A Practical Approach toward Implementing Automated Intersection Management

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Abstract: The introduction of automatic intersection management (AIM) promises higher traffic flows and air quality by increasing the effective capacity of the intersection. Unfortunately, automatic control is only possible in a fully autonomous environment without legacy vehicles and vulnerable road users like cyclists and pedestrians. In this paper we introduce hybrid intersection management: a concept which makes it possible to gain the benefits from autonomous vehicles in the situation with mixed traffic. A new message protocol, the individual Space & Time message (iSPaT), is introduced to effectively send instructions to autonomous vehicles. The iSPaT message is also used to guide autonomous vehicles safely over the intersection in a “woven” manner. The development of hybrid intersection management can be started today, and shifts towards automatic control when the amount of autonomous vehicles increases.

Key words: AIM, cooperative automatic vehicles (CAVs), mixed traffic.

1. Introduction

In the far future of automated and cooperative driving the question rises whether traffic lights at intersections are still necessary. Well-known visions sketch the situation of traffic crossing the intersection in a “woven” manner supported by autonomous intersection management (AIM). From the nowadays green periods, a transition is made towards very adaptive and flexible individual, automated vehicle-bound, occupations of space and time.

Before we reach this far future we will have to find solutions for the reality of a transition phase, in which traffic is partly “legacy” and/or disconnected and partly “cooperative automated vehicles” (CAVs). Legacy traffic is a mix of motorized and vulnerable traffic, like pedestrians and cyclists. This adds to the complexity of mixed traffic in an urban environment and leads to the term of a “hybrid intersection”: an intersection where CAVs, regular motorized vehicles and vulnerable road users compete for capacity.

Other trends within mobility are concepts like Mobility as a Service (MaaS) and the sharing economy. These trends make it difficult to assess what the future mobility system will look like. (Long term) economic growth and MaaS are expected to greatly increase the number of travelled kilometres adding to the need for a higher capacity on intersections.

This paper focuses on an urban environment and urban intersections. The paper analyses a practical approach to enable automated and legacy vehicles on a hybrid intersection in an urban context within a transition phase of 10 to 20 years, from our current legacy traffic system towards a system with CAVs as a given. For this transition phase studies have been performed to assess how this mix can be handled.

Looking at simulations of these future intersections three key concerns arise.

• First, there will be a transition period from the current system towards a traffic system in which all traffic is automated. In this transition period current vehicles will be mixed with CAVs. CAVs are vehicles that drive autonomously or at least highly automated and are connected with their environment, so that cooperation is possible. Especially in urban setting this gives a challenging situation because space is scarce, the traffic situation is complex and the availability of
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reliable data of CAVs in this transition phase is a challenge. Also in the future scenario that all vehicles are CAVs, it is likely that data are splintered among stakeholders.

- The second concern is the extra complexity of the interrelated space and time reservations. On an intersection with numerous vehicles of multiple brands and types the possibility of a successful continuous group negotiation to organize these interrelated crossings can be expected to be close to zero. Next to that the group of vehicles lacks the (anticipatory) insight on an urban scale to optimize traffic flows starting from a larger distance and the group of vehicles can not be responsible for assigning priorities based on policy.

- The third concern is for vulnerable road users (VRUs) like pedestrians and cyclists, they will either have no chance of crossing unless some kind of supervisor claims space and time for them; or they cross anyway expecting the AVs to stop reducing the efficiency or blocking the traffic flow. It is unlikely that this is acceptable from the local policy viewpoint. A kind of supervisor will require input to detect these road users and require a way of communicating the space and time reservation towards these users.

Above concerns come together within traffic management where a public authority is responsible for safe, fast and reliable journeys. This responsibility is translated in policies and priorities for types of traffic.

The shift towards a system in which traffic management and control are autonomous as well as the vehicles is complex from a functional and technical perspective. Within this paper we perform an analysis on a technical level and come to a proposal to enable AIM and facilitate the transition towards the fully automated future.

2. Autonomous Intersection Management Concepts

With the future promises of fully automated driving new opportunities arise for managing the traffic on intersections, which is called autonomous intersection management (AIM). Where current signalled intersections are only able to communicate decisions to groups of traffic participants, AIM uses the possibility to do this to individuals. When observing classical intersections and AIM from a distance eventually all comes down to a space-time reservation. A group reservation is for classical intersections, an individual reservation for automated vehicles.

These individual reservations prove a method to greatly improve the effective capacity of an intersection [1]. They enable very tight safety margins and intersection crossings in a “woven” manner. Anyone who has seen Minority Report has had a glimpse of what may be possible. Optimization methods will make it possible to approach the highest theoretical capacity of an intersection: 100% car coverage of the intersection at the highest speed possible.

Currently there are two major approaches for the interaction with CAVs. The first is from Texas University focussing on a multi-agent solution and a (first come first serve) reservation system (still named the original AIM) [2, 3]. The second is from MIT (Massachusetts Institute of Technology) focussing on slot reservations using a cloud based solution (Light Traffic) [4].

