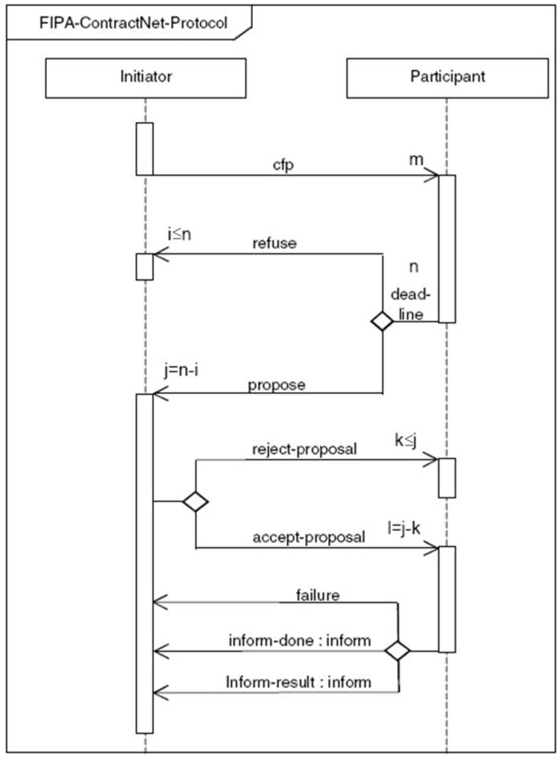

Fig. 2. FIPA Contract Net Protocol (corrected figure from [13])

Example 2. Figure 3 shows an intersection where some vehicles already have acquired a time slot, some can acquire a time slot and some currently cannot acquire a time slot.

To implement the auction, we use the FIPA Contract Net Protocol [13] (see Fig. 2) and its terminology in the following. The intersection agent asks the candidates for proposals. It chooses the proposal with the highest offer and sends an accept-proposal to the sender of the proposal chosen and a reject-proposal to all others. The vehicle agent receiving an accept-proposal (including the second highest bid, i.e., the amount of money to be paid) confirms the transaction using inform or reports a failure otherwise. For instance, if the auction of a time slot takes too long, it is possible that the winner vehicle cannot use its time slot any more because the begin is already in the past. In this case, the vehicle agent would report a failure. If the winning vehicle agent confirms the transaction, it must pay an amount corresponding to the second highest bid reported. So its budget is reduced by this amount.

The basic variant is incentive compatible. This is because we use a second-price sealed-bid auction [9,12]. It does not guarantee an upper bound of the waiting time and – at least without any extensions – does not avoid starvation.

Example 3. An example of an extension to avoid starvation is that the auction is suspended after the waiting time of a vehicle exceeds an upper bound. After the vehicle has crossed the intersection, the auction is resumed.

However, such constraints typically influence the bidding behavior, and an analysis of the interplay with incentive compatibility would be necessary. In Sect. 5, we examine whether starvation actually occurs in practice.

Because the basic variant does not specify when to allocate the time slots, both early or late allocation can be implemented.

Finally, if an intersection agent keeps the money earned with auctions, the mechanism is not zero-sum. Note that we can achieve zero-sum in a straightforward way, by returning the money to the drivers. Several variants of doing so are conceivable: The money returned could be equally distributed among all vehicles crossing the intersection, or it could be proportional to the waiting times. However, the problem with returning money is that this tends to influence the bidding behavior, too. Thus, an analysis of the interplay with incentive compatibility would be necessary as well.

Variant with Subsidies. The basic variant has the following characteristic which might yield suboptimal outcomes: The vehicles behind a vehicle without a time slot cannot influence the outcome of the auction.

Example 4. Let l and h denote two vehicles arriving from the same direction. The valuation of the driver of the first Vehicle l is very low. The valuation of the driver of the subsequent Vehicle h is extremely high. In all auctions where l is a candidate it only sends low offers. Thus, h is stuck behind l even though its valuation is high.

Vehicles waiting behind a vehicle without a time slot do not have to be inactive. They can try to improve their situation by subsidizing the candidate of their direction. The candidate with the highest accumulated bid wins the auction. If their candidate wins the auction, the subsidizing vehicles will be able to take part in a subsequent auction earlier. Instead of sending a call for proposals only to candidates the intersection agent sends it to the vehicles behind candidates as well, together with the information that their offer would only be a subsidy for the candidate of their direction. Once a candidate is chosen, the vehicles of its direction receive an accept-proposal (see also Fig. 3).

