How Agents Can Help Curbing Fuel Combustion – a Performance Study of Intersection Control for Fuel-Operated Vehicles[*]

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ABSTRACT

Traffic causes pollution and demands fuel. When it comes to vehicle traffic, intersections tend to be a main bottleneck. Traditional approaches to control traffic at intersections have not been designed to optimize any environmental criterion. Our objective is to design mechanisms for intersection control which minimize fuel consumption.

This is difficult because it requires a specialized infrastructure: It must allow vehicles and intersections to communicate, e.g., vehicles send their dynamic characteristics (position, speed etc.) to the intersection more or less continuously so that it can estimate the fuel consumption. In this context, the use of software agents supports the driver by reducing the necessary degree of direct interaction with the intersection.

In this paper, we quantify the fuel consumption with existing agent-based approaches for intersection control. Further, we propose a new, agent-based mechanism for intersection control, with minimization of fuel consumption as an explicit design objective. It reduces fuel consumption by up to 26% and waiting time by up to 98%, compared to traffic lights. Thus, agent-based mechanisms for intersection control may reduce fuel consumption in a way that is substantial.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*multiagent systems, intelligent agents*

General Terms

Algorithms, Economics, Measurement

Keywords

Agents, fuel consumption, traffic control, intersection control

1. INTRODUCTION

Mobility is a challenge for public authorities. Traffic causes pollution and – next to other factors – the climate change. Further, emissions of vehicles are closely linked to fuel consumption. The unsteady oil price and the expected oil shortage in the future make fuel consumption not only an issue for society but also for individual drivers.

When it comes to city traffic, intersections tend to be a main bottleneck. Traditional approaches for intersection control like traffic lights or roundabouts aim to increase throughput and to reduce waiting time. But they have not been designed with the intent to do any optimization with regard to an environmental criterion. This, with regard to fuel consumption, is the objective of this article.

If a vehicle does not know when it will be allowed to cross an intersection, it approaches it and – if necessary – decelerates or stops just before. Afterwards, it accelerates again. If a vehicle was informed about when to cross the intersection in advance, it could reach the intersection just in time, with less deceleration and acceleration. This decreases fuel consumption [7]. It also allows the intersection-control mechanism to orchestrate vehicles entering from different directions flexibly and efficiently. Thus, intersections should inform vehicles about their exact time slot in advance.

Doing so not only allows a vehicle to arrive at the intersection just in time, but also with sufficient speed. This leads to shorter time slots and to a higher throughput.

The fuel consumption of a vehicle depends on characteristics like size, engine capacity and rolling resistance. Dynamic parameters like speed and acceleration are important as well. With existing intersection-control mechanisms, those various parameters are unknown to the mechanism. The mechanisms envisioned have to consider not only static, but also dynamic parameters which can change at any time. Thus, the mechanisms sought require a specialized infrastructure both in vehicles and at intersections which allows them to communicate.

Another observation that is important here is that it is easy to arrive at the intersection at a certain time or with a certain speed. But doing *both* is difficult for human drivers without any driver-assistance system. This means that the infrastructure does not only have to support communication, but should also provide sophisticated driver-assistance techniques. The design and the validation of such an environment is not trivial.

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Software agents are a key technology for the infrastructure envisioned. Intersection agents and what we call driver-assistance agents can negotiate the time to cross an intersection in advance. Recent proposals already feature agent-based intersection control, to reduce average waiting time or other target variables [5, 16]. These approaches yield good results. However, though the authors expect positive environmental effects, they have not investigated them systematically.

The contribution of this article is twofold. First, we investigate the effects of existing agent-based mechanisms for intersection control on fuel consumption. We show that these mechanisms reduce fuel consumption by up to 28% compared to traffic lights (TL). This is a significant reduction given that city traffic requires crossing intersections frequently. Second, we propose a novel agent-based mechanism for intersection control with minimization of fuel consumption as an explicit design objective. The reduction is between 22% and 26% compared to TL. This is significant as well, but less than what we had expected, in the light of the first contribution. We further show that our new mechanism reduces average waiting time in certain situations by up to 98% compared to TL and is better than the existing approaches of [5] and [16]. Summing up, our study shows that agent-based mechanisms for intersection control may result in a reduction of fuel consumption that is substantial.

Paper outline: We discuss related work in Section 2. Then, we describe agent-based intersection control in Section 3. In Section 4, we present our estimation model for fuel consumption. We introduce the various mechanisms for intersection control in Section 5. We evaluate these mechanisms in Section 6 and conclude in Section 7.

2. RELATED WORK

This section reviews related work on intersection control whose purpose is to reduce fuel consumption. We start with simple approaches which are already used in the real world, like roundabouts with and without traffic lights, and continue with more complex ones. Finally, we review agent-based approaches on intersection control.

[18] shows that roundabouts reduce fuel consumption by 28%, by avoiding waiting time during off-peak hours. On the other side, the waiting time for some vehicles increases during peak hours. This problem is addressed in [2], by additional usage of traffic lights during peak hours. This ensures that vehicles coming from directions with little traffic do not have to wait too long. In this case the signals are red when the vehicle queue in one direction reaches the queue detector. This creates a gap in the circulation flow.