While AIM is aimed at fully autonomous intersections, there are studies providing solutions for the transition path as well. One of the examples is the Texas paper on mixed autonomous and human-operated vehicles at intersections [5].

3. Transition towards Automated Intersection Management

Automated intersection management is only possible in a fully automated environment. Each user of the intersection needs to be connected to the controller, and instructions received by the controller need to be followed exactly. As long as not all vehicles are connected and automated, and vulnerable road
users are still crossing the intersection, automated intersection management is not possible.

New technologies offer possibilities to realize future benefits of automated intersection management already. Incorporating these new communication, sensor and processing technologies in traditional traffic light controllers, both the road users and road authorities can benefit of an increased traffic flow and reduced pollutions resulting in the increased liveability in cities.

In this paper we distinguish four phases in the transition towards automated intersection management:

1. conventional traffic light control;
2. connected traffic light control;
3. hybrid intersection management;
4. automated intersection management.

Phase 1 consists of current well-known technologies for traffic light control. The second phase describes the current state-of-the-art in the field of traffic light control. In this paper we introduce the new phase 3 required for the transition towards Automated Intersection Management (phase 4).

3.1 Conventional Traffic Light Control

Conventional traffic light control is either fixed timed, vehicle actuated or adaptive [6]. Fixed timed controllers use a predetermined cycle in which directions are served in a fixed sequence with fixed green, amber and red times. Each cycle of the traffic light controller is same; the traffic lights are not adjusted to the actual traffic state at the intersection. Fixed timed controllers are extremely predictive but are not responsive to the actual traffic demand at the intersection.

In response the fixed timed control, vehicle actuated traffic light controllers were introduced. Using loop detectors in the road surface, the green time of each direction is extended until a large enough gap between two successive vehicles is detected to change the light safely to amber. The durations of the green phases are adjusted to the actual traffic demand; however the predictability of the traffic light controller is very low.

Adaptive traffic light controllers, like TRANSYT, UTOPIA and SCOOT [7-9] use an internal traffic model to predict future traffic flows at intersections. The sequence in which directions are served is fixed; however the duration of the green phases is optimised based on the expected traffic flows. Vehicle actuated control may still be used for optimal switching between phases. Adaptive traffic light controllers are also responsive to the actual traffic demand and are more predictable compared to vehicle actuated controllers.

3.2 Connected Traffic Light Control

Conventional traffic light controller uses indirect communication channels with the road users. Road side sensors, e.g. induction loops, are used to detected vehicles approaching the intersection. Traffic signals are used to communicate the state of the intersection (green, amber, red) to the drivers. With the recent introduction of connected traffic lights direct communication with traffic becomes possible. Both ITS-G5 and cellular technologies make it possible to transmit data between the traffic light controller and nearby vehicles.

The communication between the traffic light controller and vehicles is two-way. While arriving, vehicles continuously broadcast their current position and speed to the traffic light controller using the cooperative awareness message (CAM) and decentralized environmental notification message (DEMN) protocols [10]. This enables the traffic light controller to make reliable predictions of the expected arrival times of vehicles and to efficiently schedule its green phases [11].

The scheduled green phases are transmitted from the traffic light controller to all arriving vehicles using the Signal Phase and Timing (SPaT)/Mobile Application Part (MAP) protocol [12]. The SPaT message describes for each lane of the controlled intersection the expected state switches of the traffic light for the near future. Together with the MAP message,
describing the topology of the intersection, the SPaT message is broadcasted to all approaching vehicles. Inside the vehicle the SPaT is translated into time-to-green and/or time-to-red information, informing the driver about the remaining waiting time or green time of the traffic light.

SPaT/MAP messages are often related to a third use case: green light optimal speed advice (GLOSA). The driver gets an individual speed advice enabling him to pass the intersection without stopping. Unfortunately a reliable speed advice only based on the SPaT-message is not possible, additional information of the surrounding traffic is required in order to calculate an appropriate and reliable speed advice.

3.3 Hybrid Intersection Management

Connected traffic light controllers receive information from individual vehicles, CAM and DEMN messages, and use the information for efficiently scheduling green phases. However the information sent back to the approaching vehicles is collective and for all the vehicles the same. It contains for example the start and end times of scheduled green phases. This information alone is not enough to calculate a reliable speed advice for approaching vehicles: also the amount of downstream vehicles is required to calculate a reliable speed advice.

With the introduction of hybrid intersection management we propose a new message-format: the individual Space & Time message (iSPaT). The iSPaT message contains for each individual vehicle a unique space-time reservation in which it may cross the intersection. In the hybrid situation, these reservations are off course within a green phase of the related traffic light for safety reasons. The big advantage of the iSPaT is that arriving vehicles receive the time they are expected to arrive at the intersection, taken into account the number of downstream vehicles. This makes it possible to optimise the arrival of vehicles at the intersection, with a positive impact on the driver comfort, the air quality and the traffic flows.