Compared to the basic variant, only one desideratum is different: Incentive compatibility is not guaranteed. A driver might hope that drivers waiting behind him subsidize him. He could be tempted to offer less than his true valuation. In our evaluation, we assume that drivers do reveal their true valuations. Even though this might be too optimistic, we do so to quantify the potential of this variant. Note that it is not clear who would offer less, after all. The drivers of vehicles waiting behind could offer less as well, because it is still unclear if they will actually benefit from subsidizing vehicles in front. As future work, we will investigate if sealed-bid combinatorial auctions are a better solution to this problem.

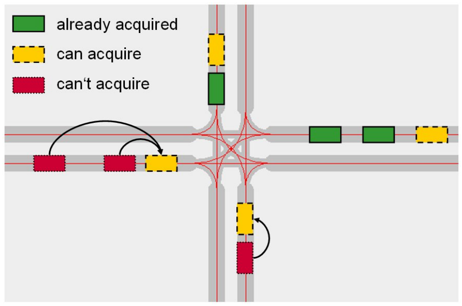

Fig. 3. Auction with subsidizing vehicles

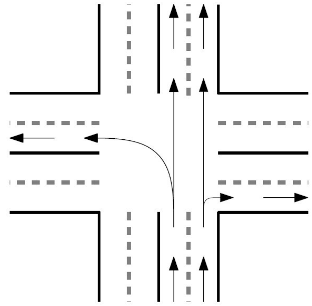

Fig. 4. Intersection layout

Both variants of *ITSA* take valuations of waiting-time reduction into account in the initial time-slot-acquisition phase already (Step 2). Nevertheless, they could also be combined with mechanisms of Step 3. Vehicles arriving late can acquire time slots which have been auctioned off before their arrival.

5 Evaluation

To evaluate the benefits of the proposed mechanisms we use simulations. This is in line with other research on traffic management at intersections, e.g., [2,14,15]. We have developed a simulation framework of our own, using a space-continuous and time-discrete simulation model. This simulation framework allows simulating drivers, driver-assistance systems and vehicles at intersections. We have used the Java Agent DEvelopment Framework (JADE, http://jade.tilab.com) for the implementation of the multi-agent system. Agent-based simulation frameworks are not applicable because we do not use agents for simulation. Instead, we simulate the traffic environment for agent-based driver-assistance systems.

5.1 Settings

Our simulations have the following characteristics. We investigate a symmetric intersection consisting of four directions. Each direction has two incoming (right and left) and two outgoing (right and left) lanes. For each direction the right incoming lane allows to turn right and to go straight (both into the right outgoing lanes). The left incoming lane allows to turn left and to go straight (both into the left outgoing lanes) (see Fig. 4).

On every lane the maximum speed is $50km/h$, the speed limit within German cities. The length of incoming and outgoing lanes is $230m$. There is a virtual traffic sign $200m$ before the intersection indicating that vehicle agents can request time slots from the intersection agent. The radius of the intersection is $20m$. Thus, a vehicle crossing the intersection in straight direction drives $230 + 20 + 20 + 230 = 500m$ in total. Vehicles can accelerate with at most $3m/s^2$ and decelerate with at most $8m/s^2$.

Each simulation run simulates 40 minutes. We ignore the vehicles leaving the neighborhood during the first 10 minutes to avoid biased results (*initial phase*). We use the vehicles leaving during the next 30 minutes (*observation phase*) to compute the average waiting time $\overline{T_w}$ and the average weighted waiting time $\overline{vT_w}$. Vehicles arrive with interarrival times exponentially distributed with mean $\frac{1}{\lambda} = 36s$ from every incoming lane. This means that 100 vehicles arrive per hour on average on each incoming lane. The exponential distribution is common in queuing theory and in stochastic scheduling for arrival processes [16]. A vehicle can choose two different directions where to go, as mentioned before. The two possible directions are chosen randomly with probability $p = 0.5$. The driver valuations of waiting-time reduction are modeled as an exponential distribution with mean $\frac{1}{\lambda} = 0.01$. Since valuation-aware traffic-control mechanisms do not yet exist in the real world, we could not rely on any empirical data when specifying this parameter.