Another approach which does not need any construction changes of the intersection is introduced in [11]. There, the cycle length is optimized by minimization of a performance index. This index does not only take into account the delay and the number of stops but also the fuel consumption. Orthogonally to our approach, [11] examines the optimal cycle length based on the traffic density and traffic volume. It is however determined a priori and does not change with new vehicles arriving. Our approach in turn determines dynamically which vehicle should cross the intersection next, based on the current state.

A more advanced way to optimize/synchronize the signal settings is to use real-time video-traffic monitoring. [13] suggests to use color-image sequences combined with a definition of search windows around areas of interest. This allows to anticipate the arrival of vehicles at an intersection and gives way to adaptive and predictive traffic-light control. A high-level traffic-light controller can use these images to reduce waiting time and fuel consumption.

[8] combines the real-time video-traffic monitoring with induction loops and a multi agent control system. Every intersection is controlled by an autonomous agent, which communicates with adjacent agents. Vehicle queues represent each incoming intersection lane. When a vehicle leaves the intersection, the adjacent intersection agent in the direction of the vehicle is informed about the probability that the vehicle will arrive there. In this way, the intersection agent can identify the best traffic-light phase possible.

3. AGENT-BASED INTERSECTION CONTROL

The mechanisms discussed in this paper use agent technology. It lets intersections and vehicles negotiate the time slot when to cross an intersection, and vehicles can adapt their speed autonomously when approaching an intersection. As a prerequisite, vehicles are equipped with an additional control unit, subsequently referred to as *driver-assistance system*. Further, intersections have a traffic-control unit, referred to as *intersection-control unit*. These control units consist of hardware and of software components.

Driver-assistance systems and intersection-control units have to communicate. To this end, they use *intersection agents*, which represent intersection-control units, and *driver-assistance agents*, which represent driver-assistance systems. These agents are a software component of the respective control unit.

While driving, a driver-assistance system can recommend a certain speed to the driver. If the driver does not overrule the driver-assistance system, it may also directly control the driving behavior of the vehicle [17] (Figure 1).

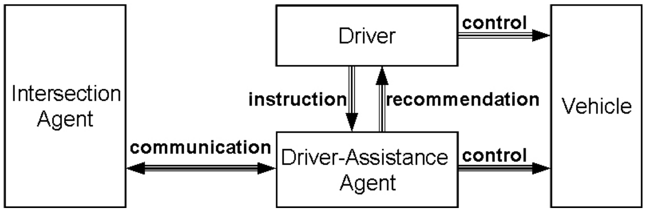

Figure 1: Agent-based traffic control

The driver-assistance system can be seen as an extension of an adaptive cruise control (ACC) system, which is state of the art in vehicles. ACC systems assist the driver to keep a certain distance to vehicles in front. He does not have to react when vehicles in front accelerate or decelerate. This is done by the ACC system. In addition, the driver-assistance system described here also adjusts the speed to reach the intersection at a certain time. [17] calls such a system adaptive cruise and crossing control (A3C) system.

If vehicles are equipped with driver-assistance agents, we can design mechanisms for intersection-control where driver-assistance agents and intersection agents negotiate the right to cross an intersection. A *time slot* is the right to cross an intersection in a certain direction within a certain period of time. Each driver-assistance agent tries to obtain its *next* *free time slot*, i. e., the earliest slot which the vehicle can still reach in time, and which the intersection can assign to the vehicle. Vehicles typically have different next free slots.

The intersection agent is responsible for the allocation of a time slot. Because vehicles can cross an intersection concurrently, the allocation of time slots follows certain rules. There already exist various allocation rules like 'priority to right', 'four-way-stop' or 'preference road'. For agent-based intersection control, new allocation rules are possible. [17] proposes four different allocation rules, with a distinction on the degree of concurrency allowed. To formulate these rules in a clean way, we use the following terminology: An intersection consists of several *intersection lanes*. If two intersection lanes share common space, we say that they are *conflicting*. We call the shared space *conflict area*. If two intersection lanes emerge from one incoming lane, the conflict area is *diverging*.

With *intersection exclusive*, the intersection agent allows one vehicle to enter the intersection after all other vehicles have left it. With *lane exclusive*, a vehicle may enter the intersection only when all vehicles on the desired lane and on all conflicting lanes have left the intersection. *Lane shared* lets a vehicle enter the intersection if there are no more vehicles on other conflicting intersection lanes. However, a vehicle may enter the intersection while other vehicles cross the intersection on conflicting intersection lanes with diverging conflict areas. *Conflict-area exclusive* only blocks the conflict areas of an intersection. Vehicles may cross the intersection concurrently as long as not more than one vehicle is in each conflict area. Clearly, the possible throughput increases from intersection exclusive to conflict-area exclusive. Because lane shared is already state of the art, we only consider lane shared and conflict-area exclusive in what follows.

These degrees of concurrency are particularly meaningful in the context of agent-based intersection control. In principle, it would be possible to build traffic lights as strict as intersection or lane exclusive. However, traffic lights usually allow vehicles to cross an intersection in a way similarly to lane shared. Several vehicles can enter the intersection from the same lane while they have green light. It is not possible to use standard traffic lights for conflict-area exclusive. This is because conflict-area exclusive switches between vehicles from different directions too quickly.