The iSPaT messages are, comparable to the SPaT/MAP messages, publicly published and available to all road users at the intersection. This has two main advantages. Firstly, no peer-to-peer direct connection between the traffic light controller and an approaching vehicle needs to be established. Secondly, other vehicles can benefit from knowing the time-space reservations from other vehicles. Knowing what to expect at the intersection can further optimize the crossing of vehicles.

The iSPaT information can be used to inform the human driver in an approaching vehicle. The received information will be in-vehicle translated into a personal speed/lane advice for the driver. This advice is comparable to GLOSA with a higher reliability and extended with a lane-advice. For autonomous vehicles it is also possible to connect the incoming instructions directly to the motor management system. By this way the autonomous vehicle will be “guided” over the intersection in the most efficient way.

3.4 Automated Intersection Management

The transition from the hybrid intersection to the automated intersection is relatively small. When the penetration rate of autonomous vehicles increases it becomes possible to schedule autonomous-only phases in the hybrid intersection or to shift to a full autonomous controller: Automatic Intersection Management. In this case, all vehicles are guided over the intersection in a “woven” manner. As previous studies showed, the effective capacity of intersections will be maximized [1].

In contrast to the hybrid intersection, the automated intersection does not schedule green phases anymore. All vehicles are served individually with tight safety margins. This is possible with the iSPaT-messages, which instruct vehicles about their individual time-space reservation. Connecting the iSPaT to the motor management system makes it possible for a vehicle to cross the intersection in its own timeslot.

Autonomous vehicles are expected to rely heavily on
their own sensors. If a vehicle detects a (moving) obstacle within its safety range, it will automatically take actions to increase the safety distance. Possible actions are slowing down or adjusting its driving direction, both resulting in releasing the reserved timeslot. This may cause a chain of reactions of other vehicles, ultimately leading to a chaotic situation at the controlled intersection.

Autonomous vehicles continuously broadcast a CAM to the controlled intersection. By sharing the CAM-messages together with the iSPaT-messages between all vehicles, it becomes possible for a single vehicle to check if nearby vehicles are following their reserved timeslot. Knowing that the timeslots are not conflicting, it can safely follow its own timeslot as long as the other vehicles are within their reserved timeslot. This concept makes “woven” traffic at intersections possible with respect for road safety.

By distinguishing autonomous and non-autonomous phases by the automated controller, vulnerable road users are still able to pass the intersection in a safe manner. Traditional traffic lights indicate when pedestrians and cyclists may cross the intersection, which can be considered as a combined time-space reservation for these users.

4. Conclusions

The introduction of autonomous vehicles is expected to have a significant impact on the traffic flows at currently traffic light controlled intersections. Recent studies show that the effective capacity of intersection can be maximized. Automated Intersection Management controls traffic using individual time-space reservations. Autonomous vehicles are able to cross the intersection in a “woven” manner. Optimization methods will make it possible to approach the highest theoretical capacity of an intersection: 100% car coverage of the intersection at the highest speed possible.

AIM is only possible in a fully autonomous environment. As long as there are “legacy” vehicles on the road and vulnerable road users (pedestrians and cyclists) make use of the intersection, this most efficient control of intersections is not possible without compromising road safety. The challenge arises how the effective capacity of the intersection can be maximized making use of the possibilities of autonomous vehicles in a hybrid environment.

The current state-of-the-art traffic light controllers are connected and communicate with connected vehicles, which have either a connected on-board device or a mobile phone with a specific app. Approaching vehicles may communicate their current position, speed and even route to the controller (DAMN, CAM), which uses this additional information to optimize its control. On the other hand, the controller broadcasts the scheduled green phases and intersection topology (SPaT/MAP) to all vehicles in its surround.

In this paper we introduced a new message-protocol: the individual Space & Time message (iSPaT). For each approaching vehicle the controller determines a time-space reservation. This reservation can be considered as a timeslot on a specific lane at which the vehicle may cross the intersection without encountering other vehicles or road users. In the hybrid environment the scheduled timeslots are within regular green phases, meaning communication from the controller to the road users happens in three ways: with regular lights, with the SPaT-messages and with the iSPaT-messages.

When the penetration rate of autonomous vehicles increases, the traffic controller shifts more and more from hybrid intersection management towards autonomous intersection management. In this paper we proposed a concept which uses the same technologies with various penetration rates of autonomous vehicles. Our proposed hybrid controller makes it possible to benefit from an improved traffic flow and air quality even with low number of autonomous vehicles, and is able to process larger amounts of autonomous vehicles.

The development of hybrid intersection
management can be started today, making intersections ready for the first (semi-)autonomous vehicles. Benefits of Automatic Intersection Management, like improved traffic flows and air quality, can already be gained. When the number of autonomous vehicles increases the proposed controller slightly shifts from hybrid to automatic.

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