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Efficient intersection control for minimally guided vehicles: A self-organised and decentralised approach

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A R T I C L E I N F O

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A B S T R A C T

An important question for the practical applicability of the highly efficient traffic intersection control is about the minimal level of intelligence the vehicles need to have so as to move beyond the traffic light control. We propose an efficient intersection traffic control scheme without the traffic lights, that only requires a majority of vehicles on the road to be equipped with a simple driver assistance system. The algorithm of our scheme is completely decentralised, and takes into full account the non-linear interaction between the vehicles at high density. For vehicles approaching the intersection in different directions, our algorithm imposes simple interactions between vehicles around the intersection, by defining specific conditions on the real-time basis, for which the involved vehicles are required to briefly adjust their dynamics. This leads to a self-organised traffic flow that is safe, robust, and efficient. We also take into account of the driver comfort level and study its effect on the control efficiency. The scheme has low technological barrier, minimal impact on the conventional driving behaviour, and can coexist with the traffic light control. It also has the advantages of being easily scalable, and fully compatible with both the conventional road systems as well as the futuristic scenario in which driverless vehicles dominate the road. The mathematical formulation of our scheme permits large scale realistic numerical simulations of busy intersections, allowing a more complete evaluation of the control performance, instead of just the collision avoidance at the intersection.

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1. Introduction

The importance of traffic control at road intersections has been well recognised especially in large cities where the population and vehicle densities are high. The predominant methods of such control in modern cities utilise the traffic lights, and many schemes in optimising such control are proposed. A single traffic intersection can be more efficiently controlled with either pre-signal systems (Xuan et al., 2011) or with readily available sensing technologies, so that the traffic light can adapt to the real time demand of the intersection (Helbing and Mazloumian, 2009; Jiang et al., 2006). Multi-layer agent control of a system of intersections in either a centralised or decentralised way has been intensively studied (Lammer and Helbing, 2010; Roozemond, 2001; Bazzan, 2005; Choy et al., 2003; Srinivasan et al., 2006; Bazzan et al., 2010; Chang and Sun, 2004). Effective vehicle to vehicle communications can also lead to traffic signals being optimised for connected vehicles (Li et al., 2014; Guler et al., 2014). More innovative approaches including cooperative driving where intersection manager sends out individual traffic signals to each vehicle are also reported (Li and Wang, 2006; Perronnet et al., 2012; Wu et al., 2011; Ahmane et al.,

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2013), so that the traffic flow across the intersection can be optimised with the sequence-based protocols. Retaining the traffic light for the intersection control has the advantage of high robustness in terms of safety and ease of adaptation.

Research on signalised intersection control will continue to be of great importance in the foreseeable future in most parts of the world. On the other hand, in developed countries and mega-cities where the infrastructure is mature but strained, it is entirely possible that within 5–10 years a significant number of vehicles on the road will be autonomous or semi-autonomous (Anon). In some of the technologically advanced cities the driverless cars can even become the mainstream method of transportation. Thus more recently, many researches have been focusing on lightless (with no traffic light) intersection control with autonomous vehicles in which the drivers are just passengers (Raravi et al., 2007; Dresner and Stone, 2008; Zohdy and Rakha, 2012). In these proposals, all the incoming vehicles relay information about their positions, velocities as well as their intentions to a central management system; such a central system sends out instructions to each of these vehicles, based on those information and an optimised algorithm (Panait and Luke, 2005; Junges and Bazzan, 2008). In general such intersection control is vastly superior as compared to the signalised intersection control; on the other hand, a centralised intersection control also tends to be expensive for the infrastructure, especially when the number of vehicles it has to manage is large for busy intersections. More importantly, it requires near 100% market penetration of autonomous vehicles, vehicles equipped with the adaptive cruise control, vehicle-to-vehicle as well as vehicle-to-infrastructure communications. Mixture of human drivers will again involve traffic lights as an auxiliary system (Dresner and Stone, 2008).

It is, however, unlikely that the urban traffic is going to be dominated by the autonomous vehicles in the near future. We would anticipate a long transition period, during which the conventional vehicles coexist with autonomous or semi-autonomous vehicles. For transportation theory and engineering, this is thus an interesting period of time when we are on the verge of a major paradigm shift, while at the same time the inertia of conventional methods and technologies is equally great. Identification and development of a suitable set of tools and technologies that are compatible with both the new paradigm with the next generation technologies, as well as with the transition period before that, are thus very important, especially due to the uneven technological and economic progress across the world.

Faced with these challenges, in this paper we propose a new approach for the lightless intersection control that focuses on practicability, compatibility and upgradability, as well as ease of implementation with mature technologies. The National Highway Traffic Safety Administration (NHTSA) of the United States proposed a formal five-level classification of the autonomous vehicles (U.S. Department of Transportation Releases Policy on Automated Vehicle Development, 2013). Our scheme only requires autonomous vehicles at Level 1 or above. Specifically, the vehicle only needs to be able to throttle or brake automatically based on the algorithms we have designed, in addition to the ability to communicate with the infrastructure at the intersection. Such "feet-off" smart vehicles can be easily achieved with the mature technology, so we can focus on the lightless intersection control itself.

In particular, our scheme aims to cater to the following characteristics:

1. The proposed intersection control should offer significantly great advantages over various types of signalised intersection control, especially in terms of the intersection capacity. While such advantages will be gradual when the penetration of the "feet-off" smart vehicles are low, there should be disruptive improvements in terms of the efficiency when such smart vehicles dominate the road.
2. The technological barrier of the new intersection control should be low.
3. The new intersection control should be able to accommodate a mixed traffic consisting of conventional vehicles with human drivers and the (semi-) autonomous "feet-off" smart vehicles.
4. The new intersection control is completely distributed and decentralised; the agent at the intersection only collect and distribute information about the speed and position, while each vehicle decides its motion individually. Decentralised or distributed control is essential for reducing the infrastructure investment, vulnerability against attacks and system failures, as well as for allowing a mixed traffic.
5. The new intersection control can coexist with the conventional signalised control and can be adapted in stages.
6. The impact to the conventional driving experience is minimal.
7. The scheme architecture can be easily upgraded with more sophisticated algorithms that are commensurate with the sophistication of the hardwares.

Several schemes of the fully decentralised intersection control have been proposed in the literature (Gaciarz et al., 2015; Naumann et al., 1997; Crunewald et al., 2006). The focus has been on avoiding collisions in the intersection region via communication and negotiation between vehicles (Naumann et al., 1997). Generally, vehicles negotiate for the right of way, especially for a few specifically defined spaces within the conflict zone: vehicles with the right of way can pass through the intersection, and collisions are avoided by allowing only one vehicle to be present in those pre-defined spaces at any instant.

What is new in our scheme is that the impact of the intersection is completely modelled by the simple interactions between vehicles, just like the interactions between neighbouring vehicles travelling in the same lane on the highway. This naturally leads to a self-organised traffic flow through the intersection without the need of the traffic signals. As will be detailed in Section 3.2, we do not explicitly focus on the notion of the right of way in our decentralised scheme. The velocity and acceleration of the vehicles close to the intersection are updated real-time based on the vehicle's environment. Maintaining safe distances between any two approaching vehicles are thus achieved dynamically; only relative positions and

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