4. MODELS TO ESTIMATE FUEL CONSUMPTION

To consider the fuel consumption of vehicles approaching an intersection, we need an estimation model. In this section we describe the model used here in detail.

4.1 Existing Models

Various models have been proposed in order to estimate the fuel consumption of vehicles. These models can be categorized based on the parameters used to estimate the fuel consumption. For example, *average speed models* are based on the average speed of a vehicle [4]. In contrast, *nonlinear regression models* distinguish between acceleration and deceleration phases of a drive [1]. Similarly to the nonlinear regression models, *modal models* split a trip into four driving modes: idle, acceleration, deceleration and cruising mode [4, 10]. The focus of these models is on the strict distinction between the driving modes. However, they do not specify explicitly the way to determine the fuel consumption within a mode. *Energy-based models* take the energy demand of a vehicle while driving as the basis for estimating the fuel consumption [4, 12, 14, 15].

We have analyzed different models to estimate fuel consumption. We have compared the necessary degree of detail and the availability of calibration data. As a result, the Instantaneous Model [4], which is both an energy-based and a modal model, has turned out to be most suitable within an intersection-control mechanism.

4.2 Instantaneous Model

The Instantaneous Model [4] determines the fuel consumption based on the energy demand of a vehicle. In order to compute the energy demand it uses the instantaneous speed v (in m/s) and acceleration a (in m/s^2). In this way, it reflects the different situations within a drive and is able to provide a very accurate prediction of the fuel consumption of an individual vehicle.

Using the Instantaneous Model, we can determine the fuel consumption of a vehicle by the following equation:

$$F = \begin{cases} \alpha + \beta_1 R_{tract} v + [\beta_2 a R_{inertial} v]_{a>0} & \text{for } R_{tract} > 0 \\ \alpha & \text{for } R_{tract} \leq 0 \end{cases}$$

where F is the fuel consumption in ml/s. This formula combines three different fuel-demand types:

Idle.

The fuel consumption which is needed just to run the engine is the *idle fuel consumption* α of a vehicle (in ml/s).

Movement.

The additional fuel consumption for the movement at constant speed is the product of the *efficiency parameter* β_1 (in ml/J) and the *tractive energy demand* $R_{tract} \cdot v$. R_{tract} denotes the *tractive force*. If it is not positive, the movement causes no additional fuel consumption.

Acceleration.

The additional fuel consumption of an accelerating vehicle is the product of the *efficiency parameter* β_2 (in $ml/(J \cdot m/s^2)$) and the *inertial energy demand* $a \cdot R_{inertial} \cdot v$. $R_{inertial}$ denotes the *inertial force*. If the acceleration is not positive, no additional fuel consumption has to be taken into account.

The tractive force R_{tract} is the sum of *drag force* R_{drag}, *inertial force* $R_{inertial}$ and *grade force* R_{grade}. R_{drag} comprises *rolling resistance* $R_{rolling}$ and *air drag force* R_{air}: $R_{drag} = R_{rolling} + R_{air}$. The *inertial force* $R_{inertial}$ is the product of *vehicle mass* m (in kg) and acceleration a:

$$R_{inertial} = m \cdot a$$

Grade force combines *gravitational acceleration* ($g = 9.81\frac{m}{s^2}$), vehicle mass and *road grade* G (in %):

$$R_{grade} = m \cdot g \cdot G$$

4.3 Refinement of the Instantaneous Model

In [4], average values, calibrated on the basis of a certain vehicle fleet, are used for idle fuel consumption α, air drag force R_{air} and rolling resistance $R_{rolling}$. These average values are not very accurate, because they only are aggregate values of a certain test fleet. Therefore, we compute the actual values for each vehicle like speed, frontal area etc. from the data available instead of using average values.

Idle fuel consumption.

The idle fuel consumption α (in ml/s) of a vehicle can be derived from its *engine capacity* V_h (in l) [9]:

$$\alpha = \frac{0.220}{10^3 s} V_h - \frac{0.0193}{10^3 s\, l} V_h^2$$

For trucks, we always use $\alpha = 0.7 ml/s$ as idle fuel consumption [3].

Air drag force.

The air drag force R_{air} is based on *air density* ρ (in kg/m^3), *drag coefficient* C_D, *frontal area* A (in m^2) and instantaneous speed v of a vehicle:

$$R_{air} = 0.5 \cdot \rho \cdot C_D \cdot A \cdot v^2$$

Air density relates to air temperature and to the height above sea level. To keep things manageable, the temperature is assumed to be 15°C and the height above sea level $200\, m$ [9]. According to [9], this results in an air density of $\rho = 1.2\, kg/m^3$. The drag coefficient as well as the frontal area of a vehicle can be determined relatively easily, because they are often stated in the specification of a vehicle. If the values are not included in the specification at least the frontal area can be derived for passenger cars from maximum height h and maximum width w of the vehicle as follows [9]:

$$A = 0.9 \cdot h \cdot w$$

Rolling resistance.