Clearly, if the volume of traffic exceeds the capacity of the intersection, drivers will be unsatisfied with any traffic-control mechanism. With the numbers given so far, the volume of traffic is in line with the capacity of the intersection: We allow only one vehicle to cross the intersection at the same time. Thus, its capacity is $3600s/4s = 900$ vehicles per hour. This is because the crossing time is $4s$ for every vehicle independent of the direction. Our average traffic volume in turn is 800 vehicles per hour.

5.2 Mechanisms Evaluated

We have implemented two mechanisms, *ITSA* without subsidies ($ITSA^-$) and *ITSA* with subsidies ($ITSA^+$) in Step 2. Both mechanisms do not include any further activities in Step 3. We compare both $ITSA^-$ and $ITSA^+$ to *FIFO* without any further activity in Step 3.

In our setup, the allocation of a time slot with both $ITSA^-$ and $ITSA^+$ takes place 12 seconds in advance. I.e., a time slot is auctioned 12 seconds before it begins, three times the duration of a slot. For each auction candidates and subsidizing vehicles compute their offer by multiplying their true valuation per second v with the duration of a time slot $T = 4s$. This duration is the maximum time a vehicle needs to cross the evaluated intersection. Because budgets do not influence effectiveness, all vehicles in our experiments have budgets that are high enough to pay their valuations. In other words, vehicles can always afford to pay their bid.

The performance of a mechanism does not only depend on the average number of vehicles arriving at an intersection, but also on the distribution of arrival times. Therefore, a comparison of mechanisms is meaningful only if we compare equally initialized simulation runs. This means that every vehicle has the same type, start time and route in all simulation runs compared. We use 25 randomly chosen numbers as seeds for the runs, to compare the i-th run of *FIFO* to the ones of $ITSA^-$ and of $ITSA^+$.

Table 1. *FIFO* vs. *ITSA*$^-$

	mean	σ	99% CI
$\Delta\overline{T_w}$	-0.045	0.296	[-0.210, +0.121]
$\frac{\Delta\overline{T_w}}{\overline{T_w^{(FIFO)}}}$	-0.005	0.024	[-0.019, 0.008]
$\Delta\overline{vT_w}$	0.048	0.024	[0.034, 0.062]
$\frac{\Delta\overline{vT_w}}{\overline{vT_w^{(FIFO)}}}$	0.306	0.077	[0.263, 0.349]

Table 2. *FIFO* vs. *ITSA*$^+$

	mean	σ	99% CI
$\Delta\overline{T_w}$	-0.232	0.245	[-0.369, -0.095]
$\frac{\Delta\overline{T_w}}{\overline{T_w^{(FIFO)}}}$	-0.018	0.018	[-0.028, -0.008]
$\Delta\overline{vT_w}$	0.067	0.025	[0.053, 0.081]
$\frac{\Delta\overline{vT_w}}{\overline{vT_w^{(FIFO)}}}$	0.430	0.044	[0.406, 0.455]

5.3 Results

We compare the differences of average waiting time $\overline{T_w}$ and of average weighted waiting time $\overline{vT_w}$ of equally initialized simulation runs between *FIFO* and *ITSA*$^-$ and between *FIFO* and *ITSA*$^+$. For all 25 simulation runs we compute the mean, standard deviation σ, and the 99% confidence interval (CI) of the differences.

$T_w^{(FIFO)}$ is the waiting time with *FIFO*, $T_w^{(ITSA^-)}$ and $T_w^{(ITSA^+)}$ are the ones with *ITSA*$^-$ and *ITSA*$^+$. When comparing *FIFO* and *ITSA*$^-$, the absolute difference of average waiting times is $\Delta\overline{T_w} = \overline{T_w^{(FIFO)}} - \overline{T_w^{(ITSA^-)}}$, and the one of average weighted waiting times is $\Delta\overline{vT_w} = \overline{vT_w^{(FIFO)}} - \overline{vT_w^{(ITSA^-)}}$. The relative difference of average waiting time is $\Delta\overline{T_w}/\overline{T_w^{(FIFO)}}$, and of the weighted one is $\Delta\overline{vT_w}/\overline{vT_w^{(FIFO)}}$. When comparing *FIFO* and *ITSA*$^+$, the notation and the formulae are analogous.