The computation of the rolling resistance is intricate because it is based on properties like road surface and tires used. Because this data is very hard to obtain, an average value, calibrated in [4], is used:

$$R_{rolling} = 333\, N$$

5. MECHANISMS

In this section we present different mechanisms for intersection control. First, we describe the mechanism *Traffic Light* (TL). Then, we describe *Time-Slot Request* (TSR) which allocates the next free time slot to cross an intersection to the first driver-assistance agent which requests a time slot from the intersection agent. Thereafter, we present ITSA Valuation which allocates the next free time slot to the vehicle with the highest valuation of reduced waiting time. Then, we introduce a new environment-aware mechanism ITSA Fuel Consumption. It allocates the next free time slot to the vehicle which causes the minimal total increase of fuel consumption. Finally, we describe ITSA Delay as a variation of ITSA Fuel Consumption.

5.1 Traffic Light

Traffic lights (TL) are one of the most common intersection-control mechanisms. Therefore, TL serves as our yardstick for the environment-aware ITSA Fuel Consumption.

Using TL the green light phases are computed in advance based on the expected traffic volume. For TL we use a static traffic-light mechanism. There also are dynamic mechanisms which adapt the duration of the green light phases according to the current traffic volume. Because the expected volume does not change within a run of our evaluation, a static mechanism is adequate. Note that our evaluation in turn will cover different volumes of traffic.

The duration of a traffic-light phase depends on the expected traffic volume. To determine the adequate duration of such a phase, we use the AKF Schema [6]. It considers the traffic flows from all incoming to outgoing lanes. The AKF Schema considers traffic flows which are in conflict with each other and therefore have to pass the intersection in sequence. For example, the vehicles driving on the left incoming lane turning left are in conflict with vehicles from the opposite direction going straight and cannot pass the intersection at the same time. But if vehicles can go straight on several lanes of a direction, the traffic lights of these lanes have to be synchronized.

The so-called AKF Matrix is based on the conflicting traffic flows. Each column contains the expected traffic volumes of traffic flows which are in conflict. The values in every column are added up, and the maximum column sum is determined. For the intersection evaluated, the maximum column sum and, consequently, the traffic volume of the critical traffic flows at a traffic density of 50 vehicles/hour on every lane is 400. These values let us compute the time of circulation and, consequently, the lengths of single phase durations. The *time of circulation* is the time between two green phases of the same direction. It depends on the volumes of the conflicting traffic flows, the saturation-traffic volume, the minimum duration of a green light phase and the time between the green light phases for two different directions, called buffer time t_z.

The buffer time combines intersection-crossing time t_{cr} (in seconds), intersection-clearance time t_{cl} (in s) and intersection-entering time t_e (in s): $t_z = t_{cr} + t_{cl} - t_e$ This equation shows that t_z is based on the crossing distance and that it depends on the driving direction. To determine the time of circulation of the traffic light the maximum value of t_z is chosen and decomposed into a yellow phase (typically 2-3 s), a yellow-red phase (typically 2-3 s) and a red phase for all directions (typically 1-2 s).

Using the value of t_z just determined, the time of circulation t_u is computed according to the following equation given in [6]:

$$t_u = \frac{\sum_i t_z + \sum_i t_{min}}{1 - \frac{Q_{max}}{Q_s}}$$

where i is the number of conflicting traffic flows, t_z is the time between the end of the green phase for one direction and the begin of the green phase for another direction, t_{min} is the minimum duration of a green phase (10 s per conflicting direction, according to [6]), Q_{max} is the traffic volume of the conflicting traffic flows, which pass the intersection (in vehicles/hour), and Q_s is the saturation-traffic volume, which describes the expected number of vehicles being able to pass the intersection in all directions in one hour of green phases (2000 vehicles/hour).

Using the prior values the circulation time for vehicles going straight is

$$t_z = 3\, s + 5.6\, s - 2.25\, s = 6.35\, s \approx 7\, s$$

$$t_u = \frac{4 \cdot 7\, s + 4 \cdot 10\, s}{1 - \frac{400}{2000}} = 85\, s$$

This results in a green phase duration of $10\,s + \frac{(85\,s-4\cdot 7\,s-4\cdot 10\,s)}{4} = 14\,s$ and a red phase duration of $85\,s - 14\,s = 71\,s$.

5.2 Time-Slot Request

[5] has proposed a mechanism which uses agent technology for intersection control. [16] describes an extension of it dubbed Time-Slot Request (TSR). With TSR, the intersection agent allocates the next free time slot to the first driver-assistance agent which requests such a slot. In other words, TSR uses a first-in first-out scheme to allocate slots. [5] has shown that a system which uses such a scheme can outperform traffic lights regarding average waiting time. Note that waiting time is different from standstill time because we define waiting time as the difference of travel time and minimal travel time [17]. [5] does not evaluate environmental measures. We will show that TSR reduces fuel consumption compared to TL.

5.3 ITSA Valuation

The main idea of ITSA Valuation is to allocate the next free time slot to the vehicle whose driver has the highest valuation of reduced waiting time [16]. ITSA stands for Initial Time-Slot Auction. It uses auctions to allocate the next free slot to vehicles. With ITSA, a vehicle, once it has received a slot, cannot trade it for another one.

ITSA Valuation executes two algorithms concurrently. Algorithm 1 describes how driver-assistance agents contact the intersection agent. Algorithm 2 shows how the intersection agent chooses the driver-assistance agent to assign the next slot.

ALGORITHM 1 (CONTACT STEP).

1. Driver-assistance agents whose vehicles approach the intersection request time slot from intersection agent
2. Intersection agent adds vehicle to virtual queue which represents its incoming lane
3. Intersection agent confirms request but does not provide time slot immediately

The first vehicle in each queue which has not received a time slot so far is called *candidate*. Candidates (from different lanes) are the only vehicles which can receive the next free time slot. The intersection agent executes allocations rounds continuously, to allocate time slots to candidates (Algorithm 2). In each allocation round, one candidate receives a time slot.

ALGORITHM 2 (ALLOCATION ROUND).

1. Intersection agent calls all vehicles currently queued for bids
2. Vehicles reveal their valuation per second of reduced waiting time, their current speed and distance to the intersection
3. Intersection agent computes the queue with maximal sum of valuations and assigns time slot to the candidate of the respective queue
4. Intersection agent removes candidate from the virtual queue

While ITSA Valuation has been designed with the purpose of reducing the average valuation-weighted waiting time [16] we will show that it also curbs fuel consumption.

5.4 ITSA Fuel Consumption

The main idea of the novel environment-aware mechanism ITSA Fuel Consumption is to consider the estimated fuel consumption of each vehicle. To do so, the mechanism chooses the vehicle whose intersection crossing results in the minimum additional fuel consumption for all vehicles close to the intersection. ITSA Fuel Consumption uses the same protocol as ITSA Valuation. In contrast to ITSA Valuation, vehicles do not have to report their valuation of reduced waiting time. Instead, the intersection agent considers the influence of the allocation of the next free time slot to each candidate in each allocation round. I. e., the intersection agent computes the increase of fuel consumption induced by each allocation possible.

An allocation of a time slot typically delays other vehicles. The delay d_j^k is the time Vehicle j has to wait longer if the intersection agent allocates the next free slot to Vehicle k. Thus, the delay d_j^k is the difference between the next free slot of Vehicle j after an allocation to Vehicle k and the next free slot of Vehicle j before the allocation.

EXAMPLE 1. *Let the next free time slots of Vehicles j and k be $t_j = 20s$ and $t_k = 22s$. Suppose that the intersection agent allocates its next free time slot to Vehicle k. Further, suppose that this changes the next free time slot of Vehicle j to $t_j^* = 26s$. Then, the delay is $d_j^k = t_j^* - t_j = 26s - 20s = 6s$.*

Now suppose that Vehicle j and k can cross the intersection concurrently because the lanes used are non-conflicting, an allocation to Vehicle k does not change the next free slot of Vehicle j. Thus, the delay is $d_j^k = 0$.

Note that vehicles waiting behind a candidate are not delayed if the intersection agent allocates the next free time slot to 'their' candidate.

A delay of a vehicle increases its fuel consumption. In many cases it has to decelerate and accelerate. For each candidate, the intersection agent computes and accumulates the increase of fuel consumption of all other vehicles. To do so, it uses the estimation model from Section 4.3.

Finally, the intersection agent compares the increase of fuel consumption for all allocations possible and allocates the next free time slot in the best way. Like with ITSA Valuation, the vehicle waiting behind the former candidate becomes a new candidate, and the intersection agent initiates a new allocation round.

5.5 ITSA Delay

ITSA Fuel Consumption is rather complex because it needs detailed information about each vehicle approaching. Therefore, we propose ITSA Delay as a variant of ITSA Fuel Consumption. ITSA Delay needs less information because it does not compute the increase of total fuel consumption but the increase of total waiting time. It computes the increase of total waiting time for all allocations possible and allocates the next free time slot in the best way.

6. EVALUATION

To evaluate all intersection-control mechanisms discussed, we use a home-grown simulation framework. It allows the