***FIFO* vs. *ITSA*$^-$.** Table 1 lists both the absolute and the relative differences of the average waiting time $\overline{T_w}$ and the average weighted waiting time $\overline{vT_w}$ for *FIFO* and *ITSA*$^-$. *ITSA*$^-$ reduces the average weighted waiting time $\overline{vT_w}$ by 0.048 units, i.e., by 30.6% on average. The 99% confidence interval shows that these results are reliable. The relative difference is between 26.3% and 34.9% in 99% of all cases. *ITSA*$^-$ increases the average waiting time only slightly by 0.5% on average, compared to *FIFO*. Thus, *ITSA*$^-$ is effective regarding this waiting time. At the same time, it leaves the average waiting time nearly unchanged.

***FIFO* vs. *ITSA*$^+$.** Table 2 lists the absolute and the relative differences of the average waiting time and the average weighted waiting time for *FIFO* and *ITSA*$^+$. *ITSA*$^+$ *reduces* the average weighted waiting time $\overline{vT_w}$ by 0.067 units, i.e., by 43.0% on average. The 99% confidence interval tells us that these results are very reliable. The relative difference is between 40.6% and 45.5% in 99% of all cases. *ITSA*$^+$ increases the average waiting time $\overline{T_w}$ only slightly, by 1.8% on average, compared to *FIFO*. In other words, *ITSA*$^+$ is very effective regarding average weighted waiting time, and the average waiting time remains nearly unchanged as well.

Table 3. Characteristics of the 10% of the vehicles with the lowest valuation

	***FIFO* vs. *ITSA*$^-$**	***FIFO* vs. *ITSA*$^+$**
$\Delta\overline{T_{w;10\%}}$	-23.402	-14.454
$\frac{\Delta\overline{T_{w;10\%}}}{\Delta\overline{T^{(FIFO)}_{w;10\%}}}$	-1.518	-0.970

Avoidance of Starvation. To evaluate the influence of an auction on vehicles with low valuations, we compare the average waiting time $\overline{T_{w;10\%}}$ of the 10% of the vehicles with the lowest valuation. Table 3 lists both the absolute and the relative difference of the average waiting time $\overline{T_{w;10\%}}$ for *FIFO* vs. *ITSA*$^-$ and for *FIFO* vs. *ITSA*$^+$. *ITSA*$^-$ increases this waiting time by factor 2.518, *ITSA*$^+$ by factor 1.970. These increases are not surprising because an auction affects the participants with low valuations negatively. Even though both mechanisms do not guarantee avoidance of starvation, we think that their negative effects are limited. We will examine the extensions described earlier to avoid starvation as future work, to foster social acceptance of our mechanisms.

Subsumption. The results so far are promising. The variants evaluated reduce average weighted waiting time significantly, without increasing average waiting time by much. Compared to *ITSA*$^-$, *ITSA*$^+$ reduces average weighted waiting time by an additional 12.4%, while loosing incentive compatibility. To decide if this additional gain is worthwhile, we plan to carry out experiments with real users, as motivated earlier. *ITSA*$^+$ also improves the average waiting time $\overline{T_{w;10\%}}$ of the 10% of the vehicles with the lowest valuation. $\overline{T_{w;10\%}}$ increases much less than with *ITSA*$^-$. Our experiments also show that an auction mechanism which considers all vehicles at an intersection and not only the candidates can outperform variants which do not do so.

6 Conclusions

Traditional approaches for traffic management do not consider the different driver valuations of waiting-time reduction. But valuation-aware traffic control is expected to increase overall satisfaction significantly. In this article we have proposed a new mechanism for traffic control at intersections which takes the different valuations of waiting-time reduction into account, *Initial Time-Slot Auction* (*ITSA*). We have proposed and discussed refinements of this mechanism which avoid starvation and allow other vehicles to subsidize vehicles in front.

As part of our evaluation, we have compared our new mechanism to the state-of-the-art *FIFO* mechanism. We have seen that all evaluated variants reduce average weighted waiting time significantly, without influencing average waiting time a lot.

An important conclusion from this study is that a valuation-aware traffic-control mechanism at intersections should include as many vehicles as possible. The refinements proposed here head for this direction.

As future work, one issue which we will investigate is vehicles crossing a sequence of intersections. In such a setting, vehicle agents will have to plan its expenses, and intersection agents may cooperate.

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