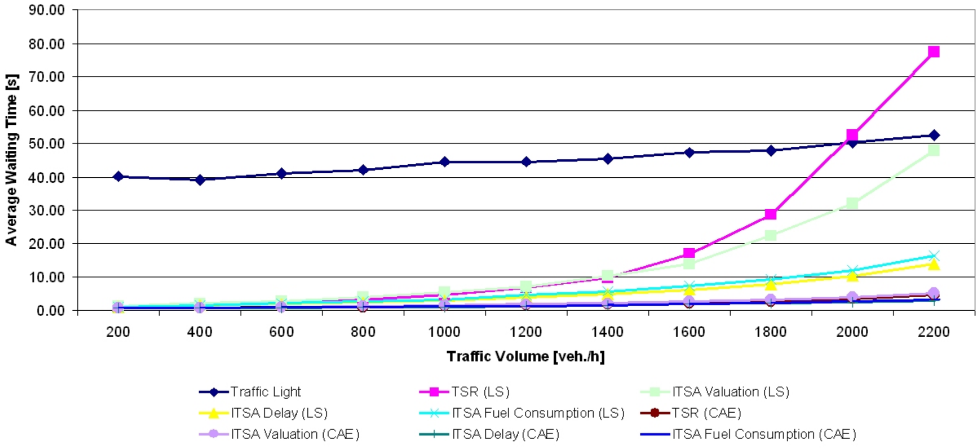

Figure 2: Average Waiting Time

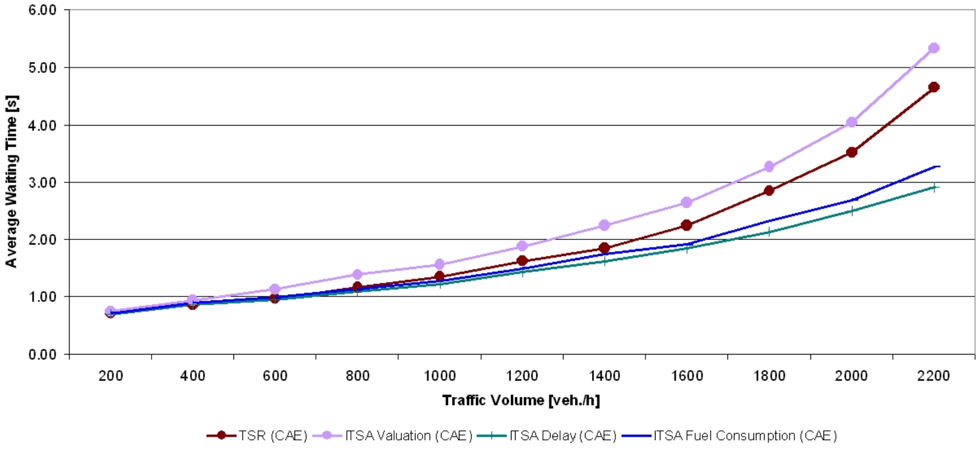

Figure 3: Average Waiting Time (CAE only)

simulation of traffic at an intersection. In the simulation, agent-based driver-assistance systems interact with agent-based intersection-control units. The behavior of vehicles and drivers is simulated.

6.1 Experimental Setup

For the evaluation we use a symmetric intersection consisting of four directions. Each direction has two incoming and two outgoing lanes. For each direction one incoming lane (right) allows to turn right and to go straight, and the other incoming lane (left) allows to turn left and to go straight.

To analyze the impact of traffic volume, every mechanism is evaluated with traffic volumes between 25 vehicles/hour and 275 vehicles/hour on every lane (in 25 vehicles/hour steps) respectively between 200 vehicles/hour and 2200 vehicles/hour in total. We assume the traffic volume to be exponentially distributed with the desired traffic volume as average. Each vehicle goes straight or turns right respectively left with equal probability. The maximum speed on the lanes is 50 km/h. The one on the intersection is 45 km/h.

Our simulation is space-continuous and time-discrete. We simulate 23 minutes in each simulation run. In the first three minutes, vehicles fill the intersection, and we only consider the vehicles of the last 20 minutes to avoid startup effects. The simulation consists of several stochastic components like interarrival times, valuations of reduced waiting time, or route choice. We use a seed which configures the stochastic components of a simulation run. To alleviate the influence of this seed, we always execute five simulation runs using the same five seeds (which of course are different) for each setting. While different seeds lead to a different simulation behavior, the average values remain the same for each setting. This allows us a pairwise comparison of simulation runs of different settings. We always compare simulations runs with the same seed. I. e., we compare only simulation runs with the same stochastic behavior.

6.2 Experiments

We use the same setting to evaluate the average waiting time and the average fuel consumption of the following intersection-control mechanisms. Next to Traffic Light we evaluate TSR, ITSA Valuation, ITSA Fuel Consumption and ITSA Delay for the two degrees of concurrency *lane shared* (LS) and *conflict-area exclusive* (CAE).

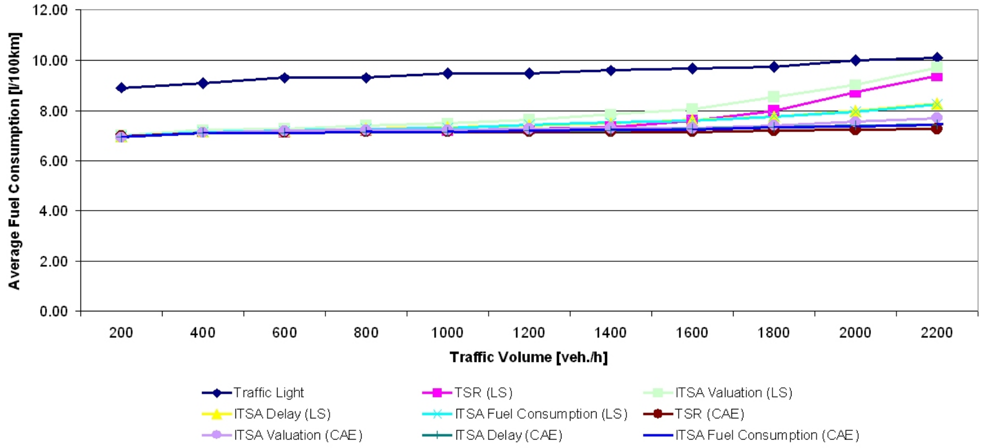

Figure 4: Average Fuel Consumption

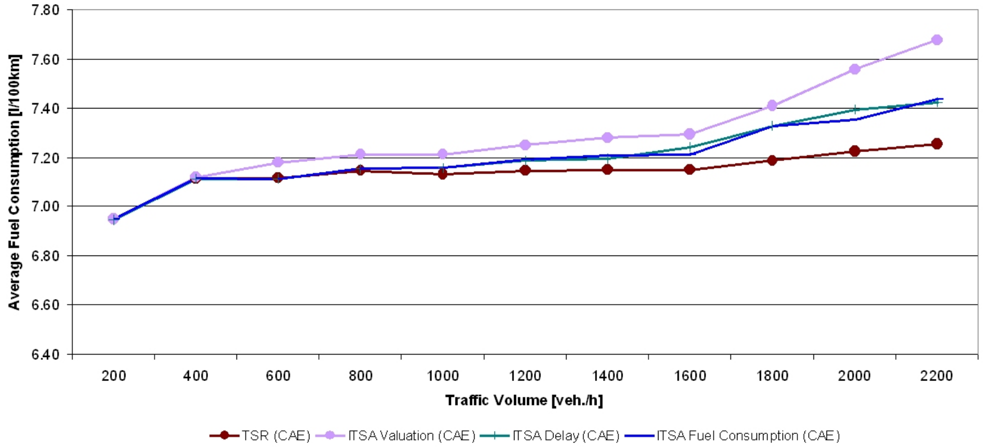

Figure 5: Average Fuel Consumption (CAE only)

6.2.1 Waiting Time

Figure 2 describes the average waiting time of all nine evaluated mechanisms: Traffic Light, TSR (LS), ITSA Valuation (LS), ITSA Delay (LS), ITSA Fuel Consumption (LS), TSR (CAE), ITSA Valuation (CAE), ITSA Delay (CAE), ITSA Fuel Consumption (CAE). The results of the mechanisms which use CAE are very similar. Thus, Figure 2 does not allow to distinguish the results of the mechanisms for CAE. Therefore, Figure 3 describes the average waiting time of these mechanisms separately. The results show that all mechanisms outperform Traffic Light for all traffic volumes evaluated, except for TSR (LS) and ITSA Valuation (LS) regarding average waiting time. TSR (LS) reduces the average waiting time up to 1800 vehicles/hour and ITSA Valuation (LS) up to 2000 vehicles/hour significantly.

As an example we list some average values and the 95% confidence intervals for 2000 vehicles/hour in detail: The average waiting time is 50.36 s [48.03, 52.69] for Traffic Light, 4.04 s [3.37, 4.70] for ITSA Valuation (CAE), 3.52 s [2.83, 4.21] for TSR (CAE), 2.69 s [2.28, 3.09] for ITSA Fuel Consumption (CAE), and 2.49 s [2.09, 2.90] for ITSA Delay (CAE). I. e., ITSA Delay (CAE) is slightly but not significantly better than ITSA Fuel Consumption (CAE). For 2000 vehicles/hour the relative reduction of the average waiting time compared to Traffic Light is 95% for ITSA Fuel Consumption (CAE) and ITSA Delay (CAE).

6.2.2 Fuel Consumption

Figure 4 describes the average fuel consumption of all mechanisms evaluated. It does not allow to distinguish the results of the mechanisms for CAE. Therefore, Figure 5 describes the average fuel consumption of these mechanisms separately. All mechanisms outperform TL significantly regarding fuel consumption.

For 2000 vehicles/hour, the average fuel consumption is 9.98 l/100 km [9.75, 10.20] for Traffic Light, 7.56 l/100 km [7.42, 7.69] for ITSA Valuation (CAE), 7.39 l/100 km [7.28, 7.51] ITSA Delay (CAE), 7.36 l/100 km [7.21, 7.50] for ITSA Fuel Consumption (CAE), and 7.22 l/100 km [7.13, 7.32] for TSR (CAE). I. e., TSR (CAE) is slightly better than ITSA Fuel Consumption (CAE) and ITSA Fuel Consumption (CAE) is slightly better than ITSA Delay (CAE). But in both cases the difference is not significant. For 2000 vehicles/hour the relative reduction of the average fuel consumption compared to Traffic Light is 26% for ITSA Delay (CAE), 26% for ITSA Fuel Consumption (CAE), and 28% for TSR (CAE).

6.2.3 Conclusion

Taking the results both for average waiting time and fuel consumption into account we come to the following conclusions: TL performs worse than any other evaluated mechanism in almost any case. The reduction of waiting time and fuel consumption is considerable, e. g., for 2000 vehicles/hour up to 95% respectively up to 28%.

As expected, all mechanisms for conflict-area exclusive outperform the ones for lane-shared significantly. ITSA Delay and ITSA Fuel Consumption lead to very similar results. ITSA Delay is slightly better regarding average waiting time, ITSA Fuel Consumption is slightly better regarding average fuel consumption. ITSA Valuation and TSR perform always worse than ITSA Delay and ITSA Fuel Consumption except for average fuel consumption using TSR (CAE). In this case TSR (CAE) leads to the best results.

Given our evaluation, we recommend to use ITSA Delay if one is interested in average waiting time and fuel consumption. ITSA Delay is always best regarding the average waiting time and nearly as good as ITSA Fuel Consumption. Further, ITSA Delay needs no detailed information about the actual vehicle type and can be computed more easily than ITSA Fuel Consumption.

7. SUMMARY

Intersections are a main bottleneck in vehicle traffic. Traffic causes pollution and fuel consumption. Existing mechanisms for intersection control optimize throughput and waiting time but not fuel consumption. To deal with this issue, we have designed a novel, agent-based mechanism for intersection control. We compare it both to traffic lights and to other mechanisms. For the comparison, we deploy a sophisticated estimation model for fuel consumption.

We show that agent-based intersection-control mechanisms outperform traffic lights both regarding waiting time and fuel consumption. This even holds for mechanisms which have not been designed with the explicit intention of reducing fuel consumption. Compared to traffic lights, ITSA Fuel Consumption (CAE) reduces fuel consumption by between 22% and 26%. ITSA Delay (CAE) reduces waiting time by between 94% and 98%. This is a substantial reduction.

Our mechanisms can be adapted to other objectives. Given appropriate estimation models, we can readily come up with mechanisms which aim to reduce other environmental target variables, e. g., CO^2 emissions or vehicle noise.

8. REFERENCES

[1] K. Ahn. Microscopic fuel consumption and emission modeling. Master's thesis, Faculty of the Virginia Polytechnic Institute and State University, 1998.

[2] R. Akcelik. Operating cost, fuel consumption and pollutant emission savings at a roundabout with metering signals. In *22nd ARRB conference: research into practice*, 2006.

[3] R. Akcelik and M. Besley. Operating cost, fuel consumption, and emission models in aasidra and aamotion. In *25th Conference of Australian Institutes of Transport Research (CAITR)*, 2004.

[4] D. P. Bowyer, R. Akçelik, and D. C. Biggs. Guide to fuel consumption analysis for urban traffic management. Special Report SR 32, ARRB Transport Research Ltd, Vermont South, Australia, 1985.

[5] K. Dresner and P. Stone. A multiagent approach to autonomous intersection management. *Artificial Intelligence Research*, 31:591–656, 2008.

[6] A. W. Gleue. A Simplified Method to Compute Signal-Controlled Intersections (In German). *Straßenbau und Straßenverkehrstechnik*, Volume 136, 1972.

[7] Green Vehicle Guide - An Australian Government Initiative. Fuel Consumption Label. `http://www.greenvehicleguide.gov.au`, 2010. Last accessed: 22/10/2010.

[8] D. Greenwood, B. Burdiliak, I. Trencansky, H. Armbruster, and C. Dannegger. Greenwave distributed traffic intersection control. In *AAMAS*, 2009.

[9] I. D. Greenwood. *A New Approach To Estimate Congestion Impacts For Highway Evaluation - Effects On Fuel Consumption And Vehicle Emissions.* PhD thesis, The University of Auckland, 2003.

[10] W.-T. Hung, H.-Y. Tong, and C.-S. Cheung. A modal approach to vehicular emissions and fuel consumption model development. *Journal of the Air & Waste Management Association*, 55(10), 2005.

[11] R. Ikeda, H. Kawashima, and T. Oda. Determination of traffic signal settings for minimizing fuel consumption. In *International Conference on Intelligent Transportation Systems*, 1999.

[12] D. Leung and D. Williams. Modelling of motor vehicle fuel consumption and emissions using a power-based model. *Environmental Monitoring and Assessment*, 65(1-2):21–29, 2000.

[13] P. Payeur and Y. Liu. Video traffic monitoring for flow optimization and pollution reduction. In *IEEE/AEI International Workshop on Advanced Environmental Monitoring Technologies*, 2003.

[14] K. Post, J. H. Kent, J. Tomlin, and N. Carruthers. Fuel consumption and emission modelling by power demand and a comparison with other models. *Transportation Research Part A*, 18(3):191–213, 1984.

[15] M. Ross. Automobile fuel consumption and emissions: Effects of vehicle and driving characteristics. *Annual Reviews of Energy and Environment*, 19:75–112, 1994.

[16] H. Schepperle and K. Böhm. Auction-Based Traffic Management: Towards Effective Concurrent Utilization of Road Intersections. In *IEEE Joint Conference on E-Commerce Technology (CEC'08) and Enterprise Computing, E-Commerce and E-Services (EEE'08)*, pages 105–112, 2008.

[17] H. Schepperle and K. Böhm. *Handbook of Research on Multi-Agent Systems for Traffic and Transportation Engineering*, chapter Valuation-Aware Traffic Control – the Notion and the Issues. Information Science Reference, 2009.

[18] A. Várhelyi. The effects of small roundabouts on emissions and fuel consumption: a case study. *Transportation Research Part D: Transport and Environment*, 7(1):65 – 71, 2002.